Living and Learning: 
Research for a Better Built Environment 

49th International Conference of the Architectural Science Association 

Proceedings 

Edited by 

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Foreword

The Architectural Science Association (ASA), formally known as the Australian and New Zealand Architectural Science Association (ANZAScA), was established in 1963 with the goal of promoting architectural science, theory, education and practice. A particular focus of ASA is the development, documentation and application of innovative approaches to environmentally sustainable design. Annual conferences have been held since 1966.

The built environment and our understanding of the effect that it has on our natural environment have developed dramatically over the last several decades. With the deepening evidence of the effect that humans are having on the degradation of global ecosystems, there has never been a greater need for research in the field of architectural science. The ASA2015 Conference coincides with the coming together of world leaders at the 2015 United Nations Climate Change Conference in Paris. While the aims of ASA2015 may be slightly less ambitious, they are nonetheless just as important in understanding how to develop and apply the knowledge and solutions needed to address the pressing environmental concerns of our time and the central role that the built environment has to play in this.

This publication contains the 115 papers that were accepted for presentation at the 49th International Conference of the Architectural Science Association (ASA2015), hosted by the Faculty of Architecture, Building and Planning at The University of Melbourne, Melbourne, Australia from 2 - 4 December 2015. These papers are also available individually from the ASA website (http://anzasca.net).

The conference theme, Living and Learning: Research for a Better Built Environment, reflects our view of a sustainable built environment as a maturing industry and field of research, but one that we still have a lot to learn about in order to achieve real change. The role of research in improving the built environment is reflected across the 13 different themes of the conference which encompass the breadth of architectural science.

Each paper in these proceedings has undergone a rigorous peer review process. Following the call for abstracts in March 2015, a total of 309 abstracts were submitted for peer review. Each abstract was double-blind peer reviewed by the International Scientific Committee, made up of members from 15 countries, across six continents. Of these, 227 abstracts were accepted for development into a full paper. There were 142 full papers submitted, each of which was then double-blind peer reviewed by two to three members of the International Scientific Committee. Based on the reviewer recommendations, 115 papers were accepted for presentation at the conference. This represents the largest number of papers ever presented at an ASA/ANZAScA conference.

These proceedings, as well as the diverse range of research presented within them, are testament to the importance and diversity of the field of architectural science. This, combined with the involvement of delegates from 17 countries highlights the relevance of the Architectural Science Association, more than 50 years since it was established.

We are excited to be able to welcome all conference delegates to ASA2015, particularly as this is first time in thirty-three years that the conference has been held in Melbourne. This is timely as it coincides with the construction of the new Melbourne School of Design Building, which provides a ‘living’ example of many of the theories, learnings and techniques developed within the field of architectural science.
On behalf of the entire organising committee we would like to express our profound gratitude to the many people who have contributed to making this conference a reality. To the many authors, we thank you for your insightful and thought-provoking papers and presentations. The international standing of ASA and the quality of the papers presented would not have been maintained if it were not for the commitment of all members of the International Scientific Committee and we extend our sincerest appreciation to every single one.

We are honoured to have had this opportunity to maintain and progress the field of architectural science and promote its importance not just as a discipline of research, education and practice, but one that has an important role to play in addressing one of the most critical global issues of our time.

Robert H. Crawford and André Stephan (Editors)
December 2015
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Architecture and Environment
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Adoption of water conservation measures in buildings: case study in Johannesburg, South Africa

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Abstract: The paper presents a study on adoption of water conservation measures in buildings in the Johannesburg area of South Africa. The study is a follow up to an initial pilot on water use policies, availability of water conservation technologies for buildings and the nature of their dispersal. A review of relevant conservation measures and the initial pilot formed basis for further investigations into the adoption of water conservation in buildings. A case study approach implemented through a building science class project was used to collect data on 20 multi-story facilities of various occupancy types. The data scope was kept at a manageable level, being envisioned as another pilot. Identified levels of adoption suggest an appreciably growing awareness of conservation measures but an absence of structured introduction of such measures in buildings. There were indications of non-adoption, despite cost implications of current wet services. Identified constraints include lack of awareness, cost and possible lack of management support in some areas.

Keywords: Water conservation; sustainability; efficiency measures; 5R principle.

1. Introduction
The Brundtland report classically defined sustainability or sustainable development, emphasising the broad areas of thinking as economic, social and environmental (United Nations, 1987). In addressing the triple bottom line concept of people-planet-profit issues, sustainability has over the years been applied to every area of life. One of the primary areas of application is the built environment, specifically the performance of buildings. The emphasis on efficiency of resource use in buildings is due in part to the continuous impact on resource availability and environmental health originating from building related consumption and waste generation. According to Jason McLennan in Hitchcock (2008), when the embodied energy in a building and its resource usage in operation are added together, buildings essentially become the single most contributing factor to climate change. A closely linked and equally impactful issue is the consumption of water, related to building design and occupancy. In addition to
climate change and extreme weather events; population growth and emergence of stronger economies increase the demand for natural resources including water. There is the danger of unbearable pressure on already weakened aquifer systems due to inability of such natural systems to recharge at a rate commensurate to the rate of water withdrawal for use by human beings (Delgado et al., 2011). Essentially water efficiency is critical, because water scarcity and uncertainty needs to be reconciled with the demands of modern society, environmental issues and affordability of the resource (Baker, 2014). Similarly water efficiency is important for buildings because of their water consumption capacity. In the USA for example, an estimated (12%), 47 billion, out of 400 billion gallons of water consumed in the US per day is ascribed to buildings (Coyle, 2014). Similarly in Europe, there have been serious concerns about the quality and adequacy of water supply in the past four decades, with policies and regulations evolving through the years to address the relevant issues (Prior and Hadi, 2015). In addition deductions from Silva-Afonso (2014) emphasise the threat to water availability, emanating from the appreciable level of water wastage, especially in buildings. There is therefore a need for the practice of water conservation in buildings, regardless of the region and particular location.

2. Water conservation/efficiency in buildings

Water conservation in buildings falls under water demand management, which aims to reduce demand by improving efficiency of use, essentially focusing users on more sustainable approaches to water consumption (Sadr et al., 2015). It entails minimising wastage, protecting the resource, and efficiency and effectiveness of use (Department of water affairs and forestry 2004). A more elaborate definition includes, reduction in quantity; use of lower quality water; loss-proofing of the system; re-designing tasks to demand less water and utilise more of low quality water; and re-programming water usage to off-peak time frames (Brooks, 2006). While water conservation is generally a major concern, daily consumption of large volumes of water in buildings is not as equally emphasised (Gibberd, 2009). From sustainability perspective there is need for water efficiency in all aspects of human life, including buildings. There are various environmental implications of water usage in existing buildings which can be substantially altered through the application of sustainability measures of efficiency. Such implications include reduction of energy use and carbon emissions (Fidar et al., 2010). In dealing with resource conservation generally, the sustainability principle of 3R is applied, in terms of green, circular, or ecological economy. The 3R – Reduce, Reuse and Recycle principle aims to reduce consumption; utilise a resource many times in order to extend its useful life; and revert used resource to usable form, wholly or partially (Ying and Li-jun, 2012). With regard to water efficiency in buildings, Silva-Afonso and Pimentel-Rodrigues (2014) and Silva-Afonso (2014) offer a further development of the 3R principle. The authors describe a five point principle, with specific focus on water efficiency measures in buildings: Reduce consumption - Technical measures and non-technical measures (economics, general awareness); Reduce loss and waste - Control of losses (volume and heat); Re-use water - Rechanneling used water to another area of use; Recycle water - Recycling & re-introduction of water for another use; and Resort to alternative sources - Involving other sources (rainwater, groundwater, saltwater etc.).

There is reasonable need to apply such measures of efficiency in the effort towards sustainable water use in buildings. In view of causative factors such as population explosion, urbanisation and rapid development, it is arguable that application of such principles in emerging economies such as South Africa would be a critical need.
2.1. Adoption of water efficiency measures in South Africa

Aduda and Ozumba (2011) discuss existing literature such as Otieno and Ochieng, (2004); Creemers and Pott (2002); AMCEN/UNEP (2002); and Statistics South Africa (2006), which describe the gravity of South Africa’s water situation and the need for water conservation in the nation’s buildings. The discussion refers to the scarcity of water; reliance on surface water through dams and inter-basin transfers; the largely arid nature of the land mass; variable rainfall; population growth; and increase in economic activities. The South African government aims at 100% access to water for all, in line with the millennium development goals of the United Nations, realities of climate change and improvements in financing (South African government, 2013). The stated aim arguably demands equal emphasis on efficient use and minimization of wastage. The government has accordingly enacted a number of laws and policies towards water conservation: The National Water Act of 1998; Water Services Act, 1997 (Act 108 of 1997); Water Research Act, 1971 (Act 34 of 1971); National Environmental Management Act (Nema), 1998 (Act 107 of 1998); and National Water Policy, which is focused on equity, environmental sustainability and efficiency (South African government, 2013). Such efforts especially when integrated with a combination of bottom-up and top-down approaches as described by Aduda and Ozumba (2011) would advance the adoption and dispersal of water efficiency measures in buildings locally.

The view in this paper is that improved water management cannot be effectively achieved downstream without adequate knowledge of their current response to water supply shortages and costs. Downstream here refers to the building-owner-user level of adoption. It is important to ascertain the adoption of water conservation measures, possible innovations occurring and the current challenges facing building owners and users.

Rogers and Shoemaker (1971) described adoption in terms of encounter, decision, and the act of taking up of an innovation, over a period of time. Diffusion would then refer to adoption within a group, over time (Straub, 2009). The process is also common across various social systems (Rogers et al., 2006). It could therefore be reasonably expected that the regulatory frameworks and enabling civil environment in democratic South Africa, would facilitate the advanced adoption of water efficiency measures. Furthermore such advanced stage of adoption would have a higher occurrence in cities, where appreciable number of available buildings experience density of occupation, regardless of building type.

However Still et al. (2008) in a South African study highlighted the limited scope of measures to conserve water in South Africa, which include, replacing automatic flushing urinals; installation of displacement devices in high volume toilet cisterns; and sensor-operated taps and urinals. Adoption of such measures notably occurred more in public and institutional buildings. Aduda and Ozumba (2011) identified, that available technologies include dual flush toilets, bath basins and showers. More advanced technologies such as waterless urinal, sensor-controlled taps, water-efficient dishwashers and laundry machines were not available. In addition aesthetics, costs and choice of style were the stronger determinants of purchase decisions, as opposed to water conservation. Furthermore there seemed to be limited awareness and knowledge of water efficiency measures and available opportunities for their application. Moreover the findings suggested minimal diffusion of knowledge about available opportunities for water conservation.

From deductions in Aduda and Ozumba (2011) some degree of adoption of water conservation measures seemed to be occurring, especially in the area of technologies. However (Gibberd, 2009) argues that it is easier to apply conservation measures at the design stage of new buildings, rather than
on existing stock. The assertion referred to the use of grey water and rainwater systems. However it is arguable that other water efficiency measures can be adopted in existing building stock with minimal challenges. In this regard, existing research has focused mostly on policies, service providers and suppliers, and technologies and green building specifications. Essentially the downstream section has not been explored thoroughly in terms of the adoption of water efficiency measures. Currently there is no known research performed with focus on the operationalization of the 5R principles, at the level of existing buildings, within South Africa. Therefore the study presented in this paper was aimed at exploring water efficiency in South Africa's buildings further, with a focus on the 5R principles. The research findings help to build a better understanding of the current situation with adoption of water efficiency measures in South Africa’s buildings, using the Johannesburg city area.

3. Method, data analysis and findings

On the basis of deductions from the preceding discussion, the lens of 5R principle was used to derive a better understanding of the adoption of efficiency measures. The study was essentially exploratory in nature, and envisioned as a pilot. It was designed and carried out in 2011, to build more background information, in order to derive clearer directions for a wider more comprehensive study. The current paper is based on a case study approach implemented through a building science project. Case study is relevant for deeper investigation into a thing, person, or group over a period of time (Creswell, 2009). However the research design developed out of a class project, where members of the class had to be trained for the research project and coordinated throughout the data collection period. The modes of data collection were field observation, verbal interviews and content analysis. In the research plan, weekly site visits were used for a period of about 1 month and a week. After an initial training, class members were continuously briefed on a weekly basis, before going out for data collection. Training and coordination of data collection was performed mostly by the lead author. For ethical purposes, the first visits were to educate respondents, obtain permission to use the facility and obtain a formal document as informed consent. Data was then collected and lodged in weekly, immediately after each site visit. Site visits started with observations of the exterior, then the interior, followed by verbal interviews. Where relevant documents such as water consumption rates and costs were obtained, they served for purposes of confirming interview responses. In terms of variables explored, the focus was on (a) breaches in the system which results in wastage; (b) points of excessive consumption; (c) water conservation measures applied; and (d) proposed improvements and challenges. Other relevant highlights or emergent issues were noted. Data collection instruments were made up of a field observation schedule with field notes provided, and a verbal interview schedule. Due to the design of the current study as a second pilot and the use of field officers for data collection, the scope of data collected was kept manageable. The data collectors went out in groups and collected data simultaneously. The individual field notes were compared with logged data in order to determine admissibility. The scoping, sequence and control of the data collection aspect also minimised issues of reliability and validity in the research, and improved the consistency of the data set. As such only 17 buildings/facilities, out of the initial sample of 20 buildings/facilities, were selected for analysis.

3.1. Results of data analysis

Results of data analysis are presented according to the themes investigated in the case study approach. Analysis is presented in textual form mostly, from which meanings are drawn in order to address the
3.1.1. General description of data

Out of the 17 buildings selected for data analysis, 15 were mixed use facilities, which where the residential floors were predominantly student hostels. One of the buildings is an entertainment facility while one is an office block. All buildings were more than ten years in age and were all multi-storey, ranging from 4 floors to 19 floors. For the mixed use types, mostly the ground floor levels were commercial while the rest of the floors were residential. They are all located within the larger Braamfontein CBD area of Johannesburg City, South Africa.

3.1.2. Observations of breaches and points of excessive water consumption

In terms of breaches in the plumbing system resulting in water wastage, there were observations of major breaches in 3 out of the 17 buildings investigated. Such breaches occurred in the piping system, wash basins and troughs. With regard to excessive water consumption, one building manager admitted to the existence of such challenge at the time of the study. The bathrooms, kitchen and toilets seemed to consume the most water, more than garden sprinklers, laundry and washing of external objects such as cars. Other specific areas of identified water wastage are continuous flush urinals, old single flush toilets, and non-efficient shower heads. Behavioural patterns were also suggested from interviews.

3.1.3. Observations of water conservation measures applied in the buildings

Observed water conservation measures were mostly under the reduction of consumption and reduction of losses principles. In addition observations were mostly of a technical nature. The following technologies were observed: Flush valve toilets, dual flush toilets, interruptible flush toilets, low capacity cisterns, manual flush urinals, low-flow shower heads, fine spray shower faucets, faucet aerators in shower faucets, use of storage tanks, use of non-storage water heaters, mini boilers at point of use, under-counter geyser, single lever mixer taps, wash basin-toilet shank combo grey water system, use of showers without bath tubs, and automatic garden sprinkler with ground moisture sensor.

On the less technical aspects of the principles applied, behavioural issues around water use were addressed mainly through the use of wall-hung signs to educate occupants and advocate for reduction of individual water footprint. Another highlight was the effort to encourage the use of water cups when brushing one’s tooth. This was applied by educating occupants and providing cup holders in the bathrooms, near the wash basins. Some of the identified measures of water efficiency are presented in Figures 1, 2, and 3.
3.1.4. Proposed improvements and challenges to adoption of relevant technologies

Findings from interviews suggest that building managers were mostly facing increasing water bills. Despite such challenges, improvements were not expedient. Out of the 17 facilities studied, only 4 were being considered for improvements by their respective building managers. Two building managers out
of the stated four buildings did not have any clarity on the details, especially the timing. The other two buildings were going to be retrofitted in about two years from the study date. However in one instance the combination of applying some water conservation technologies and educating occupants seemed to have resulted in subsequent lower water bills. A particular building management hinted of a plan to apply differential billing in the future, by metering each units water usage. The measure was proposed as a way to separate water cost while encouraging personal water use efficiency. Apart from regulatory constraints and possible owner reluctance, the major challenges identified from interviews are cost and lack of workable funding mechanisms. Generally there was insufficient clarity on the part of building managers, with regards to a systematic or ordered approach towards lowering the bills and managing the water usage profile of their buildings.

4. Discussion

Firstly the use of mini boilers close to points of use, or under-counter, was to reduce redundancy which results in wastage as the user waits for heated water to flow through. Secondly while the use of cold water storage tanks did not reduce water use in the buildings which deployed them, the measure reduced energy demands significantly for buildings with lower number of floors. When water pressure increased, tanks could store water without need for much additional pumping during peak periods. Thirdly the efficient use of ground moisture sensor which controlled automatic garden sprinklers resulted in appreciable water savings, especially during the rainy season. Fourthly while the sole use of efficient showers without bath tubs could save water theoretically, findings suggest that the measure was aimed primarily at curbing wasteful user behaviour. Similarly, combining such measures with user education and persuasion achieved reduction in water usage and wastage in some cases. Measurable reduction in water demand was achieved by providing the meanings of statistical facts on water use and educating users on efficiency measures. Board notices, signs and wall posters were used to communicate such facts. Findings from a recent UK study by Hendrick (2015), on shower habits, concluded that users’ shower habits can be changed by applying such measures of efficiency. The ‘whole town approach’ described in Russell (2015) relied heavily on marketing and communications to achieve measurable savings through behavioural change in targeted users. Findings from the current study thus indicate some awareness of the need for user-centred approaches. Furthermore the non-storage water heaters were controlled electronically by thermostat and sensors. They heated water to comfortable use temperature as it passed through the system, thereby reducing redundancy at the point of use. Another innovation identified in the study is the wash basin-shank combo grey water system which is low-tech, but improves water use efficiency through its design. The toilet shank and wash basin were merged, thereby creating a grey water system, which achieved the re-use principle. Grey water from hand washing after using the toilet drains into the shank, thereby partly filling it up. Therefore the shank does not draw as much water from the mains, as its capacity would allow. Though further innovation could enhance the system, it reduces water demand in its current state.

Generally findings suggest that principles of Re-use water; Recycle water; and Resort to alternative sources are probably perceived as being more challenging to achieve in the study area. In this regard there might be need for more investigation into the basis for certain regulations guiding wet services in the locality. One of the building managers interviewed, referred to City Byelaws which prohibited the creation of alternative sources of water such as boreholes, and water re-use and re-cycle systems within the main city area. The restrictions are due in part to a number of environmental, health and safety issues. Smith and Hyde (2015) stated that health risk perceptions could result in low application of the
re-use and recycle principle. It possible therefore, that such challenge could emanate from regulators or users. Despite the challenges, building owners and managers still made efforts to adopt innovations. In coping with the water demand situation, measures seem to have been applied in isolation. It seems that needs were addressed when the threat escalated and when an opportunity to take up an innovation was encountered.

Programmed retrofitting was not identified. As such, applications of the 5R efficiency measures occurred alongside the continued use of inefficient points of use, and breaches in the system. Following from the South African studies reviewed in the paper and findings from the current study, more technologies and other less technical efficiency measures have been highlighted. Furthermore the application of the economic and behavioural aspect of the *Reduce consumption and Reduce loss and waste* principles seem to have been identified by some stakeholders. Such findings indicate efforts to apply different measures together, albeit in a non-systematic way.

5. Conclusion

The study presented here focused on the adoption of water conservation measures in South Africa’s buildings, using Johannesburg City area as the setting. It was approached through a case study strategy, making use of trained field officers through a building science project. Delimitations of scope were placed on the study for proper management at this stage. Further limitations were placed as a result of some data being discarded due to rules of admissibility of data. As such cases were reduced from (20) to (17). However the appreciable number of cases and management of the process ensured meaningful achievement the research aim. Exploration of various themes also helped to provide more clarity on the situation of water conservation in local buildings.

In relation to recent studies, the scope of efficiency measures adopted is still appreciably less than the range of possibilities presented by the 5R principles. In addition not all buildings had water conservation technologies. For example, one of the buildings which had various breaches in its plumbing system did not have any water conservation measures applied. Furthermore this building’s management was not considering improvement soon, on the basis of challenges with funding. Moreover about (9) of the sampled buildings had only three items of conservation technology applied. Such findings support existing literature on the scarcity of water efficiency measures in South Africa’s buildings (Still et al., 2008; Aduda and Ozumba, 2011).

While the identified level of adoption suggests increasing awareness, there does not seem to be a systematic approach to introducing water conservation measures in the buildings investigated. Despite cost implications arising from current water profiles of buildings, there were indications of non-adoption of efficiency measures. Possible lack of awareness, cost, funder reluctance and lack of proper funding mechanisms were suggested, in addition to regulatory constraints. Nevertheless there are important lessons from the study regarding the use of low-tech adaptations and application of economic and user behaviour measures. However at this stage, the depth of information needs to be deepened. Further studies which include facility owners and managers, and regulators, with a focus on structured implementation of such measures and technologies in facilities, would be an appropriate next step. Policies linking water consumption, adoption of measures, and tariff design and structure for various building types could benefit from current deductions, and future research. Furthermore modalities for the application of differential billing to individual units in existing buildings should be studied. Moreover identified innovations would need more refinement and improvement, in terms of efficiency, ease of use, ease of installation, availability, and affordability.
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References


Drivers and barriers to heatwave-resilient building retrofitting in the Australian context

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Abstract: Heatwaves have a mounted interest in the last decade due to their negative impacts on infrastructure, the ecosystem and public health. Population exposure to heat stress is substantially influenced by the resilience of the built environment as people spend the majority of their time indoors. Retrofitting the existing building stock could profoundly improve heatwave resilience, however, the current knowledge of the population’s heatwave-resilient retrofitting willingness is limited. An online survey about population perception of, adaptation to and retrofitting against heatwaves was conducted with a representative sample from the Adelaide metropolitan region in March 2015. The survey results about the retrofitting relevant questions presented in this paper suggest that the perceived financial limitations and missing tenant/landlord incentives represent the key barriers to domestic retrofitting. Beyond air-conditioning, the improvement of shadings was the most prevalent retrofitting measure. The number of known and applied retrofitting measures, nevertheless, were limited. Solutions, such as taking advantage of increased garden vegetation or changing the roof colour were underrepresented. Special attention should be paid to older population since they are not only more vulnerable to heatwaves but also less willing to retrofit their homes.

Keywords: Heatwave resilience; energy efficiency; building retrofitting.

1. Heatwave-resilient building retrofitting

Heatwaves are responsible for more deaths in Australia than all other natural hazards combined (Coates et al., 2014). Beyond the excess death rates, heatwaves have miscellaneous negative impacts on infrastructure, the ecosystem and public health (Zuo et al., 2014; Reeves et al., 2010). Since one of three heatwave-related deaths occurs indoors (Coates et al., 2014), the role of the built environment in population resilience against heatwaves is fundamental.

Heatwaves negatively affect indoor thermal comfort, posing heat stress on building occupants. Although air-conditioning is the most prevalent adaptation technique to cope with heatwaves (Saman et al., 2013), its use raises further concerns. Air-conditioning contributes significantly to the rise of urban
air temperature and increases electricity demand (Santamouris, 2014). The increased electricity demand raises noticeably the yearly peak demand in cooling-focused regions, such as most of Australia, resulting in an inefficient electricity grid. The additional maintenance cost contributes to the soaring electricity prices, and increases the vulnerability of the less affluent population. Fuel poverty, referring to the condition when population cannot afford adequate heating or cooling, is rising in Australia and worldwide (VCOS, 2005; Santamouris and Kolokotsa, 2014). Considering climate change, Australian projections show further increase in peak electricity demand (Saman et al., 2013). Meanwhile, the increase in number of highly insulated buildings can foster overheating in summer, raising the cooling demand (Ren et al., 2014). The differentiation between energy efficient and heatwave-resilient design and retrofitting, therefore, is necessary.

Australian households are responsible for the 25% of the total national net energy use (Australian Bureau of Statistics, 2015). To decrease the energy consumption, building retrofitting has to be addressed because of the relatively slow building stock turnover rate. Retrofitting, beyond reducing domestic energy consumption, extends the life-cycle of the existing building stock and saves embodied energy and carbon (Pullen, 2010). Even though a considerable body of scholarship concerns with the population uptake of energy efficient retrofitting (Achtnicht and Madlener, 2014; Elsharkawy and Rutherford, 2015; Long et al., 2014; Hall et al., 2013), many fewer studies have been conducted about heatwave-resilient retrofitting (Saman et al., 2013).

South Australia is especially exposed to heatwaves, with the highest number of heat-related deaths recorded nationwide (Coates et al., 2014). Adelaide, South Australia, with a population of more than 1.2 million people, suffered from a series of subsequent, extreme heatwaves in January and February, 2009. During the 13 day-long heatwave period, the daily temperature reached 45.7 °C, with eight days exceeding 40 °C. This heatwave caused up to 16% excess ambulance call outs (Nitschke et al., 2011) and an excess 68% electricity demand (Energy Supply Association of Australia, 2015), compared to usual summer days.

To enhance urban heatwave resilience, three aspects should be considered, including the built environment, population adaptation and vulnerability to heatwaves. Air temperatures of the urban microclimate can be decreased with mitigation techniques, such as the increased green space ratio (Adams and Smith, 2014) and the decreased waste heat generation (Santamouris et al., 2014). Passive adaptations, such as adopting summer clothes or night time ventilation, furthermore, increase human thermal comfort without compromising the energy consumption. Nevertheless, thermal comfort and potential heat-induced health issues are also influenced by demographic characteristics, that increase vulnerability, such as age, level of isolation and pre-existing health conditions (Bi et al., 2011; Li et al., 2015). Although the impact on heatwave resilience of these factors are established in the literature, comprehensive survey about their interplay has not been conducted yet. To assess these aspects, a survey, with a representative sample in the Adelaide metropolitan region, South Australia, was conducted about the population heatwave perception, adaptation and heatwave-resilient building retrofitting. In this study, the analysis results concerning retrofitting are presented. The study aspires to define which demographic characteristics predict retrofitting activity and what drivers and barriers are to heatwave-resilient retrofitting.

2. Survey data collection and analyses methods

Quantitative data were collected via an online survey with closed questions. An online survey method was selected as the most time-efficient method to explore household behaviour and belief. To ensure
the representative sample for age and gender, within the Adelaide metropolitan region, a survey panel provider was commissioned. A panel provider recruits participants for a representative sample of the whole population. Only people who lived and/or worked in the Adelaide metropolitan region and aged 18 or over were eligible for participation. In March 2015, 393 responses were received.

The survey addressed three topics, namely heatwave perception, adaptation to and retrofit against heatwaves. Research surveys about heatwave perception and adaptation (Nitschke et al., 2013; Loughnan et al., 2014a; Loughnan et al., 2014b; Akompab et al., 2013), retrofitting for heatwave resilience (Saman et al., 2013) or energy efficiency (Australian Bureau of Statistics, 2013; National Centre for Social Research, 2010) were reviewed, since previous research with comprehensive survey about all these three aspects has not been undertaken yet. Questions with potential answers were adopted and further developed. Information about participants’ demography and their built environments was also collected for in-depth analysis of different subgroups, based on the findings and limitations of earlier research. The survey was comprised of 59 single- and multiple-choice questions with rating, constant sum-scale and paired choice answers. Although closed-ended questions were used, when respondents were asked about their adaptation and retrofitting choices, an additional option to list not covered techniques was included. The survey was designed, distributed and coded using Qualtrics online survey software (2005). The questionnaire was piloted to ensure that all difficulties and ambiguities were resolved. Statistical analysis of answers about retrofitting, covered in this study were conducted using SPSS and Minitab (IBM Corp., 2013; Minitab Inc., 2010). The distribution of responses were significant, tested by Chi-square goodness of fit test, unless otherwise stated. Connections between variables were evaluated by using Chi-square and Spearman’s rho tests.

3. Results of the survey analysis

The magnitude of heatwave-resilient domestic retrofitting was explored accounting for both past and possible future measures. Less than one third of the respondents stated that they had retrofitted their homes in the past 5 years (30%). Even less respondents (20%) intend to undertake retrofitting in the following two years ($\chi^2 = 9.79$, df = 1, N = 392, $p < 0.05$). The difference was due to the fact that only 29% of the past renovators planned to make further changes in the near future and only 16% of the respondents, who had not retrofitted, planned to take measures in the next two years ($\chi^2 = 7.118$, df = 1, N = 392, $p < 0.05$).

On average, 2.2 retrofitting measures were taken per renovators. More than two-thirds of the respondents undertook one or two measures and only 14% took four or more measures. A more efficient air-conditioning was installed and/or the shadings were improved by more than half of the past renovators (Figure ). Solar panels were installed in a little more than one third of the cases. Roofs or walls were insulated and water-retaining vegetation was planted in about one-fourth of the cases. The rarest undertaken retrofitting techniques included changing external doors and windows, roof colours and applying reflective foil on windows. The responses were further analysed to explore whether the popularity of different techniques changed with the number of measures taken. Changes in air-conditioning and in the house shadings were the most popular techniques (44% and 41%, respectively) among participants taking only one measure. Techniques, considered only when more than one measures were taken, included the insulation of the walls and/or roofs ($\chi^2 = 17.05$, df = 1, N = 118, $p < 0.05$), planting more water-retaining vegetation ($\chi^2 = 1311.96$, df = 1, N = 118, $p < 0.05$) and the installation of a solar panel ($\chi^2 = 23.75$, df = 1, N = 118, $p < 0.05$).
Participants planning to retrofit in the next two years were the most likely to invest in the shading of their homes, followed by installing a more efficient air-conditioning system and planting more water-retaining vegetation (Figure 2). The same amount of people were likely to install solar panels as those who were not. Note, however, that the distribution of the received responses on the likelihood scale, regarding to air-conditioning and solar panel installations were not significant. Changing the roof colour, replacing the external windows and doors, following to the insulation of the walls and roofs were the least likely to occur. On average, the respondents were planning to take 2.6 measures ($\chi^2 = 71$, df = 9, N = 79, $p < 0.05$). Almost half of the participants who were planning to retrofit (44%) were undecided about asking for professional advice, while only one quarter were willing to seek advice. One third (29%) of the respondents who were willing to retrofit were inclined to spend money up to $2000 and another 29% up to $5000. The maximum retrofitting budget peaks at $10,000 for almost one-fifth of the respondents (19%), and another 10% of the future renovators were willing spend even more.

When people were asked about specific retrofitting, the energy efficiency of their roofs was more important for them than the appearance (84%/62%). Meanwhile, the lesser time and money spent on garden maintenance were preferred to having a garden with lush vegetation. Amongst people who...
selected insulations, the roof or ceiling insulations were more popular than the wall insulations. Note that the size of the sub sample was very small (n=20).

In general, all listed drivers to heatwave-resilient retrofitting were rated as important (Figure 3). Financial saving and minimising heat stress were rated as the most important drivers. More than half of the respondents found the utilisation of government subsidies, carbon emissions and the increase of market value important.

In response to the question about the factors to retrofitting selection, the efficiency (32%), the fact that other retrofitting techniques were not necessary (19%) and the expenses of retrofitting (17%) were mentioned the most frequently. The limited opportunities as a tenant was cited only by the 6% of the renovators (Figure 4), showing a low retrofitting activity among tenants. The compliance with Housing South Australia and the durability of building materials were also included under the other category.

Exploring the barriers to retrofitting, only less than half of the non-renovators (29%) stated that their homes cope well with summer heat. The main barriers included being a tenant and the expenses of retrofitting for 21% and 20% of the non-renovators, respectively. More than a tenth stated they did not know enough about the topic and 7% argued that they planned to move in the next two years. The number of respondents was only marginal who stated that it would not save money for them or would
spoil the appearance of their homes (Figure 5). The low number of concerns about the home appearance is low compared to the significant number of heritage-like buildings in Adelaide.

![Figure 5: Barriers to retrofitting.](image)

In general, no statistically significant differences were found in past retrofitting between groups with different age, income, gender and qualification. Regarding future retrofitting, people over the age of 65 and/or people out of the labour force were less willing to retrofit ($\chi^2 = 8.087, df = 1, N = 392, p < 0.05$), ($\chi^2 = 6.46, df = 1, N = 392, p < 0.05$). Respondents with higher household incomes were inclined to spend more money on retrofitting (Spearman’s rho $r = 0.507, n = 69, p < 0.00$). Also respondents with lower income, who did not retrofit, were more inclined to cite cost as an obstacle ($\chi^2 = 10.86, df = 3, N = 194, p < 0.05$). The lack of knowledge about retrofitting was mentioned the most frequently by middle-income earners, with household income of $1500-3000 per week ($\chi^2 = 9.49, df = 3, N = 194, p < 0.05$).

4. Discussion

This study shed light on the population’s drivers and barriers to heatwave-resilient retrofitting and the influencing demographic factors, in Adelaide. Although only one-fourth of the survey participants stated that their homes cope well with heatwaves, more than half of those living in homes without sufficient coping capacity did not engage in retrofitting activities. These results indicate that the majority of the existing residential building stock was not heatwave-resilient and the occupants were not willing to retrofit. The key barriers to heatwave-resilient retrofitting included being a tenant, the expenses of retrofitting and the lack of knowledge. These results are consistent with the main barriers of energy efficient building retrofitting according to the latest national Household Energy Consumption Survey, listing property renting, financial constraints and not seeing the need and motivation (Australian Bureau of Statistics, 2013). Increasing household income, however, did not increase retrofitting activity. This finding challenges if financial constraints are only perceived barriers to retrofitting for middle- and high-income earners, and only influence the volume and type of retrofitting. Future research should investigate this issue in the context of the level of heatwave resilience of the existing built environment.

The number of retrofitting measures considered by the survey respondents is limited with two most popular interventions, including the improvement of air-conditioning and shadings. The utilisation of greenery around the house was an unpopular solution, since the majority of people preferred limited time and costs spent on garden maintenance. Unfortunately, the changing of roof colour was an
Drivers and barriers to heatwave-resilient building retrofitting in the Australian context

unpopular measure, even though potential energy savings and reduced electricity infrastructure costs would be significant (Saman et al., 2013). As respondents reported that the energy efficiency of the roof was more important than the colour, a missing knowledge about this retrofitting measure appears. Nevertheless, an increased willingness to change roof colour and external windows, doors was found in regard to the future compared to the past retrofitting measures. Future retrofit programs should concentrate more on advocating these less popular, still highly efficient retrofitting interventions.

Future heatwave-resilient retrofitting was less likely to be undertaken by respondents above the age of 65 and/or out of the labour force. While Long et al. (2014) in the United Kingdom found that recently retired people were more likely to retrofit, Achtnicht and Madlener (2014) in Germany discovered that older people were less inclined to retrofit their homes. Note that in the study of Long et al., the retrofitting expenses were subsidised by the local council. Considering the higher vulnerability to heatwaves of the older population (Bi et al., 2011) compounded by an increasing risk due to the ageing population, the issue of retrofitting by older household owners should be addressed (Loughnan et al., 2014b). Further research should be conducted about the underlying reasons of the missing willingness to retrofit among older people.

The findings of this study show that financial constraints were revealed as a perceived barrier to retrofitting and as a limitation in the retrofitting measure selection, especially for people with lower income. Both the perceived lack of financial sources and the unwanted professional advice lead people to purchasing a new air-conditioner instead of considering other passive retrofitting. The problem is also highlighted by the 13% of the participants who did not consider retrofitting, due to the lack of knowledge about the topic. The concept of building energy performance certificate (EPC) (Szalay, 2008; EC, 2003), adopted by the European Union (EU) since the early 2000s’ could address this issue. The certification must be issued after the construction and in case of acquisition or tenure, longer than one year. The EPC evaluates the building overall energy performance and includes a list of recommended retrofitting techniques. Based on the learnings from the EU, EPC could be completed with the financial implications of retrofitting (Amecke, 2012). The introduction of the EPC would enhance the population’s knowledge of the built environment and present energy-saving opportunities that was cited as primary driver to retrofitting. Furthermore, EPC could increase the importance of energy efficiency in property market value and raise the population awareness about carbon emission. Both issues, ranked as only secondary drivers to retrofitting by the survey respondents.

5. Conclusions and implications for policy makers

This paper provides insights into the key drivers and barriers to heatwave-resilient domestic retrofitting in Australian context. The key aspects that should be addressed, include the population’s limited financial opportunity perceived, the deterrent impact of property renting and the lack of knowledge about heatwave-resilient retrofitting. Government retrofitting schemes should target population with lower income, over the age of 65 and ones being out of the labour force, particularly as these people are more vulnerable to heatwaves. Further education programs, especially on unpopular solutions such as cool roofs and increased garden vegetation should be promoted. The proposed building EPC would, furthermore, encourage the uptake of future retrofitting. Future research should address the reasons for lower retrofit activity among older respondents and the perceived financial constraints related to retrofitting among middle and high income earners.
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Fads, façade and face of building: a proposal for an urban university campus expansion

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Abstract: Preoccupations with the aesthetics of a building’s envelope, and the pursuit of technological advancement, have led to a singular understanding of the façade as a mechanical boundary. This investigation challenges the hermetic nature of the contemporary façade and its legitimacy as a subject matter of architectural design within the overall architectural discourse. Drivers for this project include the need to revisit historical precedents, the ambivalence of the label ‘façade’, and a speculative siting as a campus expansion of Victoria University of Wellington, New Zealand. The design response to the site’s topography via the theory-charged, re-oriented, and as a heterogeneous space, and threshold redefined, façade enables a novel way of projecting a building’s images without depleting the façade’s autonomy. The paper reports on the theoretical background and case studies and their application to the initial design stages.

Keywords: Façade; face; heterogeneous space; campus.

1. Introduction: the design hypothesis

Material innovation and environmental urgencies over the last twenty years have made notable advances to a building’s perimeter – the façade. However, this lead to a predominantly exclusive understanding of the façade as a pure and generally extremely thin hermetic envelope. These developments are conditioned by a willful ignorance toward the historical precedents that define the term ‘façade’.

Façade has predominantly shifted away from being purely the layer of environmental control and structural barrier between public and private through the Chicago Frame. Its catalyzing effect on the divorce between structure and surface promptly removed any bodily representation of hierarchy, legibility and symbolism (Sharif, 2003; Leatherbarrow, 2002). Hence this investigation concentrates on building surface and its dialectic between support and skin. As grasping for a historically rich and complex surface allows for emancipation form naive and reactionary ideologies (Sharif, 2003). The context of historicism and functionalism allows to reintroduce orientation and circulation into the purely through visibility and imagery understood façade. Surface becomes the site of formal experimentation.
As production and representation are in conflict in contemporary architectural practice the concern with the difficulties and opportunities of external surface of buildings has to begin with the theoretical and practical isolation of that surface as a subject matter of architectural design (Leatherbarrow, 2002).

This investigation examines the accepted understanding of the term ‘façade’. Particular attention is given to the architectural ambivalence that this label bring to our understanding of the faced as a technical as well as visually expressive approach to the building envelope. To achieve this the research begins with takes on Rowe and Slutzky’s presentation of the façade as a function of literal and phenomenal transparency. These explorations are modified through James Stirling’s unique approach to University architecture and campus organization. Which is shaped by his compositional and theoretical interpretation of a range of historical precedence (Lawrence, 54). While acknowledging the significance in their work this research argues for extending the definitions of façade to accommodate – literally and figurative – a spatial dimension (ranging from macro through to micro occupancy).

Adding the contemporary preoccupation with visual aesthetics in architecture where the historic bodily representation has become obsolete leads to the opportune question of sincerity. The façade as a cover vs the façade as an expose of the interior. Conversely the verticality and geometry of the façade is challenged through its orientation: from the vertical into the horizontal, slicing through the interior volumes and extruding it out. This not only challenges the strong near iconic symbolism of a University’s façade but also offers a novel take on the axially of program distribution, access across site and the individual’s engagement with the façade geometry (Figure 1).

![Figure 1: Bodily engagement with the Vertical vs Horizontal (Kuepper, 2015).](image)

As part of the research-by-design methodology, this proposition is tested as a speculative addition to Victoria University of Wellington’s Kelburn Campus, Wellington, New Zealand thus rationally arguing autonomy for architectural surface.

Hence a student focused cluster of programs will be introduced, primarily targeted at post-graduate students. Through vertical and horizontal arrangement it generates a more direct entrance – threshold - to Kelburn Campus in its speculative siting. This is testing the reciprocal relationship between the overall threshold and its urban context and the internally focused facades. Both the theoretical and applied components of the initial design stages are presented.

2. The background story

Victoria University’s Vice Chancellor Grant Guilford’s vision is to expand the University by doubling student numbers over the next decade. Additionally the University recently purchased a campus adjacent piece of land which warrants a future expansion of Kelburn Campus. Hence the stretch of land leading up to Kelburn Campus provides a great opportunity to hypothetically test this architectural master’s research (Figure 2).
Given the location and nature of the site’s topography a façade development is required that challenges the ridgeline façade typology as is traditionally employed in a University setting. Hence site becomes the primary design driver in the initial design stages to explore the development of a hillside façade. This requires a constitutive stance towards the slope which will strongly impact the communicability of image not only through construction but also the process of appearance (Leatherbarrow, 2002).

Gordon Gee strongly emphasized that it is in the area of our physical campuses that a particular vulnerability exists as only a few short-sighted decisions need to be made (incorporating the latest building fad) before the physical quality of a campus reflects the scattered and distracted spirit and administration of the institution (Kenney et al, 2005). This demands the need to return to core values; Victoria University of Wellington’s mission is to undertake excellent research, teaching and public engagement in the service of local, national, regional and global communities (Dober, 1992; Kenney et al., 2005; VUW, 2015).

Architecture facilitates the return to the University’s core mission and sustains its values under the philosophical proposition that space and mission are synonymous (Kenney et al., 2005). Hence the University itself is treated as façade and contextualized against history. The research develops a continuous façade system transcending various scales to achieve greater circulation, orientation and increased connectivity. This is between Wellington’s City Centre below and Kelburn Campus, across Campus and within the individual faculty buildings it will comprise of. It becomes an urban threshold that shifts the notion of façade as well as positions the university and its image towards the city from the confrontational horizontal to the engaging vertical (Figure 3).

For Victoria University, in this research context, a design outcome of a staggered nature is envisioned. The aim is to not only establish a new image for the University but also provide space of opportunity to enable students to take control of their own education. Creating an intellectual home that provides for the multi-media classroom of the 21st century and facilitates a healthy lifestyle.
3. Methodology

Initial extrapolation of pattern in this research is undertaken in a scholarly based approach. The focus is on readings around the façade and surface terminology and analogies in architecture yet branches out into heterogeneous space. This literary canvasing brought forward a terminological scope of façade, threshold, transparency and interior space.

Following the initial scholarly approach a motif has tentatively been defined as ‘reconciliation of vertical movement across the site against geometry that is façade’. This reiterates site as a point of departure for design as the potential for the program to vertically transcend through existing spaces is recognized. This in turn triggers the necessity for a consistent method in the design to enable a visual conceptualizing of the project. Movement through and across segregated spaces suggests the notion of stepping. This is explored in a both literal and figurative manner with the aim of resolving issues of student movement across site and the University presenting itself through its facades to the public domain below. An initially envisioned outcome is of a building complex development scaling up the topography while allowing connectivity across site through threshold circulation within the domain that is façade (Figure 4).

Three highly relevant Case Studies have been analyzed to aid the in scholarly research identified principles of fragmentation and spatial stratification. To achieve autonomy for architectural surface under consideration of heterogeneity of space and elements the selected case studies have strong historic roots while challenging the norm of modernist spatial organization within educational spaces. Furthermore they negotiate the necessity of how the definition of a location involves a corresponding
act of dislocation, a centering of the building outside itself in favour of the overall organization (Leatherbarrow, 2009).

Additionally the typology of façade is revisited via massing and geometric studies to aid in an exploration and organization of the potential in the scale of chosen context and site. Thus a contemporary understanding of ‘threshold’ is applied to the site across multiple scales, orientating the public within Wellington through its strong image (micro-facades, internal facades and disoriented facades).

3.1. Scholarly approach – stirling as catalyst for Rowe and Slutzkys ‘Transparency’

Critical engagement with the theory of the façade enables this project to be more than simply a revivification of the debate on surface. As surface is the unconscious of architecture, invisible due to its overexposure (Chatterjee, 2014).

“Despite being a key part of the discipline, surface only occupies the interstice or the space of the unconscious in architectural discourse, from where it defends its legitimacy as architecturally valuable as opposed to visually pleasurable” (Chatterjee, 2014).

Transparency as point of departure is understood as an optical quality in both literal (materialistic) and phenomenal (geometrical) terms. The focal characteristic in Rowe’s argument is the ability for the layers of transparency to interpenetrate without optical destruction of each other (Rowe and Slutzky, 1997). This brings forward a continuous dialectic between fact and implication as depth and subtraction allude to the interior space, layout and occupation through fragmentary geometry and spatial stratification in the façade. As the third dimension that is architecture is unable to suppress these qualities, why does the façade consistently attempt to assimilate a two-dimensional existence? (Rowe and Slutzky, 1997). This brings forward a continuous dialectic between fact and implication as depth and subtraction allude to the interior space, layout and occupation through fragmentary geometry and spatial stratification in the façade. As the third dimension that is architecture is unable to suppress these qualities, why does the façade consistently attempt to assimilate a two-dimensional existence? (Rowe and Slutzky, 1997). There is an ever present visual continuum across the internal-external threshold through external surface as a three-dimensional medium. The existing problem, however, is that idiosyncratic architectural projects have progressively become one of a sculptural total exterior that alludes to a two-dimensional existence (Hensel, 2013).

Focus on environmental control within the façade nowadays led to a denial of frontality of façade, creating an in-between spatiality belonging as much to the inside as it does to the outside. It becomes a potent three-dimensional instrument that simultaneously connects and changes opposite situations by being both passive (see-through) and active (seen) (Leatherbarrow, 2009). Adding this legibility of occupation enables the integration of openings into surfaces/facades and pushes to construct alternative frameworks for contemporary social practice. This is further explored through case studies.

Additionally to its visual ambiguity surface in the third dimension constitutes of heterogeneous qualities by being both superficial and pervasive, symbol and space, meaningful and functional, static and transitory, object and envelope (Chatterjee, 2014). The concept of heterogeneous space, relating to both surface and University, has an interchangeable terminology including ‘complex’ and ‘multiplicitious’. Thus it avoids neo-modern functionalism coupled to a minimalist architectural formalism (Hight, 2009). To further combat heterogeneous three-dimensional space to be purely seen as a product of formal operations Stirling’s geometry is consulted through case studies.

Foucault (1986) argues that we do not live in a homogeneous and empty space but in a space that is in itself heterogeneous through a set of relationships. These relations are architecturally expressed by ‘something’ (cloister/hallway/corridor) through which one passes, as means of proceeding form one
point to the next. Its defining elements could prompt temporary halt and arrangements of rest. This take on threshold and transitional space offers great insight into how vertical movement across site can be broken up and organized into a transitional hierarchy.

The invention of the corridor and its multiplicity of connection suggests a deliberate ambiguity to avoid conventional forms and prescribed interpretations (Hensel, 2013). Moving away from purely styling the building envelope to fit the interior directs the research towards the extended threshold: Distributing the threshold by not perusing a full enclosure with the outer layer as the exterior extends beyond the first layer of the multiplied envelope. This results in the distribution of the exterior-to-interior transition by increasing the number of layers that are partially or fully open with interstitial modulated micro façades. Hence spatial organization occurs via layering of multiple envelopes. Envelopes can therefore become spatial devices (Hensel, 2013) (Figure 5).

![Figure 5: Extending facade into threshold diagram (Kuepper, 2015).](image)

Surface architecture can provide distributed thresholds that articulate heterogeneous spatial and environmental conditions to make versatile provisions for habitation (Hensel, 2013). Principles for production of heterogeneous micro façades manifest through degrees of interiority. Most prominently the grid where two or more simple pattern are overlaid to produce secondary and tertiary effects, shimmer and transform as these patterns move in relation to each other (Hensel, 2013; Hight, 2009). This ties back into the initial function of transparency to “interpenetrate without optical destruction of each other” (Rowe and Slutzky, 1997).

Hight (2009) argues that all space is essentially interior volume considering heterogeneous spatial qualities in extended threshold conditions. By diminishing the difference between visible and invisible new ways of representing degrees of transparency of the porosity of boundaries may provide alternative ways of negotiating threshold in surface architecture (Barrie, 1999). This is where topography can become genuinely communicative as the individual building’s freestanding self-governance is sacrificed for the configuration of an ensemble. (Leatherbarrow, 2002).

### 3.2. Case studies

The selected three architectures bring unique and insightful value to the development of the project. Especially in relation to internal facades of extended threshold conditions, visibility and geometric mass as design strategies.

Herman Hertzberger’s “Centraal Beheer Development” (Apeldoorn, Netherlands. 1972) is selected to investigate at the reduced scale: micro-façades and their incorporation and impact on the internal program. Despite the basic geometrical grid applied to the overall layout of the building Hertzberger creates interesting and intrinsically potential laden zones for detailed development. This slots right into
the theoretical proposition of spatial organization occurring via layering of multiple envelopes. This will be applied in modelling and massing studies.

The interpretable zone houses extreme potential to be filled with program thresholds that articulate heterogeneous spatial conditions. Hence it is categorized as an ideal zone for micro-facades. Spatial stratification and fragmentary layering allows to not only look at the horizontal but also the vertical stacked organization of spaces as Hertzberger constantly keeps the human body in mind.

In particular these principles will be taken into consideration when negotiating program orientation, organization and design movements against the envelope.

While physical modelling and iterative/investigative open-ended small scale tectonic models are employed to kick off the technical part of the investigation the main aspect taken on from this case study is the thorough understanding and exploration of mass and form (Figure 6).

Through diagrammatic analysis of their Vitra House project (2006) it becomes clear that Herzog and De Meuron are similarly very focused on the façade, in particular the detail and junctions within. While the Vitra House experiments with geometrical form in the vertical and horizontal it is somewhat hesitant to stronger articulate it in the interior.

Through more thorough analysis (Figure 7) it becomes evident that the carefully thought out plan design in relationship to the 3D orientation of the different complexes combats or this lack of resolution. I will investigate how the interior outline, layout and circulation can be achieved through the façade alone expended as a threshold within as the space itself becomes circulation. Space starts to orientate people in space by acting as a threshold that simultaneously divides and joins level. Elevation of levels will be transferred when façade threshold is applied to the site below Kelburn Campus integrating with the hill. This integration will be resultant and evident from the massing studies.
Stirling and Rowan’s competition entry (Figure 8) stood out through its unique take on campus organization as response to the post-war increase in student population and University expanding its capacity (Lawerence, 2012). It featured a square walled-in two-storey residential enclosure on an otherwise vastly open site. Proposed to be encompassed within were two main residential blocks with their own internal courtyard and two composite buildings. This impressive architectural idea was driven by the courtyard internal buildings rising above the enclosing peripheral wall of rooms (Figure 12). Yet is was this bold move that the judges saw as an undesirable grouping of undergraduates despite the courtyard predominance and internal orientation being the main design strategies (Lawrence, 2012; Stirling, 1975).

These key design decisions following a strong axiality that provided a novel circulation and orientation within the complex and the challenging scale make this a highly relevant case study for this investigation of vertical movement through facades. The internal environment aims to be private, enclosed and protected by solely providing staircase access yet when viewed from the outside still maintaining a degree of monumentality. This is achieved through the slightly more complex silhouettes of the interior buildings. Circulation up and through the external ring of accommodation is achieved through levels of elevated walkways/cloisters with staircases leading into the overall internal courtyard (Stirling, 1975).

Additionally it is not only Stirling’s novel take on campus organization and circulation that gives value to this investigation but also viewing this project as a response to growing historicization of functionalism (Lawrence, 2012). Stirling, ahead of his time, moves away from a strictly modern pedigree to incorporate a range of historical precedents by locating modern vernacular qualities within them irrespective of their time period. Particularly in this project where he desires to abstract the universities’ core principles (Lawrence, 2012). Through repetitive design moves across scales he diffuses the rigidity of the courtyard yet enforce it as an overall principle through fractals: courtyard within a courtyard – thus accentuating circulation. This highlights the inverted interiority of the overall courtyard (Lawrence, 2012). Rowe praises it to be an impeccable thesis as to what a college should be as its form corresponds to some disposition which the mind can immediately digest as a functional expression of use (Arnell and Bickford, 1984).

3.3. Massing studies

Massing studies on a 1:500 routed site model explore the organizational gesture of movement uphill while testing iterations of modules of a slipped grid in plan and stepped grading in section against the topography of the site. This provides a geometrical mass framework (Figure 9) to situate the programmatic development within and against.
Figure 9: Geometrical framework to resolve movement uphill (Kuepper, 2015).

4. Results of initial design iterations

The main preliminary result of the theory and case study informed massing studies is the effect of rotating the orientation of the geometry by 90 degrees from the horizontal into the vertical. This flip in orientation of the façade versus the now novel experience of and engagement with the façade brings forward strong options for resolving vertical movement uphill.

Through explorative physical modelling of vertical movement initial design iterations of breaking up the façade under the premise of transparency are visualized. This relationship of the angular dynamic towards the existing Kelburn Campus with its movement and alignment across the site is explored by breaking down the site into modules. Thus threshold is brought back into focus through the concepts of gateway, façade and educational space ranging through the layers of heterogeneous space through to internal micro façades (Figure 10).

Figure 10: Layering of facades throughout interior (Kuepper, 2015).

5. Conclusion and future outlook of research

This paper has taken a brief look at the initial stages of the author’s Research-through-design Master’s Project. It argues for a pursuit of the redevelopment of the façade into a heterogeneous threshold ranging from micro to macro occupancy. Given the programmatic context of a University campus this research could develop into a modular prototype for an international context by incorporating multiple views on modern University and campus. The next steps to undertake require careful consideration to avoid losing the relationship between façade and building as, if completely removed, façade would become an entity with its own facades. Hence program is induced to refine massing studies and develop a hierarchy for program organization, public thoroughfare, and vertical and horizontal circulation across site. Continuous shifting of scale throughout the research will lead to a strong, legible and technically resolved outcome. Conclusively it is expected that micro- and macro-facades have reciprocal design principles where their layering is transparent yet interpenetrates without optical destruction of each other which is integral to the relationship of technology and symbolism.
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Living and learning in practice: University of Arizona engineering innovation building (EIB)

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**Abstract:** The aim of this paper is to showcase the living and learning approach taken in the design of University of Arizona’s EIB. The design process focused on creating a highly energy efficient design by integrating passive environmental design techniques, producing renewable energy on-site and meeting building energy performance standards. The EIB has a floor area of 136,000 GSF and was budgeted at a cost of US$42 Million. The 5-storey building serves all advanced engineering research disciplines at the University of Arizona. The objective of this building was to create a learning experience for the building users by emphasising innovative techniques within the building. One of the key enablers for this living and learning approach was the adoption of an integrated design process. As part of this design process, key environmental considerations drove the building’s geometry, which included maximising access to natural daylight and ventilation as well as a focus on water efficiency and the use of Xeriscaping and shading. Analysing its performance using the software tool e-Quest in conjunction with the wind tunnel modelling and overcast sky simulation validated the as-designed performance of the building. The building is targeted to be LEED Platinum certified. As results of simulation and experiments, more than 85% of the internal spaces are daylit and 65% of the spaces are naturally ventilated resulting in a 20% saving in total electricity consumption, of which 25% saving on lighting and a 15% saving on cooling loads compared to a conventional building of this type. In addition, a wind tunnel evaluation was conducted to assess the EIB’s performance when exposed to prevailing wind. This was also used to define the most effective locations and sizes of openings in order to funnel the wind into the building’s atria and main courtyard resulting in a further reduction in cooling loads.

**Keywords:** Living and learning; integrated design; energy; case study.
1. Introduction

The EIB, Engineering Innovation Building, is a Platinum LEED Certified educational building at the University of Arizona (UA) – USA. It is allocated between major streets and buildings on campus, which reflects great importance due to its pivotal location at the UA’s campus. The building is intended to serve all engineering advanced research disciplines consisting of Research Labs, Student Innovation Centres, Student/Faculty offices and the Dean’s quarter. The intent of this building was to combine all the research disciplines into one building to ensure cohesive collaboration between different trades. The main goal was to provide a user-focused design approach, to facilitate continuous formal and informal collaborations between all the students and faculty whom are conducting research. Therefore, University of Arizona referred required collaboration between the graduate students and the Architect/Designer firm (Smith Group JJR) to provide state-of-the-art strategies to fulfil their goal. Although the proposed strategies recommended were not merely innovative, the collective team process clearly re-identify “the users” as the main idea behind University of Arizona’s Iconic Engineering Building by opting to embrace passive sustainable strategies that evoked the hot arid climate.

Figure 1: Main street’s View - The Users in lieu of Flexibility, Collaboration, & Innovation (by PI)

Figure 2: Main courtyard’s experience, a high traffic route within the project that connects students with the rest of campus. (by PI)

Figure 3: Flexible, high-tech collaborative nodes, through writable walls and windows, allowing every walking experience to become a learning experience.

EIB demonstrated that sustainability could be achieved without being dependent on a financial arm. The design’s main philosophy was to foster an energy saving design that educates the stakeholders, by developing a living + learning building and embracing passive environmental techniques while producing renewable energy. The effective passive design process paved for an efficient energy modelling and design assumptions that fulfilled the client’s aim without additional cost. Not only did the design promote reduction of energy usage, but also encompassed an adaptive bio-skin façade to generate renewable energy while reusing grey water (ELZomor-AZ water conference, 2015); that said, the
prophecy was to feature a learning experience to building users, by highlighting sustainable techniques within the building as a living tool of education. This intent is answered as the following statement: “The Environmental Factors Forced the Building’s Geometry”. The EIB is a living building in terms of being an interactive and structure that shall be used as a dissemination tool to teaching its users.

2. Design drivers

2.1. Natural daylight

EIB is an education building, therefore the users will generally utilize the building during daytime, and thus the design ensured that 85% of the spaces are naturally daylit. Sufficient natural daylight will entail reduction in artificial light and energy use of the building. A study has been conducted to ensure penetrating 100% natural light to lab spaces requiring light.

2.2. Natural ventilation
Sculpturing the design of the building’s form to accommodate 3 atria and a courtyard, has governed the natural airflow into the spaces. Based on the movement of air, the design warranted that 65% of the spaces are naturally ventilated.

2.3. Collaboration

Collaboration within the design is not about one dedicated space; it’s about creating spaces that bring the different users together. The design strategy that was executed was to alter all the circulation/corridors into interchangeable collaboration nodes encouraging the users to collaborate.

2.4. Flexibility

Crafting responsive spaces to different users and climatic changes. Since this building serves anonymous/changeable users, flexibility was a major concern while designing. Therefore, the designers decided to introduce a 15x15 grid then crafting responsive spaces fulfilling the users’ needs; the 15x15 grid serves the depth that light travels into spaces, which could be increased by the borrowed light theory.
2.5. One lobby and campus connectivity

Figure 9: Celebrating ONE double height Entrance Node to the Building to act as a showcase to the users (by PI).

2.6. Interaction with Speedway street

Figure 10: Elevating the Frontage Ensured Inner Views to the Courtyard from the Street (by PI)

As an Iconic building, it is very important to showcase the inside of the building, therefore elevating the ground floor of the south building overlooking the main streets, to increase the depth of vision in addition to allowing the southeast prevailing winds to enter the court and flood the building with natural ventilation.

2.7. Innovation

Figure 11: Renewable Energy - PV Sockets & Algae Facade (by PI)
As this building indicates, the out of the box factor was implemented by utilizing flexible photovoltaic sockets, writable walls, transparent flexible organic PVs, Screen Columns... etc.

2.8. Façade treatments

Figure 12: Each façade was treated differently based on the usage behind it and its orientation. (by PI)

The design considered the solar heat gain and the usage when designing the facade; therefore, the effective façade design paved for an efficient design modeling. As previously mentioned the building elements need to provide a learning environment for the users, as well as achieve the intent of its design. As the sun shines onto each façade differently a corresponding treatment must be considered. For example, the north façade pre-calculated fin lengths to block the low angle sun and allow diffused lighting, while the east façade has a copper double skin with perforations designed differently for north and south facing orientations.

3. Environmental and passive design strategies

The EIB fulfilled all the design intended goals by incorporating passive strategies in addition to magnifying the user’s flexibility and educational experience. Some of the major architectural attributes that were proposed were, providing natural daylight for more than 86% of the interior spaces thus reduces the need for artificial daylight. Correctly elongating the building to the East/West orientation to assure reducing the heat gain on the facades. Elevating the building on Speedway’s frontage plus funneling the prevailing wind into the main courtyard of the building. Introducing three atria within the building that facilitate supplying natural ventilation to 65% of the spaces. Providing Bicycle racks and showers to the users to promote and encourage the Users to use sustainable means of transportation, further to utilizing an access to the building from the nearby bus station. Installing more than 50% of the landscape pavement as an open grid system that is pervious materials. Further to designing seasonal seating areas within the landscape. The roof is to be painted white to assure high reflectivity surface. Further, to adopting sustainable materials within the project. The titled roof on top of the Atrium will include photovoltaic panels to generate renewable energy of the offices. A storage/recyclable room was allocated beside the loading bay to facilitate the reduction of waste generated by the Users and avoids disposing them into landfills. Ensuring controllability to the Lights and windows within each space so that the users achieve their comfort zones. Instilling an under floor ventilation system that operates with less amount of energy; moreover, it provides convenience switch to the user of each space. Providing a clear line of sight to the outside courtyards for the Users, which increases the productivity rates and decreases absenteeism.
3.1. Building operation water strategies

Water and energy are fundamental components of our 21st century life, but they can no longer be considered separated. This project describes the integration of water efficiency principles in tandem with energy conservation. The water/energy nexus is approached through a proposed four-legged body of knowledge addressing 1) Water Harvesting, 2) Water Reduction, 3) Water Reuse, and 4) Water Energy Generation technologies. Although water harvesting and water reduction have recently become common methods in building design, water reuse and water energy generation are relatively newer technologies that demonstrate greater promise to contribute to the affordability of water and its use as alternative energy sources. The environmental benefits gained from integrating water saving strategies to modify thermal conditions inside spaces. The modified environments would otherwise use energy to be achieved while the saved water will facilitate techniques for exterior landscape development. All technologies will include calculative methods; use of computer simulation, design monographs, and hands on inquiry based learning through laboratory sessions. Xeriscaping is an integral part of the design, thus the design provided seasonal seating areas to serve the users all year round; furthermore, installation of low water usage and native plants. The design developed a grey water system that collects water from bathroom and classroom sinks, shower, drinking fountains, air conditioning condensate and landscape to generate an evaporative cooling strategy by feeding a fountain that is allocated along the prevailing wind. The ordering system of the design was based on: (1) Environmental: Provide shades to the users & keeping the mass of greenery, (2) Economics: Maximize the number of users & cooling the air entering the site thus reducing the energy usage inside the building, (3) Functional: Continuation of the surrounding landscape & inviting users “when building meets plazas”, (4) Sociocultural: Offer the users an indoor/outdoor experience and (5) Aesthetics: Blending the landscape elements & features into the building.

3.1.1. Landscape design

Figure 13: Incorporating seasonal outdoors seating and proposing low water use/native plants (by PI)

3.1.2. Legged water research venue

Figure 14: Utilising science to reduce uncertainty by "Developing and Integrating a 4-legged water curricula in architecture education and design application" (Youssef - Universities Council on Water Resources Las Vegas, 2015) (by PI)
3.2. Educational paradigm cloud

Celebrates the users and invites participation to think about the making and engineering of surrounding structures. The unexpected performance provides the user with a dynamic dance experience, as it provides different sources of shades, shadows and light reflectivity. Structural performance results in environmental and socio-cultural benefits.

Figure 15: The Cloud wraps the building providing a double skin/shading, an indoor lighting feature; Different perforations based on the orientation formation of the Cloud (by PI)

The Cloud is a formal concept protection for the Dean’s quarter and Sponsors. The Double Skin Cloud protects the exposed East façade of the building from the harsh desert sun; furthermore, integrated LED lighting that helps define the circulation route during dark days or nighttime. It acts as an engineering showcase providing shade for the users on the campus and especially shading the green way connection, with the assistance of surrounding trees. The perforations on the parametric cloud, have different sizes that vary towards the south and north orientations. The bigger perforations point towards the North and smaller perforations point towards the south. Not only does the cloud provide an iconic shading system and way finding mechanism, but also it was utilized as a water collection, storage and delivery of rainwater to the EIB. The scarce source of water in the hot arid region convinced the design to opt for such an innovative solution for rainwater harvesting.

3.3. Furniture design

Figure 16: Flexible, Adjustable & Refurbished furniture (by PI)

Different collaborative nodes have been designed to tailor all potential needs of the users. Furniture designs enhance the brainstorming and collaboration thus providing unique approaches to multi-purpose spaces supports a variety of collaboration styles. Transparent walls balance workers’ desire for access to daylight and exterior views with the need to acoustical privacy. Moveable walls can be easily reconfigured to convert individual offices and conferences areas to an open environment. Maximize space utilization and transparency with an open benching application. Provides a welcoming touchdown space for mobile workers or creates a shared space that promotes negotiation and the exchange of
Living and learning in practice: University of Arizona engineering innovation building (EIB)

ideas. Freeform, freestanding workspaces are to be designed and reconfigured to meet team needs and differing work styles; the open atmosphere encourages the quick exchange of ideas.

3.4. Generating renewable energy

Although the widely used strategy of generating energy is the PVs, another new technology was proposed for further development and research that is an intelligent bio-adaptive algae façade. The algae façade not only highlights a vivid façade, but also provides a venue for researchers at EIB. Nevertheless EIB has adopted a new technology that has been researched at UCLA, which is the tandem cells that almost doubles the panels absorption of light (Dou et al., 2012).

3.4.1. Photovoltaic panels

3.4.2. Bio-adaptive algae façade

4. Validation Methodologies

4.1. Wind tunnel testing

The wind tunnel test was conducted using the Wind tunnel equipment allocated within the House Energy Doctor Lab at the University of Arizona, one of few founded at United State schools. Building a one to one model to facilitate testing and validating the impact of wind on the structure; therefore, endorsing the location and sizes of opening that funnel the wind into the building’s atria and main courtyard. The assurance that the required wind passes into the programmed spaces reflects minimizing the amount of energy required for cooling.

The Stack effect in the atriums is tested to ensure the sizes and performance of the wind movements. Furthermore, the wind tunnel confirmed the successfullness of the cross ventilation within the spaces. Finally since some of the roof slabs were designed to be tilted, testing the strategy of generating different pressure zones which act as a pulling force to hot air from the atria was confirmed by the wind tunnel test.
4.2 Overcast sky simulator

Due to that EIB is allocated in Arizona which is a hot arid region, the shading strategy was the most crucial to insure the merit of the design. A physical model was used to investigate light movement and render calculated through space. This exercise is both a qualitative and quantitative study of daylighting conditions. Using the House Energy Doctor’s “Artificial Sky Simulator,” the assessment of light distribution pattern was analysed through photometric measurement. This test resulted in evaluating the shading strategies that confirmed its effectiveness in minimizing the electrical and cooling loads.

A section through the artificial overcast Sky simulator shows the component of Mirror-box that facilitates testing the impact of the lighting intensities during the overcast (1700 lux) and clear skies (2200 lux). Sensors are placed inside the model to test for glare conditions and light intensities.

4.3. Parametric analysis

The design was validated by the e-Quest energy software, which facilitated the emphasis of the user’s experience in terms of the human comfort along with the user’s collaborative liveable spaces. The evidence based design strategies were utilized, as a living building to aid University of Arizona’s students and researches realize the impact of an energy efficient healthy building. The parametric analysis proves the positive impact of the sustainable design. Referring to U.S Energy Information Administration / Annual Energy review 2011, lighting load represents the highest percentage electricity consumption in commercial buildings. Thus reducing the lighting load in IEB was one of the main priorities within the design. After studying different alternatives, the design was evaluated incorporating the atria by e-Quest software to validate the results of reducing the artificial loads.
5. Conclusion

EIB will leverage knowledge and evidence based design strategies that optimize health and wellbeing to the building users. The design display the developing passive tools, techniques and approaches to support design, research, and practice, including sustainability-focused and renewable projects: computer modelling, data acquisition systems, light sensor loggers, and advanced photography techniques were all used to fulfil the design intent and goal of the project. The aim of this research is not to explore the intricacies of an innovative research, but rather illuminate the fallacies that obstruct the implementations of such designs. The University of Arizona took the initiative and opted to get an active design from students whom will inhabit the EIB, thus guaranteeing that most of the user’s requirements would be fulfilled and achieved. That being said, this research is based on a living case study that will foster the learning of its users everyday. Students tend to learn by various means, one of which is the living learning experience that usually lasts forever. The users will inevitably learn and apply the basic concepts of sustainability to various researches when living within the EIB’s showcase. Not only engineers and architects, but also bio medics, chemists, nuclear scientist and any other researcher will learn from the EIB. The EIB is regarded as a dissemination tool that educates all its users along with the public.
Acknowledgments

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LEEDv.4.0, Reference Guide for Building Design and Construction
Precipitation and buildings: estimation of the natural potential of locations to sustain indirect evaporative cooling strategies through hot seasons

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Abstract: Precipitation is a relevant climatic variable for building and urban design in hot climates, because of its potential to naturally mitigate heat excess in buildings and cities by evaporative cooling; and as a primary source of water to artificially reproduce this cooling mechanism, particularly in the humid tropics and subtropics. However, precipitation is commonly neglected in the analysis and development of climate responsive architecture and is rather seen as a cause of problems. This paper proposes a practical graphical method for building designers and planners which facilitates the meaningful “reading” of a climate, to reveal the potential use of precipitation in architecture. This method supplements existing climate analysis tools by defining a scale and benchmarks that easily link potential water requirements of buildings with water availability from precipitation. To complement this method, the concept of Urban Precipitation Surplus is also proposed, a measure of the excess of precipitation that is usually discarded which could be exploited for building cooling and contribute to regenerate the water cycle and improve microclimates in cities. Finally, a brief discussion is given about the analogy between buildings and vegetation, and the importance of enriching architecture with concepts from fields like agriculture and climatology.

Keywords: Precipitation; indirect evaporative cooling; hot climates; climate analysis.

1. Introduction

Precipitation is an important factor for planning of buildings and cities in regions with seasonally or permanently hot climates. Research in locations with these climates has recognized the potential of rainfall as a natural way to mitigate heat excess in buildings and urban heat island effects through evaporative cooling (EC) (Rao, 1990; Saneinejad et al, 2011; Saneinejad et al., 2014). Other research examines building cooling and energy saving strategies based on EC principles, like water spraying (He and Hoyano, 2008; Kitano et al., 2011), cyclic water film (Qahtan et al., 2014), etc.; which do not make direct use of the rain but require adequate water. The necessary amount of water could be readily provided by precipitation in various places in the humid tropics and subtropics.
Despite all the above, precipitation is an overlooked variable in the analysis and development of climate responsive architecture and its value as a primary source of water is usually neglected (Kinkade-Levario, 2007). Additionally, most research gives little attention to water availability and the substantial water surplus in locations of the Hot Humid Tropics is largely ignored, even in cases where the potential of EC is recognized (Figure 1). All this shows the need for a better understanding of the potential of precipitation and its importance architecture.

Figure 1: Relation of water availability from precipitation and regions with most research on building and urban EC. a) By zonal means (base graph source: NASA, 2010), b) By annual patterns.

2. Precipitation and buildings

The relation between precipitation and buildings is not commonly perceived as constructive. On the one hand precipitation is seen as an element from which buildings must be protected (e.g. Harriman and Lstiburek, 2009). On the other, buildings are seldom considered as active factors among the urban strategies for control and reuse of water from precipitation, even though they cover a significant portion of the total area of a city. Even so, a positive relation between precipitation and architecture is possible, which can be identified in two directions:

From precipitation to architecture:

- Precipitation can provide water required for human use as well as for other needs of the building.
- Precipitation has a natural cooling effect over the building fabric, which is favourable for buildings in hot environments. This is useful to balance the thermal performance of buildings and reduce the impact of extreme heat waves (Figure 2).

From architecture to precipitation:

- Buildings can contribute to the control and management of the water from precipitation, to minimize the impact of extreme events and to reduce the load on stormwater infrastructure.
- Buildings can be an integral part of systems to recover and maintain natural water cycles.
Figure 2: Reduction of building surface temperatures after incidence of light showers (30 min difference).

However, this positive relation is broken when precipitation is only seen as affecting the integrity of the building, or if the building is seen as a passive element which does not influence its surroundings. Thus, a circle of negative impacts is usually developed: buildings alter natural water cycles and convey the problems to other environments, which in turn contributes (to some extent) to extreme events of precipitation with adverse effects over the built environment. This could be avoided if there is more concern for precipitation in the processes of building and urban design, particularly in those areas with abundant precipitation such as the humid tropics and subtropics.

3. Precipitation analysis for building design

In climate analysis for architecture there is a bias to the four climatic variables which directly influence human thermal comfort, especially to temperature and humidity. Analysis tools for these variables allow intuitive interpretation and direct association to the configuration of the building (e.g. wind rose, sunpath diagram, etc.), which is very practical for building design. However, this is not the case for precipitation because its influence is not usually associated with building function and performance.

Although charts of annual precipitation patterns are very common in climate analysis for architecture, little tangible information is extracted from these for building design purposes. The diagrams usually seen in architecture are limited to describing precipitation profiles and patterns without providing elements which could enrich their interpretation (Figure 3).

Figure 3: Typical precipitation analysis found in architecture literature. a) Annual precipitation histogram (source: Szokolay, 2014), b) Minimal description of precipitation (source: Lechner, 2014).
Deeper interpretation of precipitation data is important to discern its influence over the function and performance of buildings and their surroundings. For this reason there is a need for methods that help to enable meaningful use of the precipitation data for architecture applications as it happens in the cases of solar radiation, wind, etc.

4. Proposed practical graphical method

This paper proposes a graphical method which emphasizes the analysis of precipitation, with the purpose of helping building designers and planners to carry out meaningful “readings” of climate data and to assess applications of EC for buildings. This method supplements existing climate analysis tools by defining benchmarks and a scale that easily links potential water requirements of buildings with water availability from precipitation. It observes three climate variables at once: Temperature, Humidity and Precipitation, and defines one benchmark for each variable. For instance, the ones used in this paper:

- **Hot**: Dry Bulb temperature (DB) of 23 °C, the lowest temperature of the 0.5 clo ASHRAE Comfort Zone (this could vary according to the sensitivity of the population).
- **Humid**: Dew Point temperature (DP) of 16.8 °C, based on the upper boundary of the ASHRAE comfort zone (widely applied for building design and thermal comfort).
- **Precipitation Surplus**: This benchmark is dynamic, according to the water requirements of buildings. This is defined through a basic calculation which is explained in Section 4.4.

The values of these benchmarks are not fixed. They serve as references for contrasting and analysis, and can be defined according to the needs of the analysis and the user, as long as they are supported on reasonable criteria. Once the benchmarks are defined, it is possible to look for relations and patterns in the climate data which are useful to estimate if EC strategies are suitable for buildings in the location that is analyzed; for instance, rainy seasons in phase with hot seasons, days with low humidity, etc.

The method is based on monthly precipitation data, which is readily available, sufficient for preliminary analyses and remains simple and practical for designers and planners (analysis based on daily or weekly precipitation require long historical records and sophisticated calculations). It is applied through adapting diagrams and charts which are conventionally used for the analysis of climates: Ombrothermic Diagrams, Thermohyet Diagrams and Psychrometric Charts.

4.1. Ombrothermic diagrams (climate diagrams)

This diagram combines monthly averages of temperature and precipitation over a year to determine the length of dry, wet, and extremely wet periods. It can reflect how the amount and distribution of precipitation determines native vegetation in an area.

The effectiveness of precipitation (P) is related to the temperature (T) by a simple aridity index where $P=2T$, an expression of the limit between the dry season ($P<2T$) and the wet season ($P>2T$) (Bagnouls and Gaussen, 1953). The relation is valid for units in C° and mm. (it does not work for F° and/or inches). This index is good enough for architecture applications due to simplicity and because a more accurate definition is not as critical as for other fields (e.g. agriculture, stock farming, etc.).

In the original application of the diagrams, an interval where $P>100$ mm is considered a surplus period. In the adaptation proposed here for architecture applications, this benchmark would change according to type of buildings and their water demands (See Figure 4). The calculation of this benchmark is explained in section 4.4.
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Figure 4: Ombrothermic Diagram: a) Original (source: Walter and Lieth, 1967), b) Proposed.

At the bottom of this diagram, the DB line (red) defines the levels where \( P=2T \). Conditions of precipitation below this line would define arid periods and those above the line define wet periods (in purple). When wet periods surpass the precipitation surplus benchmark these are defined as hyper wet (surplus) periods, where water availability exceeds the demand and can be stored for future needs.

Below the DB line is the DP line (blue). The area filled with vertical stripes shows the Dew Point Depression (DPD), which indicates the levels of moisture saturation in the location. Up to 8 °C, each degree of difference approximates a reduction of 5% in Relative Humidity (RH) from 100% (e.g. DPD=7°C equals about 35% reduction, then RH=65%). From 8 °C to 30°C, each degree of difference approximates a 3% to 1% RH reduction.

The precipitation scale above the 100mm line is adjusted by a factor of 10, to control the height of the vertical axis when there are major levels of precipitation.

4.2. Thermohyets diagrams (hythergraphs)

This diagram is plotted in a Cartesian system using monthly rainfall data in the abscissas and temperature in the ordinates. Its primary use was intended for agriculture.

This sort of graph can identify patterns of climate regimes and trends which indicate the dominant air mass influences of the location. Although its use is not seen in architecture it provides a very convenient way to combine temperature, humidity and precipitation in one diagram with practical meaning for architecture applications (Figure 5).

The diagram proposed here has two loops of monthly average points combining temperature and precipitation: a) The Dry Bulb (DB) loop (red) and b) the Dew Point (DP) loop (blue). The plane is divided in quadrants by the Hot and the Surplus benchmarks. All points of the DB loop located in the upper right quadrant (Hot-Surplus) indicate the months in which the hot season is in phase with abundant rain. Months located in the Hot-Surplus quadrant have a significant potential for EC strategies.

Like in the case of ombrothermic diagrams, the vertical distance between the points of the DB loop and the DP loop (that is, the DPD) depicts the level of moisture saturation in the air.
4.3. Psychrometric chart

The psychrometric chart is based on air temperature and humidity, and from these two variables other properties of moist air can be determined. In our proposal the chart is adapted for combined analysis of temperature, humidity and precipitation in order to assess the feasibility of EC strategies.

The adapted chart plots hourly conditions of the air at the same time with monthly averages of temperature, humidity and precipitation (connected in an annual loop), and adds concentric circles indicating the precipitation levels (Figure 6-a). It differs from the previous diagrams because it allows contrasting water availability with detailed conditions of the air, both relevant to weigh the feasibility of EC for buildings. This provides a complete picture of the water source, the actual influences over evaporation and potential EC performance (Figure 6).
The possibility of filtering data (e.g. individual month) and to see extreme conditions (e.g. heat wave) is particularly valuable for the analysis of hot humid climates, which are traditionally considered not suitable for EC techniques. As seen in Figure 6-b, even a permanent hot humid climate with annual RH of 67% can have hours with RHs between 30% to 40%. These low saturation conditions together with the significant water surplus signal the good potential for EC in this location. Therefore, for the particular case of Figure 6, EC deserves consideration as a key cooling strategy for buildings in the location.

4.4. Precipitation benchmark

Before defining a benchmark for precipitation is necessary to associate the units of precipitation with those of water demand. This makes the interpretation of the diagrams and charts direct and simple.

The relation of precipitation and water demand scales is influenced by the runoff efficiency of the roof or other element from which the water is collected. This is illustrated in Table 1 and is exemplified graphically in Figure 7. Also, the relation can be easily plotted over any of the three diagrams and chart proposed in section 4, and is the base to depict the precipitation benchmark.

Table 1: Relation of collected to supplied water for different runoff efficiencies.

<table>
<thead>
<tr>
<th>Runoff coefficients</th>
<th>Effective catchment (L/m² day)</th>
<th>mm to supply 1 L/m² day</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>C=0.95 (Metal Roof)</td>
<td>0.95</td>
<td>0.03167</td>
<td>31.6 Metal</td>
</tr>
<tr>
<td>C=0.70 (Clay Tile Roof)</td>
<td>0.90</td>
<td>0.03000</td>
<td>33.3 Metal, concrete, asphalt</td>
</tr>
<tr>
<td>C=0.50 (Green Roof)</td>
<td>0.80</td>
<td>0.02667</td>
<td>37.5 Clay, concrete, asphalt</td>
</tr>
<tr>
<td>C=0.50 (Green Roof)</td>
<td>0.70</td>
<td>0.02333</td>
<td>42.9 Clay, gravel, shingle</td>
</tr>
<tr>
<td>C=0.50 (Green Roof)</td>
<td>0.50</td>
<td>0.01667</td>
<td>60.0 Green roof</td>
</tr>
</tbody>
</table>

Figure 7: Graphical relation of precipitation and water demand for different runoff efficiencies.

The precipitation benchmark (PB) is the minimum level of precipitation required for a building to fully meet its demand of rainwater, and any amount above this level is exceeding precipitation which could be stored by the building for future needs. It can be calculated from the simple formula:

\[ PB = \frac{(Dt \times 30 \text{ days})}{(\text{CRa}/\text{HFa}) \times C} \]  

(1)

Where:
PB = Precipitation benchmark (mm or L/m²); Dt = Total water demand (L/m² day); CRa = Collectable roof Area (m²); HFa = Habitable floor area (m²); C = Runoff Coefficient (unitless).

The denominator in equation (1) is termed the Building Factor (BF), because all its variables depend on the configuration of the building. The minimum precipitation required to satisfy the water demand of the building will vary according to its BF (the requirement increases when BF is <1 and decreases when BF is >1).

If water is required for different purposes (e.g. laundry, toilets, EC, etc.) DT must be calculated previously with the formula:

\[ Dt = De + \left( \frac{Da}{HFa} \right) \]  

Where:

De = Water demand for EC (L/m² day); Da = Supplementary water demand (L/day).

This water demand may vary according to the climate and the specific needs of each building. Even very similar buildings may have differences in the amounts of water required (e.g. due to orientation, surrounding influences, etc.). Thus, the particular demand of a building must be individually calculated. Water demands for building cooling used in the examples below are taken from diverse research about EC in buildings. Many of the values found in literature converge in a range between 4 to 10 L/m² day.

Table 2 gives examples of the calculation of PB for three cases:

- Case a: 1 story house, 80 m², 2 people, demand for EC, toilets and laundry – hot humid climate.
- Case b: 2 story house, 120 m², 4 people, demand for EC and toilets – hot dry climate.
- Case c: 2 story office building, 250 m², 12 people, demand for EC and toilets – hot humid climate

<table>
<thead>
<tr>
<th>Case</th>
<th>De (L/m² day)</th>
<th>Da (L/day)</th>
<th>Dt (L/m² day)</th>
<th>CRa (m²)</th>
<th>HFa (m²)</th>
<th>C</th>
<th>Roof Type</th>
<th>BF</th>
<th>PB (mm or L/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>4.11</td>
<td>250.00</td>
<td>8.02</td>
<td>100</td>
<td>64</td>
<td>0.8</td>
<td>concrete</td>
<td>1.25</td>
<td>192.39</td>
</tr>
<tr>
<td>b</td>
<td>8.50</td>
<td>280.00</td>
<td>11.30</td>
<td>80</td>
<td>100</td>
<td>0.95</td>
<td>metal</td>
<td>0.76</td>
<td>446.05</td>
</tr>
<tr>
<td>c</td>
<td>5.20</td>
<td>220.00</td>
<td>6.77</td>
<td>120</td>
<td>140</td>
<td>0.5</td>
<td>green roof</td>
<td>0.43</td>
<td>474.00</td>
</tr>
</tbody>
</table>

5. Urban precipitation surplus (UPS)

Once we have a practical way to discern the significance of the precipitation amounts, it is possible to estimate if the location has a natural potential to support EC strategies for buildings. For this purpose, this paper proposes the concept of Urban Precipitation Surplus (UPS).

The UPS refers to the excess rainfall of an urban area, usually discarded, which could be exploited for building cooling and could contribute to regenerate the water cycle and improve microclimates in cities. This is limited to the rainfall over buildings which is generally conveyed to the surrounding areas and finally sent to drainage systems without being used. Thus, it does not include the direct rainfall over outdoor areas and streets.

The UPS is the difference between the average monthly precipitation and the precipitation benchmark for a standard building (UPS = P - PBs). This standard building has to be representative of the majority of buildings of an entire urban area (e.g. city, district, neighbourhood, etc.). In this way, it provides a reference for analysis and design of buildings and urban ensembles.
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If the value of the UPS is 0 this means that the typical precipitation of the location merely satisfies the demand of water for the function of the standard building and its cooling through evaporation. When the value is >0 the surplus might be sufficient for buildings with low BF (e.g. multistory buildings or buildings with a reduced area to collect water). When the value is <0, the UPS can cover only part of the water demand and its use must be prioritized (e.g. for essential functions or for parts of the building with critical heat gains).

To illustrate the concept of UPS, the city of Cairns in Australia is used as an example. Satellite images and statistics of this city show that a big proportion of its buildings are detached houses, covering between 25 to 30% of the land in urbanized areas; of which 65% have 1 to 3 bedrooms (.id, 2015). From the above, we deduce that the dominant type is the detached single story house, which consequently becomes our standard building to determine the UPS. The BF for this type of dwelling is estimated in 1.44 (based in a floor area of 150 m²), and if we assume a water demand for EC of 10 L/m² day, the building would require minimum monthly precipitations (PB) of 209 mm.

| Table 3: Average monthly precipitation and UPS for the city of Cairns, Australia. |
|-----------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| Jan     | Feb      | Mar       | Apr       | May       | Jun       | Jul       | Aug       | Sep       | Oct       | Nov       | Dec       |
| Precip. | 396.9    | 422.1     | 448.9     | 224.5     | 107.1     | 49.7      | 25.6      | 22.3      | 33.4      | 43.6      | 100       | 190.3     |
| UPS     | 188.0    | 213.2     | 240.0     | 15.6      | -101.8    | -159.2    | -183.3    | -186.6    | -175.5    | -165.3    | -108.9    | -18.6     |

The resulting UPS is positive from January to April (+16 to +241), which means that rainfall in these months can cover the whole demand of the standard building. The UPS is negative between May to December (-19 to -187). However, the period from June to August is not in the hot season, and in December the UPS is close to 0. Then, the critical months are May, September and October, which would require defining priorities for the use of rainwater. Therefore, we confirm that there is a potential for exploiting rainfall during the summer season, when it is most needed.

In brief, the UPS is useful for a preliminary analysis of a location and can help us to identify opportunities for exploiting natural water resources for building cooling, even for cases where the humidity is high (see Section 4.3). It appeals to further investigate and analyse the feasibility of applying EC techniques for buildings, and prevents discarding them due to incorrect assumptions.

6. Conclusions

Throughout this paper we have discussed ideas which suggest an essential analogy between architecture and vegetation. To begin with, all points listed in Section 2, about the positive relations between buildings and precipitation, are equally applicable to plants. The reciprocal influence that exists between buildings and their environment resembles the importance of plants in balance with their natural context. This analogy is confirmed by the suitability of the diagrams in Section 4 for architecture applications, which were originally developed for applications related to vegetation and refer to critical aspects for agriculture and climatology which also have significance for architecture (e.g. aridity, evapotranspiration, rain interception, etc.).

Is also crucial to consider that in locations which are inherently wet, the growth of cities generate a process of “desertification”, where the pre-development vegetation is replaced by impervious materials that repel water and store heat in proportions which are not normal. Dry cities with high levels of runoff are inconsistent with the wet nature of numerous locations in the Humid Tropics and subtropics; in the
same way that cities in desert areas (e.g. Dubai, Las Vegas) are inconsistent with excessive demands for water.

The issues presented here highlight the need to observe the relation between precipitation and buildings, and to integrate buildings as active elements with positive influence on their environments. One way to achieve this is through a general implementation of EC strategies, like roof and wall spraying, in those locations with significant water surplus. In doing so, buildings could create a significant demand on the stormwater which is usually rejected during the rainy seasons, generate a substantial reduction of sensible heat in urban areas and bring improvements in the local water cycle. Thus, besides improving their own conditions, buildings would contribute to other issues like stormwater management, urban heat island mitigation and adaptation to climate change. All this confirms the need for more research and tools that help to enhance our understanding of the relation between precipitation and buildings and its positive application in architecture.

References
Residential adaptive reuse in inner city Melbourne

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Abstract: This paper assumes an industry lens to examine the on-going practicality of small-scale, low-rise adaptive reuse of unused building as residential developments. It includes an illustrative case study that tracks a local development company’s recent redevelopment of a small commercial building in Inner Melbourne, to be used as residences. The paper analyses its development in terms of profitability, sustainability and preservation, including design imperatives, administrative and regulative constraints, energy and sustainability ambitions and real estate market fluctuation. The paper concludes with a brief and speculative discussion on the practicality of adaptive reuse projects in Inner City Melbourne.

Keywords: Adaptive reuse; preservation; sustainability; profitability.

1. Introduction

There is no hard and fast definition in terms of geographical boundaries of what is included in the term “inner-city Melbourne”. It is generally acknowledged that it includes the Central Business District, albeit that there is no real consensus as to what the CBD includes. To a large degree it depends on who is providing the definition, with realtors tending towards the most inclusive and urban planners tending towards the least inclusive. This paper assumes an equally open-ended definition: inner city Melbourne refers to CBD plus the parts of the surrounding suburbs that immediately border it: principally Docklands & Southbank, North Melbourne, Parkville, Carlton, South Yarra and East Melbourne. A rule of thumb is that residents can easily walk to the business district from their residences: a criterion that re-emerges later in the paper.

Any reference to population density requires contextualization. According to the Australian Bureau of Statistics (ABS, 2014), inner city Melbourne’s 2013 population density, the number of residents per square kilometer, was the highest anywhere in Victoria. Overall, Victoria had a population density of 25/km²; Greater Melbourne had a population density of 440/km² while inner city Melbourne had a population density of 12,400/km². However, the data presented by the City of Melbourne indicates that in 2013, the City had a population of some 120,000 residents living in 40 square kilometers, which means a density of 3000/km². The discrepancy is mainly the result of which areas and which residents are included in the statistics.
The ABS records that inner city Melbourne’s residential population is growing at an average rate of about 4% annually, compared with a rate of 2.2% for Greater Melbourne (ABS, 2014). In fact, the growth of inner city Melbourne’s residential accommodation has barely kept up with the rate of re-population over the last two decades, which to a large degree is the result of the City’s urban accumulation strategy developed in the 1990s (Weller & Van Hulten, 2012). The vast proportion of the increased population that resides in the inner city is accommodated in high-rise apartment buildings. Some areas, like Docklands, Southbank and the southern end of Carlton have seen the construction of large scale developments such as, for example, the Eureka Tower, a single construction that includes 556 residential apartments accommodating some 2000 occupants. What all high-rise residential constructions have in common is that whatever was there before has been razed.

Regardless of any societal, heritage and energy consideration, it is overall more immediately profitable to build a new apartment block than to adapt an existing building, which in effect means that adaptive reuse of extant buildings depends to a large degree on making their demolition illegal and therefore unlikely, which in turn may make their adaptive redevelopment desirable and profitable. In most cases, desirability depends on artificially imposed constraints such as protecting the exterior by enforcing heritage overlays; by requiring the functionality of the building to be sustainable, and by enforcing the preservation of a streetscape that is adjudged to be socially or culturally worthwhile. It often is these heritage overlays that allow small-scale developers to re-imagine and reconstruct such buildings, either as commercial or residential redevelopments.

2. Sustainability

Two basic defining characteristics of adaptive reuse recur throughout the literature: preservation and sustainability (Bradley and Kohler, 2007; Van Beuren and de Jong, 2007; Wilkinson et al., 2009; Victorian Government, 2006; Velthuis and Spennemann, 2007). However, there is widespread contestation as to what is meant by the terms. Yung and Chan (2012) confirm that while adaptive reuse inherently aims for sustainability, there is on-going disagreement firstly about how it is defined and secondly about how it might be best achieved. Tomlan (2015), for example, argues that adaptive reuse’s focus on preservation is increasingly subject to factors that range from the pragmatically economic to socio-politically esoteric.

Most (if not all) small-scale companies that specialise in redeveloping commercial buildings for residential purposes focus in their public rhetoric primarily on the two drivers, preservation and sustainability, emphasising the desire to ensure that a particular building retains its function in a streetscape and a commitment to ensuring that the redevelopment of an existing building restructures the building as a sustainable entity. However, a third factor, profitability, also impacts significantly on both strategic and construction decision-making. Beyond the simple bottom-line, profitability is intertwined with preservation and sustainability at every stage of the project.

Preservation of old buildings in the inner city is not true historicity. Often the building assumes a patina of worthiness simply by having survived for long enough. Any building exists within a specific albeit mutable environmental context, and whenever that context is changed the building’s relationship to it is changed. Cityscapes, perhaps the most dynamic of all built environments, are constantly evolving, and architectural relics therein run the risk of assuming an exhibitive role: serving as an example of something worth preserving. For preservation to be meaningful beyond the fragmentary it needs to be locale-based, and as Been et al. (2014) argue, officially sanctioned, a status that is put into effect in the first instance by a council heritage overlay.
Heritage overlays are part of local council planning schemes and designed to protect the heritage of a local area, generally in terms of places that are of aesthetic, archaeological, architectural, cultural, scientific or social significance, or otherwise of special cultural value:

*Under the Heritage Overlay, a planning permit is required from the council to:*

- subdivide land;
- demolish or remove a building (including part of a building);
- construct a building (including part of a building or a fence);
- externally alter a building;
- construct or carry out works;
- construct or display a sign;
- externally paint an unpainted surface;
- externally paint a building if the painting constitutes an advertisement.

Sometimes, external paint controls, internal alteration controls and control over trees may also apply. The Schedule to the Heritage Overlay will identify any such additional controls.¹

Beyond the provisions placed on the area by the Melbourne City Council, there is also a provision for a building to be of significance to the State or the Nation rather than to the locality, which means it falls under the Victorian Heritage Act of 1995 rather than a local council’s Heritage Overlay. The Act provides much greater protection for a building than a council overlay but even having been identified as significant under the Act does not guarantee it will not be demolished – as evident in the recent fracas over the demolition of the Palace Theatre in the CBD. At the time of writing a series of legal challenges that have halted the demolition work and protest against the development continues to call for the building and its function to be retained. One suggestion put forward is that developers be required to maintain the building’s Bourke Street façade and build behind it. At this stage, the developers have indicated in the media that they have no intention to incorporate any part of the existing building in the new structure: a practice known as façadism.

Whether façadism is seen as minimising compliance with heritage overlays or as a compromise between retaining heritage and razing it for new development, there is little doubt that its occurrence is increasing in Inner City Melbourne. Melbourne Heritage Action expressed concerns that the approach of preserving a small proportion of the original building within the construction of the new one is “increasingly being regarded as a satisfactory outcome for heritage in our city”. MHA president Rupert Mann ‘called for more planning protection so that Melbourne’s character was not reduced to “paper-thin façades devoid of their soul”’, referring to the C186 amendment to the City of Melbourne Planning Scheme (City of Melbourne, 2015) as the keystone for the City of Melbourne’s strategy to list several inner city buildings for full heritage protection, a status that to be realised, requires ministerial support. As it is, façadism is little more than a nod to heritage and a wink to investors. The principal reason why façadism is attractive to a developer is that incorporating a token amount of the existing building into the construction allows the development to proceed – regardless of the appearance of the completed building. Moreover, in this case both the developers and the protestors contest it as unworkable.

The example that informs this paper is the redevelopment of the disused North Melbourne Masonic Lodge by Re:CONSTRUCTION, a small-scale local development company. Originally constructed as a shop

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with residence in 1855, the building was remodelled into the lodge in 1875. The 2014/5 re-development created five residences, which, according to the company, combined “historic detail and the finest contemporary fittings.” The preservation aspect of this build is primarily limited to the outer shell, referred to initially as “original massive walls” and subsequently as “bluestone walls dating from 1855”. The building was constructed as a stained glass workshop for Ferguson & Urie, a company whose output survives in numerous places throughout Victoria and Tasmania. The earliest photograph of the building is dated 1887 and shows that both the external walls and the internal weight-bearing walls, although originally rendered, are indeed bluestone. As Kate Mitchell (2015) points out, Melbourne’s bluestone, sandstone and granite buildings are a palimpsest of the Colonial city, still visible when the surface of the modern city is scratched. When Melbourne is referred to as one of the world’s great Victorian cities, the reference is most often to its architecture.

In practical terms, the original building no longer exists. Rather, it is an imbroglio of styles, materials and affects that as such is little more than a couple of decades old. Its historic context is retained not in the original construction but in the subsequent additions, alterations and adaptations. As it is, the original bluestone walls neither were nor are evident from the street view but feature prominently and decoratively in the apartments. Interestingly, this aspect is used obliquely in the realtor’s rhetoric:

> Unfolding over multiple levels, this two-bedroom (each with sweeping Northerly views) two-bathroom North Melbourne apartment offers a riot of diverse materials, textures and shapes, including bare and painted brick, bluestone walls and exposed steel.²

If the building exists as “a riot of diverse materials”, it seems reasonable to ask what is it that was actually being preserved in this adaptive reuse project. Any historical significance was in the building’s function rather than its construction or architecture, and if that function no longer exists, then the reason for a heritage overlay can also to be argued to be no longer applicable.

### 3. Preservation

Adaptive reuse necessarily negotiates a compromise between the destruction and the preservation of buildings, while generally considering façadism as too near the destruction end of the spectrum. The practice’s emphasis on sustainability, as well as appealing to the contemporary zeitgeist, therefore offers the most likely point of difference:

> Re:CONSTRUCTION has a strong emphasis on sustainability; both in the way we build and also in the eco-friendly nature of running the homes we create.³

The Victorian Government’s stated sustainability aims for the inner city to be carbon neutral. Its ‘1200 Buildings’ initiative ‘aims to encourage and support building owners, managers and facility managers to improve the energy/water efficiency and reduce waste to landfill of commercial buildings in the municipality of Melbourne’⁴ excludes residential buildings and commercial buildings that are adapted for reuse as residences. The reasoning for this emphasis is curious. The website states the ‘City of Melbourne boldly aims to be carbon neutral by 2020. Fifty percent of the municipality’s greenhouse gas emissions are generated by the commercial sector’. The initiative does not provide equivalent

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incentives to the residential sector to reduce its share of the municipality’s greenhouse gas emissions. Perhaps the Government’s emphasis on commercial development refers to the notion that until relatively recently much of the redevelopment in inner Melbourne concerned heritage buildings repurposed as community spaces, retail outlets or small businesses rather than residential developments (Tan et al., 2015). In any case, although the subsidy for creating residences that decrease greenhouse gas emissions is not accessible for it, Re:CONSTRUCTION continues to create sustainable residences.

To some degree at least, Re:CONSTRUCTION’s strategy to preserve a particular ambience is driving its decision to recycle as much of the original material as possible. Whereas it is often cheaper to build with new rather than recycled materials, the use of extant materials adds substantially to the appeal of the preserved building. Further, recycling is a key component of sustainability, particularly in the notion of “whole of life’ sustainability, which measures “embodied energy”, that is to say the energy required to extract, process and manufacture and transport the products used in the build. While van der Flier and Thomson (2006) assert that an adaptive reuse project is only worthwhile if it results in a more sustainable building and consumes less energy in its reconstruction than a new build, Ellison et al. (2007) point out that to ensure sustainability increases the cost of an adaptive re-use project by an average of 12% and that few small-scale developers have a profit margins that can buffer that as a matter of course.

In its advertising rhetoric on the above-mentioned website, the company emphasizes what it refers to as “whole of building” recycling, which to a large degree serves as an assertion that its builds are not simply façadism:

The ultimate in “whole-of-building” recycling meets superb location in this warehouse-style conversion of a 150-year old Masonic Hall. Converted by Re:CONSTRUCTION Pty Ltd, it delivers all the advantages of inner-city living in a designed environment that respects its historical context. Flooring comprises Baltic pine, kauri pine and oak timbers, edged by glazed balustrading with overhead Oregon trusses … Care has been taken to preserve original features including bluestone walls dating from 1855 and cast-iron re-enforced trusses.

A further aspect of sustainability might be referred to as complementary retrofitting. This refers to installing future-focused technologies to extend the functionality of the rebuild in a sustainable manner. For example, the internal architecture of the residences within the North Melbourne stained glass workshop is designed to maximize natural airflow, sunlight and ergonomic functionality. The solid walls are incorporated as passive thermal receptors, which along with 1.5 kilowatts solar power system will supplement the reverse-cycle air-conditioning system. All glass surfaces are double-glazed and external walls, ceilings and floors are fully insulated. Moreover, there is no on-site garaging but rather emphasis is placed on the fact that public transport is nearby and the design includes a space dedicated to bike storage. The company experience with earlier projects that took these ideas further, using copper piping to flow hot water for heating, angling eaves for seasonally adjusted shading and so on, formed the basis for decision making for this project.
4. Profitability

In practical terms, both preservation and sustainability are dependent on profitability because even small-scale developers need to make a profit in order to survive. In a series of personal communications, the directors of Re:CONSTRUCTION identify three main barriers to profitability.

First, as mentioned previously, in practical terms the costs of conversion are substantially higher than the cost of new builds. Although the concept of sustainability can be reasonably broadened to accommodate the material’s whole-of-life energy cycle, it makes little impact on profitability. The building’s immediate functional sustainability has greater influence on a buyer’s decision to purchase. In a personal communication, the realtor opined that none of property’s buyers delved into how their apartments were sustainable beyond the advertising rhetoric. In a personal comment the realtor claimed that sustainability was one of a number of “fashionable” and “cosmetic” selling points that address changeable market demand. Candidly, the realtor ranked “sustainable” alongside “funky” in terms of effectiveness in advertising terms.

Second, the unpredictability of the state of the building can lead to unplanned costs, especially where the quality of the initial construction was low (Bullen and Love, 2011). The profitability of Re:CONSTRUCTION’s redevelopment of the North Melbourne stained glass workshop was negatively impacted by the collapse of an external wall that upon excavation was found to have insubstantial footings. The location of the wall precluded full access to its footings during the due diligence process but there was no prima facie evidence that it had been constructed without a proper base. Having to reconstruct the wall after it collapsed obviously impacted negatively on profitability.

Third and perhaps most influential in the long term is that the directors of the company assert that there are fewer and fewer properties available to convert. The repopulation of Melbourne’s inner city was lead by the City council and over the past three decades has seen an enormous reinvigoration (City of Melbourne, 2013). However, the revitalization of the inner city also created (or was created by) a sharp increase in residential demand, and consequently a demand for gentrification (Van Hulten, 2010), which brought its own inherent concerns:

Residential conversions and increasing rents displaced low income residents and businesses. Public spaces were privatised, heritage-listed buildings were demolished and some of the new developments were disappointingly formulaic. (Shaw, 2014: 142)

The repopulation of the inner city resulted in property prices rising to the point where retaining much of that which gave the inner city its distinct atmosphere as a residential option is no longer profitable.

It is difficult to reconcile the City’s Planning Department’s rhetoric about Melbourne’s distinctive characteristic while at the same time allowing that which makes it distinctive to be demolished. As a result of the strategy, current retail value of inner city property makes it profitable for high and medium rise developers to acquire property for demolition than it is for small-scale developers who seek to preserve a particular streetscape and create sustainable residences within its extant buildings. Heritage constraints or height limitations can serve as levelers but the laws need to be enforced to be effective, and as has been discussed, that is not always the case.

In the last decade, the ‘apartment industry’ has continued unabated in the inner city. In 2015, the Reserve Bank of Australia warned that the inner city rental market was approaching saturation, suggesting, “the risk of oversupply appears most evident in inner-city Melbourne, where the level of
high-rise apartment construction has been elevated for a number of years”. Industry voices were less delicate. Terry Ryder (2014) described the growth as “toxic”:

Vacancies in the Melbourne CBD, Southbank and Docklands have been fluctuating between 5% and 10% recently - and will get worse, given the weight of new construction. State Planning Minister Matthew Guy appears determined to aid and abet any developer who wants to build another tower, to the point where you have to wonder about his motives. (Ryder, 2014: unpaginated)

Political skullduggery aside, the rampant development of medium to high-rise apartment blocks has certainly altered the ambience of the inner city Melbourne’s urban streetscapes but there is a counter-argument that cities are by their nature dynamic locales.

The precinct where Re:CONSTRUCTION operates, primarily North Melbourne but increasingly further afield, consists of factories and industrial sites that have been abandoned because of economic reasons or the buildings have outlived their usefulness and the property on which they sit have increased in value to the point where it is profitable for the businesses to sell and move into purpose-built industrial parks on the outskirts of the city. There is a case to be made that its industrial streetscape is what gives it its distinctive ambience. The precinct’s proximity to the CBD as well as to hospitals and universities make it an ideal place for residential redevelopment that incorporates that ambience. However, its location also makes it attractive to large-scale developers. The mix of large-scale low-cost (and often rental/temporary/seasonal) accommodation with increased demand for the sanitized gentrification of the extant building stock by more affluent owner residents usually displaces low-income residents, forcing them into more affordable suburbs (Dovey et al., 2013).

5. Conclusion

Despite (or possibly because of) its short history, the inner city of Melbourne is an eclectic mix of architecture, with a handful of discernible areas that qualify as locales, both historic such as the top end of Collins Street and the laneways, and contemporary such as Docklands and Federation Square. How the increased demand for residential accommodation in the inner city is allowed to manifests itself is fundamentally a cultural sustainability issue. Hyde (2015) suggests the role Architectural Science in cultural sustainability includes its theorisation; the retrofitting of historic buildings for sustainability and the environmental performance of historic buildings, amongst others. This paper has illustrated the interconnectivity of those themes by way of a specific project.

Generally, the redevelopment of small commercial buildings garner little public attention beyond their immediate locale but it is often their removal that impacts heavily on the local streetscape and ambience. Particularly in the inner city areas of sizeable metropolises, very few are restored and thereafter preserved and even fewer are repurposed as domestic residences. There are numerous reasons for this: the restrictions placed on redevelopment by agencies such as local councils; the unprofitability to retain the building compared to demolishing it; the unpredictability of costs and the vagaries of the real estate market may make it impractical.

On the other hand, repurposing an existing building for residential purposes has three fundamental capacities. First, it affords an opportunity to maximise a building’s sustainability. Second, it affords an opportunity to preserve a valued streetscape. Third it affords an opportunity provide residences to those who seek an inner city lifestyle different to the uniformity of the ubiquitous residential tower block.
Profitability influences every aspect of the adaptive reuse process, and ultimately over-rides concerns and ambitions in terms of preservation and sustainability. Small-scale developers are increasingly unable to compete for stock in a market where large commercial enterprises are able to circumvent regulations designed to retain specific streetscapes. This means that even though the adaptive reuse of smaller commercial building into residences can mitigate the loss of ambience in a locale that is the inevitable result of large-scale demolition and rebuilding, it has become increasingly unprofitable to do so.

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Sustainability vs. pedagogy: synergies and tensions to be resolved in the design of learning environments

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Abstract: Learning environments in schools are purpose-built spaces. They are designed to be places of learning and are inclusive of the building structure, the furniture, fixtures, incorporated technology and learning resources. In the 21st century, it has become common practice for the design of new learning environments to be driven by issues of contemporary pedagogy and environmental sustainability. However, the question that remains unanswered is what are the synergies and tensions between achieving environmental sustainability and contemporary pedagogy within the same learning environment? The purpose of this paper is to stimulate conversation around this topic. The findings relate to three researcher’s observation over a seven year period of learning environments research, undertaken at The University of Melbourne as part of the Learning Environments Applied Research Network (LEaRN) and two Australian Research Council Linkage Projects Smart Green Schools and Future Proofing Schools. Discussion of these observations highlights some of the issues and/or opportunities, which include more targeted research on how to deliver learning environments that are 3D textbooks; holistically integrated biophilic design, and greater occupant control of indoor environment quality.

Keywords: Sustainability; architecture; contemporary pedagogy.

1. Introduction

Over the past decade, there has been substantial growth within Australian schools regarding levels of awareness and action for environmental sustainability. The majority of this growth was triggered by the United Nation’s proclaiming 2005 to 2014 as the ‘Decade of Education for Sustainable Development’ (DESD). Governments across the world were invited by the United Nations to strengthen their contribution to issues of environmental sustainability through initiatives aimed at specifically learning and education (UNESCO, 2005). In Australia, the Federal Government’s DESD strategy was communicated through the ‘Caring for Our Future’ report (Australian Government, 2006). It broadly outlined specific initiatives aimed at embedding issues of sustainability into schooling through the National Environmental Education Statement for Australian Schools; the Australian Sustainable Schools
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Initiative; the National Goals for Schooling; and the National Statements of Learning (Australian Government, 2006).

Of specific interest to this paper is the Australian Sustainable Schools Initiative (AuSSI) – a national program “providing practical support to schools and their communities to live and work more sustainably” (Australian Government, 2015). In 2010 there were approximately 3000 public, private and Catholic schools participating in AuSSI – a number equal to 30% of schools nationally (DEWHA, 2010). An evaluation into the operational effectiveness of AuSSI revealed that collectively these schools were “achieving immediate and measurable improvements in their use of resources, grounds and facilities” with reductions of 80% in waste collection; 60% in water consumption and 20% in greenhouse gas emissions (Australian Government, 2015; DEWHA, 2010). However, as learning environments are made more sustainable through the revised use of resources, grounds and facilities, what impact is this having on desired pedagogy?

The purpose of this paper is to stimulate conversation around this topic by identify some of the synergies and tensions that exist between achieving sustainability goals and desired pedagogy within the same learning environment. The findings do not relate to an exhaustive research methodology, but instead relate to observations made during a seven year period of learning environments research at the University of Melbourne, in Australian primary and secondary schools.

2. Literature review

This paper begins with a literature review of the current and historical paradigms of environmental sustainability; contemporary pedagogy; and learning environments. As well as provide important background information this review highlights that growing interest in schools regarding issues of environmental sustainability, occurred alongside an emergent shift amongst educators towards contemporary pedagogies, thus providing opportunity for solutions to be holistic (Dovey & Fisher, 2014).

2.1. Environmental Sustainability & Schools

The Australian Sustainable Schools Initiative (AuSSI) was launched nationally in 2004. It is a program overseen by the Australian Government, aimed at assisting schools in the public, private and Catholic sector to invest in whole-school approaches to sustainability (DEWHA, 2009). The AuSSI program’s definition of sustainability is modelled on the Brundtland Commission Report (1987), which calls for sustainable development that “meets the needs of the people today without compromising the ability of future generations to meet their needs” (DEWHA, 2010, piii). By ‘whole-school’, AuSSI advocates for the entire school community to be actively involved in activities and learning that promotes sustainability. AuSSI’s is invested in opportunities that enhance education, environment, social and economic outcomes for the environment (DEWHA, 2010). Broadly categorised, AuSSI is concerned with curriculum development and investment/management of school infrastructure and grounds.

Regarding curriculum development, Education for Sustainability (EfS) is the preferred term amongst Australian educators for educational initiatives in schools directed at environmental issues. EfS is not a concept that is exclusive to AuSSI. In Australian schools, EfS has been an evolving concept since the first education conference hosted by the Australasian Science Education Research Association Ltd (ASERA) at Monash University in 1970 (DEWHA, 2009; ASERA website, 2015). The significance of AuSSI is that it provided EfS with a framework that has
“assisted schools and teachers to develop the skills and knowledge to make effective sustainability decisions and for schools to implement sustainability as part of their everyday operations...across the curriculum within a whole-school plan” (DEWHA, 2009, p.5).

With the introduction of AuSSI, there has been a shift in how EfS is taught in schools. For example, rather than focus on giving students only knowledge of the threats posed to natural ecosystems by overuse and depletion of resources, EfS focuses on also empowering students to make informed and sustainable decisions. This is done through a diverse curriculum that includes components such as: Envisioning a better future; Critical thinking and reflection; Participation; Partnerships for change; and Systemic thinking (DEWHA, 2009). It is intended that EfS components be integrated into the day-to-day life of the school through promoting and implementing initiatives such as recycling and compost, kitchen gardens, rubbish free lunches, energy and water audits, permaculture, biodiversity walks and environmental hero class awards (DEWHA, 2009). AuSSI support schools implementing EfS by providing links to a range of educational resources on their website. However there remain barriers to EfS, including the time required to develop lesson plans; the level of general knowledge about EfS amongst educators; the lack of professional development for educators about EfS; the availability of appropriate resources; and the C2C curriculum, which focuses on literacy and numeracy (Evans, et al., 2012; Simoncini, et al., 2012; Stevenson, et al., 2012).

Outside of the classroom, AuSSI schools are required to show their commitment to sustainability by outlining their action plan to reduce waste, water and energy through improved management of school infrastructure and grounds (DEWHA, 2010). To aid in this process, AuSSI connects schools with environmental initiatives and programs offered by all levels of government. At a state and territory level the programs promoting sustainability in schools are Energy Smart Schools, WasteWise, WaterWise and Landcare (DEWHA, 2010). At a national level, one notable initiative was the Commonwealth Government funded ‘National Solar Schools Program’. It resulted in over 5000 schools receiving grants of $50K to install solar panels and other energy efficient technologies aimed at offsetting energy expenditures (GBCA, 2014). A 2010 evaluation into the operational effectiveness of AuSSI revealed that through the sustainability commitment made by 3000 schools, there had been reductions of 80% in waste; 60% in water consumption and 20% in greenhouse gas emissions (DEWHA, 2010).

While AuSSI is a government-led program, there are important contributions to sustainability being made by the private sector. One such organisation is the Green Building Council of Australia (GBCA), who is also an advocate for improved sustainability in schools. In the decade directly following the creation of GBCA (2002-2012), it certified over 500 GreenStar buildings, of which 10% were in the education sector (GBCA, 2012; GBCA, 2014). The GreenStar Education tool, released in 2008, promotes the use of environmentally sustainable design features (ESD) in schools, such as controlled daylighting through correct building orientation, fenestration design and window coverings; minimised heat gain and loss through sun-shading, double glazing and insulation with high R-values; enhanced thermal comfort through thermal mass and energy efficient heating and cooling systems; good air quality through natural ventilation, reused and recycled materials and/or materials with low volatile organic compounds (Taylor, 2009).

2.2. Contemporary pedagogy and space

The term ‘pedagogy’ refers to the instructional style or strategy employed by teachers to educate learners. The pedagogies that teachers employ involve not just the types of tasks that they set for
students, but complex sets of relations, practices and behaviours. Pedagogy also includes the social and intellectual climate that teachers create to promote learning, such as through different forms of questioning and methods of responding to students’ interests and ideas.

Historically, instructivist or didactic (teacher-centred) teaching strategies were most common in Australian schools; however, in recent years there has been growing promotion and acceptance of constructivist, or student-centred, approaches to teaching and learning (Carrington, 2006; Pendergast & Bahr, 2005). Constructivism challenges the validity and effectiveness of education based on the transmission of knowledge via the traditional teacher-student relationship. Strommen and Lincoln (1992) described how learners actively construct knowledge and invent ideas through the integration of new information with simple, pre-existing notions. They suggested that through a constructivist process learners “develop critical insight into how they think and what they know about the world” (p. 468).

The design and construction of a range of ‘innovative’ learning spaces has followed the shift towards the adoption of constructivist pedagogies in schools (both in Australian and other parts of the world). This shift follows the belief that the physical spaces in schools effect the ways students learn (Weinstein, 1981; Upitis, 2004) and that non-traditional learning environments can aid the development of student-centred approaches to education (OECD, 2009).

Based on findings from environmental psychology studies into person-environment relations, Weinstein (1981) suggested that the physical spaces in schools can facilitate or inhibit learning through both ‘direct effects’, such as noise or crowding, and through ‘symbolic effects’, such as when poor conditions communicate to students a lack of respect for them on the part of the school they attend.

The built environment may also affect how students learn and teachers teach is through communicating pedagogical intent (Upitis, 2004). To this end, Upitis (2004) identified traditional classrooms as learning environments that embody a transmission model of teaching and learning. She concluded that traditional classrooms, born out of the Industrial Revolution, have perpetuated a transmission style of education based on core subjects such as English, mathematics and science, usually at the expense of interdisciplinary studies.

Over the past decade considerable money has been spent by the state, Catholic and private education sectors in Australia on more open and interconnected learning spaces (see below). These spaces are intended to support contemporary approaches to teaching and learning based on constructivist pedagogies. While the designs of such spaces in the early 2000s were somewhat rudimentary, more recent designs have incorporated some of the anecdotal and research-based lessons learned to create stimulating and engaging environments for learning and teaching.

### 2.3. Learning Environments & the Building the Education Revolution

The term ‘learning environment’ is used liberally in educational discourse. It describes a place that

“supports multiple and diverse teaching and learning programs and pedagogies, including current technologies; demonstrates optimal, cost-effective building performance and operation over time; respects and is in harmony with the environment; and encourages social participation, providing a healthy, comfortable, safe, secure and stimulating setting for its occupants” (OECD, 2011, p.1, citing OECD, 2006).

This definition elicits different images about the physical space requirements of learning environments. In recent decades, researchers have undertaken studies aimed at translating into a set of
guidelines the “intrinsically vague and fuzzy” ideas that exist in response to the question ‘what is a learning environment’ (Mononen-Aaltonen, 1998, p.164).

Research undertaken by Dovey and Fisher (2014) proposes that the physical layout of a learning environment can be explained using a spectrum of typologies that range from “traditional classroom through various degrees of convertibility to permanently open plans” (p.1). The notion that such a spectrum of learning environments exists, is a point of view is shared by the OECD (2011, p.2) who describe physical learning environments “in the narrowest sense” as being conventional classrooms and “in its widest sense as a combination of formal and informal educational systems, where learning takes place both inside and outside of schools”.

Through an analysis of 59 plans of middle schools, Dovey and Fisher (2014) identified a continuum of five learning environment typologies, which they labelled Types A, B, C, D and E. Type A is a cluster of traditional classrooms connected by a central corridor. Type B is identical to Type A, except that the corridor between is widened to create a breakout space, identified as ‘streetspace’. In Type C, the walls between two or more adjoining classrooms are made flexible, enabling these classrooms to be opened up, creating a new space identified in as ‘commons’. In Type D, the walls between adjoining classrooms and the streetspace are flexible, allowing for the entire learning environment to become one larger space, whilst also retaining the ability to close it down into single cell classrooms. In Type E learning environments, the space is open plan where “the bridges to traditional pedagogy are burnt and doorways are largely abandoned” (Dovey & Fisher, 2014, p.12).

A study of learning environment typologies is relevant to this paper as both the defined areas of space, and the physical boundaries that define the space, are factors that can influence pedagogy opportunities and environmental sustainability. Contemporary pedagogy and environmental sustainability were amongst the issues addressed by the architects leading the Victorian Government’s first round of school projects (known as the ‘template designs’) during the 2008 Federal Government’s Building the Education Revolution (BER) (OECD, 2011). The BER was part of an Australian economic stimulus package. It was the Rudd Labour Government’s response to concerns about threats posed by the Global Financial Crisis to the Australian economy. Nationally, the BER program was worth $16.2 billion. In Victoria, $2.5 billion was invested into 2904 government school projects across three programs: Primary Schools for the 21st Century; National School Pride; and Science and Language Centres for 21st Century Secondary Schools (Victorian Department of Education and Training website, 2015). For the BER program, Victorian Architects Hayball and Gray Puksand developed 34 template designs for classrooms and libraries, multipurpose centres, gymnasiums, science centres and other facilities (OECD, 2011). A report on the BER by the Victorian Auditor-General (2013, p.vii) found that the opportunity to evaluate the success of the program and the new learning environments still existed, after the Victorian Government (specifically the Department of Education and Early Childhood Development (DEECD)) had “not evaluated these programs in a comprehensive and timely manner and it may have missed an opportunity to apply the lessons learned from these programs to improve its asset management practices”.

3. Methodology

The purpose of this paper is to set the agenda for future research by identify some of the synergies and tensions that exist between achieving sustainability goals and desired pedagogy within the same learning environment. The findings do not relate to an exhaustive research methodology, but instead relate to general observations made during a seven year period of learning environments research, by
Sustainability vs. pedagogy: synergies and tensions to be resolved in the design of learning environments

three researchers working at the University of Melbourne as part of the following research teams and Australian Research Council linkage projects:

- **Smart Green Schools** (2007-2010), investigating the links between pedagogy, space and sustainability using methods such as environmental monitoring, ethnographic observation, interviews, spatial mapping and participatory action.
- **Future Proofing Schools** (2010-2012), investigating new opportunities to improve the quality of Australian prefabricated classrooms, using an international ideas competition, environmental monitoring, interviews, questionnaires, participatory action and ethnographic observation.
- **The Learning Environments Applied Research Network (LEaRN)**, established in 2009 to provide a multidisciplinary forum, a portal and an international network for academia and industry to research, imagine and discuss physical learning environments in schools, vocation, university, medical and corporate contexts (LEaRN, 2015). Learning environments research undertaken by LEaRN utilises a mixed methodology with methods such as interviews, questionnaires, environmental monitoring, participatory action and ethnographic observation.

4. Discussion

4.1 Synergies: Sustainability & Pedagogy

The first synergy relates to opportunities for overcoming the challenges identified in the literature, for schools trying to embed EFS into the curriculum. In *Linking Architecture and Education*, Taylor (2009) outlines the rich opportunities that exist to use the physical learning environment as a resource in teaching and learning. It requires what Taylor (2009, p.32) calls the ‘knowing eye’:

“a visual literacy that opens eyes and minds to the ideas and principles that are embedded in and govern the physical world, and that constitute the order of the universe”.

During the **Smart Green Schools** ARC, Hes and Soccio (2012) used Taylor’s ideas as a framework for research that explored how sustainable school buildings could be used as a 3D textbook. To assist educators develop relevant EFS lesson plans, Hes and Soccio (2012) created a series of adaptable ‘off the shelf modules’ that highlighted how the learning environment could be used to develop in students an ‘ecological knowing eye’. The benefits of the ‘ecological knowing eye’ related to raising the general knowledge of EFS amongst educators and enabling the physical school building to become a resource for teaching EFS. Hes and Soccio (2012) explored their ideas inside four case study buildings located in three Victorian Schools. In this paper there is only the scope to discuss the research from one school.

Hes and Soccio (2012) worked with students inside Type A and Type E learning environments. The Type A learning environment was the science facility, opened in 2002. It was single storey building with a long rectilinear plan, constructed with steel and concrete, containing single cell classrooms accessible from an external covered walkway. The Type E learning environment was the agriculture/horticulture (Ag-Hort) facility, opened in 2006. It was a smaller single storey building constructed with straw-bale walls, reclaimed ironbark posts and timber cladding. ESD considerations had been part of both
architectural briefs and design responses of the two architects to ESD were dramatically different. In the Type A classroom, the main ESD consideration was for good access to daylight. The external covered walkway was a deep eave that provided summer-time shading to floor to ceiling glass walls, which faced north. There were strip skylights allowing daylight to penetrate into the back of the classrooms. Concrete would provide thermal mass and time-lag to for thermal comfort benefits on warmer summer days. In the Type E learning environment the building employed traditional passive design principles, with an exposed concrete slab and north-facing windows for thermal mass, double glazing, daylight access and sun shading, photovoltaic array, radial-sawn timber cladding and straw-bale walls.

The different design responses to ESD on display in the two buildings provided rich educational opportunities that Hes and Soccio (2012) leveraged from with the aid of environmental monitoring equipment. Inside the two buildings, students used light, acoustic, temperature (ambient and radiant), humidity, ventilation and energy-use meters to investigate how the design of two buildings responded to the surrounding environment, asking questions such as: ‘How efficient it is? Does it do its job well? Is it comfortable and does it support a good learning and teaching space?’ The equipment was not prohibitively expensive, with each meter ranging in cost from $40-$60; the exception being the infrared camera used to measuring and communicate the performance of radiant temperature. For the activities this item is not critical and can be substituted with an infra-red scanner ($80-$100).

Hes and Soccio (2012) observed how engaged the students were during the activities. The environmental monitoring equipment gave them a unique lens in which they could develop their ecological knowing eye. The students took ownership of their learning, often choosing to explore options that were not part the prescribed activity. The learning later informed the work that students did towards the redesign of their homestead buildings, and a much-needed composting toilet building for the Ag-Hort facility.

A second synergy relates to indoor environment quality (IEQ), which is the combined impact of acoustics, thermal comfort, lighting and air quality inside a space (Soccio, 2014). IEQ performance inside a space will be influenced by how a building has been designed, constructed, operated and maintained (Vittori, 2002). IEQ is one of the sustainability markers assessed by the GreenStar Education tool. The other sustainability markers are energy, water, emissions, land use and ecology, management and innovation (GBCA website, 2015). Inside learning environments, IEQ performance is an important issue that can have a positive and negative impact on how well students learn (Coalition for Healthy Schools, 2013). There is a relationship between poor IEQ and the energy performance of school buildings, however there is not the scope in this paper to explore this issue (Newton, 2012). Instead, the focus is on describing how IEQ can enhance pedagogy, using observations from Soccio’s PhD fieldwork (2014), undertaken as part of the Future Proofing Schools ARC.

The research by Soccio (2014) centred on the development of a methodology for evaluating IEQ performance inside learning environments. Over 2011-2012, Soccio collected data about the performance of 16 IEQ components, which through a literature review were identified as having the potential to impact of effective teaching and learning. Eight of Soccio’s case studies were prefabricated learning environments. Five of these case studies were single cell classrooms, which resembled Type A learning environments. Two of these case studies were Type B learning environment, with multiple single cell classrooms that connected to a commons. One of the case studies was a Type C learning environments; though the shared wall between two classrooms was not used over the data-collection period. Working inside her case studies over four seasons, Soccio (2014) observed cases of where careful design of IEQ systems, complemented the desired pedagogy. One of the most important related
to the level of control given to educators and students over lighting and thermal comfort. This allows for the classroom conditions to be matched to specific activities and programs. For example, in one of the Type A classrooms, the teacher had the ability to override the heating and cooling system and open large windows located on two sides of the classroom. At the time, the students were engaged in an art project and were instructed to draw inspiration from the sound of the Eucalypt trees moving in the wind and the birds nesting. In this case, the synergy between sustainability and pedagogy goes beyond IEQ, to highlight the place-based opportunities to integrate Biophilia into the curriculum. Biophilia is the term used to explain human’s affiliation with nature (Kellert, 2005). In the literature there exist arguments that biophilia can strengthen student’s affinity with nature and preparedness for act with environmental stewardship (Hensley, 2015).

4.2. Tensions: Sustainability & Pedagogy

Under Version 1 of the GreenStar Education tool, the IEQ category accounts for approximately one fifth of the available points (GBCA, 2015). This highlights the important standing of IEQ performance inside learning environments, due to the potential for IEQ to impact on effective teaching and learning. As outlined above, giving users control of IEQ systems can be complementary to pedagogy. In the same vain, removing user control of IEQ systems, to enhanced sustainability, can prove detrimental to pedagogy. This was observed to be the case in research undertaken by LEaRN, which involved piloting the School Spaces Evaluation Instrument (SSEI). The case study was a newly constructed Type E learning environment – built using funding from the BER. Through the provision of a mezzanine level with clerestory windows, operable sliding doors and full height glazing around the perimeter of the space, the open plan learning environment had an abundance of daylight. However without any window treatment, the uncontrolled access to daylight created challenges with glare and reflection for educators and students when they wanted/needed to use audio-visual (AV) equipment to support a specific learning and teaching activity. Lux measurements undertaken by Cleveland and Soccio (2014) revealed that switching off the artificial lights inside the learning environment only accounted for a 29% reduction in the illumination levels on the smart board. The educators and students did not have a satisfactory way to resolve the issue and often had to resort to relocating into a dedicated space for using AV equipment, or “swivelling the board away from a specific glare spot” (Cleveland & Soccio, 2013, p.33).

There were other instances where automatic systems aimed at improving sustainability performance, created a tension with pedagogy. A Type A learning environment under evaluation by Soccio (2014), as part of the Future Proofing Schools ARC, was fitted with motion detectors for controlling the artificial lights. The teacher commented to Soccio that one of his frustrations was with the sensitivity of the motion sensor, which turned the lights off during period of low movement. However, the researchers also observed instances were educators were given full control over manual systems for IEQ, but received inadequate training and information about how to optimally use them. This was the case inside the newly constructed Type E learning environment, discussed above, which was one of the learning environments evaluated by LEaRN with the SSEI tool. The open-plan learning environment with operable sliding doors, mezzanine level and clerestory windows was designed to be natural ventilated. The only provision for cooling in summer was ceiling fans and in winter, semi-commercial space heaters. Cleveland and Soccio (2014) noted that the educators may “overlook” opportunities to optimize the building’ environmental performance “due to a lack of specific knowledge about the preferred operations of the space in different weather conditions” For example, to
encourage air ventilation, the learning environment occupants must open the clerestory windows using a motorised system activated with a button. Once open, the clerestory windows would start the convection cycle, where fresh air would be pulled through the space while less fresh, hot air rose and was expelled.

The issue was not educating the teachers about how to press the button, but instead about when to press it. Data collected about carbon dioxide levels inside the learning environment, revealed major problems with ventilation. On average, carbon dioxide levels inside the learning environment during winter exceeded the levels set out by Australian Standards 1668.2-1992 for 1000ppm, 88% of the time. For 50% of the time, the carbon dioxide levels were 1.5times AS1668.2 recommended levels; for 20% of the time, carbon dioxide levels 2 times AS1668.2 recommended levels (Cleveland & Soccio, 2013). Through observation, the researchers noted that carbon dioxide levels peaked after activities that involved students being quite active. On such occasions, it would be recommended that the educators take action be taken to increase the volumes of fresh air circulating through the space, even if this means counterintuitive behaviour, such as opening a window in winter. High concentrations of carbon dioxide in the air can reduce the effectiveness of good pedagogy, as students can experience headaches, fatigue and/or respiratory tract irritation (USEPA, 2014). Newton, et al. (2012) exposed similar problems with high concentration of carbon dioxide inside learning environments, evaluation of three BER learning environments (Type J Templates). They concluded that “the environmental systems installed needed further adjustment to ensure both temperature and carbon dioxide levels were within acceptable limits” (Newton, et al., 2012, p.200).

4.2. Agenda for Future research

The set of synergies and tensions discussed in this paper relate to observations made by the researchers during an extended period of learning environments research. The period of observation sensitized the researchers to a set of issues that were broader than those which they originally set out to understand. By providing background information and a summary of the issues, the aim of this paper is to highlight the potential more targeted research to be undertaken into realizing how tensions may be resolved and synergies leverage from, particularly in pursuit of better understanding cross disciplinary issues.

5. Conclusion

During the first decade of the 21st century there has been unprecedented change in Australian schools. Alongside a shift by educators towards the use of contemporary pedagogy, there has also been the provision of new learning environments through the BER and increased pressure on schools to integrate environmental sustainability into their infrastructure and curriculum. The intersection of these elements has created synergies and tensions between achieving desired pedagogy and sustainability goals. The synergies discussed in this paper related to the opportunities to (1) use the learning environments as 3D textbooks, which teach students about environmental sustainability through showcasing the application and use of environmentally sustainable design (ESD) features; and (2) integrate biophilic design features that strengthen the relationship between students and the natural environment, complimenting lesson plans and learning objectives. The tensions discussed in this paper related to the amount of control that users have over ESD design features, particularly those which can impact on indoor environment quality (IEQ). Two case studies highlighted how giving educators’ little-to-no control over can cause IEQ issues that prevent optimal use the space. However, a third case study highlighted that full control over the systems coupled with inadequate training can also cause IEQ issues that prevent optimal use the space.
This paper does not propose what the answers are, instead the authors have reflected on observations made during an extended period of learning environments research to advocate for more targeted, interdisciplinary research into the issues.

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Sustainable schools as pedagogical tools for environmental education

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Abstract: There has been extensive research about the association between school physical environment and children’s educational performance. However, the relationship between the sustainability of school physical environments and children’s environmental awareness via education has been rarely addressed in the literature. This paper evaluates the possible differences between the environmental attitudes and behaviours of children in schools designed for sustainability and conventional schools in Victoria, Australia. The New Environmental Paradigm (NEP) and General Ecological Behaviours (GEB) scales were employed to measure the environmental awareness of 275 grade 4-6 children in seven primary schools. Quantitative analysis was conducted to look for significant differences between the environmental attitudes and behaviours of two groups: children attending conventional schools and children attending schools assessed as being designed or refurbished with sustainability in mind. The results of the analysis indicated that there was a statistically significant difference between the two groups. Factor analysis revealed the NEP and GEB to be multidimensional scales. Considering the relationship between school design and the identified behaviour and attitude factors showed the presence of sustainability features had the greatest impact on the factor Children’s Attitudes via ESD (Environmentally Sustainable Design) at School. This result invites professionals in the built environment design disciplines to re-think the pedagogic importance of environmentally sustainable design in schools.

Keywords: Sustainably designed schools; conventional schools; children’s environmental awareness.

1. Background of the research

1.1. Environmental characteristics of school and children’s educational attainment

A large number of empirical studies have been conducted on the impact of environmental characteristics on school occupants (Colven et al., 1990; Moore et al., 1994; Hathaway, 1995; Dudek, 2000; Clark, 2002; Higgins et al., 2005). These characteristics include thermal factors, lighting quality, natural ventilation, air quality and acoustics. It has been proven that keeping these elements at an
adequate level has a direct positive effect on children’s concentration, mood, wellbeing and attainment (Woolner et al., 2007).

The physical design characteristics of schools also have an educational impact, for “student’s interaction with physical settings often becomes their primary medium for learning” (Tanner, 2000). It is believed that architecturally well-defined settings contribute to greater level of engagement of children in learning activities (Moore et al., 1994). Schneider suggests that “those involved in school planning and design should see it as an opportunity to enhance outcomes by creating better learning environments” (Schneider and National Clearinghouse for Educational Facilities, 2002). Different architectural approaches can therefore be seen to facilitate and accommodate different education styles by shaping children’s pedagogical engagement.

1.2. Sustainable school design as a pedagogical tool for environmental education

Children’s environmental attitudes and behaviours are two of the main objectives of Environmental Education (Musser and Malkus, 1994; Leeming et al., 1995; Stern et al., 2008). Literature shows that the designed environment has the potential to shape its occupants’ behaviour and also govern and support interactions between them (Weinstein, 1977). There is considerable evidence regarding the relationship between school physical settings and students’ and teachers’ behaviours and attitudes (Moore et al., 1994; Day, 2007; Durán-Narucki, 2008). Implicit in the work of Ann Taylor is the idea that visual literacy (“knowing eye”) can make the pedagogic link between sustainable design and environmental education. Designed artefacts, including buildings, are informed by an idea or concept. Occupants of a space can read these concepts and assimilate them if they are articulated. Thus, sustainable school design might have a pedagogic value, because “physical elements in the environment can act as visual cues or prompts for learning” (Wilks, 2010). Although there has been much research about the relationship between school physical environments and educational outcomes (Woolner et al., 2007; Leiringer and Cardellino, 2011), few studies have considered the impact of the sustainable school design on children’s environmental awareness (Newton et al., 2009; Uzun, 2009; Cole, 2013). Cole believes that the school building is “the largest and most visible artefact of school sustainability and one that changes less often relative to other aspects of the school environment such as curriculum” (2013). Lyons also suggests that sustainable school buildings will positively affect the overall culture of sustainability (Lyons Higgs, 2006). As such, this study investigates the potential role of sustainable school design as a pedagogical tool for children’s environmental awareness.

2. Method

Comparing the environmental attitudes and behaviours of children in schools designed for sustainability and conventional schools entailed a number of research considerations, including: differentiating sustainable schools from conventional schools, isolating the impact of extraneous variables other than school design¹, and developing appropriate scales for measuring children’s environmental attitudes and behaviours. The following sections describe each these considerations in detail.

¹ This paper reports on a part of the findings of a far larger study that considered the impact of many extraneous variables other than school design, such as parents’ environmental attitudes and behaviours, and teachers’ environmental attitudes and behaviours.
2.1. Rationale for selecting sustainable schools versus conventional schools

In order to select sustainable schools, three of the possible environmental rating methods in Australia are discussed: Green Star, The Victorian Architecture Award, and ResourceSmart AuSSI Vic. To find out which of these approaches could be the best for the purpose of this study, the advantageous and disadvantageous of each is debated.

The Green Building Council of Australia developed a Green Star environmental rating system in 2003 to encourage and evaluate sustainable design and construction in Australia with consideration of occupant health and operational cost savings. Green Star evaluates environmental performance of buildings in terms of: management, energy, water, materials, indoor environment quality, emissions, transport, land use, and ecology innovation. Although this tool has the advantage of considering encompassing essential criteria for sustainability, this is not a very popular tool among primary schools in Victoria. As such this method does not seem the appropriate method for selecting schools designed for sustainability.

The Australian Institute of Architects has run a national annual award program since 1981. Prior to entering the national level, entries are submitted by architects to be refereed by state judges. The Victorian Architecture Awards go back to 1929. After passing the Victoria state stage, winners are entered to the national pool of entries. Sustainable Architecture is one of the categories for the Australian national awards, which identifies the projects demonstrating innovative approaches to and superiority in environmental sustainability. The award winners of the sustainable architecture category of Australian Institute of Architects Award are considered exemplars of sustainable design. Although this award is well-recognized and encompass comprehensive sustainable design strategies, it was not appropriate for this study, because only two primary schools in Victoria won the award, and therefore, this award program does not provide an appropriate pool of primary schools for the researcher to select the case studies from.

Unlike previous mentioned methods for evaluating sustainability which encompass a wide range of building types, AuSSI (Australian Sustainable Schools Initiative) is a program specifically addressing schools. This initiative considers not only schools’ performance in terms of water, energy efficiency, waste and biodiversity, but also advocates a whole-school approach to sustainability from community and management points of view. ResourceSmart AuSSI Vic is a version of AuSSI contextualized for Victorian schools that aims to support schools and their communities to live sustainably. While the initiative does not directly focus on design, it helps schools embed sustainable resource consumption through a consideration of school performance in terms of water, energy, biodiversity and management; qualities that can be improved through design. Resource Smart AuSSI Vic defines the highest level of sustainability as 5stars and provides a 5star certificate for those schools that qualify (Sustainability Victoria, 2014). 5star gives schools the opportunity to show continuous improvement in their environmental performance through the five levels. This method was recognized as the most appropriate for this study, as it has lots of common criteria with the two previously described methods, which are more feasible for schools to meet. There are also large numbers of schools which have been awarded the 5Star sustainability certificate, and this makes it possible for the researcher to randomly select a few of them for the purpose of this study. Thus according to ResourceSmart AuSSI Vic, St Macartans, Epping View, and Gembrook primary schools were selected as sustainable schools. Geelong East, Rollin’s, Belmont, and St Partick’s primary schools were also selected as conventional primary
schools of this study since they did not have 5Star sustainability certificate, and consisted of old buildings constructed in the last 40 years.

2.2. Participants

Data for this study was collected from 275 students of grade four to six from seven primary schools. Of 275 children, 132 were from schools designed for sustainability and 143 from conventional schools. There were 15 children from School 1 (conventional), 31 children from School 2 (conventional), 31 children from School 3 (conventional), 69 children from School 4 (sustainable), 49 children from School 5 (sustainable), 14 children from School 6 (sustainable) and 66 children from School 7 (conventional).

2.3. Environmental attitudes and behaviours scales

In order to develop the NEP for children, which is called NEP (Children@school), the 10-item NEP for Children questionnaire developed by Manoli et al. (Manoli et al., 2007) was employed. While the NEP for Children developed by Manoli et al. covers many aspects of environmental attitudes, it lacks items specifically related to school-based learning spaces. Therefore, six items were added to develop a scale which includes environmental attitudes that have the potential to be fostered in connection with the ecologically sustainable design of the school. Some existing items were also paraphrased to make them more comprehensible for Australian children. NEP (Children@school) was tested for content and face validity, and was a five-point Likert scale from strongly disagree to strongly agree with a neutral midpoint. This scale was also subjected to principal factor analysis to identify any potential underlying dimensions. Analysis indicated that NEP (Children@school) is constituted from three dimensions: Children’s Environmental attitudes towards Human Intervention, Children’s Environmental attitudes via ESD at school, and Children’s Environmental Attitudes towards Eco-right. It is worth underlying that all of the items within ‘Rights of Nature’ factor in Manoli et al. (2007) study have fallen into ‘Eco-right’ factor in this study. Moreover, the items classified in ‘Eco-crisis’ and ‘Human Exemptionalism’ in Manoli et al. study have been classified within the ‘Human Intervention’ factor in this study with some deletions and modifications. The newly added items in NEP (Children@School) scale were grouped within the ESD at School factor. Estimate reliability of omega was calculated for all the three identified factors. Results showed that all the three factors had a respectable omega value. NEP (Children@school) could be found in appendix (Table 2).

The behaviours scale used in this thesis for measuring children’s environmental behaviours was adapted from the 8-item Evans et al. jumping game (2007), and was called GEB (Children@school). Although the content of the GEB (Children@school) was adapted from Evans et al. study, the researcher used a questionnaire with 5-point Likert type answers rather than the jumping game format that Evans et al. used. The modification applied on the Evans et al. behaviour scale included: first, re-phrasing all items so to convey school-related ecological behaviours; and, second, adding two more items. Thus, the GEB (Children@school) asks students about their actual actions in school daily life in which environmental consideration can be an issue. This scale was initially tested for the content and face validity. It was also subjected to principal factor analysis, and the result suggested that GEB (Children@school) is constituted from two dimensions of: Children’s Pro-active Eco-behaviours, and Children’s Environmental Behaviours towards resource and energy Conservation. Omega, as the measure of reliability, was calculated for each of the two identified factors, and results indicated that both of the factors had a respectable reliability estimates. GEB (Children@school) could be found in the appendix (Table 3).
3. Analysis

Employing multivariate analysis of variance (MANOVA), this study investigates the possible significant differences in children’s environmental attitudes and behaviours in schools designed for sustainability and conventional schools. This test was expected to answer the following questions:

- Do children in schools designed for sustainability differ with children in conventional schools in terms of their environmental attitudes and behaviours?
- Are children in schools designed for sustainability better adjusted than children in conventional schools in terms of their Attitudes towards Human Intervention, ESD at School, and Eco-rights, their Pro-active Eco-behaviours, and Resource and Energy Conservation Behaviours?

In order to answer these questions, the impact of other probable influential variables such as curriculum needed to be isolated. Because of the ‘centralization of control over curriculum through the National Curriculum in Australia (Palmer, 2002), the potential influences of contrasting curricula between the schools was discounted.

Preliminary analysis confirmed that no serious violation of the assumptions of normality, outliers, linearity, multicollinearity and singularity, and Homogeneity of variance-covariance matrices was noted. One-way between groups MANOVA was conducted to evaluate the impact of School-design on Children’s Environmental Attitudes towards Human Intervention, Children’s Environmental Attitudes via ESD at School, Children’s Environmental Attitudes towards Eco-rights, Children’s Pro-active Eco-behaviours, and Children’s Environmental Behaviours towards Resource and Energy Conservation.

Analysis output indicated that there was a statistically significant difference between children in schools designed for sustainability and children in conventional schools on the combined dependent variables, $F (5, 269) = 28.14, p = .000$; Pillai’s Trace = .343; partial $\eta^2 = .343$ (Figure ). As the significant result was obtained in this stage, further investigations determined whether children in schools designed for sustainability and children in conventional schools differed on all of the dependent variables (Children’s Environmental Attitudes towards Human Intervention, Children’s Environmental Attitudes via ESD at School, Children’s Environmental Attitudes towards Eco-rights, Children’s Pro-active Eco-behaviours, and Children’s Environmental Behaviours towards Resource and Energy Conservation), or only some of them. When the result for the dependent variables were considered separately, using Bonferroni adjusted alpha level of 0.01 (Pallant, 2013), all the dependent variables except Children’s Attitudes towards Eco-right reached statistical significant difference: Attitudes towards Human Intervention, $F (1, 273) = 14.552, p = .000$, partial $\eta^2 = .051$; Attitudes via ESD at School, $F (1, 273) = 103.333, p = .000$, partial $\eta^2 = .275$; Pro-active Eco-behaviours, $F (1, 273) = 35.553, p = .000$, partial $\eta^2 = .115$; and Resource and Energy Conservation Behaviours, $F (1, 273) = 42.569, p = .000$, partial $\eta^2 = .135$. School-design appeared to be more associated with Children’s Attitudes via ESD at School, representing 27.5% of the variance in this variable which is considered a large effect size (Cohen, 1988), compared to Attitudes towards Human Intervention (5.1%) with a medium effect size, Pro-active Eco-behaviours (11.5%) with a large effect size, and Resource and Energy Conservation Behaviours (13.5%) with a large effect size.
Although it was clear that children in schools designed for sustainability and children in conventional schools significantly differed in four variables of environmental attitudes and behaviours, the mean scores were compared to determine which type of school had higher scores and for which dependent variable. The results suggested that children in schools designed for sustainability reported higher levels of Environmental Attitudes and Behaviours in all of the significant dependent variables as summarized in Table 1:

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Schools designed for sustainability</th>
<th>Conventional schools</th>
</tr>
</thead>
<tbody>
<tr>
<td>Children’s Environmental Attitudes towards Human Intervention</td>
<td>M=3.54, SD=.725</td>
<td>M=3.17, SD=.884</td>
</tr>
<tr>
<td>Children’s Environmental Attitudes via ESD at School</td>
<td>M=4.45, SD=.631</td>
<td>M=3.44, SD=.958</td>
</tr>
<tr>
<td>Children’s Pro-active Eco-behaviours</td>
<td>M=3.35, SD=.951</td>
<td>M=2.67, SD=.943</td>
</tr>
<tr>
<td>Children’s Environmental Behaviours towards Resource and Energy Conservation</td>
<td>M=4.32, SD=.617</td>
<td>M=3.77, SD=.768</td>
</tr>
</tbody>
</table>

4. Discussion and conclusion

Figure 2 illustrates that School-design is most associated with Children’s Attitudes via ESD at School, and can explain 27.5% of the variance in this dependent variable, which is considered a large effect size (Cohen, 1988). This result invites professionals in design discipline to re-think the importance of environmentally sustainable design in schools.

Interestingly, the mean scores of Children’s Environmental Attitudes towards Human Intervention, Children’s Pro-active Eco-behaviours, and Children’s Environmental Behaviours towards Resource and Energy Conservation were also significantly different in schools designed for sustainability and conventional schools. This implies that School-design have a determinant role in most of the identified
factors of children’s environmental awareness, and thus, is worthy of attention if we are to educate children with pro-environmental inclinations. Further analysis to understand the differences between the two types of schools indicated that schools designed for sustainability outperformed the conventional schools in all of the significant dependent variables (Figure 3). In other words, children in schools designed for sustainability better adjusted than children in conventional schools in terms of their Attitudes towards Human Intervention, ESD at School, Pro-active Eco-behaviours, and Resource and Energy Conservation Behaviours.

Figure 2: The percentage of the variance in dependent variables that could be explained by school-design.

Figure 3: Mean differences of the dependent variables for children in two types of school-design.
The effectiveness of sustainably designed schools as teaching tools has been looked at from different discipline perspectives. Some educationalists, environmentalist, and architects believe that sustainable school buildings, also known as ‘green’ school buildings, will positively affect the overall culture of sustainability (Lyons Higgs, 2006). It is claimed that “sustainable architectural design of the schools can be an important aspect in raising educational standards or altering the perception of a school” (Edwards, 2006). It is also believed that buildings with a low environmental impact provide a unique teaching opportunity (Newton, Wilks, & Hes, 2009). Moreover, Cole suggests that the school building is “arguably the largest and most visible artefact of school sustainability and one that changes less often relative to other aspects of the school environment such as curriculum” (2013). Thus, the physical environment of a school has been referred to as a three-dimensional textbook (Taylor & Enggass, 2009), or silent curriculum, which might not be palpable but which can effectively lead to positive or negative environmental experiences.

Some departments have been directly involved in promoting school buildings and grounds as tools for sustainability education. The Department for Children, Schools and Families, UK, recommend a number of ‘doorways’ for change for schools to become sustainable by 2020. Alongside ‘energy’, ‘water’, ‘travel and traffic’, ‘inclusion and participation’, etc., there is a ‘buildings and grounds’ category that encourages schools to manage and design their buildings and grounds to visibly represent sustainability. Such design is intended to create a connectedness to the natural world for pupils, giving them “the chance to contribute to sustainable living, and demonstrate good practices to others” (Department for Children, 2008). It can also “symbolize the school’s commitment to sustainability in a unique way” (Cole, 2013).

It is worth underlying that this paper reports on the findings of a far larger study that not only considered the role of School-design, but also considered the influence that parents’ and teachers’ environmental attitudes and behaviours might have on children’s environmental attitudes and behaviours. The results of this larger study suggest that School-design is the most powerful predictor of children’s environmental attitudes and behaviours compared to parents’ and teachers’ environmental attitudes and behaviours. As such, and because an individual’s environmental attitudes and behaviours is moulded by many variables, it is suggested that future researchers measure other potential influential variables such as the socio-economic situation of children’s families, older sibling’s role modelling, and the physical context of schools (such as proximity of natural environments and parks).

References


## Appendix:

### Table 2: NEP (Children@School).

<table>
<thead>
<tr>
<th>Scale item</th>
<th>Three identified factors for NEP (Children@School)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10. If things don’t change; we will have a big disaster in the environment soon.</td>
<td>Human Intervention</td>
</tr>
<tr>
<td>9. People will someday know enough about how nature works to be able to control it.</td>
<td></td>
</tr>
<tr>
<td>5. When people mess with nature it has bad results.</td>
<td></td>
</tr>
<tr>
<td>3. People are clever enough to keep from ruining the earth.</td>
<td></td>
</tr>
<tr>
<td>8. People are treating nature badly.</td>
<td></td>
</tr>
<tr>
<td>2. There are too many people on earth.</td>
<td></td>
</tr>
<tr>
<td>11. I would be willing to go to a school which has a focus on nature.</td>
<td></td>
</tr>
<tr>
<td>12. I believe that artificial light in classrooms should be generated by solar panels.</td>
<td>ESD at School</td>
</tr>
<tr>
<td>14. I would be willing to grow food in the school garden.</td>
<td></td>
</tr>
<tr>
<td>15. I feel more connected with nature when classes are held in outdoor spaces.</td>
<td></td>
</tr>
<tr>
<td>16. It makes me feel better when we have natural day light rather than artificial light all day in classrooms.</td>
<td></td>
</tr>
<tr>
<td>4. People must still obey the laws of nature.</td>
<td>Eco-Rights</td>
</tr>
<tr>
<td>6. Nature will survive even with our bad habits on earth</td>
<td></td>
</tr>
<tr>
<td>7. People are supposed to rule over the rest of nature.</td>
<td></td>
</tr>
<tr>
<td>1. Plants and animals have as much right as people to live.</td>
<td></td>
</tr>
</tbody>
</table>

### Table 3: GEB (Children@school).

<table>
<thead>
<tr>
<th>Scale item</th>
<th>Two identified factors for GEB (Children@School)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-I participate in recycling activities at School.</td>
<td>Pro-active Eco-behaviours</td>
</tr>
<tr>
<td>2-I work in the school garden with teachers.</td>
<td></td>
</tr>
<tr>
<td>7-I look at books about the environment (nature, trees, and animals).</td>
<td></td>
</tr>
<tr>
<td>4-I pick up litter left behind by my friends during recess and lunch breaks.</td>
<td></td>
</tr>
<tr>
<td>10-I don’t turn on the classroom lights because there is always enough light in my classroom.</td>
<td></td>
</tr>
<tr>
<td>8-I leave the class window open while the heater is working.</td>
<td>Resource and Energy Conservation</td>
</tr>
<tr>
<td>5-I forget to turn off water after washing my hands in the school toilets.</td>
<td></td>
</tr>
<tr>
<td>6-I bring too much food to school and I have to throw away the extra food.</td>
<td></td>
</tr>
<tr>
<td>9-I turn on the air conditioner rather than opening the glass window when it is warm inside.</td>
<td></td>
</tr>
<tr>
<td>3-I forget to turn lights off when I leave a classroom.</td>
<td></td>
</tr>
</tbody>
</table>
The NSW demountable classroom: an analytical study to improve this radical building solution for education

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Abstract: The NSW demountable classroom continues to fulfil the function it was designed to fulfil and is radical because, unusually, it has always been capable of adaption. However in recent years aspects of the system have become obsolete. The technology exists to adapt it and turn it into a high performance building typology. This paper adopts a qualitative methodology based on the Building Performance Research Unit’s (BPRU) concept of buildings as a series of open systems. Using contemporary documentary evidence, open ended structured interviews and detailed physical inspections the first part of the paper shows that the demountable classroom has played and continues to fulfil an important and significant role in the provision of teaching accommodation across the state as it was originally designed to do. The second part of the paper considers the changing perception of the demountable classroom in the context of the concept of obsolescence. The paper concludes by showing that the demountable classroom was and remains a radical building solution, that is mistakenly maligned, and offers the communities and government of New South Wales an opportunity to develop a high performance, adaptable and low carbon piece of education infrastructure.

Keywords: Demountable classrooms, obsolescence, building performance.

1. Introduction

This paper adopts a qualitative methodology based on the Building Performance Research Unit’s (BPRU, 1972) concept of buildings as a series of systems with a social purpose within a larger social context. The analysis uses various sources of data including contemporary documentary evidence, open ended structured interviews, detailed physical inspections and the parliamentary record of political debate, Hansard (Hansard NSW).

Demountable classrooms account for 12% of all government classrooms in NSW. A detailed literature search by the authors outlined in previous papers has not found a detailed study of the building performance or internal environmental quality (IEQ) of demountable classrooms in NSW or more generally across Australia, and limited international research into the performance of demountable classrooms (Slee and Hyde, 2014; Slee et al., 2014a; Slee and Hyde, 2015).
In the first part of the paper an analysis of the data shows how the classroom system has played a consistent and important role in allowing a succession of governments to implement new policies in response to changing demographics, new pedagogical theories and the corresponding expectations of the population. The analysis also shows how, despite the stated need for and purpose of the demountable classroom system remaining constant, the communities’ perception of the demountable classroom has changed from being innovative to inadequate.

The second part of the paper considers this change in perception in the context of Pinder and Wilkinson’s (2000a) concept of building obsolescence, the gap between design intent and user expectations and the implications for the perception of utility.

The paper concludes by showing that the demountable classroom system was and remains a radical building solution that offers the communities and government of New South Wales an opportunity to develop a high performance, adaptable and low carbon piece of education infrastructure. The critical issues that must be addressed for this opportunity to be realised are identified.

2. Research framework

Buildings are an intrinsically complex system and exist within other complex environmental and social systems. The framework proposed by the BPRU (1972) provides a strategy for understanding, categorising and evaluating the sub- and meta- systems that come together to create the whole.

![Figure 1: The Building Performance Research Unit framework of systems.](image)

The BPRU framework defines five categories of “system” (Figure 1), the first three of which can be thought of as “Operative Systems” and the last two as “Evaluation Systems”. The Operative Systems are the “Building System”, “Environmental System” and “Activity System”. The Building System deals with the fabric of the building and the method of construction, manufacture and deployment. The Environmental System covers the strategies that are designed to create a comfortable internal environment. The Activity System are the activities that take place in the building, in this case teaching and learning.

The Evaluation Systems evaluate the Operative Systems in terms of the purpose of the building as a social entity, the “Objective System”, and the means used to meet those objectives, the “Resources System”. Thus the framework creates a means of understanding the economic, social and environmental value of the building. This paper follows this approach to analyse the existing demountable classroom and identify a pathway to improving this radical building typology.
3. Objectives system: a continuous need and purpose

The description of the need for, and purpose of, the demountable classroom system in NSW has remained constant over the five decades that they have existed. In his pamphlet describing the changes and advances in the design of NSW schools between 1962 and 1972 Underwood (1972) explains that the new “divisible classroom” was designed by the Department for Public Works in 1965 “[to provide]

- virtually instant accommodation
- temporary facilities in special areas
- augmentation of existing schools
- a convenient means of adding to and later subtracting from existing schools.”

Today the NSW Department for Education statement on Demountable classrooms (NSW Government, 2014) explains that the purpose of the demountable is to:

- provide accommodation for peak enrolments
- meet accommodation needs in schools from increased enrolments
- meet emergency needs as a result of fires or natural disasters
- meet needs arising from capital works or maintenance projects in schools.

The interviewees tell a similar story, over the 35 years of their collective experience, explaining that the need for and purpose of the NSW demountable classroom has been and remains the provision of emergency accommodation and accommodating fluctuating school populations.

**Government education policy’s effects on the demand for classrooms**

Government policy has been facilitated by the availability and utility of the demountable classroom system. Over the last 50 years a succession of policy decisions have increased the number of classrooms needed in schools. In 1961 the Wyndham report was published and became the Education Act of 1962. The act increased the school leaving age by a year to 16 years old and expanded the number of subjects to be taught to create a broad liberal education for pupils of all abilities. In 1979 the Government cited the continuing drive to reduce class sizes as a reason for increasing the use of demountable classroom buildings (Hansard14/08/1979). Between 2004 and 2007 the Government instigated a specific policy for reducing the size of classes in Kindergarten, year 1 and year 2 to 20, 22 and 24 pupils respectively. In 2012 the school leaving age was raised further to 17 years old increasing the compulsory years at secondary school from 4 to 5. Each of these policy changes significantly increased individual school populations.

Pedagogy has also changed significantly since the demountable school was originally introduced from a “chalk and talk” approach, led by a teacher instructing pupils sitting in rows, to a student led approach to learning that requires “break out” spaces for group work and more traditional class arrangements for instruction. The development of pedagogy has led to the need for larger more flexible classrooms to accommodate the new teaching methods.

**Demographics**

The initial driver for developing the rapidly deployable classroom was the rapid growth in the NSW population between 1945 and 1971/72 and the corresponding growth in school populations. Associated with the growing population was the risk and later the reality of changing demographics within suburbs.
as young families matured. Burkhardt (1980) explores this problem in his thesis “Planning for the provision of school facilities in new communities in New South Wales” in which he illustrates that peak enrolment of a school is likely to be substantially higher than the long term average. Burkhardt compared the changing school demographics in areas of public housing projects and private housing developments. His data shows that in private housing developments, with considerably more diverse types of household than public housing projects in the 1970’s, it may take 15 years for the population of a new school to reach its peak and more than 25 years for the schools population to stabilise around the long term average.

When the rate of overall population growth in NSW became considerably more moderate after about 1980 the challenges raised by changing demographics in suburbs continued and have been raised regularly in the NSW Parliament. Examples include the development of complete demountable schools in Bateau Bay, Lake Maquarie in 1977 (Hansard24/03/1977), Baulkham Hills in 1979, and more recently in Chatswood (Interviewee E). In 1983 the construction of the Earing power station in Morisset led to a sudden increase in the local school population and the use of demountables (Hansard 01/12/1984).

The challenge of fluctuating populations and demographics is illustrated by a debate in parliament in 1989 about the closure of public schools in Mosman where the local school was no longer sustained by the changing demographic of the local population. According to the debate 197 schools were closed across NSW between 1976 and 1988 (Hansard 11/04/1989).

Core plus schools

In the 1970’s, 80’s and 90’s the NSW government had a policy of developing “core plus” schools where about 60 or 70% of the school is built as permanent facilities and 30% of classrooms are demountable (interview B) (Underwood, 1972). The concept allows teaching capacity in these schools to be adjusted rapidly to accommodate changing demand.

Emergency needs

There are many examples of demountable classrooms providing the NSW Government with school accommodation following arson, accident or natural disaster. The NSW Government maintains an entire demountable school in reserve for use in emergency situation such as these (interview D).

4. Building system: construction

Classrooms consist of 4 or 5 units approximately 8.8m (L) x 2.4m (W) x 3.3m (H). One of the primary objectives for the design of the demountable classroom system is that the units should be easy to transport. The primary objective of the design was to provide a rapidly deployable and easily transportable classroom building (Underwood, 1972). This leads to a number of key design decisions based on

- Maximum dimensions permissible for road transport without an escort
- Maximum transportable weight and deployment weight
- Deployment method
- The need for a robust modular construction system

This means that they should be robust and relatively light leading to the use of lightweight framed construction. The original drawings and the physical survey of both the mk 1 and mk 2 classroom
designs show limited insulation, well below the current statutory regulations, and considerable thermal bridging through the primary and secondary steel frames. The primary frame of the Mk. I and Mk. II classrooms is a substantial steel frame described by interviewees as “bomb proof” (Interview A). The maintenance programmes at Cessnock and Golburn jails (Corrective Services Industries) strip the old classrooms back to the primary frame and rebuild them.

**Deployment method**

The original proposal for deploying Mk. I classrooms was to use jacks (Underwood, 1972). This strategy has been superseded by the use of cranes. Mk 1 classrooms were designed without lifting points and so chain slings are used under the roof overhangs. Mk. II classrooms were designed with lifting points attached to the top of the vertical steel posts. Recently a policy of modifying the Mk I classrooms to add lifting points has been implemented. These are additional steel flanges welded to the existing frame during substantial refurbishment exercises.

**Modular construction**

The demountable classroom system has been conceived as a modular system at the macro and micro level. At the macro level classrooms, libraries and office buildings can be delivered to any site in NSW to create an entire school or augment existing schools. The classrooms themselves are made from 4 units and the walls in each unit are made from a variety of wall modules designed to accommodate the various functions the system is intended to accommodate. The Mk II panels were designed to facilitate the rapid interchange of panels and the adoption of buildings. In practice wall panels are rarely changed, typically only during substantial refurbishment work.

The ambition to create a system of interchangeable building modules was also thwarted through perhaps the most mundane of processes: The classroom modules are fixed together by bolted connections through steel plate flanges on the outside of the classrooms. For expediency and ease of installation on the initial site these were drilled and bolted on-site during the first deployment of a unit (Interview C/Observation), a very practical approach by the installation team that ensured that the holes on each adjacent classroom unit lined up. Unfortunately this has resulted in a situation where only the modules placed together during the first deployment have holes that line through so each classroom unit can only ever be erected in its original configuration!
5. Environmental system

Internal comfort does not appear to have been a priority objective in the original design brief. The lightweight poorly insulated building fabric is unsuitable for creating an “acceptable” internal thermal environment, particularly in the more extreme climates away from the NSW coast. Buildings that are constructed using lightweight construction systems closely follow, or exceed, the external diurnal temperature profile (Pearlmutter and Meir, 1995; Sugo, 2009; Cardinale et al., 2010).

Originally three passive strategies were employed to try and maintain comfort inside the classroom: shading the windows, considerable opportunity for cross ventilation through opposing opening windows and the use of fly roofs in particularly hot climates. Shading also reduces internal glare. In 2003 active environmental control was introduced to all demountables (Hansard 8/09/2003) and has superseded the fly roof. The current specification of the AC systems is two 6.5KW split cycle systems per classroom.

6. Resources system

Buildings have a local and global environmental cost as well as an economic cost. At a local level the simple pad foundations mean that there is a minimal disruption to the local flora and that when the building is removed the site quickly returns to its natural state. The rapid installation and removal also benefits the school and local community by obviating the need for a construction site.

The lightweight construction is relatively low in embodied energy although no doubt it can be reduced further. The robust construction and the ability to relocate the classrooms means that the resources embodied in the classrooms benefit multiple communities and reduces the under-utilisation of and associated redundancy in the State’s education infrastructure. The NSW government owns around 6000 of these classrooms. Assuming conservative construction cost of about $3,000/sq.m the equivalent permanent classroom would cost about $240,000 so the 6,000 demountables (NSW Government, 2014) the government owns represent considerable value on the basis of a replacement cost.

7. Value: societies’ changing expectations

Community’s expectations of how and in what condition their children are educated have changed over the 50 years the demountable classroom has existed. Society’s understanding of developments in pedagogy and our understanding of the significance of comfort is informed by experience, debate in the media, significant reports from government and universities, and political debate within and with governments. This discussion has led to a reduction in class sizes and a move to child led learning. As one interviewee observed: “a 21st century classroom is unrecognisable compared to a 20th century classroom” (Interview E).

In the 21st century the community expects the process of education to be interactive and engaging rather than being passively received and absorbed by rows of children. This new approach to the process of educating children places new demands on the spaces used for educating children.

Thermal expectations have also changed. A number of interviewees suggested that the provision of air-conditioning in classrooms is expected rather than considered to be the exception (Interviews B, C) as air-conditioning use in homes and other places has increased. A finding also observed in research by de Dear et al (2014). In the 17 years between 1994 and 2011 the use of mechanical cooling systems in Australian households changed from being the exception, 32% (Australian Bureau of Statistics, 2010) to common, 73% (Australian Bureau of Statistics, 2011).
The issue of temperature in demountable classrooms was first raised in parliament in 1980 by an MP praising the facilities at the Bateau Bay Demountable Primary School but observing that “heat in the classrooms in the summer causes problems” (Hansard 24/11/1980). In 1984 an Adjournment Debate was held in parliament concentrating on the possibility that poor indoor environmental quality (IEQ) could disadvantage the children and teachers who are trying to learn and teach in those spaces (Hansard 02/05/1984). Later the same year the MP for Hawkesbury suggested that

“The higher range of temperatures creates conditions in which primary and infant schoolchildren cannot continue to learn and receive the benefit of their schooling.” (Hansard 02/05/1984).

In 2002 Professor Vinson highlighted the issue of temperatures in demountable classrooms in his report on the provision of public education in NSW (Vinson et al., 2002). In 2003 the Government announced that all demountables would be fitted with air-conditioning.

8. The concept of obsolescence

Burton (1933) and more recently Pinder and Wilkinson (2000a) argue that the criteria for the assessment of building performance changes through time as our expectations and society adapt to improvements in construction methods and new technology. They suggest that buildings that continue to meet the objectives they were designed to fulfil may become obsolete because the objectives are no longer aligned to the expectations of the communities they were designed to serve: “Occupant expectations are the essential characteristic of obsolescence” (Pinder and Wilkinson, 2000a).

Pinder and Wilkinson (2000a) argue that buildings are utilities rather than assets and that obsolescence is a measure of their changing usefulness (utility) over time. Following Burton (1933), Pinder and Wilkinson (2000b) argue that there are two classes of causation for obsolescence:

- Locational (extrinsic) causes (e.g. changing demographics, population movement or density and changing climate)
- Building performance (intrinsic) causes (e.g. the thermal performance of the building)

Perception of quality: dawning obsolescence

When the first demountables were introduced they were regarded as a high quality modern innovation. The design won a Certificate of Merit in the Prince Philip Awards for Australian Design in 1968. In 1976 the then Minister for Education countered concern about demountables calling them “excellent accommodation” (Hansard 11/11/1976) and later “of first-class quality.” (Hansard 01/12/1976)

In 1984 an Adjournment Debate was held in parliament suggesting that poor indoor environmental quality (IEQ) could disadvantage the children and teachers (Hansard 02/05/1984).

In 2002 Professor Vinson (Vinson et al., 2002) dedicated an entire chapter of his report “Inquiry into the provision of public education In NSW” to the significance of the built environment on the quality of education and academic achievement in schools. The report explains that

“the quality of school buildings and their surrounds can also be a potent symbol of the regard (or otherwise) in which public education is believed to be held by governments and the community”

In a section dedicated to the demountable classroom he notes that
“Demountables have been the subject of incessant criticism throughout the Inquiry. …[in] the absence of air conditioning they are too hot; …. their insubstantial character detracts from the appearance and confirmed identity of a school.”

Using Pinder and Wilkinson’s categorisation of obsolescence the relocatable classroom was specifically designed to avoid the locational, extrinsic causes of obsolescence by being relocatable, possibly with the exception of tight inner city sites (interview E). The second-class, intrinsic building performance causes, have been shown to be a fundamental problem for the building typology.

Over 50 years the demountable classroom has moved from being perceived as a design innovation to “a pejorative” (interview B). They are widely perceived as providing second class teaching accommodation. this is a view exemplified by a debate in the NSW parliament in 2003 with a motion calling for the House to acknowledge “that the learning environment of a permanent classroom in regional New South Wales is a better learning environment than a demountable classroom.” (Hansard 8/09/2003).

The community’s changing perception of what is an acceptable thermal environment and our increasing knowledge of the importance of internal environmental quality (IEQ) on the efficacy of teaching and learning (Mendell and Heath, 2005) appears to be the primary cause of the perception that the demountable classroom is sub-standard or obsolete. Tight urban sites and the flexibility of the classroom spaces are two other issues that may lead to a degree of obsolescence.

9. Opportunities for adaption: a high performance building typology

The concept of obsolescence is implicit in the BPRU framework of operative systems and evaluation systems. The work of Pinder and Wilkinson makes this explicit and highlights opportunities for positive change within the meta-system framework to improve the operation of the building in response to changing social expectations, the evaluation systems. Kieran and Timberlake (2004) and Richard (2006) have argued that the industrially produced relocatable building systems provide a more economic construction method and a solution to obsolescence through relocation and adaption. More recent work on sustainable retrofitting (Hyde et al., 2012) highlights the opportunities for improving the performance of buildings by replacing elements of the building, for instance the cladding and glazing systems, that have become obsolete with new higher performance elements. For the majority of buildings this process is disruptive. What is perhaps unique about the NSW demountable is that it has been designed to, and demonstrated over 50 years, the ability to facilitate this approach by allowing the building unit to be removed and replaced on its site while the unit requiring adaption is modified in an industrial setting elsewhere: Currently the socially progressive rehabilitation and training programs operated by the NSW Corrective Services industries at Golburn and Cessnock Jails.

To date the NSW demountable program classroom has utilised the opportunity to relocate, re-use and refurbish but appears to have largely ignored the opportunity for adaption. The limited adaptive opportunities that have taken place include the addition of air conditioning from 2003, the addition of lifting points and an improved roof and gutter system.

A review of the original drawings shows that the classroom system was designed to be flexible including such recent innovations as the movable acoustic partition and walls that open to create inside/outside teaching spaces. The substantial steel frame may not have been designed for stacking classrooms on tight urban sites but may well be capable of supporting stacking classrooms with the
addition of an appropriate connection system. The substantial structural frame, previously described as “bomb proof”, offers opportunities for fixing other adaptive strategies.

Thermal performance is a more challenging problem. Recent quantitative analysis by the authors (Slee and Hyde, 2015) found that the largest thermal energy input is from the incident solar radiation. The analysis predicted that the internal conditions are, overall, warmer than the external conditions during occupied hours in all NSW climates. Interestingly the analysis also showed that the thermal flux, that is the direction of heat energy transfer, during occupied hours was from inside to outside through the opaque fabric and from outside to inside through the glazing. A review of existing research (Slee et al., 2014a) suggests that developing climate adaptive solutions for the diverse climates of NSW is possible and that a number of researchers have investigated strategies that are applicable. Passive strategies for avoiding external solar gains include the use of ventilated facades (Ciampi et al., 2003) and ventilated roof cavities (Gagliano et al., 2012) which have been shown to reduce cooling requirements by up to 50%. Internal gains from ventilation and activities can be moderated through the appropriate use of thermal mass (Slee et al., 2014b). Phase change materials can be used to provide a relatively lightweight alternative to thermal mass (Memon, 2014). La Roche and Milne (2004) have also shown how a combination of thermal mass, shading and an intelligent ventilation strategy can significantly improve the thermal performance of a space. An interesting study by Cardinale et al (2010) demonstrated how a ventilated roof combined with PCM and a ventilation strategy significantly improved the performance of a lightweight campervan.

10. Conclusion: a radical building

The demountable classroom system was originally designed in 1965 and now, 50 years later, these same buildings are still widely used to achieve the original objectives. They are, however, regarded by many as obsolete. What is remarkable is that while examples of relocatable buildings existed in 1965, most notably from the second world war and its aftermath (Underwood, 1972), the implementation of an industrially produced and adaptable solution was radical and remains radical today. This paper has shown that the NSW demountable classroom system provides the NSW population with an economically, socially and potentially environmentally efficient building system for the State’s schools that remains radical. The paper proposes the development of new adaption strategies to improve the thermal performance and flexibility of the building using quantitative and qualitative analysis to inform the design approach and create a high performance building typology that leads building design in the 21st century.

References


The physical and social aspects of retrofitting passive cooling strategies to timber school buildings and their surrounds in South East Queensland

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**Abstract:** Overheating is a problem in existing timber classroom buildings in South East Queensland. In a case study school passive cooling strategies were retrofitted to six classroom buildings and their immediate surrounds between 2012 to 2014: _stack ventilation, cool roof, shade sails over courtyards and schoolyard greening_. This research project investigates how effective the strategies are in reducing heat inside the classroom by analysing quantitative data (classroom temperature) and qualitative data (perceptions of Teachers and Principal). This paper reports how the research project began and the results of applying an overheating analysis metric to the classroom temperature across summer terms, with inconclusive results. Uncontrolled variables such as climatic factors and building use are discussed. Another strategy being investigated is the range of _adaptive actions_ Teachers engage in to reduce thermal discomfort from heat. The Teacher is regarded as the main occupant with control of the classroom environment. Understanding the current range of adaptive actions teachers engage in, especially in naturally ventilated classrooms, could provide an understanding of low energy _social practices_ in the school. This research aims to synthesize quantitative data with qualitative data to assess the effectiveness of the passive cooling strategies and create informed recommendations to increase adaptive actions within classrooms towards a low-carbon occupation of existing classrooms.

**Keywords:** Overheated classrooms; passive cooling; thermal discomfort; adaptive actions.

**1. Introduction**

Overheating is a problem in existing timber classroom buildings in South East Queensland (SEQ). Over a sunny week in November 2012 in a case study school in Brisbane, classrooms in six buildings were observed to be 3°C warmer than the maximum daily temperature for the entire afternoon. A common twentieth century solution to achieving thermal comfort for overheated houses, offices or schools in Australia, is by installing air-conditioning (Roaf et al 2010). Currently in Queensland, schools in the north and west of the State are air-conditioned in accordance with the Department of Education and Training’s (DET) policy. For schools in SEQ (defined here as the area from Noosa in the north to the New...
South Wales border in the south and west to Toowoomba) the decision to install air-conditioners is at the School Principal’s discretion and funded by the school budget and/or funds raised by the school’s Parents and Citizens Association (P&C). In the case study school, the school community decided not to install air-conditioning to the school, preferring to first fund other strategies to reduce heat to classrooms. The older timber buildings in the school are a good example of the Sectional School type, the dominant type built in Queensland between 1920 and 1950 (Burmester, Pullar, Kennedy 1996). The author is an architect experienced with designing buildings for the sub-tropics and tropics and developed a number of passive cooling strategies for the school in consultation with the P&C and the School Principal.

The author recognised a unique research opportunity in the school as a case study. The research project describes the design and implementation of passive cooling strategies in the school and considers the social and organizational context within which this has taken place. All strategies needed to be of low capital cost, have little or no running costs, suitable for retrofitting into timber buildings and cause minimal disruption to normal operations within the school. Fitting within these criteria the strategies, if effective, have potential to be rolled out to similar schools.

DET is interested in the research as it could contribute to reducing energy use in schools. An increasing amount of air-conditioners installed in schools in recent years have had an adverse impact on the overall state government budget for schools. Up until recently this school had all naturally ventilated classrooms, in 2010 and 2014 there have been air-conditioners installed to some classrooms. As the Principal has commented, there is increasing pressure from some teachers that their classrooms should be like other workplaces; all air-conditioned. Also some parents, as represented by the Queensland P&C Association, consider that the state government should fund ‘basic infrastructure’ such as air conditioning for classrooms in state schools (ABC 2014). This social context increases the complexity of the problem of finding other ways to reduce heat in classrooms than using air-conditioners, considered in the wider global need to transition to a low-carbon society (Shove et al 2008)(Swan and Brown 2013).

Between 2012 and 2014, four passive cooling strategies were developed and implemented to the case study school: Stack Ventilation; Cool Roof; Shade Sails over courtyards and Schoolyard Greening (or increasing vegetation to surrounds). Another strategy being investigated is the role of occupants in adapting their classroom environment to reduce heat perceived by them (Nicol et al 2012). The research takes the viewpoint that the teacher is the main occupant with control over the classroom environment. Previous thermal comfort studies that have investigated adaptive actions of school children resulted in low participation by the children to adjust their environment to suit their comfort; this was attributed to either having restricted spontaneous movement in the classroom to due to discipline codes (Bernardi 2006) or teachers’ preferences (De Guili et al 2012). Understanding the current range of actions that teachers engage in to reduce their thermal discomfort, especially in naturally ventilated classrooms, could lead to a better understanding of social practices in the school (Moloney and Strengers 2014). This research project aims to synthesize classroom temperature (quantitative data) with perceptions of occupants (qualitative data) to assess the effectiveness of the passive cooling strategies, to inform recommendations that increase adaptive opportunities and behaviours within classrooms, and reduce the use of air-conditioning (Kim et al 2013) (de Dear et al 2014).
2. The case study school

2.1. Brisbane location and climate

The case study school is located 6km from Brisbane City in a suburban environment. Brisbane (Latitude 27.4° S Longitude 153.1°E) has a subtropical climate with warm humid summers and mild dry winters (Cfa under Köppen climate classification). Maximum and minimum temperatures logged at the school on outside logger I(ext) are plotted in Figure 1. Extreme weather events that occur in Brisbane are tropical thunderstorms and heat waves. Occupants regard summer thermal discomfort as a greater concern than winter coolness, which can be adapted to with extra layers of clothing.

Figure 1: Adaptive comfort zone, daily max and min outdoor temps at the school 2014.

2.2. Description of school occupancy

The school is a state primary school (Prep to Year 6) with a population of 850 children in 34 classes. Classrooms of the case study buildings are occupied by 37% of the children at the school. These classrooms were anecdotally reported as being the warmest in the school and measured to be 3°C warmer than outside over a sunny week in November. During 2014 Building R, Admin and Staff Buildings I and E had air-conditioners installed. Building H had air-conditioners installed to upper classrooms in 2010 due to construction noise and dust of Building R requiring closed windows (Figure 2).

The Queensland school year has four terms, ten weeks each. Summer terms are Term 1 (late Jan to early Apr) and Term 4 (mid-Oct to mid-Dec). In 2014 there were 197 days, Monday to Friday starting 5 minutes before 9.00am to 3.00pm. During the day children move in and out of their classroom to outside, for two breaks and to attend specialist subjects in other locations in the school.
2.3. Sectional school type

The older timber buildings in the school are a good example of the Sectional School type, the dominant classroom type built in Queensland between 1920 and 1950. The first building (B) was built in 1929 and subsequent buildings added over the next decade (A, C, D, F) in a radial layout connected by verandahs. In a 1996 conservation study of Queensland Schools out of 2000 schools, only under fifty of them had brick buildings (Burmester, Pullar, Kennedy 1996). Among the 1327 state schools currently open in Queensland there are 754 schools established from 1871 to 1950 (DETE 2013). Between 1920 and 1950 the 160 Sectional Schools were established. Classroom buildings up to 1960 were all typically constructed of timber elevated off the ground with space underneath. Orientation of the Sectional School building type is optimal for the sub-tropics with long sides facing north and south with large windows for natural light and cross-ventilation. Building F remains the only intact example of the type with an open north verandah. In the mid 90’s the other buildings A B C D had their verandahs enclosed to increase classroom size; awning windows were installed and the roof overhang reduced.

These older timber buildings form part of the school’s identity and are likely to remain in use for years to come. They are of local cultural significance and are on the Brisbane City Council’s Heritage Register (BCC 2012). Addressing this volume of existing building stock within schools is an important inclusion in the transition to a low carbon society (Swan and Browne 2013).

2.4. Attributing factors to heat

The author identified a number of attributing factors that could be the root causes of overheated classrooms before developing cooling strategies. The first of these is the building envelope. Little or no insulation in the roofs, walls or floors offer little resistance to the transfer of heat into the interior. These buildings are constructed of materials similar to the Queenslander vernacular: corrugated iron roof sheeting, hardwood timber frame, timber weatherboard wall cladding, timber tongue and groove floor
boards and ceilings, elevated on posts above the ground. In January 2012 bulk insulation was installed to accessible flat ceiling areas of classrooms. Raked ceiling areas remained un-insulated.

A second factor is that spaces between and surrounding these lightweight timber buildings have ground surfaces covered with asphalt. Asphalt and concrete are hard-paved surfaces that absorb solar radiation and re-release this as heat into the air, a well-documented effect of an Urban Heat Island (UHI); Inner city urban environments are warmer than the surrounding rural areas (Akbari et al 2010). The field of UHI mitigation research has provided three passive cooling strategies: heat reflective roof paint Cool Roof (Santamouris 2012); shading the asphalt by installing Shade Sails and decreasing asphalt areas of the school by Schoolyard Greening (Block et al 2013). These strategies aim to reduce heat outside before it passes through the building envelope, open windows and doors to the classroom.

A third attributing factor is direct solar gain passing through glass of north, east and west windows. Buildings A, B, C and D have inadequate roof overhangs (300mm width) to shade north facing windows from sun. West facing windows of Buildings A, C, D are exposed to low-angle hot afternoon sun. Building G differs in orientation to the other buildings and has large southwest facing window. As a strategy, shading windows was not considered by the P&C as the preference was for strategies that could be applied across the largest number of classrooms such as roof fans, or be shared between buildings such as shade sails. Costs to install window shading elements to a few buildings was regarded as relatively high and in the realm of the DET to fund.

The next attributing factors observed relate to the low amount of cross ventilation in classrooms. Increasing cross ventilation is an important way for occupants to feel cooler. Higher air velocities increase the evaporation rate of the skin enhancing the cooling sensation. Air speeds of 0.8m/sec can make a space feel 2°C cooler, at 60% humidity (Allard 1998). Closeness of buildings in the group reduce the amount of breezes to classrooms; Building I blocks southeast and northeast breezes to Building B. Cross ventilation is further reduced by window type and use. Air movement through awning windows is limited to the bottom or sides of an open window. Casement windows are effective in catching breezes, if opened enough to do so. Some windows are not opened at all due to handles broken or out of reach. Improving the use of windows is being considered in this research. Prior to developing an adaptive actions strategy a thorough understanding of how windows are currently used and other adaptive actions is being sought through the qualitative data collection stage. A challenging aspect of classroom ventilation is that at the end of the school day windows and doors are closed, trapping warm air that has accumulated in the afternoon inside. In a house an occupant can ‘flush out’ warm air by opening windows in the late afternoon and night.

3. Passive cooling strategies

3.1. Implemented strategies

In order of implementation the strategies are Stack Ventilation (Part 1), Cool Roof Strategy, Stack Ventilation (Part 2), Shade Sail Strategy and Schoolyard Greening (Figure 3). Timing of strategy implementations was ad-hoc as funding became available from various sources.

- Stack ventilation strategy. Installation of solar-powered roof fans, ceiling vents and floor/wall vents to encourage stack ventilation. Hot air in the attic space exhausted by a roof fan creates a current that draws warm classroom ceiling air through ceiling vents. Floor vents let cooler air

- Cool roof strategy. Application of heat reflective paint ‘Cool roof’ coating to two buildings. The bright white coating reflects the full spectrum of solar radiation, visible and thermal ranges, reducing the transfer of heat through the roof (total solar reflectance value of 98%). Applied to Buildings A and D October 2013. DET. Funded by DET Cool Roof School Trial.

- Shade sail strategy. Installation of shade sails over courtyards to reduce the heat from the asphalt surface. Shade sail fabric is a light cream colour to reflect solar radiation. Sail forms are allow breezes through and provide shade mostly from afternoon summer sun. Installed to East courtyard (between Buildings A B and D) and West courtyard (between Buildings C B and F) July and August 2014. Funded by Gambling Community Benefit Fund Grant and P&C.

- **Schoolyard greening (Landscaping) strategy.** Reduction of the 800 m² asphalt area north of classroom Buildings A C and I by installation of partially raised garden beds with shade trees covering 300m². Increasing vegetation provides cooling effects in a number of ways; plants absorb solar radiation, plants cool air by evapotranspiration, trees shade asphalt surface reducing solar radiation being absorbed that would otherwise be released into the air later at night. Garden beds constructed and ten shade trees planted July-August 2014. Further planting of 200 plants over two school community events: Year Ones’ Arbor Day planting 15-17/10/14 and P&C working bee on 22-23/11/14. Funded by National Solar Schools Program, Brisbane City Council Arbor Day planting program, P&C and parent donations.

Figure 3: Summary of passive cooling strategies at the school (Source: nearmap).

### 4. Methodology

#### 4.1. Case study

The research methodology is an embedded *single case study* (Yin 2014) allowing a rich in-depth understanding to be sought of the strategies implemented to the school environment together with the social and cultural context of the school. To analyse the effectiveness of the passive cooling strategies the research uses quantitative, data classroom temperature collected by data loggers in the school over 2012-2015 and qualitative data, perceptions gathered from Teachers and the School Principal through an online Questionnaire and Interviews being conducted this year.
4.2. Temperature analysis

The effect on classroom temperature of the passive cooling strategies is being analysed by two methods. The first method measures the amount of overheating occurring in the classrooms from the ‘before’ period of November 2012 through all summer terms to Term 1 2015. A method used to evaluate overheating in a portfolio of education buildings in Australia, an Adaptive Comfort Overheating Policy, has been applied to the temperature data here (de Dear and Candido 2012). As explained by de Dear ‘the basic concept of adaptive comfort is that the comfort zone or range of acceptable indoor temperatures, drifts upwards in warm weather and downwards in cool weather, particularly in environments where occupants have a variety of adaptive opportunities at their disposal.’ This upward and downward trend is visible in the Adaptive Comfort Zone using I(ext) plotted in Figure 1.

The concept behind this Adaptive Comfort Overheating Policy is to develop an overheating metric based on ASHRAE’s Adaptive Comfort Standard 55-2010 for occupied hours. The metric tallies the frequency classroom temperature is greater than upper 90% and upper 80% thresholds of acceptability. The results for the overheating of classrooms in Buildings A B C D using the 90% threshold are in Table 1. Steps that have been followed in this method are:

- **Step 0: Identification of local threshold temperatures for heat-wave criteria.** Heat-wave days are excluded, as it is unreasonable to expect the passive design of a building to maintain a level of comfort during extreme events. The heat-wave definition is deemed to be two consecutive days with the daily maxima exceeding the third percentile of daily maxima on record and the daily minima exceeding the third percentile of daily minima on record, for that month using data from nearest weather station Brisbane 040913. Heat-wave days were removed from the occupied days (27-28 Oct 2014 and 9-10 March 2015).

- **Step 1: Monitoring indoor (classroom) temperatures in Buildings A B C D F.** Data loggers (HOBO U10 Temp/RH) were located in each building. Loggers monitor temperature and humidity at half hourly intervals. Logger placement was guided by practical reasons; away from radiant heat of windows (2m); within the height of a standing adult (1500mm from floor) and on the back wall of classroom out of sight of children.

- **Step 2: Monitoring outdoor weather** A data logger at the school I(ext) provides the outdoor temperature for the temperature analysis. This differs from de Dear and Candido’s method, which uses data from the nearest weather station. Maximum and minimum temperatures and daily mean for I(ext) have been plotted in Figure 1. A similar plot was made of temperatures from weather station Brisbane City 040913 for 2014. Comparing these two graphs, the microclimate of the school differs slightly from Brisbane city in that it has warmer minimum temperatures, of at least 1 degree throughout the year. Outside logger I(ext) is behind the building opening plaque on the shaded north verandah of Building I.

- **Step 3: Tallying the number of occupied hours in an operation year.** Only school days when children attend school are regarded as occupied days. Same logic is applied to the daily occupied period, from 9.00am to 3.00pm inclusive of these times; 13 half hour counts per day.

- **Step 4: Calculating the running, exponentially weighted mean outdoor temperature.** The daily mean outdoor temperature of I(ext) is used to calculate a value of $T_{rm}$ by using the same equation from de Dear and Candido’s Overheating Policy (2012). This equation is very similar to exponentially weighted mean outdoor temperature by Nicol and Humphreys (2010).

$$
T_{rm} = 0.32T_{od-1} + 0.23T_{od-2} + 0.16T_{od-3} + 0.11T_{od-4} + 0.08T_{od-5} + 0.05T_{od-6} + 0.03T_{od-7} 
$$

(1)

Where $T_{od-1}$ refers to the day before, $T_{od-2}$ refers to the day before that, and so on.
Step 5: Calculate daily adaptive acceptable temperature thresholds. The upper 90% acceptable temperature threshold from ASHRAE 55-2010 standard was calculated from \( T_{\text{rm}} \) for each day

\[ T_{\text{upper90}} = 0.31T_{\text{rm}} + 20.3 \, (^{\circ}\text{C}) \]  

(2)

Step 6: Tally all temperature half hour counts greater than the threshold in the summer terms. A count of how many times the classroom temperature was greater than \( T_{\text{upper90}} \) for the range of half hour temperature readings between 9.00am to 3.00pm was done for each day. The results of the \( T_{\text{upper90}} \) counts are in two values: actual counts and a percentage (counts/total counts for occupied period). Refer Table 1.

Step 7: Decision regarding remediation of comfort conditions. In Step 7 for de Dear and Candido’s client, their results indicated which rooms exceeded an overheating criterion (>1% of occupied hours exceeding 80% threshold). In this research project, whether this temperature analysis will be used in a similar way as a decision support tool for action is to be assessed. This assessment will come after the synthesis of the temperature data with qualitative data.

The second method for temperature analysis is the comparison of diurnal graphs of five-day weeks. Weeks are selected are when the maximum daily temperatures are 25-32°C and days have high (8-12) solar hours; this is when solar radiation has maximum effect on the building envelope and surroundings. Rise and fall patterns of temperature can be compared with other classrooms and outdoor temp \( I(\text{ext}) \).

4.3. Questionnaire and interview analysis

Perceptions of the classroom environment are being collected through an anonymous online Questionnaire and Interviews with teachers and the Principal. Questions include summary evaluation type questions of the classroom environment, of the Teachers’ perceptions of the most recent summer term, similar to the type of questions asked in a post-occupancy evaluation (Deuble 2014). The Questionnaire aims to capture the range of adaptive actions the Teachers engage in to reduce discomfort during summer terms; their energy conserving practices and reasons why they do so; for Teachers in air-conditioned classrooms, triggers for its use in summer terms. In the Interviews, Teachers who have occupied the same classroom for three years or more provided their view of effects the strategies have had on the classroom. An Interview with the Principal discussed the strategies and their impacts on the school in a physical and social sense; range of adaptive actions taken by teachers in classrooms to reduce heat; heat wave action procedures in the school; energy conserving practices in the school; cultural expectation of air-conditioning in workplaces influencing school teachers.

5. Results

5.1. Overheating analysis results

It was anticipated that results would show an obvious decrease in the number of times classroom temperatures were greater than the upper threshold for the summer term 1 of 2015, compared to the ‘before’ periods of November 2012 and February and March 2013. A decrease would indicate that the passive cooling strategies are having an effect on classroom temperature. However there is no such obvious trend as can be seen in Table 1.
Table 1: Classroom temperature counts above $T_{\text{upper}90}$ threshold for summer terms.

<table>
<thead>
<tr>
<th>Year</th>
<th>Month</th>
<th>Occupied Days</th>
<th>Actual % counts</th>
<th>% counts</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Building A</td>
<td>Building B</td>
</tr>
<tr>
<td>2012</td>
<td>NOV</td>
<td>11</td>
<td>100</td>
<td>70%</td>
</tr>
<tr>
<td></td>
<td>FEB</td>
<td>18</td>
<td>95</td>
<td>41%</td>
</tr>
<tr>
<td></td>
<td>MAR</td>
<td>15 Cool Roof to A &amp; D</td>
<td>62</td>
<td>32%</td>
</tr>
<tr>
<td></td>
<td>OCT</td>
<td>17 Cool Roof to A &amp; D</td>
<td>80</td>
<td>36%</td>
</tr>
<tr>
<td></td>
<td>NOV</td>
<td>21 Cool Roof to A &amp; D</td>
<td>146</td>
<td>53%</td>
</tr>
<tr>
<td></td>
<td>DEC</td>
<td>10 Cool Roof to A &amp; D</td>
<td>72</td>
<td>55%</td>
</tr>
<tr>
<td>2013</td>
<td>FEB</td>
<td>18 Stack Ventilation to A B C D</td>
<td>158</td>
<td>61%</td>
</tr>
<tr>
<td></td>
<td>MAR</td>
<td>15 Stack Ventilation to A B C D</td>
<td>105</td>
<td>38%</td>
</tr>
<tr>
<td></td>
<td>OCT</td>
<td>16 Stack Ventilation to A B C D</td>
<td>69</td>
<td>33%</td>
</tr>
<tr>
<td></td>
<td>NOV</td>
<td>20 Stack Ventilation to A B C D</td>
<td>149</td>
<td>57%</td>
</tr>
<tr>
<td></td>
<td>DEC</td>
<td>10 Stack Ventilation to A B C D</td>
<td>96</td>
<td>74%</td>
</tr>
<tr>
<td>2014</td>
<td>JAN</td>
<td>4 Shade Sails A B D, C B F / Garden Beds to A &amp; C</td>
<td>13</td>
<td>25%</td>
</tr>
<tr>
<td></td>
<td>FEB</td>
<td>21 Shade Sails A B D, C B F / Garden Beds to A &amp; C</td>
<td>158</td>
<td>61%</td>
</tr>
<tr>
<td></td>
<td>MAR</td>
<td>10 Shade Sails A B D, C B F / Garden Beds to A &amp; C</td>
<td>105</td>
<td>38%</td>
</tr>
<tr>
<td></td>
<td>OCT</td>
<td>16 Shade Sails A B D, C B F / Garden Beds to A &amp; C</td>
<td>69</td>
<td>33%</td>
</tr>
<tr>
<td></td>
<td>NOV</td>
<td>20 Shade Sails A B D, C B F / Garden Beds to A &amp; C</td>
<td>149</td>
<td>57%</td>
</tr>
<tr>
<td></td>
<td>DEC</td>
<td>10 Shade Sails A B D, C B F / Garden Beds to A &amp; C</td>
<td>96</td>
<td>74%</td>
</tr>
<tr>
<td>2015</td>
<td>JAN</td>
<td>4 Garden plants cover 25%</td>
<td>24</td>
<td>46%</td>
</tr>
<tr>
<td></td>
<td>FEB</td>
<td>20 Garden plants cover 25%</td>
<td>120</td>
<td>46%</td>
</tr>
<tr>
<td></td>
<td>MAR</td>
<td>20 Garden plants cover 25%</td>
<td>158</td>
<td>61%</td>
</tr>
</tbody>
</table>

The November % figures are indeed quite high; 61 to 71% of the time is over the 90% threshold, indicating overheating in these classrooms. Comparing the November figures of Buildings A and D after the Cool Roofs application, the percentage has dropped from 70% to 53% in A and 71% to 48% in D. This could be construed that the passive cooling strategy has had an effect. Moving onto the following November, after the shade sails have been installed to the north of D and south of A, the percentages go up 57% in A and 53% in D. This linear comparison of temperature across time periods is an inconclusive way to measure the effect of these strategies.

Counting the number of times temperature is over a threshold only counts that it is greater than the threshold; it could be by half a degree or by three or five degrees. Another measure that could be done to these classroom temperature data is to apply a degree-hour concept. For example one hour with a temperature three degrees over the threshold would carry the same weight as three hours with one degree over. This method could provide a tally of the degree of intensity of heating in the classrooms, and would require more calculations and tabulation of the temperature data. However at this point of the research it is being questioned whether applying another method of analyzing temperature data would provide compelling evidence that the strategies have had an effect. The concern is that there are other variable factors that could be influencing the temperature in the classroom that are not being directly observed at the same time of the temperature monitoring. Variables in the weather can occur from one month to another. For example, although two heat wave days were taken out for March 2015, there were two other separate days that were as hot and were included in the count. The previous March of 2014 was the wettest month of that year, with more constant temperatures from day to day.

The other method of temperature analysis, using diurnal temperature graphs, takes into account some climatic factors. Graphs show rise and fall in classroom temperature classroom during the day over a five-day week and can be compared with $I(\text{ext})$ and upper and lower thresholds of the adaptive
comfort zone. Weeks for comparison can be selected to possibly match climatic factors, such as amount of daylight hours, prevailing wind direction, rainfall, humidity levels. These are recorded at the nearest weather station Brisbane City. However other immeasurable factors that could influence classroom temperature include how the building is used from one week to another. Some classrooms have had the same teacher from one year to the next, which could mean that a similar routine to opening windows occurs over summer terms. Yet routine could change at any time and this is not monitored.

5.2. Diurnal graph comparison

Using the diurnal graph comparison method, early analysis found that Stack Ventilation (SV) on Building F was observed to have a cooling effect. Before the SV implementation in the sunny week of 12-16 November 2012 the Building F’s classroom temp at an average maximum of 30.2°C, was 2.4°C warmer than I(ext) max of 27.8°C. After SV implementation in a comparable sunny week of 25-29 March 2013, Building F’s average maximum 29.4°C was 0.4°C cooler than I(ext) max of 29.8°C. However in other weeks the cooler morning temperature only lasted till midday as outdoor air proceeded to come in through the open windows and doors. Heat load could also be coming through the roof. Building F has bulk insulation only to its central flat ceiling area (67% of the classroom floor area) with raking ceilings to along the north and south of the classroom.

After the final coat of Cool Roof was applied to Buildings A and D on 03/10/13 over the holidays an immediate effect to classroom temperature was observed. Three days before 03/10/13 in both A and D max temps were warmer than I(ext) by 2.54°C in A and by 2.64°C in D. Four days after 03/10/13 in both A and D max temps were cooler than I(ext) by 1.85°C and 1.79°C. However when the classrooms were occupied the following week with doors and windows opened the effect was less noticeable and the classrooms were only a degree less than similar sized Buildings C and B for most of the day. Classroom temperatures in Buildings A and D peaked in the afternoon in a similar pattern as before.

6. Conclusion

6.1. Physical and social aspects of retrofitting passive cooling strategies

This research addresses a volume of existing building stock within SEQ schools in the important pursuit of the transition to a low carbon society (Shove et al 2008). This research attempted to analyse the temperatures before and after implementations of strategies at the school by using a method of overheating analysis based on the ASHRAE 55 adaptive comfort standard, with inconclusive results. But perhaps more importantly the research will provide the social context that changes to the physical environment have occurred in; the range of adaptive actions that teachers currently engage in to reduce their feeling of discomfort from heat; and any existing energy conserving practices in the classroom and reasons why the teachers do so. Combining passive cooling strategies with a range of adaptive actions could inform low–energy occupation measures for typical existing SEQ classroom buildings.

Acknowledgements

Thanks to the QUT research team for assisting the inclusion of this school in the Cool Roof School trial.
References


Department of Education and Training, Infrastructure Operations and Asset Maintenance, Programs and Services, in discussion with representatives from DET in meetings at the school and Brisbane city, February and March 2015.


Architecture and Social Research
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Accessible parking: are users voices heard within the built environment sphere?

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Abstract: People with disabilities are frequently excluded from public space, including public transport, due to accessibility issues. Those who are ambulant often cannot walk far nor carry routine weekly shopping purchases. The resultant reliance on private vehicles has historically been accommodated through the provision of Disabled Parking along with permits issued by local government authorities. However, such schemes have evolved organically with little, if any, input from people with disabilities. Additionally, urban design and infrastructure architecture with current emphases on pedestrianisation, public transport facility enhancement, ‘bicycle culture’ and ‘shared space’ provision, rarely considers accessible parking, relegating it instead to the domain of traffic engineers. Often though, accessible parking is a poorly understood concern in traffic engineering, with little guidance readily available. What do permit holders have to say about accessible parking? Are the voices of the users of these bays being heard in current inner-city urban design dialogues that favour ‘street activation’ and ‘active transport’? By exploring the disconnect between users voices, urban design and traffic engineering this paper attempts to answer these questions. The findings of a research project investigating accessible parking in an inner-Melbourne local government area is presented as a Case Study.

Keywords: Accessible parking; PwDs; users voices; urban design.

1. Introduction

Wheelchair and mobility scooter users experience difficulties with public transport, ambulant people with disabilities (PwDs) often can walk only short distances and those with sensory impairments regularly struggle with confusing wayfinding in the public realm. Frequently excluded from the built environment due to such accessibility issues, PwDs often find themselves socially isolated. Historically, the resultant reliance on private vehicles has been mitigated somewhat by local councils providing spaces and permits for ‘Disabled Parking’. However with little, if any, input from people with disabilities, these schemes have tended to evolve organically. In addition, within Australia and other Anglophile countries, council-controlled Disabled Parking (hereafter, accessible parking) located on-street is not captured within any discrete built environment-based regulatory framework.
Visionary Design Development Pty Ltd (VDD), a transdisciplinary consultancy focusing on accessibility in the built environment, was commissioned by the City of Port Phillip (CoPP) a local government authority in inner Melbourne, Australia, to undertake the City of Port Phillip Disabled Parking Review Project in 2014. Via this case study this paper, building on work presented at 8th Making Cities Liveable Conference (Melbourne, July 2015), explores whether the voices of users of accessible parking are being heard. More particularly, are users’ voices being heard by built environment designers and practitioners? We argue that increasing the number of, and extent of space for, accessible parking bays can align with policies that seek ‘street activation’ and ‘active transport’ outcomes. Nonetheless, it is imperative that built environment designers and practitioners actively engage with PwDs to achieve equitable outcomes. In support of this viewpoint, the significance of the UNCRPD, the Social Model of Disability, the Rights-based Approach, the historical lack of engagement of PwDs in the design of the built environment and the notion of Universal Design are discussed through a Literature Review. Along with the results of the CoPP Disabled Parking Review Project, various CoPP’s accessibility, traffic engineering and urban design policies, strategies, plans and guidelines are presented. Finally some conclusions are drawn on the question of whether, within urban built environment design policy and practice, the voices of users of accessible parking are being heard.

2. Literature review

Multiple on-line databases: Proquest, Scopus, Web of Science, JSTOR, Academic Search Complete, Expanded Academic, Informit on Line, IBSS and Google Scholar, were searched for relevant academic peer-reviewed literature. Search terms “disabled parking”, “accessible parking”, “parking policy”, “parking theory”, “stakeholder consultation” were used. Using Google’s search engine, grey literature was similarly searched.

How to obtain a ‘Disabled Parking Permit’ from local councils was amply represented. However there appears to be virtually no academic and/or grey literature demonstrating engagement between the users of such spaces and built environment designers and practitioners regarding, for example, position and quantity of accessible parking, its physical attributes, and/or the vehicular mobility needs of PwDs.

2.1. Consultation, engagement and inclusion: PwDs and the built environment

Within Australia when enacting legislation and developing policy, government, NGOs/NfPs, and other stakeholders are, in addition to satisfying Disability Discrimination Act 1992 (DDA) requirements, bound to be guided by the articles of the United Nations Convention on the Rights of Persons with Disabilities (UNCRPD). Articles 4.3 and 33 specifically refer to active involvement of and consultation with, PwDs. Article 9 specifically refers to ‘accessibility’ in both the physical and non-discriminatory provision of services. Projects and policies intended to eliminate disadvantage, such as accessible parking and associated permits, should therefore include the participation of PwDs. The emphasis on ‘inclusion’ of PwDs resonates with the ‘Social Model’ of disability, shifting the focus from the person and their impairment(s) to the interaction between PwDs and society (Barnes and Mercer, 2003). The Social Model of Disability views disability as arising from society-erected barriers excluding PwDs from participation. Everyone is likely to experience transient or permanent disability in their lifetime (Zola, 1989) the goal, therefore, is the delivery of a public good (Wasserman et al., 2013) in the form of more accessible structures and more inclusive practices benefitting the whole community. Begun and Zarb (1996) state that “user involvement [of PwDs] is a key feature of social policy”. The Disability Rights Commission (UK) (2004) sees ‘genuine involvement’ of PwDs in the development of the built
environment as “fundamental to achieving its vision of a society in which PwDs can participate fully as equal citizens” but laments “erratic involvement of access groups in local planning and development activities” (p9). Barriers to inclusion of PwDs in planning and designing the built environment are attitudinal (discrimination), physical (mobility), resource based (power asymmetry) and representative (decision making) (Wiman and Sandhu, 2004; Asian Development Bank (ADB), 2005). The Rights Based Approach (RBA) to disability advocacy first became prominent around the ‘civil rights era’ of the late 1960 and 1970s (Hahn, 1994). In reaction, local government and road authorities established reserved parking areas and instigated permit schemes. Nevertheless, determining the location and number of reserved bays was arbitrary lacking any coherent rationale or established policy. This remains the case, today.

Universal Design (UD) aims to accommodate people with as wide a range of physical and sensory impairments as possible. Founded on the utopian concept of Universalism, this is a paradigm change from ‘special needs’ RBA-driven code compliance to a more inclusive design process for everybody. From a UD perspective all parking bays should provide for a wide a spectrum of users as possible. Alongside the implications of enlargement of spaces for parking supply/demand management, some dilemmas remain for such an equality initiative. In order to reserve parking as close as possible to likely destinations for drivers and/or passengers with disabilities permissive signage and complementary permit scheme will still be necessary.

3. Case Study

3.1. Methods: CoPP Disabled Parking Review Project

Prioritisation of upgrades to business activity centres’ accessible parking was the main project objective. Primarily, oversight was provided by Council’s Traffic Engineering unit, in collaboration with MetroAccess Officers from Council’s Access and Inclusion unit. Most of the project was completed over approximately three months, September to early December 2014, and comprised four main components: 1) Literature review plus analysis of relevant policies, local disability statistics, regulations and standards; 2) Stakeholder engagement; 3) Onsite investigation of 150 locations of on-street accessible parking (containing 200 bays in total) locations extracted from Council’s Geographic Information System (GIS); and 4) Prioritisation of Capital Works, achieved through deployment of a Prioritisation Matrix.

The literature review regarding disabled/ accessible parking was conducted with similarly unproductive outcomes, as previously described.

Three survey instruments were utilised for stakeholder engagement: one Focus Group session; trader group and council business unit input obtained via brief email questionnaire and/or telephone interviews, and CoPP Disabled Parking Permit Holder User Survey questionnaire. In the latter, eleven multiple choice User Survey questions covered topics such as: method, frequency, duration and purpose of permit use and satisfaction with quantity, position and features of accessible bays. A further 3 questions invited specific input about where users parked (or avoided) and conditions (good and bad) encountered. Lastly, respondents were asked to comment further. Trader groups and/or businesses were invited to answer a shorter question questionnaire. The first two multiple choice questions concerned whether PwDs visited the premises and whether better accessible parking would be good for business. Three further questions involved quantity, position and relocation options. (These three
questions were also asked in the User Survey and Focus Group.) Similarly, lastly, respondents were also asked to comment further if they wished. CoPP’s City Business Development Officer was interviewed by telephone. Invitations to attend the focus group were forwarded, via email, to the CoPP’s Access Network (CoPPAN) and Older Persons Consultative Committee (OPCC) as well as to persons with a CoPP Disabled Parking Permit. In order to ascertain whether the group was representative of the User Survey group Focus Group participants also completed a small section of the User Survey questionnaire. Focus Group Questions were semi-structured with the scope of questions being similar to the User Survey covering utilisation, localities, and useability. The session concluded with discussion on relevant sections of Australian Standard AS 2890.5-1993 On-street Parking.

Fieldwork captured a wide range of parking location characteristics and bay dimensions along with information about relevant surrounding features.

Informed by literature review and stakeholder engagement Recommended Best Practice Diagrams for accessible on-street parking specifications were developed. Although generally similar to AS 2890.5 – 1993 there are differences in: dimensions, kerb ramp provision, adjacent clearances and provision of tactile markers. Subsequently, each location was allotted an appropriate ‘Best Practice Diagram’ (http://www.portphillip.vic.gov.au/disabled-parking.htm) along with a ‘Complexity Classification’ from 1 to 5 representing degree of difficulty in achieving Best Practice.

Criteria and weightings for the Prioritisation Matrix, established via stakeholder consultation, are shown in Table 1.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Unit of Inter-location Comparison</th>
<th>Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost/ Complexity</td>
<td>Categorisation 1-5 of Locations</td>
<td>5</td>
</tr>
<tr>
<td>User Feedback</td>
<td>Stakeholder Consultation via Permit Holder nomination and rating of accessible parking by postcode</td>
<td>5</td>
</tr>
<tr>
<td>Percentage Accessible Bays</td>
<td>100 – Percentage of Accessible Bays by Postcode</td>
<td>3</td>
</tr>
<tr>
<td>Number of Bays</td>
<td>Number of Bays per Location</td>
<td>2</td>
</tr>
<tr>
<td>Permit Ratio</td>
<td>CoPP Known Resident Permit Holders per Accessible Bay by Postcode</td>
<td>1</td>
</tr>
</tbody>
</table>

3.2. Findings: CoPP Disabled Parking Review Project

Table 2, below, shows percentages of accessible bays by postcode. By postcode district, where parking quantities known, on-street business activity centre accessible parking percentages vary from less than 4% for St Kilda Rd Precinct (Melbourne 3004) to 7% for St Kilda and St Kilda West to 16% for Port Melbourne. Although the total on-street capacity was unavailable, South Melbourne Postcode 3205 contains the highest number of accessible parking bays (50). Permit Holders per bay outlier ratios, that is, Postcodes 3184 (Elwood) and 3184 (Ripponlea), reflect there being no major commercial activity centre, with concomitant parking, in those postcodes.
Table 2: Permit holders, bay numbers and bay ratios by postcode.

<table>
<thead>
<tr>
<th>Postcode/Suburbs</th>
<th>No. Permit Holders</th>
<th>No. of on-street bays</th>
<th>No. of on-street accessible bays</th>
<th>Percent accessible bays</th>
<th>Permit holders per acc. bay</th>
</tr>
</thead>
<tbody>
<tr>
<td>3004 St Kilda Rd Precinct Melbourne</td>
<td>131</td>
<td>494</td>
<td>18</td>
<td>3.6%</td>
<td>7.3</td>
</tr>
<tr>
<td>3182 St Kilda and St Kilda West</td>
<td>409</td>
<td>547</td>
<td>39</td>
<td>6.8%</td>
<td>10.5</td>
</tr>
<tr>
<td>3183 St Kilda East and Balaclava</td>
<td>320</td>
<td>192</td>
<td>25</td>
<td>13.0%</td>
<td>4.3</td>
</tr>
<tr>
<td>3184 Elwood</td>
<td>236</td>
<td>113</td>
<td>5</td>
<td>4.4%</td>
<td>47.2</td>
</tr>
<tr>
<td>3185 Ripponlea</td>
<td>22</td>
<td>4</td>
<td>42</td>
<td>9.5%</td>
<td>0.5</td>
</tr>
<tr>
<td>3205 South Melbourne</td>
<td>330</td>
<td>N/A</td>
<td>50</td>
<td>-</td>
<td>6.6</td>
</tr>
<tr>
<td>3206 Albert Park and Middle Park</td>
<td>368</td>
<td>290</td>
<td>26</td>
<td>9.0%</td>
<td>14.2</td>
</tr>
<tr>
<td>3207 Port Melbourne</td>
<td>542</td>
<td>205</td>
<td>33</td>
<td>16.0%</td>
<td>16.4</td>
</tr>
</tbody>
</table>

3.2.1. Stakeholder consultation

As at 29 September 2014, 91% (2,358) of CoPP permit holders were known to reside within the municipality. The remaining 9% either resided outside CoPP or at unknown addresses. CoPP resource limitations precluded multiple methods of stakeholder engagement and/or extensive follow-up. From 383 email addresses, 71 User Survey responses were returned. Ten participants, consisting of 9 people with disabilities and 1 carer/driver, attended the single focus group session. Focus Group participants were found to be representative of the wider User Survey cohort.

Although one focus group session and User Survey responses being only 2.75% of the total 2,580 permit holders undoubtedly represents a small sample, permit holder respondents feel there are insufficient accessible carparking bays reserved at all activity centres. This forces many to use regular parking that is too distant, for their comfortable ambulant capabilities, from their destination. Acland St (St Kilda) and Clarendon St (South Melbourne) were particularly criticised. Although there are safety concerns in relation to passing traffic and bicycles, in general users feel that the current locations of accessible carparking were satisfactory. Focus Group participants corroborated these findings.

CoPP’s Business Development Unit advised that, historically, parking is considered a contentious issue in activity centres due to: availability, expense and economic viability. There is, however, no history of trader-related accessible parking issues within the municipality. A short survey was distributed to Trader groups. Nonetheless, response was poor, indicating accessible parking is not a particular concern.

3.2.2. Onsite investigation

Fieldwork involved a total of 200 accessible parking bays contained within 150 locations; 92 parallel parking locations and 58 angle parking locations. Thirty six locations contained multiple bays. Whilst six existing locations (4%) were adequately sized, none of the locations assessed fully met Recommended Best Practice. Almost all locations, 144 (96%), were undersize. 126 locations (84%) lacked any kerb ramps. Line marking was inadequate at 96 (64%) locations. Only 1 location had tactile markers. Although 43 locations (29%) can be enlarged in either their current position or nearby (within 10-20m), 101 (67%) locations will most likely require relocation elsewhere, due to the presence of kerbside and/or roadside
obstructions. Of these, although 64 are likely to achieve Recommended Best Practice elsewhere in the same street, 37 locations most likely require relocation to a different street. In light of these findings, on-street Best Practice Accessible Parking bays whether ‘parallel’ or ‘angle’ not only require more physical space per bay than is current practice, larger, more accessible, ‘buffer’ spaces are required around them. This, particularly in urbanised environments, challenges the conventional notion that responsibilities for provision of vehicle parking, a ‘traffic engineering issue’, and accessibility for PwDs, an ‘urban design pedestrian mobility issue’ separates at the kerb line.

3.2.3. Prioritisation

Reflecting the high weighting given to stakeholder feedback in the prioritisation criteria (see Table 1), St Kilda & St Kilda West and South Melbourne (representing a combined 45% of the total 150 locations) were the highest two priorities, when prioritised by Postcode.

3.3. CoPP Policies, strategies, plans and guidelines

In the context of the inter-relationship between accessibility, traffic engineering and urban (built environment) design, a snapshot of the extent to which the voices of users of accessible parking within the City of Port Phillip are currently being heard is presented below.

Council’s headline document, City of Port Phillip Council Plan 2013-17 Year 3 – Revised April 2015 (Draft for public review), sets out the City’s vision for the medium term and contains words such as engaged, consultation, inclusion, accessible, connected and the like (http://www.portphillip.vic.gov.au/council_plan_budget.htm). The City’s primary disability planning instrument, City of Port Phillip Access Plan 2013 – 2018, notes: ‘Council provides accessible onstreet parking for its residents’ and accessible parking and drop-off points are needed at and near community buildings and council owned venues. Although consistent design and implementation of public space infrastructure elements, including accessible car parking, is requested and sustainable, accessible, water-sensitive urban design is championed, ‘a less car-dependent city’ is affirmed as desirable.

CoPP’s stance on vehicle management is communicated in several transport, traffic, road and parking documents. Council’s Parking Need Hierarchy for both Shopping Strips and Local Streets places ‘Disabled Parking Bays’ quite highly; respectively fourth and fifth out of 14 (http://www.portphillip.vic.gov.au/Report_6__Attachment_1__Final_Sustainable_Transport_Strategy.pdf ). However, accessible parking is not discussed in CoPP Road Management Plan 2013. While most documents state, or imply, the need to ensure safe accessibility for vulnerable users, most recent documents also highlight intentions to ‘ .... Discourage car use and longer term parking in the most accessible and connected areas....’ and to increase walking, cycling and public transport use (CoPP Sustainable Transport Strategy, p 24).

Council’s position on urban design is explained through a range of policies, strategies, plans and guidelines regarding precinct development, open space, infrastructure and sustainability. Significant upgrades to Acland Street, an iconic Melbourne destination located in St Kilda, are currently being planned. In 2016, a new Route 96 tram terminus, with central platform, will also be constructed In Acland Street. Nonetheless no direct, or indirect, questions about accessible parking requirements appear within the Acland Street Upgrade Community Survey. Although both contain numerous references to parking neither the South Melbourne Central Urban Design Framework (http://www.portphillip.vic.gov.au/default/StrategicPlanningDocuments/South_Melbourne_Central___Urban_Design_Framework.pdf) nor the South Melbourne Structure Plan & Implementation Strategy
Accessible parking: are users voices heard within the built environment sphere?

(http://www.portphillip.vic.gov.au/default/StrategicPlanningDocuments/South_Melbourne_Central_Structure_Plan.pdf) consider accessible parking. Within CoPP’s Emerald Hill Vision an ‘accessible’ Town Hall is noted as a Deliverable for the South Melbourne Town Hall Precinct refurbishment project but no reference to accessible parking is made.

4. Discussion

As no theoretical foundations for specifications or quantity of accessible bays were revealed through literature review, an investigation of various, historically comparable in planning terms, car-oriented countries’ (Australia, New Zealand, United Kingdom and United States of America) accessible parking specifications was carried out. Further searching covering compact cities (including Hong Kong and various European Union cities), Scandinavian countries considered well-developed in accessibility provisions (including Sweden and Finland) and the Benelux Union (including Luxembourg) was undertaken. Again much reference to ‘Disabled Parking Permit’ schemes, including reciprocity, was found along with some mentions of off-street parking technical requirements. On-street accessible parking remains shrouded in mystery. Anglophile countries reviewed nominate ratios of 4-6% for accessible-to-regular parking, for off-street parking. Australian Standard, AS 2890.5-1993, (On-street parking) refers to Australian Standard, AS 2890.1-1993, (Off-street parking). This (AS 2890.1) in turn refers to the “Building Code of Australia”, now part of the National Construction Code Series (NCC) which, in terms of accessible parking, refers to AS/NZS 2890.6:2009 Parking Facilities Off-street parking for people with disabilities. The NCC, however, is not applicable to on-street parking. AS 2890.5-1993, the current Australian Standard for on-street parking, pre-dates AS 1428 Design for Access and Mobility suite’s current version (published 2009), contemporary accessibility knowledge practice and the UNCRPD. Australian Standards regarding on-street accessible parking are, therefore, outmoded.

Although ranked quite highly in traffic engineering hierarchies, accessible parking is rarely considered in urban design and infrastructure architecture with current emphases on pedestrianisation, public transport facility enhancement, ‘bicycleulture’ and ‘shared space’ provision. Furthermore a key component of urban design concepts such as ‘street activation’ and ‘active transport’ is the encouragement of localised trips and social inclusion at neighbourhood level. Accessible parking at community business activity centres is therefore vital for equity of access to goods, services, employment, leisure and entertainment. However, the inconsistency of resident permit holders per accessible bay results indicates that people with disabilities have variable access to accessible carparking within their local neighbourhoods. Two postcodes, St Kilda + St Kilda West (3182) and South Melbourne (3207) contain the two areas most heavily criticised in the User Survey – Acland Street (plus side streets) St Kilda and the Clarendon Street Activity Centre, South Melbourne.

Stakeholder consultation revealed that insufficient availability of accessible parking was of greatest concern. Policies which seek to decrease car dependence and reduce parking space numbers therefore need to be informed by the imperative to retain, and in fact increase the quantity of, and the space provided for, accessible parking. The second most regularly raised issue was safety from passing traffic and bicycle lanes, the latter of course being championed in active transport circles. Some bays in quieter side streets are ‘safer’ but these are often too far away from the desired destination. Size of bay and entry/egress from the vehicle got several mentions including parallel bays not being wide enough to provide space between car and kerb for manoeuvring mobility aids. Footpath trading, a street activation stalwart, compounded width complaints. Widening of parallel bays has the potential to further conflict with footpath trading. Within CoPP there is, however, reasonable consensus that traders understand
that accessible parking bays need upgrading even though such expansion could lead to reduction of regular bays. Reductions in overall on-street bay numbers due to improvements to accessible parking are therefore likely to prove less controversial than reductions for other reasons.

4.1. Are users voices heard within the built environment sphere?

Users, with a range of impairments affecting mobility, provided feedback that confirms their reliance on car transport for visiting business activity centres. Alternatives are either unable to cart shopping and other goods, unavailable and/or inaccessible. Many users face significant barriers to parking, frequently. Despite the 4-6% ‘international average’ being exceeded in five of the eight CoPP postcode regions, a very large majority of complaints regarding, and reasons for avoidance of, certain activity centres were the lack of sufficient numbers of spaces. St Kilda + St Kilda West which includes the Acland Street Activity Centre – one of the two most highly criticised for accessible parking, primarily due to unavailability of bays – has 6.8% accessible bays. Bay Street Business Activity Centre in Port Melbourne was regarded in a, generally, positive light. Port Melbourne has 16.1% spaces reserved for accessible parking suggesting 4-6% is inadequate.

The CoPP Disabled Parking Review Project investigated the existing conditions, and role of, accessible parking around local shops and businesses. Its findings provide a window of understanding into the inclusion of PwDs in social and economic activities. Almost all (144, 96.0%) CoPP accessible parking locations were of insufficient size. Whether in-situ, nearby, elsewhere in the same street, or in a different street altogether, the vast majority of locations (121, 80.6% of 150) will require significant streetscape redesign, or relocation, to achieve Recommended Best Practice. These statistics demonstrate the historical failure of council urban planning and traffic/parking policies to provide equity of access.

Given the lack of directly applicable built environment-based legislation, designers working within the urban infrastructure realm must be guided by the requirements of the DDA and the UNCRPD. Furthermore, informed by an understanding of the Social Model of Disability and knowledge of the Principles of Universal Design built environment designers and practitioners must seek out and listen to the voices of PwDs. The shortfall of availability and the poor specifications suggest the voices of users of accessible parking are not being heard. Or, when heard by, for example, access and inclusion advocates and traffic engineers the conclusions of such dialogues are not being conveyed to the custodians of the design of the urban infrastructure realm; urban designers, built environment practitioners and the like. Or, in keeping with the historical lack of engagement between built environment practitioners and PwDs regarding local planning and development activities, (Australian) built environment practitioners are not seeking opportunities to listen. Unfortunately this is somewhat unsurprising. Across Urban Design, Planning and Architecture, no major built environment design program on offer at undergraduate or postgraduate level in Australia in 2015 contains Universal Design, Designing for Disability, Inclusive Design, People-centred Design or the like as a core course.

Throughout the ages, PwDs have faced varying degrees of exclusion. In contrast, socially inclusive communities understand the value of improving members well-being by supporting participation in cultural, civic and recreational activities, and engagement, at the local level. Nonetheless, within the CoPP, the locations, numbers and specifications of accessible parking bays have evolved organically without crosscutting strategic input from permit holders and with limited planning and oversight. This is concomitant with the historical consideration of PwDs, at best, at a peripheral, late stage. Current inner-city urban design movements favour ‘active transport’ and ‘street activation’, particularly as a means for
urban renewal. Yet when it comes to planning for the needs of PwDs, access, traffic engineering and urban design, all essentially local activities, tend to be handled in ‘silos’ within councils.

5. Conclusion

In this paper, relevant UNCRPD articles, the Social Model of Disability, the Rights-based Approach, the historical lack of engagement of PwDs in the design of the built environment and the notion of Universal Design have been presented. Within the context of CoPP’s various accessibility, traffic engineering and urban design policies, strategies, plans and guidelines, findings from the CoPP Disabled Parking Review Project were discussed. In this context, we believe that urban design approaches seeking to minimise car-use, such as ‘street activation’ and ‘active transport’, need not be compromised by increased quantities of improved accessible parking for PwDs. However we argue that the voices of users of accessible parking are not being sufficiently heard by those charged with the responsibility for Urban Design, that is, by built environment designers and practitioners.

Whether ‘parallel’ or ‘angle’, Best Practice Accessible Parking on-street requires larger, more accessible, ‘buffer’ spaces immediately adjacent. More physical space per bay than is current practice is also essential. This greatly impacts the traffic engineering-urban design interface, particularly in urbanised environments. Users unequivocally want an increased quantity of accessible parking bays; augmented availability of which will translate to enhanced social inclusion. Current urban design knowledge practices, however, appear to be blind to the vehicular requirements of people with disabilities. In providing greater numbers of accessible parking bays the space available for standard parking will be reduced. Reduced traffic volumes resulting from the exclusively signed nature of ‘disabled parking’ will assist in achieving ‘street activation’ and ‘active transport’ aims. We believe, however, that this correlation must be made explicit to avoid being overlooked. Increased quantities of accessible parking must be acknowledged as an integral requirement of urban design policies, strategies, plans and guidelines. Nonetheless, this case study demonstrates the current amount of urban space provided per bay is insufficient and suggests that the Anglophile-country accessible parking recommended ratio norm of 4-6% is inadequate. Serious reservations about whether built environment designers and practitioners are listening to the voices of users of accessible parking are put forward.

Conventional built environment practice separates urban design and traffic engineering at the kerb line, see Figure 1. Traditionally viewed as being within the traffic domain, on-street accessible parking is in fact an urban design element, due to accessibility requirements such as footpath indentations, buffer zones, kerb ramps, wayfinding features and so on. To ensure that accessibility for all is achieved, policy makers and practitioners within the urban design, traffic engineering and accessibility arenas must work together, see Figure 1.
Built environment practitioners and designers of the urban infrastructure realm have responsibilities under the UNCRPD and must rise above the ‘afterthought, retro-fit, compliance’ mindset to accept the challenge of invisible accessibility, integrated from the outset. Knowledge of the Social Model of Disability and application of the seven Principles of Universal Design, embedded through more targeted university curricula and enhanced continuing professional development for built environment practitioners, will improve design outcomes. However, ‘desktop design’ is insufficient. Built environment designers and practitioners must engage directly with PwDs to ensure that the voices of users of accessible parking are heard and translated into real outcomes. Furthermore built environment practitioners must not wait to be asked but must seek out opportunities to make themselves aware of PwDs’ needs and desires through meaningful engagement with social research.

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Exploring relations between body, communication and agency in therapeutic space

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Abstract: Self harm\(^1\) has become increasingly prevalent in society and across cultures and although it is now widely accepted that it is separate from suicidal intent, it still remains a very ambiguous mental health condition. It is suggested that individuals who self harm have a particular relationship to architecture through spatial layouts.\(^2\) The rearranging of a spatial layout\(^3\) is found to be confronting by individuals who self harm, and is avoided in order to circumvent having to face personal issues and concerns which are brought to the surface by this rearranging of physical space, yet may also be a platform for therapeutic healing and the development of agency. Several research threads from clinical literature are discussed and posed as potential explanations for why these particular users have such an experience relative to the built environment, and why the built environment can also be a catalyst for change and healing for thus become part of a therapeutic process. A key finding is the ambivalence of spaces that provoke, confront and heal simultaneously. Design initiatives are suggested which explore a sense of agency as part of a therapeutic process, and further research avenues identified.

Keywords: Self harm; built environment; interior design; therapy.

1. Introduction

Many patients who self harm are not satisfied with the mental health care they receive and experience negative reactions and behaviours from clinical staff (Taylor \textit{et al.}, 2009). This can serve to exacerbate

\(^1\) Self harm is defined within this research as the physical harming of the body without suicidal intent. Self harm usually involves self-cutting or burning of the skin, but may include other methods of injuring the body tissues. More broad definitions of what may constitute self harm, such as eating disorders, tobacco smoking, alcohol abuse, or some forms of tattooing, are correlated but clinically separate conditions, also conditions such as depression, are not included in this research.

\(^2\) This was deduced following a pilot study of interviews with individuals who have self harmed.

\(^3\) ‘Spatial layout’ in the context of this paper is defined as the physical layout of an interior space, inclusive of non-fixed objects and items of personalisation which may also be present.
self harming behaviours (Slinn et al., 2001). Self harm is also noted as a condition particularly resistant to treatment (Horrocks and House, 2010; Ougrin and Latif, 2011) and studies note “the enormous gap between national recommendations and current service provisions”(Slinn et al., 2001). Thus, the built environment is a potential avenue to explore in contribution to the treatment of self harm (Liddicoat, 2010).

There is a considerable body of literature affirming links between mental wellbeing and good design practice. A search of the Avery database indicated there were 949 articles written about mental health, a search of the Medline and PsycINFO databases revealed 272 articles which linked mental health to the built environment or environmental design. Evaluations of specific design interventions have shown that good design of a hospital’s environment leads to better clinical outcomes and less stress for the users, both patients and staff (Berry et al., 2004; Ulrich et al., 2004). Research also links environmental aspects, such as landscaping or natural elements, to the reduction of stress and the promoting of recovery from illness (Ulrich et al., 2006). Researchers have found that restorative environments have the potential to reduce stress and anxiety and promote wellness (Ulrich et al., 1991; Ke-Tsung, 2003), and these “restorative influences of environments manifest themselves in emotional, physiological and cognitive responses of humans”(Ke-Tsung, 2003).

The environment is of vital significance for those in treatment for mental health conditions as “people are not always consciously aware of the patterns of behaviour and the subtle interplay between experiences and environmental features”(Myin-Germeys et al., 2011). Further, studies have also linked various aspects of the environment to the onset of symptoms (Ellett et al., 2008; Collip et al., 2011) and where opportunities for environmental engagement with the world or environment do not exist, studies demonstrate this lack of engagement results in a reduction in mental wellbeing (Blanchard et al., 2010; Messinger et al., 2011; Myin-Germeys et al., 2011).

Fieldwork conducted by the author found that for individuals who self harm the rearranging of spatial layouts, particularly those correlated with spaces of safety, privacy or refuge, was extremely confronting.

“My ideal space is my office – I go there if I am under pressure, feeling under pressure... My office is my safety zone – it’s my personal space. I like peace and quiet. I don’t close the door too much [however]; I like to watch out for him [my husband]” (Self harmer, 2015, Personal communication).

Upon further investigation however, it seems that the orderliness of the office is in fact a negative trait, and that she would like to have flexibility in this space, and messiness, yet this was also quite confronting from a therapeutic perspective. Poignantly, she remarks on her office layout:

“I feel that if I have to change how my office looks then I have to change a part of my life that could take me deeper. So sometimes I keep it as it is, so I don’t get deeper into darkness” (Self harmer, 2015, Personal communication).

This is suggestive that a flexible layout and a disorder of arrangement enables a sense of freedom, and is desirable, yet is also confronting as the modulation of these spatial aspects involves a consideration of the inner self and inner emotions, which is confronting.

This paper seeks to explain the implications of rearrangement of a spatial layout, considering research threads from clinical literature which are discussed below and posed as potential explanations for why these particular users have such a confronting experience relative to the built environment.
These include three broad notions. Firstly, body movement/postures in relation to therapy and mental wellbeing, which forms part of engagement with a built environment; secondly, an inability to verbalise through language means, meaning the body becomes a vehicle for communication; and thirdly, problem solving abilities and sense of control, which may be articulated through physical space, relating closely to a sense of agency. Each notion is considered with relevance to the built environment and following this, potential future research directions are suggested.

2. Body movement

Body-centred strategies have links to therapeutic practice. Viewing muscular tension as a manifestation of emotional conflict, psychoanalyst Alexander Lowen created body postures to evoke and relieve stress (Lowen, 1958). The growing interest in the field of movement therapy has led to a variety of therapeutic approaches using bodily engagement as a primary means of intervention. The key driver behind such therapies is the notion that “body movement reflects inner emotional stages and changes in movement behaviour can reflect changes in the psyche” (Levy, 1988). Further, and importantly for individuals who self harm, for whom an underdeveloped sense of self is a diagnostic characteristic (Pembroke, 1996; Horrocks and House, 2010), “by bringing her attention into specific areas of the body, the client begins to develop a less diffuse sense of self” (Simonds, 1994).

The notion that an individual who self harms may find the rearranging of a room confronting, as it leads to an exploration of internal issues and aspects of the self, may be related to the body movement itself. In therapeutic treatment where the body is particularly entwined in the mental health issue being addressed, such as self harming or sexual abuse trauma, the body becomes a focal point in the therapy. As Simonds explains:

“simply being still and focusing inward on the body may be difficult… [patients have a tendency to have] used elaborate defences to avoid feeling and noticing the body, such as dissociation, intellectualisation and denial… [they may also] experience flashbacks when they become relaxed or loosen their hypervigilance on external stimuli” (Simonds, 1994).

This notion is reinforced by fieldwork conducted by the author. The notion of sensation seeking was evidenced in the interviews and found to be very important. “Anyone who self harm’s doesn’t feel it – they’re all the same – you never feel the self harm” (Self harmer, 2015, Personal communication). However, high sensory stimulation can prevent her from self harming. Further, such reconnection with the body “helps bring you back to the present, but also gives you access to memories and things.” This bodily engagement with physical environments is stated as important, as:

“Engaging with the senses can also be an escapism, and be fully present but also to escape from the overbearing nature of the psychiatric unit and the intensity of that, so it allows you to be present and in your own body but also to escape from the physical environment which is so intense, yes, absolutely” (Self harmer, 2015, Personal communication).

So although confronting, developing a connection with the body can lead to a greater sense of self control. It is also useful as “by bringing her attention into specific areas of the body, the client begins to develop a less diffuse sense of self” (Simonds, 1994). Further, a consideration of body movement, postures and the locating of emotions within the body can be utilised to work through relevant issues in therapy (Alexander, 2011).
Self harm behaviour involves an attack on the body, and this is related to particular attitudes or emotions rooted in the body (Orbach and Milkulincer, 1998). Several tools have been developed within clinical studies which aim to measure aspects of body awareness, perception, image and attitudes. Such measures explore relations between the bodily self and the mental self, and operate upon the notion that the body is the informer of a general sense of self. In the case of self harm, psychological distress is expressed through bodily injury, which elicits mental relief (Hains et al., 1995). Further, it is suggested that a more positive relationship with the body is a key factor in the regulation of self-destructive behaviours, such as self harm (Lindgren et al., 2011). Thus, it is possible that bodily engagement in the built environment, such as via a rearranging of spatial layouts, is confronting. It involves bodily action and a consideration of body, which may be challenging, particularly for these individuals who have a very particular relationship to the body. However, it is ultimately part of the healing process.

3. Communication

In the therapeutic literature, it is acknowledged that perhaps the increasing incidence rates of self harm and the poor success rates of therapy processes are due to their reliance on words for communication. However, these individuals are “communicate[ing] through... [a] body language, not in... verbally articulated terms” (Palasmaa, 1998). This is described with clarity in one account: “No one seems to notice the painful feelings inside of me so I have to carve my feelings in my arm. They’re messages of pain and desperation. I feel trapped. It is as though my pain has to be seen to be real” (Leiebenluft et al., 1987). Here the self harm serves as a representation of the patients’ agony, as if this is perhaps more tolerable, or understandable, than the emotions themselves. Individuals who practice self harm feel their speech is not worth vocalising, when it cannot express the depth of meaning that their bodies might carry: “the desire to hurt yourself is a there and then experience. Talking takes time. Speaking is very threatening, very uncomfortable. It is as though even if I did speak it wouldn’t be relevant” (Straker, 2006). It has also been noted that “physical pain does not simply resist language but actively destroys it” (Scarry, 1985). Reflecting on one account of self harm, researchers note that

“she [the patient] wishes it [self harm] were an acceptable substitute for verbal communication, but knows that it isn’t” (Leiebenluft et al., 1987).

The identified lack of a sense of voice or communication can hinder the therapy process, which is verbal language based. Layden (1993) found therapeutic interventions that focused solely on verbal interaction were less effective. Thus, the application of other techniques beyond the use of language become highly relevant in the treatment of these particular individuals. It can be surmised that for those who self harm, the mental health issues and behaviours they are experiencing

“can be linked to experiences that involve powerful images and sensory stimulation, [thus] we hypothesize that interventions that utilise only normal spoken language will be less effective in the long run than techniques that utilise imagery, dreams, tone of voice manipulations, and kinaesthetic elements as well” (Layden et al., 1993).

This is further suggestive that therapy modalities could usefully move beyond the realms of spoken verbal language, to include spatial elements and temporal dimensions. This could be supported by architecture or the built environment.

Research exists which explores the built environment as a vehicle for communication about the self. Cooper Marcus explores how the home environment can be a signifier for aspects of ourselves, and the personalisation of space speaks of the self to others (Cooper Marcus, 2006). Goffman reiterates the
notion of spacemaking as a vehicle of personal communication (Goffman, 1974). This is also supported in literature on designing for mental health, where affording personalisation and communication is important to therapeutic outcomes (Golembiewski, 2012).

Body movement, such as the rearranging of a physical room layout, may also be related to this inability to verbalise thoughts and emotions. This is a characteristic trait of self harm (Warm et al., 2003; Straker, 2006) and may relate to a patient’s relationship with the body. It is noted that through a rigidity in the body, and lack of bodily engagement, “thoughts are blocked from being transformed into emotions and emotions are blocked from being transformed into verbal expression” (Simonds, 1994). Thus, to engage bodily in room layout reconfiguring may be confronting to the patient who self harms as this may provide access to hitherto dormant emotional states, which they then have difficulty containing and verbalising.

4. Problem solving abilities and sense of agency

Clinical literature and accounts of self harm describe how self injury is often a means by which an individual aims to reassert a sense of control and to quell anxiety (Nathan, 2004; Briggs et al., 2008). As these individuals understand it, “the sight of my own blood spilling forth sets me back in control” (Anonymous). Self injury gives these individuals a choice (Huband and Tantam, 2009). Essentially, “self-injury performs the function of regaining this [lost] control and asserting oneself” (Babiker et al., 2009).

Research exists which discusses how design can be utilised to provide manageability and adaptability, which promotes user control, which is suggested as supportive of mental wellbeing and reduces anxiety (Golembiewski, 2012). More broadly, architectural discourse discusses user control as supportive of a development of sense of self and reduction of anxiety, through such concepts as the personalisation of space (Cooper Marcus, 2006), privacy and territories (Goffman, 1971; Altman, 1975) and salutogenesis. Further, as Goffman explains, we utilise boundary markers, objects of personalisation to distinguish territories and exert a sense of control. These function both as markers of boundary and as a signature (Goffman, 1971). This is also related to constructs of body, where: “personal effects, constituting a presence in their own right, are frequently employed as markers; moving them or even touching them is something like touching their owners’ body” (Goffman, 1971).

Thus, another potential link between self harm and the feelings of confrontation experienced when faced with rearranging a physical spatial layout of a room may relate to the individual’s problem solving ability. It is noted that individuals who self harm often lack problem solving abilities (Straker, 2006), and therapeutic treatment will often aim to address this. Such cognitive distortions which are the subject of therapy might impede problem solving in patients (Raj et al., 2001) and may be addressed through non-verbal techniques. Simonds details how this may be achieved through body postures and movements where the process of movement is the catalyst to bring to the surface underlying issues that have been obstacles to problem solving and issue resolution.

In fieldwork conducted by the author, one individual reflects on this process:

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4 The theory of Salutogenesis describes that designing an environment which is comprehensible, manageable and meaningful will lead to a sense of coherence, which bolsters mental health and wellbeing (Golembiewski, J. (2010) Start making sense: Applying a salutogenic model to architectural design for psychiatric care, Facilities, 28(3/4), 100-117.).
“I spend time walking the internal streets [of the psychiatric unit] in the hope that physical rhythmic exercise will help my harmed mind... as you can see psychosocial and psychological space merged in my mind. When anybody lives with an intense relationship with their surroundings they look and experience very vividly and closely” (Self harmer, 2015, Personal communication).

This research suggests that for individuals who self harm, the physical engagement via the body involved in rearranging a spatial layout may be confronting due to the symbolic notions which may have been inadvertently or unconsciously attached to the particular movements or gestures involved. These may relate to issues relative to his or her self harming, making this process difficult. It is also suggestive, however, that such engagements with a physical environment via the body also offers a vehicle to explore these issues, which may complement a therapeutic process. A spatial layout which allows such flexibility and exploration is thus emphasised. This sentiment is echoed by another interviewee, who explains how she has learnt to engage and express bodily as a coping mechanism and to assert control:

“I find it so, I just want to break out... you can’t talk to me, no! I am in my head, I need to escape somehow, and then you can’t... if I could move the furniture around the room, that flexibility would be good... in order to remain present and to remain grounded, you know, touching things, engaging with things physically, totally that’s important for me” (Self harmer, 2015, Personal communication).

Self harm may be viewed as related to a suffocation of personal agency. Agency involves an individual’s sense of instrumentality, empowerment, and effect on their surrounding environment. To be devoid of agency results in a significant absence of feeling one’s impact in the relational world and its potentials for self generation. The therapeutic impact of rearranging a spatial layout may have benefits through bolstering a sense of agency. If agency is conceived as a sense of knowing, seeing and repeating one’s impact on another or environment that makes an individual feel as though he or she exists (Slavin, 2004), then the experience of enacting a change on one’s environment, adjusting it to personal needs and possibly affecting others in this process, may be empowering. Within architectural design, the following design initiatives (Table 1) were extracted from interviews undertaken by the author as potential vehicles to support an individual’s sense of agency within an environment:

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5 The term agency is used here as it is discussed by the following authors:


6 These interviews were undertaken with consumers of mental health services, carers of individuals who self harm, practicing therapists who treat self harm and architects/mental health design experts within the field.
Exploring relations between body, communication and agency in therapeutic space

Table 1: Design initiatives to support sense of agency.

Creating comprehensibility:
- clear spatial boundaries;
- textured surfaces assisting textural perspective;
- horizontal courses in masonry assisting linear perspective;
- objects to assist in size perspective;
- lack of auditory distraction/echoes;
- objects are clear in their use/purpose;
- materiality delineates between separate objects/functions;
- materials are honest, use of veneer and similar is minimised.

Creating manageability:
- contact between individuals kept to small numbers;
- objects are moveable;
- spaces are able to be adjusted as desired.

Creating meaning:
- moveable furniture/elements assisting meaningful engagement;
- rich palate of sensory stimulation through materials, textures and similar;
- differing styles of the same object;
- informal design of objects and informal/scattered arrangement.

Creating sensory engagement:
- rich palate of sensory stimulation through materials;
- materiality delineates between objects and functions.

Changeable environments to adjust to privacy needs (responsive to user)
- Layouts with higher accessibility/highly visible public spaces
- Operable blinds/shading devices to mediate lighting levels as desired
- Lighting which can be changed in brightness and hue
- Flexibility of space: moveable objects and furniture
- Personalisation of space: shelving/display areas are afforded, soft furnishings able to be chosen/used

Further investigation into the above design initiatives with consumers of mental health services could further explore the ambivalence of spaces that provoke, confront and heal simultaneously, as outlined in interviews with individuals who self harm as discussed within this paper.

5. Implications

The layout of a counselling workspace relates closely to the therapy processes unfolding within it. Saari explains the importance of interpsychic space, that is the nonverbal, spatial expression of transferences, both positive and negative, imbued in personal space and proxemics (Saari, 2002). This field is the platform for communication between therapist and patient (Stern, 1997). The manipulation of non-fixed physical features within an environment and seating arrangements are used by patients to communicate psychological issues or states (Lindgren et al., 2011). The notion of attenuation was also raised in fieldwork undertaken by the author; this attenuation of an environment refers to the notion that if an environment is consistently familiar then it goes unnoticed, whereas if the environment is changed, moved or rearranged, it becomes noticeable, which prompts thought, consideration and anxiety, and is thus confronting.
6. Future research directions

The discussion of the confronting, yet ultimately therapeutic rearranging of a spatial layout is suggestive of design initiatives in mental health delivery spaces, particularly counselling workspaces. Further research is needed as to how to provide flexibility in such spaces, the ideal dimensions, and furniture and moveable items to include within the designs. Further research is needed in regard to the perceptions of patients who self harm and how they relate to these design aspects and what other particular spatial needs may also be related. This paper examines the patient perspective from the avenue of the experience of rearranging a spatial layout, and attempts to explore the psychology behind this reaction and the possible implications for design.

Body movement can form a key means of intervention in therapy through the development of sense of self, through exploring connection with affect-laden body parts, and through an examination of body investment relative to self destructive behaviour, such as self harm. Engagement in spatial layouts may also serve as a communicative tool, which although confronting as it provides access to hitherto dormant emotional states, this is also beneficial in the therapeutic process to disengage restricted emotions and explore containment and communication of feelings, which is essential to mental wellbeing. Engagement in spatial layouts may promote user control, and bolster sense of personal agency; the process of enacting a change on one’s environment, adjusting it to personal needs and possibly affecting others is empowering. These notions explored are suggestive of particular design initiatives, outlined in this paper, which may be usefully employed in the design of therapeutic delivery spaces, such as counselling workspaces. A key finding of this paper is the ambivalence of spaces that provoke, confront and heal simultaneously; further research is suggested relative to the specific design strategies which impact this most significantly, and in turn affect the therapeutic process.

7. Conclusions

This paper has discussed research threads from clinical literature and posed these as potential explanations for why individuals who self harm find the rearranging of a spatial layout to be confronting and challenging, yet is also a platform for and a conduit to the healing process. Firstly, body movement/postures in relation to therapy and mental wellbeing were considered; secondly, an inability to verbalise through language means was discussed; and thirdly, a discourse was provided on problem solving abilities and sense of agency and control, which may be articulated through physical space. These three notions are suggestive of particular design initiatives, which were identified. The rearranging of a physical space provides a greater consideration of body and its significance, a vehicle for communication, and a platform for the development of control and sense of agency. Although the rearranging of space is confronting, it is also a platform for exploring issues of the body and self, which are at the core of concurrent therapeutic practices.

References

Exploring relations between body, communication and agency in therapeutic space


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Green building design and visual persuasion on occupants’ pro-environmental behaviours

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Abstract: It is of interest to know whether and how green building design can communicate green messages to the occupants and lead to their pro-environmental behaviours. The distinctive power of building elements as visual objects and their use for visual persuasion has not been studied in the context of green buildings. A preliminary survey was carried out in Melbourne Council House 2 and the results showed the potential of using green building design as a persuasion tool to influence the occupants’ pro-environmental behaviours. This finding ensured the necessity of a future full-study to extract: 1) the effectiveness of the (visual) green building design on persuading occupants to behave more pro-environmentally at building-level; and 2) the effects due to the occupants’ awareness and perception of the green design at individual-level. A hierarchical regression model with Bayesian inference was proposed and tested with fake data simulation.

Keywords: Green building design; visual persuasion; pro-environmental behaviours.

1. Introduction

Buildings that have been designed in the past century exemplify the then prevailing modernistic view, which demonstrated the human dominance worldview to their occupants (Lynam, 2007). However, the last few decades witnessed fundamental changes in the prevailing social worldview alongside the environmental movement (Lynam, 2007), resulting in the emergence of green building. Aside from technical advances in building technology, humans are also an important factor in building performance (Leaman et al., 2010).

Earlier works have demonstrated that architecture influences human minds, attitudes and behaviours: "All architecture proposes an effect on the human mind” (Ruskin, 1989). "Architecture constantly touches us, shapes our behaviour, and conditions our psychological mood... architecture has the power to affect and condition human behaviour” (Roth, 1993). Yet, little research has evaluated the
operational performance of green buildings in relation to human attitudes, values, and behaviour (O’Callaghan and Hyde, 2011).

Buildings visually represent themselves, demonstrating a distinctive feature as a communicating and teaching tool. Previous studies have already showed that the visualization of sustainability is effective in sustainable education and communication. Using residential buildings in Hong Kong as study sites, (Ma, 2008) demonstrated the importance of transmitting sustainability through visual means and revealing interrelationships among the persuasive power of design and the experience of people. (Mann, 2011) suggested to communicate sustainability by visualizing sustainability through visual aids. To utilize this distinctive feature and imply future design, the visual persuasion of a green building is worthy of study.

In the following sections, we aimed to identify the potential influence of green building design on changing occupants’ pro-environmental behaviour, especially the effectiveness of its visual persuasion. In section 2, relevant studies are reviewed. In section 3, a preliminary survey with 11 people who work in the Melbourne Council House 2 (CH2) is presented, identifying the potential of green design’s visual persuasion in influencing people’s pro-environmental behaviours. In section 4, a future study is proposed, supported by findings from the preliminary survey, and hypothetical data are simulated for demonstration purposes. The discussion and conclusions will serve as the final section.

2. Literature review

2.1. Studies of influence of green building design on occupants’ pro-environmental behaviours

Behaviours are typically investigated for one of two reasons: 1) to understand why they emerge and what their associated impacts are; or 2) with the objective to change them (Gill et al., 2010). Numerous studies focused on investigating the latter part of the first reason (i.e. the impacts). Some tried to understand and measure human behaviours in regards to the actual building performance (Blight and Coley, 2013; Gill et al., 2010; Lee and Malkawi, 2014; Owens and Drifill, 2008). Some identified barriers and human factors related to building performance (Huebner et al., 2013). Others evaluated performance in regards to the occupants’ satisfaction (Abdul-Muhmin, 2007; Lee and Kim, 2008; Altomonte and Schiavon, 2013; Hua et al., 2014; Liang et al., 2014).

Considering the potential of green building to educate occupants (Lynam, 2007), it is also critical to understand the influence of green buildings on persuading occupants to behave more pro-environmentally; which would also address the first reason of studying behaviours in Gill et al. 2010 (i.e. the why question). A few studies have examined the influence of green buildings on occupants’ environmental beliefs, attitudes, and/or behaviours. Studies in Australia showed there are more positive pro-environmental attitudes among occupants in green than in conventional built environment (Deuble and de Dear, 2009; Deuble and de Dear, 2012; O’Callaghan et al., 2012; Daniel et al., 2014). Studies from the US showed there is generally no difference in pro-environmental attitudes among occupants in green/conventional built environment (Hostetler and Noiseux, 2010; McCunn and Gifford, 2012; Rashid et al., 2012)

All the above studies shared commonalities while differing in aspects regarding to their study design. All studies collected cross-sectional data, longitudinal data were not collected to reflect the changing attitudes and behaviours in response to the exposure of green design. Both non-residential and residential types of buildings/communities were studied. All residential studies embraced a broader geographical scale, in terms of green communities or all homes within a city (Daniel et al., 2014), than
studies on non-residential buildings, which scaled to individual buildings. The mean scores were compared on general environmental attitudes of occupants from green vs. conventional buildings. Most studies measured or compared the general environmental attitudes of occupants between green and conventional buildings, instead of attitudes toward a specific behaviour.

2.2. Studies of visual persuasion and the meaning of architecture

(Idler, 2014) stated that, “visual appeal can – more than anything – attract attention.” Selective attention enables us to gather relevant information and guides our behaviour (Carrasco, 2011). (Joffe, 2008) highlighted the emotional power of visual forms and the “vividness effect” – where visual material appears to be especially memorable, making it particularly forceful. While numerous literatures studied such visual impacts of mediated visuals, fewer studied the unmediated lived-in visuals.

Architecture, a form of lived-in visuals, are communicative and are viewed as a tool for visual persuasion (Ragsdale, 2011). The elements of architecture influence our attitudes and behaviour (Ragsdale, 2011). (Ragsdale, 2011) answered the question on “Why are some buildings more persuasive than others and how meaning is conveyed by architecture and how that in turn results in social influence”. In a green building context, one can ask whether and how the meaning conveyed by green design is persuasive and whether the occupants adopt pro-environmental behaviours as a result.

![Diagram of visual and conceptual-only green design, three levels of meaning of building elements, and two examples of low vs. middle level meaning of the building elements (Note: the example of low level meaning is copied from (Hershberger, 1974))](image-url)

Figure 1: Examples of visual and conceptual-only green design, three levels of meaning of building elements, and two examples of low vs. middle level meaning of the building elements (Note: the example of low level meaning is copied from (Hershberger, 1974))
According to (Rapoport, 1990) and (Goodsel, 2000), there are three levels of mnemonic meaning from the built environment: low level, middle level, and high/cosmological level. The low level communicates basic everyday ideas. The middle level indicates a more subtle meaning embedded in the environment including social mores, expectations, power, status, and identity. The high level cosmologically evokes an emotional response to ideas of culture. Examples of the three level meanings include: doors of the building indicating where to enter; exterior architectural sculptures depicting mythological figures and interior paintings portraying heroes and legends; and capitols’ domes whose rising rounded point repeats an accenting expression of sacred importance (Goodsel, 2000). (Hershberger, 1974) identified two categories of meaning that can be derived from architectural structures – representational and responsive (Figure 1). Assuming that the concept of sustainability be a deliberately embedded meaning in the green building design, could it communicate such a middle level meaning to its occupants and trigger consequent behavioural responses (Figure 1)?

The distinctive power of buildings as visual objects and use for visual persuasion has been discussed in some general architectural studies. However, to date, no single specific study on the visual persuasion of green building design in their occupants exist. The following preliminary survey was carried out to fill in this research gap.

3. Preliminary results from Melbourne Council House 2 (CH2)

To uncover the visual persuasion of buildings, it is necessary to separate the green design elements into: 1) the visual green design element; and 2) the conceptual-only green design elements (Figure 1). Visual green design such as on site renewable energies, interior design elements like wall paintings, interpretive signage, green-roofs/spaces, calm water features, and vegetation (Joye, 2007) all vividly speak of a building’s green status. On the other hand, conceptual-only green design such as low VOC materials applied, and energy efficient appliances installed do not have the vividness effect. The occupants’ awareness on conceptual-only green design might be weaker compared to those eye catching visual elements. It is reasonable to assume that visual green design is equal to a layer of conceptual green design plus a layer of vividness effect.

A simple two questions survey was distributed randomly to people who work in the CH2 during a week-day in April 2015. A total of 11 people answered the questionnaire. The first question asked was, “Do you feel that you are becoming more pro-environmental since you moved to this green building (pro-environmental behaviours such as minimize water/energy use when possible, recycle and categorize waste, use public transportation instead of car)?” Four answers can be chosen, namely “no changes”, “slight”, “moderately”, and “strongly more pro-environmental”. If the answer was other than “no changes”, then the second question being asked was, “Do you think the exposure to different types of green design (visual vs. conceptual) resulted in your different level of pro-environmental behaviour (visual exposure such as the building has solar panel, and other exterior/interior visual features (e.g., the wood shading in the west façade in CH2), conceptual exposure such as that you know the building uses recycled water, but they do not express themselves visually and vividly)?”. Four answers can be chosen, namely “no differences”, “conceptual exposure is slightly more persuasive”, “visual exposure is slightly more persuasive”, and “visual exposure is certainly more persuasive”.

Out of the 11 people, three answered “no changes” on the first question, thus the second question was not applicable to them. Six answered “moderately more pro-environmental” (Table 1). This showed that majority of the occupants might be positively influenced by the CH2 and behave more like a green occupant, to some extent. Among the eight people who were becoming more pro-environmental since
moving into the CH2, four answered that visual green design is slightly more persuasive than conceptual green design in influencing their pro-environmental behaviours, two answered visual green design is certainly more persuasive. The overall trend matches with our hypothesis that visual persuasion is a more powerful tool in influencing occupants’ pro-environmental behaviour (Table 1).

Table 1: The result of the preliminary survey from CH2. The contingent 2 by 2 table shows the answers on the first and second question.

<table>
<thead>
<tr>
<th>1st question: Pro-environmental behaviours since moved into the CH2</th>
<th>2nd question: Persuasive power of visual vs. conceptual green design on changing pro-environmental behaviours</th>
</tr>
</thead>
<tbody>
<tr>
<td>No changes</td>
<td>No differences</td>
</tr>
<tr>
<td>Slightly more pro-environmental</td>
<td>3</td>
</tr>
<tr>
<td>Moderately more pro-environmental</td>
<td>0</td>
</tr>
<tr>
<td>Strongly more pro-environmental</td>
<td>0</td>
</tr>
<tr>
<td>Sum</td>
<td>3</td>
</tr>
</tbody>
</table>

4. Hypothetical data simulation

The above preliminary results ensured the necessity of a follow-up full-study, though with a small sample from only one green building – CH2. The following specific research questions were detailed as an example for a future full-study: 1) Do the occupants from buildings with green design (either visual or conceptual, or both) have a higher mean score on pro-environmental behaviours than those from conventional buildings?; 2) Is the visual persuasion of green design more effective than conceptual-only green design in influencing the occupants’ pro-environmental behaviours?; 3) While controlling for personal background factors, what is the effects of: 3.1) the presentation of objective building characteristics (i.e. visual and conceptual green design); and 3.2) the subjective viewpoints of individual occupant (i.e. awareness and perception of visual and conceptual green design) in influencing the occupants’ pro-environmental behaviours. A hypothetical example and fake data simulation were used to demonstrate one possible analysis approach to answer the research questions.

Ideally, longitudinal data should be collected among the same cohort of building occupants before and after moving into the green building. Though, in real cases, cross sectional data are more feasible, as performed by all the studies reviewed in section 2.1. Thus, an analysis method for a comparative study among different buildings was proposed in the following.

Leaman and Bordass (1999) argued that buildings are complex systems made up of physical and human elements and their many associations, interactions, interfaces, and feedbacks and it is often fruitless to try and separate out different variables and treat them as ‘independent’ as many statistical methods require. Nevertheless, statistical analysis is a powerful tool in answering a wide range of research questions. In previous studies reviewed in section 2.1, some of them used two (or a multi-)
group comparison on environmental attitudes scores (Deuble and de Dear, 2009; Hostetler and Noiseux, 2010; Deuble and de Dear, 2012; McCunn and Gifford, 2012; O'Callaghan et al., 2012; Rashid et al., 2012; Daniel et al., 2014). Others used classic regression analysis (Deuble and de Dear, 2009; Hostetler and Noiseux, 2010; Deuble and de Dear, 2012; McCunn and Gifford, 2012; O'Callaghan et al., 2012; Rashid et al., 2012; Daniel et al., 2014). For answering the research question raised above, both a multi-group comparison (for first research question) and a hierarchical regression (for research question 2 and 3) could be applied. The fake data simulation is demonstrated for the hierarchical regression.

The most distinctive feature of a hierarchical regression is that when the study sample are collected from different clusters/levels (e.g., buildings in our example), it is a method for compromising between: 1) excluding a categorical predictor (e.g., building index) from a model (complete pooling); or 2) estimating separate models within each level of the categorical predictor (no pooling, e.g., a separate regression for each building) (Gelman and Hill, 2006). In the data simulation, we used a varying intercept hierarchical model in order to:

- Extract the effectiveness of the buildings themselves by estimating the coefficients for the group-level predictors, i.e., the building-level characteristics (i.e. whether or not the building has the visual/conceptual green design, or both) (Figure 2). From the statistical perspective, group-level predictors play a special role in hierarchical modeling by reducing the unexplained group-level variation and thus reducing the group-level standard deviation (Gelman and Hill, 2006).
- Extract the effects due to the awareness and different perception that individual occupant holds within the same building, while controlling for personal factors. These two individual predictors were selected due to the fact that, while occupants are exposed to the same green design in a building, their awareness of the green design and their perception of the green design are different, which may result in their different responses in behavioural changes (Figure 2).

Specific questionnaires (e.g., on how to measure the pro-environmental behaviours) were not provided. For the simulation, it is assumed the scores on independent variables are either binary (for objective building characteristics, and occupants’ awareness on green design), or 7 point Likert scale (occupant’s subjective perception, e.g., from not persuasive at all to very persuasive). One personal background factor was assumed for demonstration purposes, i.e., the educational level. Fifteen buildings with different characteristics were simulated, some with visually green design only, some with conceptual green design only, and others with both (Figure 2). Different sample sizes were simulated for each building, ranging from 6 to 29, with a total of 273 samples.

Hierarchical regression is in essence a Bayesian inference (in comparison to frequentist inference), the parameters estimation is non-point estimation by Markov Chain Monte Carlo (MCMC) simulation. The full simulation code can be obtained upon contacting the first author of this paper. Following steps were carried out for the simulation: 1) set-up fake dataset; 2) specify “true” parameters; 3) specify hierarchical model in Winbugs and call from R using R2winbugs package (Gelman et al., 2015) (Figure A.1). Two hierarchical model were simulated, the first one without including the group/building-level indicators and second one including those (Figure A.1).
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Figure 2: The hierarchical regression model on occupants from buildings with different characteristics

5. Discussion and conclusions

To identify how a green building itself may encourage occupants’ pro-environmental behaviours, previous relevant studies were reviewed, all which came to different results and conclusions. Studies on visual persuasion and communication roles of buildings were also reviewed, as a potential powerful persuasive medium, the visual persuasion of green buildings has not yet been studied.

A simple preliminary survey was carried out in the CH2 to find out the possible influence from the green design on influencing occupants’ pro-environmental behaviour, and in particular, the effectiveness of visual green design. The results showed it is likely that occupants could be influenced by the green design and behave accordingly, and the visual green design might have a higher persuasion power than conceptual-only green design. The preliminary survey with a small sample size restricted us in using a statistical analysis to come up with more scientific rigorous conclusions. Besides, the small sample size could not serve the representativeness of a larger population; the single study site also limited us from generalizing the findings to other locations.

Bear in mind that with the limitations on the preliminary survey, its results nevertheless ensured a future full-study is necessary to detail the research questions in more depth. Unlike the analysis method applied by previous studies, we proposed the use of hierarchical regression to match the sampling procedure that occupants are clustered within each building. A fake data simulation with varying intercept model including objective building characteristics as group-level predictors and subjective viewpoint of occupants as individual-level predictors were demonstrated. The fake data simulation certainly does not hold any empirical values, and the validity of any study design and analysis could only be achieved through a real study in the future. The hypothetical example shown, however, is innovative in that it addressed the variation through spatial differentiations of occupants from different buildings.
There are several important factors that can be scrutinized by future studies. First is the level (intensity) of the green design exposed to the occupants. For example, green certified buildings have different certification levels. This can be solved by using a scale (e.g., 0 to 5) to represent the intensity instead of using binary variables to represent the existence of visual/conceptual green design, as did in the fake data simulation. Second is occupants’ satisfaction with the physical and non-physical environment. (Rashid et al., 2012) found that the occupants’ satisfaction with the workspace related features affects their environmental awareness. Leaman and Bordass (1999) found that some employers in a building always kept the light on just to “annoy the manager”. Third, only the potential of visual green design is explored, other sensorial cues (e.g., auditory information provided, feeling of different material texture, e.g., brick vs. steel) are not explored here and shall be part of future studies.

This study looks at the effect of green building itself (i.e. the physical environment), instead of looking into the administrative and behavioural environment within the building, such as influence from the social norms. Future studies can incorporate different perspectives to find out the potential effectiveness of different means (physical vs. administrative and behavioural) of green built environment on influencing occupants’ behaviours.

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References


Figure A.1: The hierarchical regression model on occupants from buildings with different characteristics – several screenshots of the hypothetical data simulation, the results showed the two hierarchical models using Bayesian inference on the
Guidelines for personalization opportunities in apartment housing

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Abstract: One of the current problems for the architectural profession is the lack of attention given to the users of buildings and their psychological needs, especially in mass housing projects and particularly in apartments. Thus, the main question behind this research is how to design a residential complex to support different types of client needs. The aim is the creation of a dwelling in which anybody can enjoy living and establish and present his/her personality. This study seeks an acceptable relationship between architect and user based on the psychological needs of users through a historical investigation. It tries to establish new definitions of personalization by focusing on the psychological needs of human beings (especially the needs of respect and self-esteem) to introduce new ways of obtaining more user satisfaction with future homes. Following observations of a typical apartment block in Iran of how and why people personalise their apartments and the problems they encounter, guidelines are proposed for the stages of the design and building process to obtain a better context for personalisation by residents, whether owning or renting.

Keywords: Personalization; user needs; design-build process; apartment housing.

1. Introduction

Personalization is an important topic in psychology and also holds a special position in architecture. Personalization is especially important in the dwelling, which is where people have most contact with architecture, as a population satisfied with their homes is important for society. Occupant satisfaction with and a feeling of belonging to the dwelling, together with people feeling they have an identity in their community, can result from personalization and improve both quality of life and public health.

An important parameter for personalization is a proper relationship between designer and client, something easily achieved in traditional housing where client and user are the same person. An appropriate relationship between designer and user is more important when the end user is not known and, as a result, their needs are not recognized. This can lead to user dissatisfaction where opportunities for personalization are missed. Following from a case study of an apartment block in Iran, the main objective of this paper is revision of the architectural design process in the search for a way of designing
residential complexes so occupants with different tastes can enjoy living in them through finding room for personalisation.

In traditional domestic architecture, client, architect, and builder form a triangle in the house acquisition process and each plays a critical role. To make houses more tailored to the needs of their occupants, Jusan (2005) felt users should be involved in their home construction. For a successful fit between users and buildings, Lang (1987) thought it was vital to understand the relationship between clients and professionals, as the paying client is a filter between the designers and the needs of users. Such clients include dwelling owners, government, local authorities, investors, and, often by proxy, the public. Israel (2003) emphasized that participatory design in mass housing projects is hard to achieve. Where the paying client and user are not the same, what should the relationship of these parties be to best meet the psychological needs of dwelling users?

2. User needs in design

Lang (1987) assumed the goal of design is to satisfy human needs. He also believed that designers cannot have all the information about the people they are designing for but “…need to ask right questions and be good listeners”. He suggests the basic needs of users of the built environment should be met first by being based on Maslow’s hierarchy and believes “the buildings must work at this level at least” (Lang, 1987, p.237). He also considered design should meet the users’ needs as well as the basic requirements of the paying client and where these conflict, the designer must represent the user rather than the sponsor. Despite the focus on the most basic and essential user needs, some needs, particularly higher ones, are sometimes ignored or undervalued. This often occurs for esteem needs, and satisfying these could potentially (as the guidelines below suggest) lead to the presence of the user in all stages of the design process.

“Personalization refers to the marking of places, or the accretion of objects within them and thereby the staking of claim to them” (Lang (1987, p.147) from Becker (1978)). According to Jusan (2007), personalization is making a person’s territory align with their values. “The process of personalization that is in form of modification or movement tends to be inevitable and is a conscious process, due to the conscious change of user needs throughout his life span” (Jusan, 2007). Abu-Ghazzeh described personalization as the way a person modifies his environment to make it distinctly his (Abu-Ghazzeh (2000) in Omar et al. (2012)). Jusan (2007) described personalization as a significant approach in Malaysian housing through which people increase congruence with their home environment. End-users organize their environment directly in accordance with their “personal demand and characteristics” through home making decisions (Erinsel Önder et al, 2010). Lang (1987) believed the process is often unconscious and usually occurs for a purpose, such as territorial control, expression of aesthetic tastes, and to adapt the space for the desired activities. Thus the main purpose of personalization is meeting personal intentions in home making (Jusan, 2010). Furthermore, personalization creates a “dynamic and transformative” house responsive to the different life styles of the residents (Baldwin and Tomita, 2007). Tiesdell and Oc (1993) showed a correlation between personalization and individual identity defining the process as the capability for creating an environment for her/himself or having the dominant influence on personal space. Proshansky et al. (1970) in Hayward (1974, p.127) defined personalization as an individual’s attempts to organize his physical environment to maximize his freedom of choice. The personalization of places “serves many purposes: psychological security and symbolic aesthetic as well the adaption of the environment to meet the needs of specific activity patterns” (Lang, 1987, p.148). According to Lang (1987) territory is recognized through personalization.
Self-esteem is the main consequence of personalization and territorial control. Proof of ownership, sense of identity, control, security, respect for privacy, respect for personal space and place attachment as lateral consequences of personalization are all important factors that lead to more user satisfaction (Fernandez, 2007; Lang, 1987). Territorial behavior is a mechanism for controlling the boundary of a space between an individual and others, and is defined by personalization and place marking to indicate it belongs to a specific person or group (Altman, 1975). Personalization usually occurs in identifying the boundaries of public and private territories, specifically ownership boundaries and individual territory (Tiesdell and Oc, 1993). Lang’s (1987) definition of personalization emphasizes the creation of a feeling of ownership of a place, and hence marking its boundaries through personalization. Identity is associated with the need for personalization in individuals (Tiesdell and Oc, 1993). Porteous (1976) in Yu (1999, p.11) stated “personalization promotes both security and identity”. The personalization of a space is one means by which “control” can be achieved. Control might be more important than the physical aspects of a space, making it essential to give occupants opportunities to select and control an environment, so that they can organize the space to be fit for them. “Place attachment is one of the most influential factors in human’s psychological health, and is therefore powerful in constructing an individual’s identity” (Tuan (2007) and Oliver (2006a) in Asad Poor Zavei (2010, p.312)).

One of the most important and unique aspects of personalization is the attention given to the aesthetic aspects of the built environment. Israel (2003) suggested a pyramid of “housing needs” by adapting Maslow’s hierarchy of human needs in terms of design psychology. In this model, she believed that “home as self-actualization” could be reached once the lower order needs were satisfied. “Home as satisfaction of aesthetic need” is at the same level as esteem needs in Maslow’s hierarchy, meaning that satisfaction of the aesthetic need is a way to fulfill the respect and self-esteem needs. On the other hand, Lang (1987, p.110) considered personalization as a “sociophysical mechanism” for meeting esteem needs. As a result of the integration of these two theories, there is a relationship between personalization and aesthetic need (Figure 1). More user satisfaction with dwellings especially in residential complexes could, therefore, be achieved when they comply more with user needs and aspirations. In other words, user satisfaction is best achieved by providing opportunities for personalization. On the other hand, Asad Poor Zavei (2015) stated that while lower level needs are more likely to be met in early stages of housing delivery, the higher levels should be satisfied by decision makers through providing the chances for active and direct participation in the housing process.

Lang (1987) believed “central” territories or private spaces are likely to be highly personalized. In semi-private and semi-public spaces (supporting territories) the level of personalization and the ways it is achieved depend on different factors, and “peripheral” territories or public areas are less likely to be personalized. Some private spaces in dwellings are used as public spaces, such as the living and dining rooms, and these will represent the public personalization of inhabitants, while individual spaces, such as bedrooms, represent individual personalization. Asad Poor Zavei (2015) believed that to fulfill end-user needs and preferences, user participation in home making is essential, as it enhances the sense of home in housing. However, for dwellings in mass housing projects residents can only suit their variable needs and lifestyles through personalization (Omar et al, 2012).
3. Personalization of the dwelling

Dwelling style, its location, the design of its façade and external volume, the building materials and the internal layout can all reflect user personalities, but usually all the user can personalise is the internal décor and later renovations. Nevertheless, Fernandez (2007) stated that involvement at this level can increase emotional attachment to the space. Boudon (1972) observed Le Corbusier’s Pessac houses, finding a correlation between the house position and occupants’ alterations. In specific positions, the occupants paid more attention to green spaces which led to the erection of metal fences overplanted by hedges, allowing people reveal their personalities and desires through their living environment.

Despite flexibility being an architectural means of allowing for personalisation, it should be noted that user preferences for flexibility features in house design are different for different aspects of the house. Studies indicate that users are more concerned with flexibility in the design of the living room, dining room, kitchen, and bedrooms, including the master bedroom (Saruwono et al. (2012) and Jusan (2007) in Alaraji and Jusan (2015)). In research conducted by Alaraji and Jusan (2015) in Malaysia, users showed less concern for flexibility in the bathroom, house façade, porch and garden, doors, ceilings, window location and numbers, and materials. This is despite the fact the exterior façade and volumes are components which make a house like or unlike adjacent houses. In some standardized residential buildings in which the exterior components of the building are the same for all units, personalization can be observed through alterations where occupants have fenced balconies or the changed the colour of windows if permitted. Saizally et al. (2012) conducted research on personalization of terraced houses in Malaysia and found a “lack of mutual understanding” and “respect of rituals and cultural values” as two possible contributors to the immediate personalization of terraced houses. Boudon (1972) demonstrated alterations in the façades and volumes of the Pessac houses, something made easy by Le Corbusier’s framed design (Figure 2). At Pessac, the conversion of a spatial void to solid mass, such as balconies to rooms, adding an external stair to provide an access to the upper balconies, the conversion of the exterior stair boxes to ramps and adding spaces at the back of the house are examples of form changes. Interior redesign includes changes to finishes, adding a false ceiling, creating smaller rooms from a larger space, and changing the lighting type.
Figure 2: Pessac houses after alteration and as designed (Rabinowitz, 1979)

Furniture is an obvious means of personalization, as are decorative features such as pictures, family photos, awards, and house plants. The type, amount and intensity of changes made to features in the built environment are indicators of the level of personalization (Yavari, 2007). Macro changes include the layout of existing spaces, function, form and volume whereas micro changes consist of colors, landscaping, the proportion and color of openings and decorations. Research by Jusan and Sulaiman (2005, p: 505) found that modifications to Malaysian urban mass housing to achieve personalization included: “decoration, rearrangement of moveable items, altering family norms and composition, and structural modification of the houses”. Hall (1966) believed alterations are essential, as they make the built environment more habitable and personalizable. Abbott et al. (2003) in Omar et al. (2012) categorized the reasons for people to modify their homes as financial, beautification, and making it “stylish”. Modification and relocation are two approaches people take to adjusting their current house when it does not meet their needs (Baum and Hassan (1999) in Omar et al. (2012)). Jusan (2010) studied a completed housing scheme in Johor Bahru-Malaysia and found the inappropriateness of the original design was mentioned as the main reason for modifications by 82% of users. Asad Poor Zavei and Jusan (2012) developed a theoretical framework of personalization by representing the levels of need in housing provision. The framework also highlighted the process of evaluating person-environment congruence which leads to personalization. According to the framework end-users strive to make the delivered housing attributes congruent with their needs through modifications (Asad Poor Zavei, 2015). Therefore, giving more attention to end-users leads to more room for personalization and can deliver a sense of home in mass housing.

4. Methodology

The guidelines created in this study were based on interviews/discussions and systematic observation of residents currently living in the Negin residential complex in Yazd, Iran. One of the authors also lived in the same block. A systematic analysis of random samples of apartments was undertaken. This residential complex, one of the first apartment buildings in Yazd, comprised 24 blocks with 384 one and two bedroom units of two standardized types (Types C and D). It was observed that almost all apartments studied had experienced modifications or renovation to meet the residents’ expectations and needs. This echoes the study of Sazally et al (2012) who, looking at Malaysian housing, found residents who had renovated were satisfied with what they had done. The modification done at Negin was influenced by the cost of alterations, constraints of the original design, the ownership situation (whether the apartment was owned or rented), and the location of the unit. Two major structural
alterations were observed; adding a wall between living room and kitchen to avoid the undesirable emissions of cooking smells, something only possible in type C one or two bedroom units; and removing the wall between the balcony and living room leading to a larger living room at the expense of the private open space, which is possible only in type D one or two bedroom units (Figure 3). All these efforts have been undertaken by the occupants to make their dwelling, especially their living room, more personalized. Interviewees mentioned their inability to make major desirable modification due to design limitations. There is no space for a possible extension and structural modification is not possible due to the integrated structure that supports all 16 units in the same block. The occupants felt this limiting of their ability to personalize to meet their needs and requirements. Therefore, the most popular elements for modification included painting, flooring, kitchen cabinets, and windows/entrance doors and grilles. Accepting the selection of desirable furniture for different spaces is an aspect of personalization, this was identified in a resident focus group as being the easiest and most cost effective means of personalization. However, Jusan (2010) believed that “renovation promotes user participation in home making”, suggesting a need to see personalization as something more than choosing furnishings.

![Figure 3: Examples of modifications in the Negin residential complex (Left), before and after personalization, Types C and D (Right) (Source: Authors)](image)

Beautifying their houses mostly occurred in living rooms, this being the place where their collective self is shown to others and their guests. The top ranking reasons for renovation identified by the respondents included: to meet the functional requirements of the family, security purposes, especially for the lower units, to accommodate special interests, such as gardening, and seeking a better quality of material in the finishes. This information combined with the literature review provided the basis for
establishing a set of guidelines for how users might be better involved in the design process to achieve housing that would really meet their needs and aspirations.

5. Architectural design to provide opportunities for personalization

Guidelines could be useful for designers, users, clients and contractors in the different stages of housing delivery to encourage and promote personalization. One aim of such guidelines is to define the scope of design, with the aim of defining limits for involving end users in the design process as well as the time and place of these involvements.

Some architectural concepts do not let the occupant or user personalize his/her dwelling while others give her/him these opportunities. “Total Design” is a concept in which the designer is responsible for all aspects of design (from generalities to the very small details) meaning there is no chance for users to personalize their surrounding environments. Other concepts that provide more opportunities for users to personalize their dwellings include: adaptable design, flexible design, open-ended design, unfinished design, universal plan, and ‘plan libre’ (the Pessac example). In these concepts, people are allowed to shape or can change the design until it meets their needs and expectations.

To aid personalization the concept of ‘design with the community’ facilitates the presence of users and occupants at all stages of the design and building process, providing more opportunities for them to personalize their dwelling. Asad Poor Zavei (2015) suggested that to fulfill end-users needs and expectation and improve spatial personalization, a “multidimensional participatory approach” including indirect, direct, active, and even passive participation should be applied in the different stages of housing delivery and in the absence of end-users, their needs and expectations should be sought by surveying a sample of the target population. Involving users in post-occupancy modifications would be another option to make personalization possible. Jusan and Sulaiman (2005) investigated a case study where users were involved in the design and construction process of alterations including: consultation with designer/architects, material provision, supervision of building operation, selection and consultation with contractors, and managing the financial aspects of the project. In some cases, users were involved in construction of the dwelling. Tables 1 and 2 suggest guidelines for different parts of the design process to provide more opportunities for people to personalize their dwellings.

| Phase zero | Designer | • Investigation of site topography and micro climate  
|            |         | • Recognition of users and clients needs  
|            |         | • Identifying design goals and objectives |
| Client     | • Selection of appropriate designer  
|            | • Identifying budget  
|            | • Consultation with designer to confirm priorities, and recognize potential users needs |
| User       | If the user is known:  
|            | • Identifying his/her needs, priorities, and requirements  
|            | • Identifying the budget |
| Contractor | NA |

Table 1: Suggested guidelines for designer, client, user and contractor in phase 0 of the design-build process
Table 2: Suggested guidelines for designer, client, user and contractor in phases 1, 2, 3 and 4 of the 
design-build process

| Phase one | Designer | • Brainstorming to achieve personalization opportunities, flexibility and adaptability  
|           |          | • Presenting proposals  
|           |          | • Selecting the best proposal referring to the user’s opinion (if known) or client  
|           |          | • Completion of the design while maintaining personalization opportunities  
|           | Client   | • Consultation with the designer to select optimum proposal for user satisfaction and budget  
|           |          | • Explaining the designer’s proposed alternatives to the user (if known) for feedback  
|           | User     | • Consultation with user if known in the process of making proposals  
|           |          | • Consultation with the designer to complete unfinished parts from phase one and assist in design completion  
|           | Contractor | • Consultation with the designer in terms of building limitations  

| Phase two | Designer | • Preparing working drawings of structure, external construction, internal construction and climate response  
|           |          | • Consultation for selection of building materials and equipment related to user  
|           |          | • Provision of design details following user feedback  
|           |          | • Consultation with contractor to ensure the feasibility of the design  
|           |          | • Provision of entire working drawings to the contractor  
|           | Client   | • Giving feedback about proposed design related to budget  
|           |          | • Selecting an appropriate contractor for the project  
|           | User     | • Providing ideas and feedback about the interior layout of the building  
|           |          | • Selecting interior finishing materials and fittings, lighting and electrics in consultation with the designer  
|           |          | • Providing ideas and about design and other materials in consultation with the designer  
|           | Contractor | • Giving practical advice to the architectural designer  
|           |          | • Understanding the specific operational method for cooperation between the designer and user  

| Phase three | Designer | • Designing interior layouts in accordance with user’s ideas and requirements (including finishes, fixtures, windows, fittings, and landscaping features)  
|            | Client   | • Supervision of building operation and financial aspects of the project in cooperation with the contractor  
|            | User     | • Consultation with the designer about interior layout, materials, finishes, fixtures, fittings, and landscape elements  
|            | Contractor | • Construction of structures, walls and openings, and plant  
|            |          | • Installation of interior elements to meet user and designer requirements  

| Phase four | Designer | • Giving advice on how to operate the building to the user  
|           |          | • Designing any required modifications  
|           | Client   | • Agree to finance any modifications  
|           | User     | • Consultation with the designer to understand building operation and ask for required modifications  
|           | Contractor | • Provide operating details for designer to communicate to user  
|           |          | • Undertake any modifications  

Note: If the user is not known, the associated instructions are transferred to the building operation stage.
The responsibilities of designer, client, contractor and user are indicated in each phase (Phase zero: site and brief investigation, Phase one: provisional design, Phase two: working drawings, Phase three: construction, Phase four: post-occupancy alteration). As highlighted earlier, the suggestions are based on observations from the authors’ investigation of the Negin residential complex, a typical mass housing delivery process in Iran, and interview/discussion with residents.

6. Conclusion

Many studies have been conducted on the strong relationship between meeting user needs and health, suggesting user involvement in the design of living environments leads not only to a better quality of life but also to an improvement in general public health. One responsibility of the architectural profession is involvement in the provision of housing from the first stage of decision making, planning and programming, to the final one of building operation and post occupancy evaluation. All of these stages can, as suggested above, involve the user if more thought is given to the design process.

User satisfaction is best achieved by promoting and encouraging personalization in the design process. In other words, people personalize their home environment to satisfy their own needs. Friedman (2002) in Omar et al. (2012) defined personalization as a process involving “designing, planning, construction and usage”. As a first step designers need to give more attention to how people personalize their dwelling environments.

Occupant satisfaction can be established according to the concepts of personalization by carefully selecting the location of a dwelling, its shape, interior design, furniture, decoration, symbols, landscaping, and the design of nearby open spaces. With this approach, an appropriate context can be provided for improving quality of life by creating environments which could be personalized.

As a first step in this process, this paper proposes guidelines for designers, clients, users and contractors related to the different phases of the design process, which could provide more opportunities for people to personalize their dwellings. The general idea is to define the scope of design, with the aim of defining limits for involving end users in the design process as well as the time and place of these involvements. Depending on whether or when the end user is known, the responsibilities of each party and the consequences of the personalization process are different. To achieve a high level of personalization, people should be allowed to shape or change the design until it meets their needs and aspirations.

One of the advantages of clarifying the parties’ responsibilities in the guidelines is that this highlights the role of the user in each phase and emphasizes achieving an effective and close cooperation among the parties involved.

These guidelines for personalization can also be applied to mass building delivery, especially in the residential sector, which covers a great proportion of global housing projects. At present, users of these houses usually do not meet the designers and as a result their needs are ignored. This research suggests that the architectural profession could take responsibility for involving users in appropriate housing design to accommodate future modification.

References


How do people use large houses?

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Abstract: From 1974 to 2011 the average new New Zealand house almost doubled in size while occupancy reduced over the same period. A first study indicates the features of large houses include several bathrooms, double/triple garaging, extra bedrooms/living areas and specialized rooms although there is no study of how these extra spaces are used. As a part of a larger study of how resources are used in different sized houses, the aim of this pilot study is to find the overall time small households in New Zealand spend in the rooms of their houses. Two questionnaires were developed to investigate the type/number of spaces/furniture in NZ houses and ask households to report time spent in each space over 14 consecutive days. The results show that irrespective of house size, households spend most time in the usual bedroom of each member(s), and the space(s) for living, dining and the kitchen and less than 10% of time using extra rooms available. In this pilot study people with larger houses spend more time at home. Analysis also reveals time spent at home is highly patterned and very similar on working days but different at weekends.

Keywords: Large housing; occupant behaviour; time use; house size.

1. Introduction

While crowded houses remain a problem in many parts of the world (Shelter (2004;2005;2006), RIBA (2011), ODPM (2004), Friedman (2010), Murray (1974), BSHF (2013) and DBH (2010)) a new phenomenon here called large housing (in terms of floor area as it relates to the whole housing stock) has appeared in some developed countries especially in Australia, Canada, New Zealand and the United States. According to QV (2011a), the average floor area of new houses in New Zealand has increased from 112.7 m² in the 1940s to 205.3 m² by 2010 and later. Building consent figures by Statistics NZ (2014a) also show the average floor area of new houses in New Zealand has almost doubled from 1974 (108.7 m²) to 2011 (191.6 m²). The same source also indicates that most large houses are in suburbs of major cities with the top 3 in New Zealand being Shamrock Park in Auckland (306 m²), Kennedys Bush in Christchurch (279 m²) and Lake Hayes in Queenstown Lakes (274 m²) (QV, 2011b). At the same time average household size has decreased from 3.7 persons in 1951 to 2.6 in 2011 (Statistics NZ, 2008). This suggests the average floor area per person in the household has increased.
Crowding indices are used to show the relationship between house and household size, although different crowding indices have different definitions. Statistics NZ uses Canadian National Occupancy Standard (CNOS) and a study by Goodyear et al. (2011) suggests this is the most precise index for New Zealand. CNOS uses number of bedrooms as an indicator of house size. Based on CNOS each couple, any pair of children under 5, pairs of children aged 5-17 of the same sex, single adults over 18 and any other remaining unpaired children need a separate bedroom (Goodyear et al., 2011). According to Statistics NZ (2014b) in 2006, 6.9% of New Zealand households were severely crowded, 3.5% crowded, 25.1% had no extra-no spare, 33.4% had one bedroom spare and 31.1% 2+ spare bedrooms. This means studies on crowded houses are focused on 10.4% of households while other housing which covers 64.5% of New Zealand households is ignored. Statistics NZ (2014b) indicate houses with 2+ spare bedrooms increased from 22.4% in 1991 to 31.1% in 2006. Comparing the average number of available bedrooms for 2006 NZ households with having one bedroom per occupant reveals large housing mostly occurs in small households with 4 or fewer members (Figure 1). In addition, Statistics NZ (2002a, 2011a and 2014c) indicate that the number of houses with 1, 2 and 3 bedrooms decreased in 1986-2013, and those with 4, 5, 6, 7 and 8+ increased in the same period.

According to Statistics NZ (2014d) European ethnicities are most likely to live in houses with spare bedrooms, and Pacific, Middle Eastern, Latin American, African, and Maori ethnicities are least likely. While 72% of Europeans live in houses with at least 1 spare bedroom, relevant figures for Asian, Maori and Pacific are respectively 46.4%, 43.6% and 26.5%. Accepting the number of bedrooms has a great influence on total house area, according to Statistics NZ (2011b) houses with 1 and 2 bedrooms (small houses) are mostly for rent while those with 3+ bedrooms (medium and large houses) are mostly owner occupied.

Because of the lack of studies on large houses, there is little knowledge about their features. A preliminary unpublished study as part of this research showed these houses have extra bedrooms, extra living rooms, en-suite bathrooms, double and triple garaging and more rooms with specialized functions. A study by BRANZ (2007) indicates double garaging was the most important feature for people buying a
new house in New Zealand, and this corresponds with an increase in household total car ownership (Statistics NZ (2002b, 2013 and 2014c)). BRANZ (2007) also discovered a room as a study was an important feature for those buying new houses as was a games room. Vale and Vale (2009) mention separate formal and family living rooms in modern houses. While there are signs of new spaces in large houses, there is no study of how much people use them.

Large houses use more construction resources and more operating energy over their life (Vale and Vale, 2009). A study by BRANZ (2010) indicates that the typical estimated monthly winter energy costs of dwellings increases with floor area. An investigation in the Netherlands by Guerra-Santin and Itard (2012) also indicates a positive relationship between energy consumption and number of bedrooms in dwellings built after 1996. Large houses are also filled with more furniture and appliances (Mithraratne, 2013). Vale and Vale (2009, p. 134) conclude that living in smaller houses is the quickest and simplest way to reduce housing impact. Mithraratne (2013, p. 94) also believes that “Having a smaller house could also be beneficial in increasing the area of the site available for growing food and generating energy on-site, which could further reduce the dwelling footprint”. As large houses occur in richer and more developed countries an equity issue is raised, “concern about sustainability must be based on moral obligations towards future generations - not just personal self-interest” (Dresner, 2008, p. 2). It, therefore, seems vital to know how large houses are used and whether resources are being wasted.

2. Methodology

In this study time spent in different spaces of a house was selected as an indicator of occupant behavior (Brauer, 1974). Prior studies by Brasche and Bishof (2005) and Schweizer et al. (2007) use overall time spent indoors (but not sub spaces) as a necessary assessment of occupant exposure to possible harmful substances. Here, the number/size of spaces and type/number of available furniture/appliances were selected as indicators of resources used, together with presence of a garden and car parking facilities. As mentioned before, large housing is mostly seen in small families of European ethnicity living in owner occupied houses in New Zealand, so all participants surveyed were from this group, in households of single person, couples and couples with 1 or 2 children. The original list of possible rooms and furniture was developed from the Trade Me website (Trade me, 2014), although participants could add to this.

In this first pilot study the intention was to have at least two participating households from each group but in the end participants were 1 single household, 1 couple and 1 couple with a child who lived in small houses and 1 single household, 2 couples and 1 couple with a child who lived in large houses, making 7 households (1.A-1.H) and 14 individuals.

CNOS was selected as the base for defining small and large houses. Houses with at least one of the following feature were categorized as large and others as small:

- Houses with 1+ extra bedroom(s) (bedrooms with no usual nightly occupants) or
- 1+ extra living area(s) other than 1 living room, 1 kitchen and 1 dining room or any combination of these or
- 1+ specialized room(s) (i.e. play room, workshop, etc. excluding 1 study room/office/library).

A questionnaire was prepared in 3 parts and participants were asked to fill each out on 3 different days. The first asked about occupants, type/number of spaces and presence of different types of furniture/appliances in their house. The second questionnaire was then based on day 1 answers to avoid asking questions about absent furniture and spaces and to add any new ones. This asked about location of furniture and large appliances in each space. The third questionnaire was a timetable prepared
according to available spaces and number of occupants. This timetable was designed for each participant to draw a line below the time of day he/she used that space of the house in 15 minutes intervals. This form was prepared for each occupant/day separately (Figure 2). In comparison to the methodology used by Brasche and Bischof (2005) and Schweizer et al. (2007), this gives more accurate data on the time of the day a space has been used and when spaces were in shared use by occupants.

<table>
<thead>
<tr>
<th>Report for: Occupant 1</th>
<th>Reported day: Monday</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedroom</td>
<td></td>
</tr>
<tr>
<td>Combined Living room/Dining room</td>
<td></td>
</tr>
<tr>
<td>Kitchen</td>
<td></td>
</tr>
<tr>
<td>Bathroom/Toilet</td>
<td></td>
</tr>
<tr>
<td>Garage</td>
<td></td>
</tr>
<tr>
<td>Garden</td>
<td></td>
</tr>
</tbody>
</table>

Figure 2 Proforma to give use of each space by each occupant

All households were asked to fill out the day 1 and 2 questionnaires and the timetables for each family member for 14 consecutive days starting from a Monday during different weeks in June, July or August 2014. This produced data for 98 household/days or 196 person/days. Adults were asked to fill out children’s timetables. For analysis, a 24 hour timetable was categorized into 5 parts: Early morning (6-9am), Working/School time (9am-4pm), Evening/Early night (4-9pm), Sleep time (9pm-6am) and Overall time used. Figures for each participant/day/space were extracted from the original timetables into this format. Given the large amount of data for most participants (4500 entries for some) a platform file was produced in SPSS for each participant and figures were transferred to SPSS for further analysis.

3. Results

3.1. Difference between weeks 1 and 2

Overall times indoors over 2 consecutive weeks were very similar for all participants. The biggest difference was 8.65% and the smallest 1.31% with an average of 5.94% for 7 participant households. Further analysis indicates big differences were caused by time spent in living rooms and extra bedrooms while times spent in other spaces were almost constant over the 2 weeks. The situation for outdoor spaces was very different (the study was done in winter) as time patterns were completely different for the 2 weeks. The biggest difference was 100.00%, the smallest 0.00% while the average was 58.33%. Further analysis showed a combination of weather parameters was the main reason behind these big differences.

3.2. Time spent at home on different days of a week

To find differences in time usages on different days each week a “Paired-Samples T Test” was undertaken using SPSS, yielding 21 different pairs of days for each week. For each household, times
spent in weeks 1 and 2 were considered separately. Analysis showed pairs of Monday-Wednesday, Monday-Sunday, Tuesday-Sunday, Wednesday-Saturday, Wednesday-Sunday, Thursday-Sunday, Friday-Sunday and Saturday-Sunday are different for the 7 case studies over the 2 weeks, suggesting that Sunday is the only different day from all other days of the week (even Saturdays). Further analysis showed big differences between working days and weekends were mainly rooted in use of extra bedrooms and extra living areas, which were used more at weekends.

### 3.3. Average daily time spent in rooms by each household

As each house has a different combination of rooms, it is difficult to compare time usages. For this reason, spaces within a house were put into 12 categories (Table 1). For all households, bedrooms with nightly use were considered usual bedrooms and other bedrooms as extras. The living room, dining room and kitchen (or combination of these) that was used more than other similar rooms by a household is considered as the usual living area and others as extra. The same categorisation was applied to the bathroom/toilet. Garages are not considered unless they have a different function from housing cars (one in this study was a music room). For each household the average time spent in each room by the household over a day was calculated.

Analysis of average daily time usages showed very different time patterns for each household. The most constant space uses were bedrooms used for 34-43% of a day. Biggest differences came from time spent out of home and usual/extra living areas. Table 1 presents average time spent in each space category and the households which were included in each average (only households with at least one room in each space category are included in that particular average). As seen in Table 1, for an average household, the majority of time at home (76%) is spent in usual bedrooms and usual living areas.

<table>
<thead>
<tr>
<th>Space category</th>
<th>Average is from</th>
<th>Average time as percentage of 24 hours</th>
<th>Average time as hours and minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specialized rooms</td>
<td>1.C, 1.F</td>
<td>1.25%</td>
<td>0:18</td>
</tr>
<tr>
<td>Extra Bathroom/Toilets</td>
<td>1.B, 1.F, 1.G</td>
<td>0.56%</td>
<td>0:08</td>
</tr>
<tr>
<td>Sheds and sleep outs</td>
<td>1.A, 1.C, 1.D</td>
<td>0.67%</td>
<td>0:10</td>
</tr>
<tr>
<td>Storage</td>
<td>1.B, 1.G</td>
<td>0.18%</td>
<td>0:03</td>
</tr>
</tbody>
</table>

To compare time usage in different space categories in small and large houses, Figure 3 was created to represent an average for all small and large houses. The left graph in Figure 3 gives the time usage for the small houses (1.A, 1.D and 1.H) and the right graph for the large houses (1.B, 1.C, 1.F and 1.G).
Figure 3 shows, for this small sample size, that house size is highly correlated with overall time spent at home. This time at home shows as utilisation of usual living areas and extra spaces. Prior study by Brasche and Bischof (2005) shows individuals living in 6+ bedroom houses spend 1.7 hours more indoors in comparison to those living in 3-bedroom houses and this difference is bigger for males. However, this could also be related to demographic factors, as older people might have larger houses as a result of having bought them when house prices relative to income were cheaper, or have larger houses because children have now left the family home. This will be something investigated in the larger study. Time spent in usual bedrooms is very similar in both size categories. In addition, households who have extra bathroom/toilets divide their usages between the main and the extra bathroom/toilet(s), with the main bathroom/toilet being used for 81% of all uses and the extra one(s) only for 19%. Time spent in the open spaces of large houses is three times that of small houses, which could be related to spending more time at home, or to having a larger outside space with a larger house.

### 3.4. Use of outdoor spaces

To find out more about outdoor space use, weather data including maximum and minimum temperatures, rainfall, and wind speed were collected (NIWA, 2014) for 16 June to 17 August 2014. Acknowledging this is a very small sample outdoor space usage, not unexpectedly, is more probable on warmer, less rainy and less windy days. However, this is not necessarily true for everyone. It seems there are priorities in the influential parameters. For instance, using outdoors at weekends is more important than temperature, noting that NZ winters are not severe and for many people the coldest days are around 9°C. The situation for wind and rain are different. It seems people will use the outside space in light but not heavy rain. High winds are also a different to using the outside space. In this study people generally use outdoors in their free time (mostly weekends) if it is not too rainy and windy, with greater usage in fine weather. It should be noted that the results only reflect winter usage.
3.5. Day and night spaces

The method used in this study for timetables not only provides information about the total time spent in each space but also the time a space was used. Time spent in each sub space is calculated as follows:

- Time spent in room A Early morning time frame (6am-9am) = \[ \frac{(\text{Subtotal of time spent in room A by household for timeframe 6am-9am over two weeks})}{14} \] \div (\text{Household population})
- Time spent in room A Working/School time frame (9am-4pm) = \[ \frac{(\text{Subtotal of time spent in room A by household for timeframe 9am-4pm over two weeks})}{14} \] \div (\text{Household population})
- Time spent in room A Evening/Early night time frame (4pm-9pm) = \[ \frac{(\text{Subtotal of time spent in room A by household for timeframe 4pm-9pm over two weeks})}{14} \] \div (\text{Household population})
- Time spent in room A Sleep time frame (9pm-6am) = \[ \frac{(\text{Subtotal of time spent in room A by household for timeframe 9pm-6am over two weeks})}{14} \] \div (\text{Household population})

Figures 4 presents average time usages for all space categories. The four time frames cover different times (i.e. early morning covers 3 hours, working/school time 7 hours, evening/early night 5 hours and sleep time 9 hours). To make time frames comparable, figures in each are divided by the relevant hours.

Figure 4: Time spent in all space categories by households over four scaled time frames as a percentage of the total time spent in each.

As seen in Figure 4, usual bedrooms are mostly used at night and in early morning and are less used over the day. The situation for extra bedrooms is very different meaning that though they have a sleeping facility (a permanent bed) they are used for other functions. Usage of usual and extra living areas is very similar indicating similar activities. They are also used during sleep time but this usage is very small and occurs between 9 pm and midnight. Study/Offices are also day spaces. Based on Figure 4, on average specialized rooms are usually used in working/school and evening/early night time frames, with the latter used more. Usual and extra bathroom/toilets are similarly used in all time frames but
more in the early morning. Laundries, sheds and sleep outs and storage are spaces used in the day but rarely at night. As seen in Figure 4, on average open spaces (gardens and decks) are mostly used in working/school time (daylight), being probably the warmest parts of the day. In addition, because this is time when people go to work/school it is clear why open spaces are mostly used at the weekends. It should also be noted that because of personal work schedules this time pattern changes for some households.

This analysis shows that a great proportion of time at home is spent over night in a very small area (the usual bedrooms), while other spaces are mostly used in the day time. This should reinforce designers to make good decisions about the internal layout of a house for good natural light/sunlight. It can also affect decisions regarding heating devices, especially programmable ones so these work most effectively. It is also important for those designing passive solar houses.

3.6. Furniture

A big difference between small and large houses is the resources, including furniture and appliances in each type. Furniture, large appliances, tools (hand held and power tools and gardening tools) and equipment were categorized into 8 types according to usage and usual location. Table 2 presents the number of furniture/large appliances/equipment and average total number of these for the small and large houses investigated. Considering this is a very small sample, for most categories large houses have more types and numbers of furniture/large appliances/equipment. The biggest difference between small and large houses seems to be in the living room/dining spaces. Bedrooms, kitchens and bathroom/toilet/laundries of small and large houses have similar types of furniture/appliances even though larger houses have more of these. Games equipment (e.g. table tennis table, exercise cycle) is only found in large houses. Large houses seem to have more types and numbers of outdoor furniture and gardening equipment/tools. In addition, both small and large houses have similar types of small appliances but larger houses have more items.

Table 2: Average number of furniture types and total number of each category in small and large houses.

<table>
<thead>
<tr>
<th>House size</th>
<th>Furniture/Large appliances/Equipment</th>
<th>Gardening equipment</th>
<th>Small appliances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bedroom</td>
<td>Living/Dining</td>
<td>Kitchen</td>
</tr>
<tr>
<td>Furniture</td>
<td>Small</td>
<td>8.0</td>
<td>10.0</td>
</tr>
<tr>
<td>types</td>
<td>Large</td>
<td>7.5</td>
<td>15.3</td>
</tr>
<tr>
<td></td>
<td>Small</td>
<td>15.3</td>
<td>16.3</td>
</tr>
<tr>
<td>frequency</td>
<td>Large</td>
<td>20.3</td>
<td>39.3</td>
</tr>
</tbody>
</table>

4. Discussion

Because of the small number of participant households the findings are mostly indicative, and need to be proved through a bigger study with more participants, for which this pilot was a preparation. However, this study has shown the times spent in different spaces of a house are good indicators of occupant behaviour. In addition, time spent at home usually follows a similar weekly pattern. Times at home on work days are similar for most people while weekends are different. Working schedules, family combination and age group all affect the time spent at home. This supports findings by Brasche and Bischof (2005) and Schweizer et al. (2007). There are signs indicating, not unexpectedly, that full time working couples spend less while families with young children spend more time at home. It is also
obvious from the pilot study that larger houses contain more furniture. Large houses tend to have more types and numbers of each type of furniture/appliance, with particularly large differences in living room furniture. Considering the energy embodied in furniture and that it has a much shorter life than the house (Mithraratne et al., 2007), this points to the increased resource use of having large houses.

This study also shows that apart from house size all families spend the majority of time at home in the same spaces, and that in all houses these have a similar floor area. In other words, people who live in large houses actually spend most of the day living in a small area within the house. The big difference between the way people live in small and large houses is that people who live in larger houses tend to spend more time at home and this spare time is spent in extra spaces (i.e. extra living rooms, extra bedrooms, music rooms etc.) noting this only covers 10% of time during a day. It seems that occupants of larger houses are able to have more activities at home. This will be further investigated in the larger study.

Environmental factors are also important when talking about large houses. Spare bedrooms and extra spaces within large houses use resources for construction, operation (cleaning, possible heating, maintenance) and furnishing. Accepting that living in larger houses could give more flexibility to occupants for 10% of each day, this flexibility in housing activities is coming at a cost. In other words, by considering the embodied energies of furniture, appliances and materials used in the extra spaces of a house it becomes clearer how inefficient these spaces are. This will also be investigated in later stages of this project on owner-occupied houses and small households. It is clear that house spaces can be categorized into night and day spaces. Usual bedrooms are the only night spaces while other spaces are day ones. Further analysis indicates almost 50% of the time households are at home (8:38 hours) is spent in usual bedrooms or night spaces. This figure is similar to the time reported in the Time Use Survey 2009/2010 by Statistics NZ (2011b) which indicates New Zealanders aged 12+ spend 8:48 hours sleeping per day.

This study is still ongoing and aims to validate the findings of this paper using a large group of participant households, by comparing results of resources used for each type of housing. The aim is to find an efficiency rate of living in different sized houses for different households.

References


Building and social housing federation (BSHF) (2013) Perception of overcrowding, public views of space in the home, Coalville: BSHF.


Learning from informal settlements: provision and incremental construction of housing for the urban poor in Davao City, Philippines

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Abstract: The incremental construction of housing for the urban poor is the main agent of progressive development in developing countries. Low income households in Davao City, Philippines, were classified into five different types from informal to formal housing. The aim of this paper is to explore the incremental construction of different housing types in the course of their development. Fieldwork revealed that the degree of security of tenure was directly related to the stages of incremental construction. For example, a simple dwelling in an informal settlement was upgraded with permanent building materials and standard methods of construction when the inhabitants’ degree of security improved. Over time, the physical condition of the house deteriorated when the inhabitants focused on payment for the land. Eventually, the completion of the house (defined here as a formal structure) coincided with legal ownership of the land. This typical incremental building pattern in informal environments, built by the urban poor, requires detailed understanding in order to provide effective housing interventions, and concomitant policy decisions, which are both appropriate and sustainable in developing countries.

Keywords: Incremental construction; informal settlements; Philippines; self-help housing.

1. Background to the study

This paper maintains that the incremental construction of housing in the lower income sector is the main agent of progressive urban development in developing countries. The link between self-help housing and the progressive development of urban settlements has been acknowledged since the 1960s. Turner (1967), most notably, cultivated appreciation for the unique opportunities that squatter settlements offered the urban poor to build their own housing in stages, as resources permitted. ‘The freedom to shape one’s own environment’, observed by Turner (1968), is how an informal dwelling could begin as a shack and end up as a permanent house occupied by its original settlers or its settlers’
children. Turner’s theories, which emerged from his experience in the squatter settlements of Lima, Peru, were influential world-wide. Relatively direct reflections, for example, were the ‘sites and services’ tactic for supporting and managing self-build housing, and the new policy of in-situ slum upgrading advocated by the World Bank in the 1970s (Pugh, 2000). Despite the further radical shift in housing policy to market oriented approaches to procurement, that was widely evident by the 1980s, Turner’s view towards squatter settlements continues to be influential in the works of recent urban scholars such as Kellet and Napier (1995), Pugh (2000), Payne (2006), and Rahman (2011), among others.

The practice of incremental housing construction (for example, the phases defined by Greene and Rojas, 2008) by the inhabitants of squatter settlements is often overlooked by professional architects and urban planners. But informal architecture such as that found in present-day slums and squatter settlements has always been a feature of urbanising civilisations. ‘Throughout history,’ as Kellet and Napier (1995, p. 8) claim, ‘...the poor have constructed their dwellings around the urban centres of the rich and powerful’. The same urban phenomenon can be observed at present especially in the case of developing countries. However, the difference in today’s scenario is the scale of activity. Following Turner’s influence, Kellet and Napier (1995) examine the relationship between squatter settlements and the qualities of vernacular architecture defined by primary theorists in the field. For instance, squatter settlements, like vernacular environments, are traditionally constructed rather than academically inspired. They respond to local culture and mediate environmental extremes (Rapoport, 1988). This kind of settlement houses the ordinary activities of the common people (Lawrence, 1982). Informal architecture in squatter settlements is also built based on inherited knowledge, collective wisdom, and social experiences which comprise generally accepted norms (Oliver, 1990). Finally, it is characterised as a transitional society in the process of evolving from one mode of production to another (Stea and Turan, 1990).

The theoretical implications of these earlier observations of parallels between squatter settlements and vernacular architecture are made clearer in more recent literature. Vellinga (2006, p. 88) for instance, includes squatter settlements as one of the categories of building that tends to be ignored in the field of vernacular architecture studies. Despite the fact that vernacular architecture still comprises the majority of buildings in the twenty-first century, it remains marginal in the purview of most design professionals and policy makers. Building on the work of the influential interpreter of vernacular, Paul Oliver, Asquith and Vellinga (2006) emphasise the value of learning from traditional knowledge, skill, and expertise to create appropriate and sustainable built environments. Furthermore according to Asquith (2006, p. 129), ‘once the vernacular is seen not as static building form, but as constantly evolving, reacting to changes in the communities that shaped its form, it will become higher on the agenda in architectural education’. In turn, sustainable human settlements can be informed by understanding of the vernacular environment from the perspective of human ecology (Lawrence, 2006). Lawrence (2006), reflecting on his studies of human habitats in the Alpine region of Switzerland, observes that societies can use legislation, behavioural rules, and socially agreed conventions reflected in their practices to ensure sustenance over many generations. Further referring to the translation of sustainable development into policies and practices by Dodds (2000, in Lawrence, 2006), Lawrence (2006) recommends that citizen participation is an integral component in the construction of settlements and one of the basic principles for professional practice.

Citizen participation is critical to house billions of people, which is a great challenge for urban planners and policy makers in the twenty-first century. Like Lawrence, Payne (2006) also places value on citizen participation in his study of initiatives by the urban poor in informal settlements in India and Turkey. He explores how people from different backgrounds have evolved rational and ingenious
Learning from informal settlements: provision and incremental construction of housing for the urban poor in Davao City, Philippines

solutions to meet their need for shelter. Payne is also influenced by the work of Oliver, Turner, Rapoport, and others engaged in the fields of housing, spatial organisation and the role of communities. For Payne, the ingenuity of the urban poor in providing their own shelter can provide lessons for professionals to address the issues of housing and urban development (Payne, 2006), most especially in developing countries. Furthermore in the study of the vernacular, Rapoport (2006) proposes to move from a natural history stage to a problem-oriented stage. This makes it possible to regard vernacular environments, including spontaneous informal settlements considered in this paper, as a laboratory of the wide range of human responses to various factors affecting their way of living. Housing and settlements for the urban poor in developing countries are affected by government initiatives and other processes such as the responses of the people to an urban policy, or their participation in the implementation of a housing programme. One way of understanding this phenomenon is from the point of view of the vernacular that motivates a dynamic and detailed understanding of the changing characteristics of informal settlements which remain an urban reality in the twenty-first century.

With its roots in the early works of Abrams (1964) and Turner (1968), the study of self-help provision and incremental construction of urban poor housing in informal settlements enjoyed a renewal in the work of later urban scholars including Payne in Delhi, India and Ankara, Turkey, in the 1970s (Payne, 2006), and Kellet in Santa Maria, Colombia, in the 1990s (Kellet, 1999; 2005). Now in the early twenty-first century, informal settlements are better recognised as a dynamic urban phenomenon that is important to understand as developing countries strive for sustainability, not least in the construction and operation of the built environment. Pugh (2000), for example, emphasises the resource and labour efficiency in the production of informal architecture in squatter settlements. Moreover, Rahman (2011, p. 144) argues that self-built incremental in-situ upgrading of informal settlements is ‘a form of affordable and hence sustainable housing for the low-income groups in the developing countries’. Informal settlements in general share the same characteristics. Primarily, they are independently conceived and constructed by the occupants themselves. Secondly, occupation and construction activities take place simultaneously. Finally, such settlements are ‘in a process of dynamic change and demonstrate considerable ingenuity and creativity within limited resource constraints’ (Kellet, 2005, p. 22). To build on these observations and findings, this housing construction pattern in informal environments requires detailed understanding in order to provide effective housing interventions, and concomitant policy decisions, which are more appropriate and sustainable in developing countries.

2. Aims and objectives

This paper argues that the transition to formal architecture coincides with the legalisation of land tenure and improvements to sites and services. This argument is informed by a pilot study of one informal settlement in Davao City, Philippines, which was undergoing transition towards a more formal status (Malaque III, 2013). A subsequent study of 74 households in 11 settlements, in the same city, revealed that urban households can be classified into different types in a range of contiguous categories from informal to formal housing. Within the range of different housing categories, it was also observed how householders moved from one type to another until they became owners of formal housing (Malaque III et al., 2014). This multi-step transition process tended to happen in two ways. Firstly, an inhabitant moved from one housing ‘step’ to another in a different location. This trend is similar to the multi-step transition model defined by Lim (1987). This is an established paradigm whereby a household undergoes a multi-step transition through different housing submarkets (specifically in different locations) to improve their quality of life and shelter. Secondly, an informal housing unit in a progressive urban
settlement was upgraded to become a formal housing unit in the same location. This trend, also a form of the multi-step transition process, enables the inhabitants and their children to progress towards formal housing and secure tenure in the same location. This phenomenon is more reflective of the culture found in in-situ progressive urban development. Thus, the incremental construction of urban poor housing and its increasing formalisation in-situ merits further exploration.

The aim of this paper, then, is to explore the incremental construction of different housing types in the course of their development. Specifically, it will: present the five different housing types identified in the previous paper (Malaque III et al., 2014); investigate the construction of housing units over the course of their development; and, discuss the incremental status of housing units in relation to the formalisation of land tenure and improvements to sites and services. This physical phenomenon is analysed and discussed in relation to various government programmes, NGO assistance, and self-help initiatives by the inhabitants themselves.

3. The study area

This study was conducted in the progressive city of Davao, Philippines, located a thousand kilometres south of Manila. The Philippine population reported by the National Statistics Office (NSO) (2012) was 92.34 million in 2010 with an annual growth rate of 1.90 per cent. In the case of Davao City, the NSO (2012) reports that of the 33 highly urbanised cities in the country, it is the only city outside the National Capital Region that has a population of more than one million. In 2012, Davao City’s total population was 1.45 million. Like other major cities in the country, it has experienced significant immigration of impoverished people who have settled in precarious informal settlements. Typically, then, housing provision is one of the major issues in local urban development. In an attempt to solve the housing problems, there are some government programmes and NGO assistance aimed to provide shelter for the urban poor (Malaque III et al., 2006). Despite these initiatives from the government and NGOs, urban poor housing in Davao City demands further attention because of the scale of the phenomenon and the observable characteristics of progressive development in-situ.

4. Methodology

Data collection was conducted in accordance with fieldwork protocols approved by The University of Adelaide Human Research Ethics Committee (January 2014). Extensive fieldwork was conducted from February to April 2014, accessing a total of 74 household cases in 11 settlements. As discussed more thoroughly in a previous paper (Malaque III et al., 2014), the selection of settlements and representative household cases reflected a balancing of recommendations from both government housing agencies and NGOs, who also coordinated access to study areas. Selected cases therefore include recipients of assistance through government housing programmes as well as from NGOs, and cases of self-help housing as well as progressive settlement. Hypothetically, these also cover a range of different housing types from informal to formal. Finally, the selection of study sites was also mediated by their accessibility for fieldwork where safety and security could be ensured. Household names presented in this paper were used with the formal consent of the survey participants. In the classification of 74 household cases, a method of hierarchical cluster analysis using IBM SPSS Statistics 21 software was used. Multiple variables indicating the formality of housing structure, and legality of land occupation and completeness of sites and services were applied in the classification. As a preliminary result, five different housing types were identified (see Table 1). Upon further qualitative data analysis, it was
observed that these five different housing types are in contiguous categories from informal to formal housing, which are briefly described in Section 5 of this paper.

This paper explores the incremental construction of a representative sub-set of 16 of the 74 household cases examined in the larger research project. The 16 housing cases presented in Table 1 were selected from progressive urban settlements to represent the range of respective housing types identified in the previous paper. The data informing the analysis was derived from the physical documentation of housing ‘steps’ and interviews by the first author with householders. Qualitative variables to indicate self-help provision of living spaces and incremental construction of housing were cross-tabulated with the coded housing cases. Significant findings were based on the pattern of commonalities exhibited in the table, which is supported with physical documentation recorded through photographs and sketches. Results were validated with qualitative information from key informants in government housing agencies and NGOs pertaining to various housing programmes and assistance.

<table>
<thead>
<tr>
<th>Case number</th>
<th>Household name</th>
<th>Settlement location</th>
<th>Housing type</th>
</tr>
</thead>
<tbody>
<tr>
<td>D36</td>
<td>Domingo</td>
<td>Matina Aplaya Shanghai Village</td>
<td>Type I – ‘formal’ housing</td>
</tr>
<tr>
<td>D42</td>
<td>Rafales</td>
<td>Matina Aplaya Shanghai Village</td>
<td>Type I – ‘formal’ housing</td>
</tr>
<tr>
<td>E43</td>
<td>Amad</td>
<td>Toril II settlement</td>
<td>Type II – ‘almost formal’ housing</td>
</tr>
<tr>
<td>F53</td>
<td>Sereno</td>
<td>Piapi I settlement</td>
<td>Type II – ‘almost formal’ housing</td>
</tr>
<tr>
<td>D40</td>
<td>Nacorda</td>
<td>Matina Aplaya Shanghai Village</td>
<td>Type III – ‘semi-formal’ housing</td>
</tr>
<tr>
<td>F47</td>
<td>Albios</td>
<td>Piapi I settlement</td>
<td>Type III – ‘semi-formal’ housing</td>
</tr>
<tr>
<td>F50</td>
<td>Linasa</td>
<td>Piapi I settlement</td>
<td>Type III – ‘semi-formal’ housing</td>
</tr>
<tr>
<td>F54</td>
<td>Talin</td>
<td>Piapi I settlement</td>
<td>Type III – ‘semi-formal’ housing</td>
</tr>
<tr>
<td>A01</td>
<td>Abarquez</td>
<td>Arroyo Compound</td>
<td>Type IV – ‘in-transition informal’ housing</td>
</tr>
<tr>
<td>A02</td>
<td>Agan</td>
<td>Arroyo Compound</td>
<td>Type IV – ‘in-transition informal’ housing</td>
</tr>
<tr>
<td>A03</td>
<td>Albos</td>
<td>Arroyo Compound</td>
<td>Type IV – ‘in-transition informal’ housing</td>
</tr>
<tr>
<td>B27</td>
<td>Rabara</td>
<td>Kobbler settlement</td>
<td>Type IV – ‘in-transition informal’ housing</td>
</tr>
<tr>
<td>B30</td>
<td>Wagas</td>
<td>Kobbler settlement</td>
<td>Type IV – ‘in-transition informal’ housing</td>
</tr>
<tr>
<td>C31</td>
<td>Abellana</td>
<td>Peace Avenue settlement</td>
<td>Type IV – ‘in-transition informal’ housing</td>
</tr>
<tr>
<td>A19</td>
<td>Truya</td>
<td>Arroyo Compound</td>
<td>Type V – ‘informal’ housing</td>
</tr>
<tr>
<td>B24</td>
<td>Lamanilao</td>
<td>Kobbler settlement</td>
<td>Type V – ‘informal’ housing</td>
</tr>
</tbody>
</table>

5. Results

This section briefly describes the five different housing types identified in the previous paper (Malaque III et al., 2014). Furthermore, this section presents the selected housing cases which represent the respective housing types as the focus of this paper for analysis and discussion on the phenomenon of self-help provision and incremental construction of urban poor housing.

5.1. Type I - ‘formal’ housing

Type I housing is described as having secure land tenure, built in accordance with the building code. This type is usually delivered as completed single-detached housing units by the government and private developers. However, this type also includes dwellings that have undergone a transition from less formal types located in progressive urban settlements. Contrary to the more typical cases of completed housing units (which is the usual response to perceived housing crises by the authorities), the cases
included in this paper were initiated and developed incrementally by the inhabitants (from informal housing units to formal ones over time). For example, in the case of the Domingo house in Matina Aplaya Shanghai Village, the initial dwelling comprised approximately 40 square metres of floor area for a basic living space, a dining room, kitchen, toilet and bath, and two bedrooms. Later, an additional bedroom was added increasing the total floor area to 60 square metres (current at the time of the fieldwork in 2014). In terms of its incremental construction, the initial dwelling unit was made of discarded timber and light-weight building materials. During the course of development, cement was poured for the ground floor, and a concrete structure and galvanised iron sheet roofing was used to construct the additional rooms. The Domingo family secured legal tenure during the transition process as a beneficiary of the Community Mortgage Programme (CMP).

5.2. Type II - ‘almost formal’ housing

Type II housing may be described as having secure land tenure. However, it was observed that the houses needed further improvements to comply with the building code. This type includes dwellings that have undergone transition from informal housing units; they are described as ‘almost formal’. For example, in the case of the Amad house in Toril II settlement (Figure 1.c), the initial floor area comprised 20 square metres with combined living and dining areas. The same space served as a sleeping area at night time. Eventually, the house was doubled to include separate living and dining areas, a kitchen, toilet and bath, and two bedrooms. A neighbourhood variety store was also included in this upgraded dwelling. When the Amad family first moved into the settlement, their house was primarily constructed of coconut-tree timber mixed with hardwood for the structure, and galvanised iron roof sheets. As a result of deterioration, temporary building materials were incrementally replaced with concrete and other more permanent materials. In addition, the living spaces were increased. The Amad family was a beneficiary of a slum upgrading programme funded by the national government, which is implemented through the National Housing Authority (NHA) that secured their tenure of the residential lot.

Figure 1: The Truya house, a Type V - ‘informal’ housing (a); Albos house, a Type IV - ‘in-transition informal’ housing (b); and, Amad house, a Type II - ‘almost formal’ housing (c).

5.3. Type III - ‘semi-formal’ housing

In the case of Type III housing, there was no compliance with the building code. A certain degree of secure land tenure was recorded. Most houses in this category had become dilapidated over time. For example, in the case of the Nacorda house in Matina Aplaya Shanghai Village, the dwelling unit was initially a simple shack comprising a bedroom. Since the late 1980s, basic spaces were added including a living room, a dining area, a kitchen, toilet and bath. Two bedrooms are added with the help of the community of homeowners and personal initiative. At the time of the fieldwork in 2014, the house had a
total floor area of at least 60 square metres. The initial dwelling unit was built like a tent made of hardwood, coconut tree timber, bamboo, and other light-weight building materials. With the addition of more rooms, more permanent building materials such as concrete hollow block and plywood were installed. The household head of the Nacorda family claimed that they were beneficiaries of a land tenure assistance programme known as the CMP. They were in the process of paying for the land.

5.4. Type IV - ‘in-transition informal’ housing

Type IV housing is mostly incomplete and is described, here, as informal. The fieldwork revealed that the inhabitants were in the process of upgrading their dwelling. The householders were also organising themselves to negotiate the purchase of land from legal land owners, or to seek government assistance, or assistance from NGOs. There are cases which may have minimal assistance from the government but receive assistance from an NGO. For example, in the case of the Albos house in Arroyo Compound (Figure 1.b), the NGO was the main agency which initially provided a 60 square metre lot. Consequently, the informal dwelling unit was self-built by the inhabitants. The basic living spaces currently occupy the entire lot. The householder applied for a minimal loan from the NGO for the construction of the dwelling unit. The institutional support from an NGO motivated the inhabitant to invest in permanent building materials. These were used for the construction of their informal dwelling unit. This is evident in the case of the Albos house where permanent building materials, such as concrete, were already used in the construction of some parts of the house (Figure 1.b).

Another group of Type IV housing was located in informal settlements with inhabitants who were beneficiaries of government assistance for land tenure. The houses may appear physically informal but it was noted that the government was in the process of implementing a programme similar to the CMP known as the Land Tenure Assistance Programme (LTAP). This programme was either implemented on the same site where an informal settlement was formed (in-situ), or on another new site (elsewhere) developed for an association of urban poor beneficiaries. An example of an in-situ LTAP beneficiary was the Abellana family in the Peace Avenue settlement. When their settlement was informal, the house began as a traditional hut made of light-weight building materials such as wood and bamboo. Despite this informality, the dwelling covered over 100 square metres and included all required living spaces. Eventually when the inhabitant applied to the government programme in 2004, the house was refurbished with concrete and galvanised iron sheet roofing. Despite this description given by the respondent, the fieldwork revealed that the same housing condition was evident. According to the head of the Abellana family, when the interview was conducted, they were still in the process of paying for the land.

5.5. Type V - ‘informal’ housing

Type V housing is described as informal, the land occupation is illegal and the site lacks services. In addition, it was apparent that houses were self-built by the inhabitants and they did not comply with the minimum standards of the building code. For example, in the case of the Truya house in Arroyo Compound (Figure 1.a), the dwelling unit started as core house including a toilet and bath with a floor area of 12 square metres. Eventually, basic spaces comprising living, dining, kitchen, toilet and bath, and bedroom are added covering an area of 35 square metres at the time of fieldwork in 2014. Initially, the dwelling unit was made of light-weight building materials including thatched palm roofing. In the incremental construction of the house, the ground floor was roughly poured with concrete, the walls
were replaced with wooden frames and plywood, and the roof was replaced with galvanised iron sheets. The present housing condition is shown in Figure 1.a. It was further noted from the personal interview that this informal household did not benefit from assistance from either the government or an NGO.

6. Analysis and discussion

The incremental construction of houses in low-income settlements observed here offers evidence of progressive self-help provision of living spaces. The physical documentation of the dwellings conducted during the fieldwork, together with interviews of the householders, demonstrate the different types of incremental construction evident in Davao City. It was observed that the incremental housing construction accommodated the growing needs of the inhabitants and that this was specifically influenced by the degree of security of tenure. Typically, a housing unit was initially made of light-weight building materials. Unless there was an indication of formal land tenure (with assistance from either the government or an NGO), the housing unit remained temporary in nature, evident in the Type V - ‘informal’ housing cases. On the other hand, the house may be upgraded using more permanent building materials and standardised construction methods when the inhabitant gains a certain degree of security. This is the point in the course of development that an informal housing unit is in transition towards a more formal status, demonstrated in the Type IV - ‘in-transition informal’ housing. The housing units of this type may appear informal but a certain degree of security gained by the inhabitants motivated them to invest in the physical improvement of their home. This is exemplified in the case of the Albos (Figure 1.b) and Agan houses in the Arroyo Compound. The institutional support from an NGO motivated the inhabitants to invest in permanent building materials to improve their informal dwelling. In the same way, a government programme such as LTAP influenced the inhabitants of the same housing type to invest in more permanent building materials. Other than the recent LTAP initiative, other active government land tenure assistance programmes include the CMP, conceptualised in the mid-1980s, and slum upgrading and sites and services which have their roots in the 1970s to early 1980s.

![Figure 2: Google Maps satellite photo of Piapi I settlement (a); and, the Linasa housing case (b).](image-url)
legal land ownership was attained, observed in many cases of Type II and Type I, the inhabitant was able to refurbish his house incrementally until it became a permanent structure compliant with the building code. This is how the Sereno house in Piapi I settlement and the Amad house (Figure 1.c) in Toril II settlement (Type II housing units) progressively attained an ‘almost formal’ status. Apart from these cases, this is the same way the Domingo and Rafales houses in Matina Aplaya Shanghai Village (Type I housing units) have achieved formal status.

The phases of incremental construction began with access to land, followed by the construction of a basic nucleus, and the incremental improvement of dwelling units (Greene and Rojas, 2008). Furthermore, this study demonstrates that the incremental construction of low income housing is being influenced by the degree of security of tenure and various initiatives to achieve legal land ownership. This exemplifies Payne’s (2001) claim that there is a continuum of tenure categories that range in different levels of security, which means that a pavement dweller that initially has no security will undergo a series of tenure categories to become a freehold owner as the ultimate legal tenure category. In other words, the series of contiguous tenure categories is reflected in the progressive nature of low income housing, which is physically evident in the incremental construction of houses, as observed in this study.

7. Conclusion

This study demonstrates that housing as a material expression of the status of the urban poor in progressive settlements reflects the socio-political process of legal land ownership that defines the security of tenure. The incremental construction of low-income housing started when the urban poor chose to live in informal settlements. Despite the precarious conditions, the inhabitants of informal housing units speculate that they can formalize land ownership. In the process, legal land ownership is achieved in part from government assistance for land tenure which leads to the completion of construction, when the dwelling becomes permanent and legal. In addition to assistance for land tenure, policy makers might consider this incremental construction process in the formulation of strategic housing solutions which offer an alternative to the traditional one-step regularization model that has rarely proved to be successful in developing countries. The early stages of this incremental construction process, discussed here, may seem disordered, especially when the inhabitants were in the process of paying for the land to achieve legal ownership. However, this incremental process offers valuable lessons for urban planners, architects and policy makers who must consider interventions that are best suited to progressive settlements as an alternative to traditional approaches such as slum clearance and demolition and the one-step regularization model. It is beyond the scope of this paper to offer detailed recommendations for housing policy. However, this examination of the incremental construction of housing offers important lessons about effective and sustainable housing interventions which are better suited to developing countries and the well-being of the urban poor.

References


Measuring the impact of openness, enclosure, mystery and complexity: a meta-analysis of the results

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Abstract: Contemporary design manuals for architects often refer to the psychological benefits of particular spatial and formal configurations. However, the research which these works cite as evidence is largely qualitative and only a small number of quantitative studies are ever referenced. The origins of the quantitative research can be traced to the 1970s, where the first of a growing number of environmental and psychological studies suggested that various spatial and visual characteristics of environments can potentially shape or influence psychological wellbeing. Four key factors that have been repeatedly discussed in terms of perceived comfort are prospect or openness, refuge or enclosure, mystery or enticement and complexity. However, many of the studies that architects reference in design manuals are not actually about architecture, and others have strongly conflicting results. In response to this situation, the present paper undertakes a review of twenty-five studies testing preference for spaces which exhibit openness, enclosure, mystery and complexity. The results of these studies are then categorised to develop a meta-picture of the evidence. The paper does not test specific results, or interrogate the methods used, rather it holistically identifies evidence-based claims that have been made about these spatial properties, and summarises the complete set of findings.

Keywords: Design assessment; environmental preference; prospect-refuge theory; isovist analysis.

1. Introduction

Since first being proposed in the 1970’s, specific facets of environmental preference theory and prospect-refuge theory have been both debated and tested. For example, quantitative studies have shown that a close visual connection between habitable space and nature is beneficial for psychological wellbeing, recovery and stress relief (Kaplan and Kaplan 1999). Studies have also observed that restricted views may cause negative reactions (Heerwagen 2008) while visual connections might encourage movement and evoke pleasure through the exploration of space (Kaplan 1987). All of these factors would seem to support Hildebrand’s (1999) reading of prospect-refuge theory, and of the spatial properties and transitions found in Frank Lloyd Wright’s residences that make them so ideal for human inhabitation. These findings would also seem to reinforce Hildebrand’s argument that it is not just
prospect and refuge which shape emotional response, but also mystery, complexity, enticement and light. However, Stamps (2006, 2008a, 2008b) conducted a series of detailed experiments to test ratings for comfort and preference for both natural and built environments, and concluded that the statistical significance of prospect, refuge and light factors, in shaping emotional response, was “very near zero” (Stamps 2008b, 141).

Given such conflicting evidence, the present paper sets out to summarise and classify the results of twenty-five studies that have used quantitative means (generally data derived from surveys, interviews or computational analysis) to comment on the veracity of four specific factors – prospect, refuge, mystery and complexity – as part of spatial preference theory. The first two of these factors are the most commonly tested, as they were the earliest proposed by Appleton (1975), while research into the latter pair is less common, and is often associated with Hildebrand’s identification of them as being equally significant.

The results of the twenty-five studies examined in this paper are each classified in terms of whether their findings support the efficacy of each of the four factors, or are neutral, or contrary in terms of their role shaping environmental preference. Furthermore, the focus of this paper is on studies of landscapes and interiors, excluding studies of urban environments. This comparison is important to assist in differentiating which evidence can most reasonably be used to support arguments about architecture and interior design. Significantly, some of the most widely cited research was developed for the study of natural settings, as the theory was originally proposed for and applied to landscape environments. However, the largest percentage of the selected studies examines interiors.

A final reminder in regard to interpreting the content of this paper is that while findings associated with the four specific factors – prospect, refuge, mystery and complexity – will be considered holistically in the conclusion, many results are specific to the environment or venue they were tested in. Thus, the results of the various studies analysed here may be valid in their particular context, but not necessarily in any other.

2. Method
The twenty-five quantitative studies chosen for this meta-analysis all examine one or more key criteria of prospect-refuge theory (the most common variant of environmental preference theory used in architecture) before offering a conclusion about the validity of the factor or factors being considered, Importantly, only their findings are compared in this paper, not their methods, rigour or empirical validity.

For the purposes of comparing the twenty-five studies some common psychological and computational mappings of these definitions are required. First, prospect is defined as being associated with the perceptual properties of outlook, depth of view, spaciousness and openness, and the geometric properties of isovist area and maximum radial line length. Refuge is associated with the perceptual properties of enclosure and safety, and the spatio-visual geometry of occlusion and minimum radial length. Similarly, mystery relates to the luminosity, transitions between spaces and degree of occlusivity whereas complexity refers to the volume of information present in a space, along with the number of occluding edges (or vertices) and the jaggedness of its geometry. Some concepts, like openness and isovist area, can be indicators of both prospect and refuge, while others serve only a single factor. Hazard, identified as a criterion by Appleton, is not considered in this paper as it is not directly relevant to architectural and interior spaces.
For each of the twenty-five studies analysed in this paper, an assessment was made about the degree to which each study's findings supported the validity of prospect, refuge, mystery and complexity. For example, a "supportive" result would be one that confirms the standard view of the importance of a factor found in the writings of Appleton or Hildebrand. Neutral studies are ones wherein the findings are either not statistically significant, or comment only on a meta-principal, like the consistency of an argument, or spatial property. In the former case, partially supportive findings were categorised in the neutral group if they relied on less than 75% of the data or equivalent confidence indicators. In the latter case, many of the neutral studies used computational-mathematical approaches to test the presence or absence of a pattern in space and form, and only indirectly tested specific factors for their support of prospect-refuge theory. Contrary results are examples of the failure to find evidence to support a prospect-refuge theory factor, or of clear evidence against the significance of one or these factors.

3. Results

3.1. Findings relating to environmental preference in landscapes

Appleton (1975) explains the existence of a preference for natural environments as an innate characteristic of humankind, which can also be affected by social, historical and cultural influences. Many qualitative studies refer to this general human preference for natural settings (Kaplan and Kaplan 1989, Heerwagen 2008) and some specific studies, that involve children as participants, also confirm a preference for a natural rather than built environment (Nettleton 1987, Conrad 1993). However, across the seven studies included in this first category, six found evidence for the significance of prospect and five for refuge, a result that has been interpreted as being associated with the need for comfort (Table 1). According to Ruddell and Hammitt (1987) an immediate refuge is most preferred while prospect dominance is least preferred. Conrad's (1993) multiple experiments indicate a preference for prospect-refuge balanced scenes, whereas Hagerhall's (2000) data demonstrates a connection between preference, exploration potential (mystery) and feelings of safety (refuge). In total in this category, there were no contrary findings, and only two neutral, although all but one of the tests were concerned with prospect and/or refuge, not mystery and complexity.

Table 1: Findings relating to environmental preference in landscapes. Key: √ = supportive; O = neutral; X = contrary; - = not considered in the study; P: prospect; R: refuge; M: mystery; C: complexity.

<table>
<thead>
<tr>
<th>Landscapes</th>
<th>P</th>
<th>R</th>
<th>M</th>
<th>C</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nasar et al. 1983</td>
<td>√</td>
<td>O</td>
<td>-</td>
<td>-</td>
<td>survey (in situ)</td>
</tr>
<tr>
<td>Ruddell and Hammitt 1987</td>
<td>√</td>
<td>√</td>
<td>-</td>
<td>-</td>
<td>survey (stimuli)</td>
</tr>
<tr>
<td>Kaplan and Herbert 1988</td>
<td>O</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>survey (stimuli)</td>
</tr>
<tr>
<td>Conrad 1993(1)</td>
<td>√</td>
<td>√</td>
<td>-</td>
<td>-</td>
<td>survey (stimuli)</td>
</tr>
<tr>
<td>Conrad 1993(2)</td>
<td>√</td>
<td>√</td>
<td>-</td>
<td>-</td>
<td>survey (stimuli)</td>
</tr>
<tr>
<td>Conrad 1993(3)</td>
<td>√</td>
<td>√</td>
<td>-</td>
<td>-</td>
<td>survey (stimuli)</td>
</tr>
<tr>
<td>Hagerhall 2000</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>-</td>
<td>survey (stimuli)</td>
</tr>
<tr>
<td>supportive √</td>
<td>6</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>neutral O</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>contrary X</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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</tbody>
</table>
3.2. Environmental preference in interiors

There are eighteen studies in this category associated with environmental preference and interior space (Table 2). Four of the studies rely on surveys, five use computational simulations of environmental geometry to gather data, and nine use a combined approach drawing on both methods. A total of sixteen of the studies consider prospect (spaciousness) with nine confirming that it is a critical spatial property shaping preference while another seven were more neutral. In several of the positive cases, people rated views from the interior to nature or to adjacent spaces as being more preferred than a lack of views or of being tightly enclosed in space. None of the studies found contrary results for prospect.

Table 2: Findings relating to environmental preference in interiors. Key: √ = supportive; O = neutral; X = contrary; - = not considered in the study; P: prospect; R: refuge; M: mystery; C: complexity.

<table>
<thead>
<tr>
<th>Interiors</th>
<th>P</th>
<th>R</th>
<th>M</th>
<th>C</th>
<th>Method</th>
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<tr>
<td>Scott 1993a</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>survey (stimuli)</td>
</tr>
<tr>
<td>Scott 1993b</td>
<td>-</td>
<td>-</td>
<td>√</td>
<td>√</td>
<td>survey (stimuli)</td>
</tr>
<tr>
<td>Franz et al. 2003</td>
<td>√</td>
<td>O</td>
<td>-</td>
<td>-</td>
<td>combined approach (isovists)</td>
</tr>
<tr>
<td>Franz et al. 2004(1)</td>
<td>√</td>
<td>O</td>
<td>-</td>
<td>-</td>
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</tr>
<tr>
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<td>√</td>
<td>O</td>
<td>-</td>
<td>√</td>
<td>combined approach (isovists)</td>
</tr>
<tr>
<td>Stamps 2006(1)</td>
<td>√</td>
<td>X</td>
<td>O</td>
<td>-</td>
<td>survey (stimuli)</td>
</tr>
<tr>
<td>Stamps 2006(2)</td>
<td>√</td>
<td>X</td>
<td>X</td>
<td>-</td>
<td>survey (stimuli)</td>
</tr>
<tr>
<td>Wiener et al. 2007(1)</td>
<td>√</td>
<td>O</td>
<td>-</td>
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<td>Wiener et al. 2007(2)</td>
<td>√</td>
<td>O</td>
<td>-</td>
<td>√</td>
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<tr>
<td>Wiener et al. 2007(3)</td>
<td>O</td>
<td>O</td>
<td>-</td>
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<td>combined approach (isovists)</td>
</tr>
<tr>
<td>Dalton et al. 2010</td>
<td>O</td>
<td>O</td>
<td>-</td>
<td>O</td>
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<tr>
<td>Dzebic 2013(1)</td>
<td>√</td>
<td>O</td>
<td>-</td>
<td>√</td>
<td>combined approach (isovists)</td>
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<tr>
<td>Dzebic 2013(2)</td>
<td>O</td>
<td>O</td>
<td>-</td>
<td>O</td>
<td>combined approach (isovists)</td>
</tr>
<tr>
<td>Ostwald and Dawes 2013</td>
<td>O</td>
<td>-</td>
<td>X</td>
<td>-</td>
<td>computational (isovists)</td>
</tr>
<tr>
<td>Dawes and Ostwald 2014a</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>computational (isovists)</td>
</tr>
<tr>
<td>Dawes and Ostwald 2014b</td>
<td>O</td>
<td>-</td>
<td>O</td>
<td>-</td>
<td>computational (isovists)</td>
</tr>
<tr>
<td>Dawes and Ostwald 2014c</td>
<td>O</td>
<td>O</td>
<td>O</td>
<td>-</td>
<td>computational (isovists)</td>
</tr>
<tr>
<td>Vaughan and Ostwald 2014</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>X</td>
<td>computational (fractal analysis)</td>
</tr>
</tbody>
</table>

Several of the isovist-based computational studies developed evidence which offered only a low level of support for prospect-refuge theory, or were more concerned with secondary evidence pertaining to the buildings used by Hildebrand to develop his argument. For example, Dawes and Ostwald (2014a) examined five of Frank Lloyd Wright’s Textile-block houses in terms of their spatial properties as understood in relation to prospect and refuge characteristics. They did this over several stages: first considering the spaces individually (in terms of area, height and radial length) and then as a paired measure with height – to test their degree of “reduplication”, which is represented by the Pearson’s correlation coefficient for each combination of prospect and refuge indicators (238). According to Hildebrand (1999) multiple prospect and refuge indicators operate together to enhance Wright’s pattern. However, not all indicators recorded by Dawes and Ostwald (2014a) confirm this claim. The strongest, positive correlations were found between height and minimum radial length as well as between height and area.
Altogether fourteen studies examined refuge in interiors mostly with relatively neutral findings. Some of these studies presented a combined approach using computational analysis and survey methods to ask, for example, people to identify the smallest area (or best place to hide), and then compare this rating with the smallest isovist area (refuge). Only one study confirmed a need for partial enclosure (refuge) (Scott 1993a), while another study presented contrary results confirming a preference for large rooms and substantiating (in a second test) width as the main criterion for comfort (Stamps 2006). Further relatively neutral measurements or evidence for prospect-refuge theory included those derived from isovist area (prospect and refuge) and minimum radial line (as an indicator of refuge) (Dawes and Ostwald 2014a, 2014c).

Studies of environmental preference in interior settings include the largest percentage examining mystery and complexity. Only nine studies consider mystery, of which eight are concerned with interiors. Two of Scott’s studies present findings for a preference for “interiors [...] that imply that there is more to the environment that can be experienced from the observer’s present vantage point” (Scott 1993b, 31). One of Stamps’ (2006) tests presents findings contrary to the hypothesis that views from small to large rooms would be rated as more comfortable as “views from large, bright, high rooms were judged as being considerably more comfortable” (Stamps 2006, 649) while his first test result was categorised as neutral, having a non-statistically significant result. Also Ostwald and Dawes (2013) present a contrary finding for mystery as only two of the five examined Frank Lloyd Wright’s Prairie houses confirm the anticipated pattern. Four other studies have been categorised as neutral as they are only partially supportive.

Another criterion which Hildebrand argues plays a significant role in interior environmental preference is complexity. Eleven out of the total of twenty-five studies consider complexity all of which are in the interior category. Six studies confirm Hildebrand’s argument for the importance of visual complexity in spatial preference, which makes complexity (after prospect) the second most relevant criterion for interior settings. Of these six, two surveys (Scott 1993a, 1993b) confirm a preference for “interiors that offer more rather than less complexity” (1993b, 31). Of the other four supportive tests that used combined approaches, all suggest a relationship between complexity and spaces which are aesthetically pleasing or interesting (Franz et al. 2004, Wiener et al. 2007, Dzebic 2013). Four other combined approaches, however, present relatively neutral findings which relate, for example, to measured properties of supposedly complex spaces. For example, Dawes and Ostwald (2014b) examine five of Frank Lloyd Wright’s Usonian houses using seven isovist measures. Their data provides only limited evidence in support of Hildebrand’s version of prospect-refuge theory as for each measure at least one house presented values contrary to Hildebrand’s assumptions. Only proportional occlusivity was directly supportive, as an indicator for mystery, which “might form the basis of a more sophisticated measure of the seen and un-seen properties of a design” (Dawes and Ostwald 2014b, 19). This is an interesting finding because – as with many modern interiors – Frank Lloyd Wright’s houses consist of a series of visually connected, open-planned designs, a property that allegedly works to evoke a sense of mystery. Whereas the majority of the computational studies used isovists, there is one exception, a study that used fractal dimensions to examine the experience of complexity in Frank Lloyd Wright’s Robie House (Vaughan and Ostwald 2014). Hildebrand’s argument is that the path from the road to the entrance and then to the living room in the Robie House commences with a higher degree of visual complexity (and mystery) and ends with a lower level. Data developed by Vaughan and Ostwald (2014) shows that Hildebrand’s argument is partially confirmed for the exterior section of the path, but the findings are strongly contrary for the interior.
4. Discussion

Altogether, findings of twenty-five studies are summarised in this paper of which seven are related to landscapes and eighteen investigate interiors. Most of the studies involving landscapes were conducted in the nineteen eighties and nineties while the others were more recent, including the majority of mathematical-computational studies or those using combined approaches. Eleven out of the twenty-five studies (44%) used a survey-based approach to test prospect-refuge characteristics. Most of these studies used stimuli (40%) and only one test interviewed participants on site. Five studies use a purely computational approach (20%), four of which relied on isovist properties and ratios as measures for spatial dimensions while one study examined visual complexity using fractal analysis. Nine studies (36%) used a combined approach of survey methods and isovist analysis (Figure 1). All of these studies present results that clearly confirm a correlation between mean ratings and the data of computational measures. However, many of these studies present relatively neutral results. All studies that used computational methods examined interiors. Only four out of the eighteen studies examining rooms used purely survey methods.

Figure 1: (1) Findings by all venues and (2) methods used in all twenty-five studies.

While acknowledging that the veracity of each set of results is most strongly pertinent within its venue grouping, considering the complete set of results is also informative. With thirty (48%) supported results for factors, twenty-eight (44%) neutral and five contrary (8%) (Figure 1), the evidence, *prima facie*, is not overwhelming convincing. The complete set of results shows that the most examined characteristic is, not surprisingly, *prospect* (37%) (Figure 2), and it is also the most confirmed (50%). *Prospect* is a dominant topic of testing especially in interior studies where it is excluded in only two out of eighteen tests, and it is also the lead factor in landscape studies. *Refuge*, an indicator for *safety* and *privacy*, is the second most supported factor (20%) (as well as complexity), but it has the highest rate of both neutral (43%) and (as well as mystery) contrary findings (40%). *Prospect* has the second highest percentage of all neutral findings (29%) of which most belong to the results for interiors (7 out of 8). Certainly, very few studies present results that are completely contrary (8%), of which most reject, as just indicated, *refuge* and *mystery* (40% each), followed by *complexity* (20%). None of these findings reject *prospect*. *Complexity* and *mystery* are the least examined characteristics (17% and 14%) and have been tested predominantly in interior settings. Within its category, *complexity* has more supportive results (six) than neutral (four) or contrary (one). In total, when examining the results of all of the twenty-five studies in this way, there are not enough supportive findings to emphatically substantiate prospect-refuge theory.
The most supportive findings associated with prospect have been presented in interior studies. Nine out of eighteen studies confirm that wide, open rooms are perceived as more comfortable than enclosed ones. Curiously, only one of these interior studies presents a preference for a balance of openness and enclosure, while in landscape studies three out of seven studies confirm a preference for balanced settings. According to Scott (1993a), “people like vertically and horizontally expansive settings that are subdivided into smaller spatial zones” (13), which confirms also a need for enclosure in interiors.

Originally, Appleton (1975) proposed that environments which offer a balance of both outlook and enclosure would be preferred most. In a later revision he advised that in many cases a “balance [...] can be achieved from serial vision, involving the successive experiences of exposure to strongly contrasting landscape types, strong prospect and then strong refuge, is more potent than that which comes from trying to achieve a balance all at once” (Appleton 1984, 102). This suggestion, which was developed to describe landscape preference, may also relate to the experience of interiors, as appealing designs were often composed of large, clearly opened and smaller, enclosed spaces rather than offering both properties in one room. Perhaps, because of this uncertainty if there is need for enclosure or not, refuge is the least supported characteristic within the interior group with eleven (out of fourteen) neutral findings.

A preference for complexity has been confirmed by the four interior studies which used combined approaches (Figure 3). Also two survey-based studies confirm a preference for spaces that have more complex geometry (Scott 1993a, 1993b). In addition, a second test also presents a preference for spaces that permit internal views and which offer natural content and daylight. Altogether, this is the only study in the entire set that confirms all four key factors of prospect-refuge theory (Scott 1993a).
Another factor arising from a review of the twenty-five results is that only a small number of studies draw on large survey samples and produce statistically thorough results and analysis. Interestingly, one of the interior studies that used a combined approach contradicts an earlier finding as isovist area (openness) did not correlate any more with the rated factor of beauty but only with spaciousness, complexity and sociability (Dzebic 2013). Another (neutrally categorised) finding is unexpected, as more complex spaces (which can be related to a low isovist area to perimeter ratio) seem to allow a higher recognition rate of words and images that had to be memorised in such complex interiors while the area (large or small) made no difference on such ratings (Dalton et al. 2010).

Significantly, many of the studies that have been categorised as neutral are based on mathematical or computational analysis of interiors testing more than one measure. This often leads to discrepancies in their results. So far, there is no clear determination of which measures are the most relevant, but there are assumptions that, for example, in isovist analysis (which thirteen of the examined interior studies use), ratios or proportional values relate better to spatial dimensions than pure measures (Dawes and Ostwald 2014a, 2014b). Such works are part of the recent trend to examine prospect-refuge theory mathematically or in a combined approach with survey methods and computational analysis. However, there is still need to refine these new research methods by implementing clear, controlled changes.

5. Conclusions

On balance, the complete set of findings is relatively neutral, providing some limited support for the validity of prospect-refuge theory in some contexts or venues. This overall lack of a clear answer may relate to the fact that most of the twenty-five studies examined here considered only specific isolated factors derived from prospect-refuge theory and ignored others. However, it is also notable that, in recent years, researchers have focussed on the prospect-refuge characteristics that appear to be more relevant to their disciplines. Refuge, for example, has a much less significant function for interiors in comparison to natural or urban environments where it represents safety.

Some of the results from the twenty-five studies seem obvious in hindsight and have been widely acknowledged. For example, the benefits of a close visual connection to nature and of inhabiting a space that is relatively balanced (offering both open areas that are proportional to the human scale as well as comforting zones for privacy) have been supported by past research. However, which spatial dimensions
create an ideal balance is certainly not clear in the results of the past research. Also, there is a lack of understanding of the aesthetic properties of the interior, including the balance of mystery and complexity required to make space appealing or interesting and to encourage exploration. According to Hildebrand (1999) such triggers include visual connections, changing levels of light and varying ceiling heights, but the way these properties have to be composed to provide the ideal balance is unknown.

Altogether, this summary of the findings of past research reveals that there is still a clear need to continue investigating prospect-refuge theory and environmental preference to find out more about minimum and maximum parameters that influence environmental preference and especially in interior spaces.

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Negotiation of identities in the emergent cosmopolitan Indian landscape – analyses of the designs of new luxury high-rise apartments in neo-liberal India

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Abstract: Luxury condominiums are among the most significant outcomes of globalisation in the built environment, post economic liberalisation in India. New high-rise condominiums evoke a new generation of urban elite aspiring to new modes of consumption, bringing into focus the complexities of projected identities in this new architecture. They redefine the norms of elite associations and aspirations and obligations in transnational and transcultural terms. The salience of these models as expressions of social mobility denote the critical role played by this new housing type in relation to the socio-cultural transformations advanced by the emergent Indian cosmopolitan landscape. A project of luxury condominium in the global node of Mumbai is investigated exploring its role in staging the social patterns and in projecting identities. The investigation attempts to understand patterns of post occupation inhabitation by using spatial analysis in addition to the initial study of user aspirations and interpretations associated with luxury condominiums through interviews and participant observation. Space syntax is employed and explored as a tool to further investigate the new typology. The spatial analysis, interviews and participant observation suggested a complex array of identity issues under negotiation in the Indian cosmopolitan landscape.

Keywords: Space syntax; condominium living; identity projection; globalisation.

1. Introduction

The built environment in India has been constantly reshaped by various social, political and economic factors over the past century. Processes like colonisation, the Independence movement, resurgence of regionalist ideas and globalisation have caused periodic shifts in the nature and character of the built environment and the architectural profession in India. The structural adjustment programs and liberalization policies of the Indian state adopted in the early 1990s brought in a new era of economic and cultural globalization and subsequent changes in Indian architecture. One of the sectors that experienced major transformations is the housing sector with exponential growth. In India post-liberalisation from 2004 to 2007, total FDI (Financial direct investment) rapidly rose from just $2.7 billion
to $8 billion per year. In 2003, only 4.5% of total FDI inflow was committed to the real estate and construction-related sectors. In 2004, the share of real estate investment increased to 10.6%. By 2007, when the total FDI reached $8 billion, the share invested in the real estate sector was 26.5%. The Indian real estate sector, which now in many ways has become a key driver of financial markets and stock exchanges, is expected to receive $25 billion in FDI in the next decade. (NRI Realty News)

The development of luxury condominiums is just one manifestation of the many changes sweeping India. This development presents a unique condition which reconfigures spatial character of residential environments, targeted at the rich clients. The shift from the colonial bungalow to the high density luxury condominiums as a preferred residential type and lifestyle choice is a giant leap for the Indian elite. This shift also employs new architecture as a qualifier to project and define the occupants of these luxury condominiums as the “New Elite” of India. This paper proposes to analyse the socio-spatial boundaries (Thresholds) in designs of luxury condominiums in India and investigate how this new architecture is exploited for identity projection. It focuses on a case study investigation in Mumbai. This research incorporated spatial analysis of apartments, participant observation, perusal of marketing and other published material and also interviews with householders of luxury condominiums. The spatial analysis, interviews and participant observation suggested a complex array of identity issues under negotiation in the Indian cosmopolitan landscape.

There exists substantial literature on the European and American middle-class with some key texts including Bourdieu (1986), Elias (1994), Girouard (1978) and King (1995) that discuss bourgeois self-fashioning in various contexts and times. Some of those ideas have been reframed in the recent surge of publications on the Indian middle-class, post liberalisation. Authors like Brosius (2010), Donner (2011), Fernandes (2006), Ganguly-Scarse (2008) and Varma (1999) discuss the new Indian middle class in terms of the embrace of digital technologies, high-rise living, transnational mobility, and entertainment and recreation choices. A new discourse on middle class lifestyles, aspirations increasingly articulates elite formation as a spatio-social process over time.

To investigate how these luxury condominiums gets inhabited there are many useful studies that explore the issue of meaning in domestic space (Hillier 1984, Hanson 1998, Marcus 2006, Psarra 2009). These studies employ various approaches like geometry, psychology, anthropology and social sciences. “By giving shape and form to our material world, architecture structures the system of space in which we live and move. In that, it has a direct relation- rather than a symbolic one- to social life, since it provides the material preconditions for the patterns of movement, encounter and avoidance which are the material realisation- as well as sometimes the generator -of social relations.” (Hillier and Hanson 1984, 9) “In that context, when considering its function and meaning, the house may be regarded as the most complex building of all” (Hanson 1998, 2). This study also employs spatial analysis to unpick the identity issues staged in the apartments. Thresholds and specific subjectivities form the main criteria for spatial analysis, where space syntax is employed to investigate spatial practices.

Brosius (2010) introduces ‘cosmopolitanism’ as a key theoretical lens to examine the post-liberalised landscape of India. Current theories of cosmopolitanism tend to be largely about the Euro-American context (Harvey 2009, Lefebvre 1991), but there has been new research which has focused on Asia and the emergence of new urban centres, rapid urbanisation and creation of an affluent middle class (King 2004, Bhabha 1996, Mignolo 2000, Appiah 1996). ‘Cosmopolitan subjectivities’ is a term that is used by Brosius (2010) to describe the new Indian lifestyle, categorised by her into ‘Urban’, ‘Vernacular’, ‘Transnational’ and ‘Aspiring’ cosmopolitans. Each type has its insecurities and its fantasies which are negotiated in social space.
In the literature on contemporary Asian housing developments, luxury mass-housing already surfaces as a marker of status and new aspirations (Marshall, 2003; Kyung, 2012 and Gelezeau, 2009). The discourse on housing in Asia reflects the association of luxury housing with progressive ideologies, status symbols and a rise of new urbanised middle or upper-middle class residents. It also demonstrates that cities are judged to be global and international when high-rise spatial types cross all programs-corporate, commercial, recreational and residential uses (Shelton, Karakiewicz & Kvan, 2011). While many existing studies address luxury mass housing in Asia, they focus on examples from Southeast Asia and very few investigate the emergent gated environments in neo-liberal India (Chalana, 2012; Kalyan, 2011; Searle, 2013; and Anand & Rademacher, 2011) from an architectural point of view.

In this paper, I focus on Lodha Bellisimo, a luxury high-rise development located in Byculla, south Mumbai as an exemplary case study of a new generation of gated condominium communities. Mumbai has been, economically, the most important city in India, first as the hub of industrial growth and now as a centre for service sector. It acts as headquarters for most major domestic and international banks and corporations. Consequently an important contributing factor for the emergence of this new typology is the growth of the new affluent class with the rising service sector accounting for more than 50 percent of the total GDP. Incomes in Mumbai have risen like elsewhere in India. According to an estimate by JLL (2012) the real disposable incomes are expected to rise by 8-10% per year over the period of 2015-25. This has transformed the demand and profile of consumer products. The growth of an affluent population along with an expansion of credit system with low interest rates and less restrictive trade barriers have transformed consumer demand and supply choice set (Weinstein, 2005). The direct influence of growing presence of transnational migrants and returnee non-resident Indians is also evident from the changing consumer culture and taste. An important implication of the growth of this consumer class is the demand for luxury condominiums closer to the CBD. This has led to competing pressure on textile mill land to develop for luxury residential uses (Tiwari, Kashyap & Tewary, 2006). To avail this opportunity of changing demands, mill landowners were lobbying for change in DC 58 to permit redevelopment of mill land to exploit commercial potential of their land. The act was finally reversed in 2001 for redevelopment allowing mill owners to sell/develop mill land for purposes other than mill redevelopment. Owing to this regulatory change, these mill lands are now often developed as luxury condominium communities by international architecture and planning companies as a joint venture with the mill owners to cater to the demands of the newly growing affluent class.

2. Lodha Belissimo

Lodha Belissimo has been completed and is inhabited since 2012. It is built on a plot of four acres and comprises two residential towers of 48 floors each (Refer to figure: 11). The overall built form is 183 m high with three acres of green landscaped space. The two towers are different in size with one tower having two wings and the second tower having just one wing. Each wing has 2 apartments per floor and there are 288 apartments in total with configuration of 3, 4 bedrooms and penthouses. The built up area of apartments varies from 222 m2 to 310 m2 consisting different apartment configuration housing around 1,150 -1,750 people. The architectural style consists of concrete frames and modern-international style of aesthetics. The project has been developed by Lodha properties, one of the biggest local developers, who hold a large portfolio of completed and upcoming luxury condominium developments in and around Mumbai. They employed local architect- Kiran Kapadia and Associates to collaborate with the in-house design team on this project. This developer was the first to introduce the concept of ‘sale by invitation only’ creating the notion of exclusivity as part of the brand. The developer
targeted a certain band of the society comprising mainly of young corporate banking professionals between the age group of 30-45 years. The project is located about 5 minutes walking distance from Mahalakshmi Racecourse capitalising on the views of the racecourse and Arabian Sea. Both central and western line railway stations of Mahalakshmi and Byculla are located at a 10 min walking distance from the development. The central business district around Victoria terminus is about 10 minutes’ drive and popular leisure spots like Marine drive, Nariman point and Cuff parade are 10-15 minutes’ drive as well.

The development offers range of amenities including communal spaces and recreational facilities, including large green open areas, jogging track, swimming pool, children's pool, play areas, tennis court, squash court, badminton court and gym. In terms of safety and security measures, there is provision of telephone exchange with video conferencing facilities, a 24 hour concierge service, and visitor tracking system, 2-way video door phone & CCTV cameras. A local committee formed by residents from the project constitutes the primary governance body regulating maintenance costs and running day to day activities pertaining to the complex. When the project was launched in the year 2000-01, the price was 4000 Rs./sq.ft. The current prices of the project have risen to 40,000 Rs./sq.ft. The maintenance cost is 25,000-75,000 Rs. based on the configuration of the apartment. In spite of steep escalation in property value, the maintenance amount increases the cost of living almost 3-fold compared to any other apartment building.

When compared to the earlier generation of apartments in Mumbai, both the typologies are gated but what set the condominiums apart are the height and scale and the creation of ‘total environment’. The earlier apartments consisted of either a stand-alone block or a cluster of 2-3 blocks; 5-10 storey tall sharing a gated compound, consisting of nothing more than common parking areas and access ways. The new generation gated communities on the other hand are based on the concept of utopian islands, where a ‘clean and well-maintained’ environment is created; providing the comfort, luxury and distance from the ‘crowds’ and most importantly the safety from the unwanted elements of the ‘outside world’. Also the people are held together by a contract and not communal ties within this utopian setup. It is a conscious effort to create an island with the provision of all amenities, effectively eliminating the need to contact the outside world or leave the premises at all. Architectural style employs concrete frame structure displaying a mixture of modernist and international style aesthetics with clean lines and a total lack of regional characteristics.

3. Spatial Analysis

Spatial Analysis is the primary tool for analysing the designs of apartments in Lodha Belissimo. Criteria based on hierarchy of thresholds through the eyes of different occupants are employed to explore the emerging cosmopolitan identity revealed through the spatial, material and the physical. This approach tackles the problematics of universal thresholds brought in from renaissance to modernism; devoid of any cultural layers.

3.1. Thresholds

- Urban to residential Threshold (Site Level)
- Actual arrival to the apartment threshold (Unit level-Entry)
- Configuration of spaces (Apartment layout)
3.2. Different occupants

- Owner (residents)
- Domestic help
- Visitor

![Figure 1: The project building and site sketch marking the thresholds. (source: Author)](image)

3.3. Urban to residential Threshold

Investigation of the first threshold manifests the idea of a gated utopia by the presence of a massive concrete wall running around the perimeter. This wall separates the development from the immediate presence of the mill workers chawls, but at the same time the massive scale undoubtedly creates a conspicuous presence. This gated environment sensibility is further heightened by the highly secured and monitored entry gate. A guardhouse with uniformed security men flank the gate, which is also watched by close circuit systems. Entry to the development needs authorisation from a resident, so as a visitor or domestic help; one had to establish contact with the resident ahead of time, who would then authorise entry upon arrival at the entrance gates. The residents here aspire to be part of this new domain- a gated environment operating on the idea of generating the gaze of surveillance. This gaze known as the panoptic gaze (Brosius 2010) is about the attitude of creating polarisation between the inside and outside and self-legitimisation, increasing the distinction between the deserving few and the underserving many.

3.4. Actual arrival to the apartment

A massive ramp directs users to the entrance foyers for the 2 different towers from the main gate. The vehicular ramp runs through the meticulous landscape staging the arrival to the main towers. The foyer is a grand entrance to each tower with marble laden floors and columns; this is yet another threshold with a concierge behind the registration desk directing you to the right apartment. The foyer then turns into a lobby with two sets of elevators for residents and guests on one side and service stairs and
elevator for service staff on the opposite side. In contrast to the international, non-regionalist approach to the design of the façade, the layout of entrance lobby follows cultural thresholds providing the distinction between resident and service staff entrances and expressing status at the same time. The same concept of two separate entrances to the apartment for the residents and the service staff is manifested in the apartment lobbies on all floors, which are generally shared.

3.5. Configuration of spaces (Apartment layout)

All apartments have similar conceptual configuration of spaces. The layouts follow cultural thresholds providing the distinction between served and service spaces. The living and dining room area is accessed through a hallway flanked by service space on one side and private space on another. The hallway opens to the main central space with a waiting area nominated right at the edge. So while this creates an invisible boundary, at the same time it creates an opportunity for the visitor to peak into the life of the residents. This demonstrates the changed attitude towards privacy and lifestyle in the globalised period. The luxury apartment stages the lifestyle, putting life on display for others to see, while services are kept hidden and more private with a notion of ‘invisible service’. This display is usually associated with exhibition of economic affluence and cultural capital and thus redefines the norms of publicising social and economic status.

Figure 2: Interior of the apartment and overlay analysis. (source: Author)

Space syntax is employed to further investigate the layouts from the perspective of the three different users. Space syntax is a kind of technique used to identify and analyse spaces in terms of relational pattern. In order to create convex maps of the apartment, the lobby space along with the apartment is included. Space configurations were analysed using step depth maps and isovist maps (Refer figure 3). Deathmap software was used to create these maps. The space depth diagrams analyses the depth of the spaces in relation to the point of reference, where dark blue colour represents the shallowest and red colour being the deepest space. The diagrams on the right hand indicate the access levels for domestic staff (top diagram) and visitor respectively (right middle diagram). This depth can be translated in terms of privacy - public to private - blue to red, and also the ability to control access to
other spaces. The isovist maps below depict the areas that are visible from nominated convex spaces. In figure 3 top left diagrams, the reference point is the entrance to the apartment and the entrance to service areas. It refers to the nature of the space and its role in controlling the visibility of further spaces for a visitor and domestic staff respectively. The maps describe the nature of the corridors as a controlling element not allowing broader vision making the spaces beyond more private. When the reference point is moved to the base of the living area (fig 3, left middle) the vision spreads out covering the living and dining space. This notion reinforces other data making the living and dining area the focal point.

Figure 3: Isovist maps(left) based on different users (top left)- Visitor & Servant at separate entrances, (middle left)- Visitor at waiting area, (Bottom left)- Visitor& servant in living area and step depth maps(right) for the apartment (top right)- servant entry, (middle right)- visitor at waiting point, (Bottom right)- visitor in living area. (source: Author)

So for the domestic help the threshold is defined by the service area with limited access to the living and private spaces. As a visitor, while the private areas remain out of vision, the living and dining area are put on display. The interior of this one particular apartment (refer figure 2) focused entirely on the
décor of the apartment. The interior is a collage of furniture, artefacts and paintings representing a fusion of European and Southeast Asian taste. The wife had travelled extensively to China and south East Asia collecting furniture and other artefacts for the apartment. This sense of decoration reflected an opulent eastern Asian sensibility with a hint of ‘self-Occidentalism’. They took great pride in their global repertoire and made sure that every person that visited the household was made aware of it. There was a conscious effort to bring the current aesthetic ideology from outside the country.

In many discussions, cosmopolitanism is a term associated with globalised way of life, less oriented on national identity than transcultural competence and cultural translation. Cosmopolitanism as described by Brosius in this context is the competence to incorporate western elements in one’s repertoire, and to know which is the most suitable and ‘cultured one’. It relates to persons aspiring to and accumulating moral values, cultural and economic forms of capital that generate a ‘world citizenry’ (Brosius 2010, 331).

Garden versus the view is also one of the highly debated issues for the owners of these new high-end apartments which is compensated by providing high-class communal amenities like garden spaces with jogging tracks, gym spaces and communal pool. The view from the top looking down into the communal garden and towards the sea matches the need for proximate green space by providing a visual connection if not a direct physical one. When speaking to the occupants, they expressed a feeling of satisfaction in still having a visual connection to the green all day long without having to worry about the maintenance of it. This reflects a bigger shift in attitude towards ownership in this globalised era, where life has become completely internalised and ownership by association emerges as a new form, attitude defining elite lifestyle.

4. Conclusion

The thresholds discussed here present a window into the persistence of the colonial thresholds in spite of being a globalised typology. It also reflects negotiations made by these new elite in the new spatial typology reflecting their socio-cultural aspirations, cultural capital and attitudes towards status and privacy played out in these newly created living domains. This new environment is a key to their guaranteed social mobility regardless of their previous social status, which would have been impossible for many of them before the typology was introduced.

This paper is only a partial attempt at disseminating fieldwork data, focussing on user negotiations in the condominiums based on only one case-study mainly employing spatial analysis and discourse analysis as investigative methods. Through this study, there are questions raised about the transformation of the typology and the stream of new elite fostered by it. These issues will be addressed in more depth once the data (drawings, interviews and discourse for three more projects) related to the processes that contribute to the making of these condominium are analysed.

These condominiums act like an isolated grid, where the aspiring cosmopolitans avail, adjust and compromise to fit into this grid in order to be part of the larger homogenous identity- an association deemed to be the quickest way to climb the social ladder. It is this new environment that shapes the identity of the new cosmopolitans, rather than the other way around.

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Negotiation of identities in the emergent cosmopolitan Indian landscape – analyses of the designs of new luxury high-rise apartments in neo-liberal India

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Pavement cafes as the activity zone in the social life of neighbourhood centres

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Abstract: This paper reports the findings from a research project that examines the relationship between urban design and the physical environment, and aspects of social and communal life in suburbs. Australian suburbs are perceived to be lacking in vitality and sociability. To address this, three suburban commercial streets were selected for investigation. Through documents and maps of the residents’ activities and behaviour, this study aims to identify the popular zones of activity and investigate the physical characteristics that encourage a sociable atmosphere in activity zones. The observation of activities in the three streets has been registered in tables relative to the date and time of occurrence. According to the behavioural mappings, the zones of activity are mostly shaped around pavement cafes and popular everyday food stores. Since more than half the activities have been observed to be initiated from the pavement cafes, this paper will investigate how the physical qualities of commercial streets such as the width of the pavements, personalization, soft edges and greenery have contributed to the pavement café culture in the selected neighbourhood centres.

Keywords: Social life; neighbourhood centre; commercial street; café culture.

1. Introduction

Social life has been defined as everything that occurs in public spaces: sitting, chatting, walking, cycling, running, standing and playing, which form “the life between buildings” (Gehl, 1987). In this sense, public life is translated into the presence of people and residents in their practice of everyday life in the public spaces of cities and neighbourhoods. According to Bianchini, social life is "the interacting of socialising or sociability...that occurs within the public realm" (Bianchini, 1999).

Over recent decades, the social life of neighbourhoods and suburbs has become a rising concern among scholars in the built environment discipline (Cohrun, 1994; Ferman and Kaylor, 2001; Sullivan, 2004; Mehta, 2013). In particular, suburbs have been criticized for their lack of vitality and social life (Davidson and Cotter, 1991; Richards, 1994). Therefore, identifying the built environment features that may contribute to the social life of suburbs and neighbourhoods can be a solution for creating vitality and life in residential settlements.
Suburbs are a combination of residential streets and commercial streets. Within the boundaries of neighbourhoods and suburbs, the commercial street is the context of social life and interaction among residents (Farahani and Lozanovska, 2014). The design and development of neighbourhood centres and suburban commercial streets can provide an opportunity for socializing behaviour among residents.

This paper aims to define the physical characteristics that may encourage the social life in commercial streets. To facilitate the process, the patterns of activities observed in three commercial streets (as the case studies of this research) have been mapped and registered in the tables of activities based on the time of occurrence (Farahani et al., 2015). The analysis of these mappings and tables shows that pavement cafes form a popular zone of activity in these streets. Therefore, in this paper, the built environment characteristics and the physical qualities that have contributed to the popularity of pavement cafes as activity zones will be investigated.

2. Theories around the café culture, third places

In recent years, theories have been formed around the importance of cafes for the social life of public spaces in cities. The theory of third places by Oldenburg (1989) can be considered as one of the key theories cited in several studies around the subject of social life (Banerjee, 2001; Mehta and Bosson, 2009; Simon, 2009; Francis et al., 2012; Henriksen and Tjora, 2013; Mehta, 2014). A third place, as described by Oldenburg (1989), is a place of refuge, where people can relax, commune and interact. They are places of satisfying social needs, where one can meet friends, colleagues, neighbours and even strangers. As opposed to the first place of home and the second place of work, third places can satisfy our desire for relaxation, social contact, entertainment and leisure. There is a wide range of third places, including cafes, pubs, local stores, bookshops, post office, restaurants, residential street gathering places or pavements and a bench in the local park (Oldenburg, 1989). “The best third places are locally owned, independent, small-scale, steady-state businesses and both government and incorporated chain operations have wreaked havoc upon them” (Oldenburg, 2009).

According to Banerjee (2001), in contemporary society, it is the appropriate mix of flânerie and third places that dictates the script for a successful public life. Flânerie refers to ‘hangout’ places such as new shopping malls that are designed to encourage this behaviour. Banerjee refers to third places and the streets that promote hanging-out as reinvented streets. These streets can be located in the heart of the city, serving city dwellers, or in the heart of neighbourhoods serving the locality.

Montgomery (1997) argued that the café culture (in the form of pavement cafes) has brought several benefits to the urban life of British cities. Pavement cafes are places of interaction and meeting new people. Cafés are not associated with particular ethnic traditions as with a pub. Additionally, they are not alcohol centred and thus can attract diverse types of people. Pavement cafes are places of great interaction with the street and improve visibility. In this sense, they help to increase the natural surveillance of streets. Compared to pubs and bars, café are able to attract a more diverse age-group of people. Cafes are also places where a great deal of business is transacted, and pavement café culture is perhaps one of the few remedies to the fully privatized public realm.

Café culture in Australia and cities such as Melbourne and Geelong has become a part of the city image, specifically for tourism and destination marketing. Until World War II, Australians, in the tradition of their British forebears, were mostly drinking tea and beer and pub culture was more dominant. An influx of Southern European migrants to Australia brought with them a love of coffee, and the social rituals that accompany it (Walters and Broom, 2013).
3. Study area

The suburban lifestyle is associated with a lack of vitality and social life (Davidson and Cotter, 1991; Richards, 1994). According to Richards (1994), suburban living has two faces: the dream achieved and the nightmare of dreary living, deprivation and isolation. To address the social life of suburban developments, this study will examine three case studies. Suburbs are usually a combination of residential streets and a few commercial streets, serving the residents in the form of neighbourhood centres. Scholars commonly interpret commercial activities as central to local community life and identity (Jacobs, 1961; Oldenburg, 1999; Deener, 2007). Researchers have viewed commerce as the source of neighbourhood safety (Jacobs, 1961), and the core of democratic participation and community vitality (Oldenburg, 1999). This study aims to focus on the social life of commercial streets in residential suburbs of Geelong as representative of the wider context of Australian suburbs. The case studies were chosen because of their different character and type of social life.

The first case study is located in Bell Park, a residential suburb with industrial areas to the east. The selected area of Separation St in Bell Park is a strip mall separated from the main high-speed lanes through a green filter and a parking area. Similar to other selected areas, the selected area is a part of a larger, commercial, educational and recreational development.

The second case study is a section of Pakington Street in Geelong West. Pakington St is a commercial street, with shops on both sides and pavements and the car lanes in the middle. The North end of Pakington St is home to a myriad of shops, including retail, fashion, restaurants, pubs and local services. The third case study, Highton Shopping Village, has a more complex morphogenesis. It has a strip mall in the north, and two pedestrian alleys, providing a bazaar-like atmosphere and access the west side of the shopping area. Car park spaces behind the retail activity provide a safe pedestrian environment in Belle Vue Ave. The urban form in the Highton shopping centre consists of small local retail stores in addition to a small supermarket, library and clinic. Belle Vue Ave performs as a miniature main street with very slow vehicular traffic (Figure 1).

4. Methodology

Observation has been characterized as “the fundamental base of all research methods” in the social and behavioural sciences (Adler and Adler, 1994). Qualitative social researchers are observers of both...
human activities and the physical settings in which such activities occur. In unobtrusive observation, the observer does not interact with participants, but simply records their behaviours. The primary tool or method for studying everyday life in public spaces is a direct (yet discreet) observation of behaviours, with a particular focus on how these relate to spatial features (Gehl and Svarre, 2013; Stevens, 2014). Direct observations provide an avenue to understand why and how some spaces are used frequently while others are quite underused. The analysis of people’s use of public spaces identifies links between observed activities and the physical environment where they occur (Stevens, 2014).

For this study, data was collected through case studies and unobtrusive observations of users in natural settings (the three commercial streets). There was no interaction with individuals or manipulation of the environment. Data was collected on the same day for each street on 4 days with similar weather conditions, from early November till early December in 2014. On each day, the temperature was between 15°C and 27°C, which is considered suitable for being outside. The selected suburban commercial streets, which are similar in length (around 280 metres) were divided into eight identifiable sections. Each section was video recorded for 30 seconds, every two hours, from 8:00 am to 10:00 pm. The short movies were inspected carefully and mapped in the format of visual tables registering the type of activities, the placement of activities, approximate age group, the time of the activities, and the connection of the activity to the related use on the street (Figure 2).

![Figure 2: Observation mappings at Highton on Monday from 8:00 am to 10:00 pm.](image)

5. Identifying the zones of activity

Gehl (1987) divides public space activities to the three categories of necessary activities, optional activities, and social activities. Necessary activities are the compulsory ones, including going to school or work, shopping and running errands. According to Gehl (1987), the activities in this group are slightly influenced by the physical setting. These activities will frequently take place throughout the year and are less dependent on the exterior condition. Optional activities include those pursuits that occur when there is a wish to do so or if the time and place encourage them, such as walking to breathe fresh air
Pavement cafes as the activity zone in the social life of neighbourhood centres

and sunbathing. When outdoor areas are of poor quality, optional activities seldom occur. Social activities are the ones that depend on the presence of others in public spaces, including children at play, greetings and conversations, and communal activities.

Although Gehl’s classification of outdoor activities sheds some light on the role of the built environment, in a suburban commercial street it was found that ‘necessary, optional and social’ activities mingled and were not clearly definable. Mehta (2013) adopted another method for classifying the zones of activity on commercial streets. He observed three zones of activity on pavements, wherever there was enough room to accommodate all of them. The first zone appears along the edges of buildings and inhabits the activities that are related to the interaction of the building edges and the pavement, such as entering and exiting, window-shopping, reading signs displayed by the stores, standing and often leaning on the building façade, and using a public phone or ATM.

The second zone located in the middle of the pavement is primarily for pedestrian movement, while the third zone, which is also the most richly furnished one, is inhibited by the majority of the stationary and social activities such as sitting, people-watching, reading, eating and drinking, talking, socializing, sleeping, playing a game and children playing (Mehta, 2013).

The mappings below illustrate the type and placement of activities on a Saturday on the three streets. We have identified the part of the street where the agglomeration of the activities was highest (the parts in the rectangles). These parts, which are considered the zones of activity, can be classified in three groups (Numbers 1, 2 and 3 in Figure 3). The first zone is created by pavement cafés. Not only do several activities happen around the cafés and restaurants, but also the duration of these activities is the longest. The most eventful spaces on the pavements are the ones claimed by the café’s temporary chairs and shades. The second zone of activity occurs around those facilities that serve the residents on a frequent basis. Everyday uses and services such as supermarket, butcher, bakery, and grocery stores usually attract a high level of frequent coming and going activities. This zone is noticeable in the part of Highton Shopping Village where a butcher, bakery, grocery and newsagent have been placed next to each other, attracting a great number of activities. The third zone, which might not be clearly visible, forms around the connecting points of the popular zones such as everyday food stores. For instance, in Highton, a pedestrian alley, followed by a pedestrian crossing connects the supermarket to the other side of the street, where the second activity zone is located (Number 3 in Figure 3). As the mapping shows, this zone is mostly occupied by coming and going activities.

Based on the observations, more than 75% of the activities have been formed around the pavement cafés (highlighted activities in Figure 3). Therefore, this study considers the café culture as a potential setting to strengthen the social atmosphere of commercial streets. However, the social atmosphere fabricated by the café culture is not the same for every café or restaurant. Not every café and restaurant façade interacts with the pavement or street. In fact, cafés adopt different approaches to communicate their social presence in the street. This study investigates the physical setting that may facilitate the success of café culture. There are 24 cafés and restaurants in the case studies (8 on each street). Based on the observations, we have selected the nine most successful cafes or restaurants (three on each street). The affordance of the streets in hosting pavement dining will be investigated through the comparison of these cafes and the result of observations (The term ‘affordance’ refers to the physical characteristics that allow or encourage specific behaviours or activities (Lang, 1987)).
6. Physical qualities of cafés and the social life of the street

Cafes, restaurants and bars may contribute to the social life of commercial streets at different levels. Pavement cafés and restaurants with a higher number of enduring and stationary activities are more efficacious than indoor ones, which merely add to the number of coming and going activities. The following analysis addresses the physical qualities that may encourage pavement dining. Based on the literature, several physical qualities that may affect the social life of commercial streets (Farahani and Lozanovska, 2014). Among these characteristics, we have selected the ones that may directly contribute to the success of pavement dining. These qualities include the width of sidewalk or front yard (outdoor sitting area), the area available for outside dining, the amount of personalization, the softness of edges, and landscaping. Although measuring the width of sidewalks and the area of
outside seating is straightforward, the three latter characteristics are not simply quantifiable. Therefore, to quantify personalization, softness of the edges, and greenery, a rating system was developed based on the definitions of these terms in the literature.

**Personalization**- Personalization is the act of modifying the physical environment toward an expression of claiming a territory (Mehta, 2009). Personalisation is usually accompanied by territorialisation or creating an identity. Kopec (2006) describes personalization as a physical marker used to identify personal identity, mark territories and hence regulate social interaction. According to Abu-Ghazzeh (2000), personalisation is a way for people to modify their environment and make it distinctly theirs and different from others. Based on the observations, five types of personalization have been identified: advertisement board, decorative features, shades and chairs, flower box, and vertical filters (barriers for defining territory). In order to quantify personalization, a value of two has been given to each item. Therefore, personalization has been evaluated between zero and ten depending on how many types of personalization have been seen on site.

**Soft edges**- “Soft edges” is a term coined by Gehl to describe indistinct boundaries between public and private spaces. According to Gehl (2010), the characteristics that contribute to the softness of edges are: scale and rhythm, transparency, appeal to many senses, texture and fine details, diversity of functions and vertical façade rhythm. Gehl (1987) argues that soft edges encourage a feeling of safety through communicating with people. Mehta (2013) uses the term “dull facades” and believes that dull building facades are dead spaces, which are not sufficiently welcoming. The quality of public spaces within the city is of vital importance in creating a vibrant and lively city. “Soft” or active edges containing many details add to the quality of public spaces. A clear demarcation between public and private, active façades and appropriate urban furniture encourage people to stay in public spaces. Active facades refer to the facades where the inside and the outside uses are “connected visually and thus can enrich and inspire each other” (Gehl and Gemzøe, 2004). Gehl argues that no other element has a greater impact on the life and attractiveness of city space than active, open and lively facades (Gehl, 2010). Based on the observations, three items that contribute to the softness of edges have been identified: level of details, visual connection of inside and outside and permeability. In order to quantify soft edges, a value of two has been given to each item. Therefore, personalization has been evaluated between zero and six, depending on how many of the items can be seen in each café edge.

**Landscape and greenery**- Landscape and greenery is believed to have contributing effects on the social life of neighbourhoods and commercial streets (Whyte, 1980). A study of neighbourhood common spaces indicated that the presence of trees and grass is related to the use of outdoor spaces, the amount of social activity that takes place within them, and the proportion of social to non-social activities they support (Sullivan, 2004). Nasar and Julian (1995) found easy access to common outdoor green space increased sense of community. Greenery and landscaping not only encourage activities by tempering the atmosphere, but may also function as a traffic barrier or shade. Therefore, in regard to the role that the landscape plays and based on the observations, five items have been identified: beautification, defining territory, traffic barrier, cleanliness, and shading. A value of two has been given to each item. Therefore, each café’s landscape has been evaluated between zero and ten depending on how many of the items can be seen.

Table 1 summarizes the physical attributes of the nine most successful cafes in the case studies. The physical attributes have been quantified in order to generate a clear picture of how they might encourage pavement dining.
Table 1: Comparison of observed activities and the physical characteristics of cafes.

<table>
<thead>
<tr>
<th>Cafe</th>
<th>Suburb</th>
<th>Number of patrons</th>
<th>Number of stationary activities</th>
<th>Width of sidewalk or front yard</th>
<th>Area</th>
<th>Personalization</th>
<th>Softness of edges</th>
<th>Greenery</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Highton</td>
<td>39</td>
<td>38</td>
<td>5-8 m</td>
<td>140</td>
<td>8</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>Highton</td>
<td>30</td>
<td>26</td>
<td>4.5-12 m</td>
<td>100</td>
<td>8</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>Highton</td>
<td>9</td>
<td>5</td>
<td>3.5 m</td>
<td>30</td>
<td>6</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>Geelong West</td>
<td>61</td>
<td>60</td>
<td>7 m</td>
<td>90</td>
<td>8</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>Geelong West</td>
<td>28</td>
<td>26</td>
<td>6 m</td>
<td>60</td>
<td>8</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>6</td>
<td>Geelong West</td>
<td>25</td>
<td>7</td>
<td>3.5 m</td>
<td>35</td>
<td>6</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>Bell Park</td>
<td>14</td>
<td>8</td>
<td>4 m</td>
<td>50</td>
<td>6</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>Bell Park</td>
<td>12</td>
<td>0</td>
<td>2.5-4.6 m</td>
<td>25</td>
<td>0</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>9</td>
<td>Bell Park</td>
<td>9</td>
<td>0</td>
<td>4 m</td>
<td>25</td>
<td>2</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

The table shows that the number of activities generated by cafes correlates with the width of pavements and seating area, personalization, softness of edges and landscape. Although analysing nine cases will not provide enough data to prove the exact effect of these characteristics, the table generates a pattern of how and to what extent these features may encourage pavement dining. According to the table, cafes with more than 25 patrons had a sidewalk or seating area more than 5 metres wide, and a seating area larger than 60 square metres. Popular pavement cafés have usually been located in the widest section of the footpath (café number 1, 2 and 4). However, sometimes the pavements are not wide enough to provide the necessary room for outdoor dining. For some cafes (number 4 and 5), the possession of an open or semi-open area is of such importance that they have allocated the outdoor space from a part of their land and interior space.

The width of pavements is not the only prerequisite for outside dining. The personalizing and defining of the outdoor dining area seems to be critical for the popularity of a pavement café. For instance, café number 5 has two separate dining areas, one on the sidewalk separated from the street by flower boxes and the other a semi-public open area within the lot surrounded by walls and separated from the sidewalk by short fences. The observations showed that the space surrounded by walls is full of customers throughout the entire day, while the space on the sidewalk is hardly used. Cafes may define and personalize the dining space by different elements, including shades, flower boxes, awnings, columns, panels, and greenery. Popular pavement cafes (all the cafes, except 8 and 9) have all used different elements to personalize the outside space. As the table shows, all the pavement cafes have used at least three modes of personalization.

Facades may achieve softness through transparency, permeability and the level of details. Softness of edges seems to positively correlate with the number of outside activities. Based on the observations, the five cafes with the highest number of activities had the highest ranking for softness. The softness of edges not only provides the interior with a view of the outside, but also benefits cafes in linking the inside space to the pavement area. It also facilitates the flow of service for outside users.

Although greenery may provide a nice atmosphere to encourage outside activities, it does not seem to be a prerequisite for pavement dining. For instance, café 6 with no greenery still had a considerable number of patrons dining outside. Usually cafes use greenery as a means of beautification and defining boundaries and also as a traffic barrier.
Among the case studies, there are two cafes in Geelong West with a branch in Highton (cafés number 3 and 4 and cafés number 2 and 6). The cuisine and menu, the quality of food, style and non-physical features among these branches are the same. However, the affordance of the built environment has caused one of the cafes to have a successful street life in Geelong West, while the other one is more successful in Highton. These two cafes and their branches make a good case for the significance of the built environment in promoting café culture and the social life of commercial streets. Wherever the environment affords, these cafes have benefited from the outdoor area for pavement dining.

Cafes can interact with the sidewalk in three ways. First, if the sidewalk is wide enough and the environment is desirable, they might claim the sidewalk as a place to put their chairs and shades. Second, if the sidewalk is not wide enough, they might sacrifice a part of their own lot as an outdoor space to provide a shaded or semi-shaded area that performs as a pavement café and contributes to the social life of the street. And if there is not enough space for dining outside, blurring the boundary and using transparency with an open front can be a solution for stitching the interior to the pavement. However, when the outside environment is not entirely desirable, cafes seek hard edges to minimize the interaction between the interior and the exterior (café 8).

7. Conclusion

Australian suburbs are associated with a lack of vitality. Certain features of the built environment may encourage activities and mitigate this lack of social life. Based on our observations, we have identified three zones of activity on commercial streets. The behavioural mappings showed that restaurants and bars, as the first zone of activity, engender most of the stationary activities on commercial streets. Pavement cafes with a high number of staying activities create a sociable atmosphere and are vital to the image of their neighbourhood centres. Therefore, outdoor dining is important for the social life of commercial streets. There are several physical qualities that may affect the social life of commercial streets. Among these characteristics, the ones that may directly contribute to the success of pavement dining are observed to be the width of sidewalk or front yard (outdoor sitting area), the area available for outside dining, the amount of personalization, softness of edges and landscape. These qualities have been investigated for the 9 most successful cafes in the three case studies and the results have been summarized for analysis.

Cafes tend to claim the storefront, where the pavements are wide and there is enough room for a dining area. The personalization or defining the boundaries of the dining area through physical elements such as panels and shades is a critical factor in the popularity of pavement cafes. A soft facade with permeability and transparency is another physical quality that may affect the success of outdoor dining. On the streets where these qualities are lacking, cafes try to avoid street dining and draw the population into their interior.

The findings improve and broaden our understanding of the physical characteristics that influence the social life and patterns of activities in commercial streets and provide evidence that pavement dining plays an important role in creating vital neighbourhood centres.

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References


Perceptions of change in office space design: redesigning Barwon Water’s office environment

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Abstract: In early 2015 Barwon Water received State government funding to rationalise and renovate its various Geelong-based administrative offices into one complex. Integral to the renovations is a new green-star retrofit of the existing Ryrie Street complex by GHD Woodhead. The project will consolidate all of Barwon Water’s offices onto one site, increase floor space, provide a new ‘green’ atrium, and adopt an open plan layout. Having set a new strategic direction, Barwon Water is now undergoing a wholesale cultural and operational change in order to realise these strategic objectives. Aspirations for workplace design have been identified as: environmentally sustainable; foster innovation and creativity; establish connections; improve communication and collaboration; provide efficient space for effective work; flexibility over time; welcoming and connected to the community; healthy; and, up to date technology. This paper investigates Barwon Water staff perceptions and apprehensions of this prospective consolidation, particularly the proposed open plan office environment. While most research in this topic is informed by an immediate pre-design workshop of staff needs, this research provides a longitudinal perspective of human perceptions about work place environment change and a review of how changes in office environment synergistically align to architectural responses and changes in corporate strategies.

Keywords: Change management; interior re-design; workplace culture; water corporation.

1. Introduction

This paper profiles an enquiry into white-collar worker perception of open plan offices prior to occupancy so as to offer an informed perspective as to staff perceptions, expectations and apprehensions of this new work place environment.

This research aims to review the values staff place on different workplace attributes and explores their current work patterns relational to their existing work place environments. The case study involves a study of Barwon Water staff prior to the refurbishment and consolidation of their new headquarters, to be completed in 2018. The research continues and builds upon foundational perception surveys completed in 2010, to assess changes in staff perceptions and work patterns over time, especially with
the release of new architectural plans for the office transformation, and reviews findings about new issues that have arisen with release of plans and images portraying the new complex

2. Open plan office conversions
Considerable architectural and interior design-related academic and professional practice literature exists on the impact of changes to physical workspace on staff satisfaction, productivity and health at work. Most of this literature, however, exists in the post-occupancy evaluation realm rather than in the pre-occupancy context.

Transformations of traditional office configurations and environments into open plan environments in particular has been subject to much consumer angst and anxiety. Notwithstanding this anxiety and apparent lack of consumer acceptance of new open plan environments created, there is little clear quantitative information or measurable data as to before-and-after impacts including staff consumer perceptions of draft designs and the potential impacts upon what they are used to experiencing.

A recent focus on open plan and enclosed workspaces by interior design practitioners, for example, has shown different levels of staff consumer satisfaction to the key factors including noise, privacy, and the ability to successfully communicate, write/type content coherently and to successfully collaborate. This research is largely contained in published result involving post-occupancy evaluations, often involving workforces that have been relocated from enclosed offices to open plan offices. Much of this research concludes that open plan offices negatively impact staff satisfaction levels and thus their work performance and production. Some of this research has indicated that there are mitigating factors and assumptions that need to be considered when validly assessing staff satisfaction with open plan workspaces; including job status, age, and individual control over one’s workstation. An additional factor is the nature and implementation of quality change management itself, including consultation and communication. The latter engagement process has been identified by several authors as a key factor in enabling a workforce to successfully transition from an enclosed/semi-enclosed office environment to an open plan office environment.

Much of this literature assumes that a causal link exists between a physical work environment and the satisfaction and productivity of consumer workers. This conclusion is clearly identified by Veitch et al. (2007) that specifically sought to explore this assumption. Research by Veitch et al. (2007) aimed to test and validate that a direct link exists between built environment satisfaction and consumer job satisfaction concluding that consumers who were more satisfied with their work environment were also more satisfied with their jobs.

Noise and privacy have been identified by several researchers as the primary negative issues of open plan office environments. Literature examining staff satisfaction with their work environment (Daniellson & Bodin, 2009; Kim & de Dear, 2013; Sandstrom et al., 1982; Maher & von Hippel, 2005) concludes that employees are negatively impacted by large amounts of noise and the lack of privacy in open plan office environments. Excessive noise has been documented as affecting staff motivation that it contributes to communication and work production distractions, and therefore affects their ability of workers to directly concentrate and perform their job at a level comparable to that in an enclosed/semi-enclosed office environment. A lack of privacy is documented as enabling uncontrollable and unwanted social contact and interruptions, unproductive computer-based communication, nurturing too much stimulation or over-stimulation, and an inability to conduct confidential tasks and discussions without ejecting one’s self from that open plan space into an alternate more semi-private space or a corridor space.
Kim and de Dear’s (2013) research, for example, concluded that the negative impact of noise and lack of privacy outweighed the perceived benefits of open-plan offices, such as easier collaboration. Additionally, Maher and von Hippel (2005) observed that workers with larger amounts of privacy and less exposure to distractions and stimulations were more satisfied than those with lesser amounts, and similarly that the more the privacy the greater the volume and quality of production and activities, thus highlighting a conclusion of the importance of privacy to staff happiness.

Several work management-biased authors identified that increased collaboration and communication was a policy aim, and thus articulated as one of the key reasons why organisations choose to adopt policies to implement open-plan floor space designs (Hua et al., 2010). In contrast, most academic generally concludes that in reality, collaboration in open plan offices is no better, and in some cases worse, than in traditional enclosed/semi-enclosed office environments. Kim and de Dear (2013) concluded that communication was perceived as being better in enclosed/semi-enclosed offices linking this to established human relationships between communication and privacy and the increased privacy afforded by enclosed/semi-enclosed offices. Rashid et al (2009) observed that office environments with greater accessibility and visibility resulted in staff having lower personal satisfaction levels due to increased face-to-face interactions. Thus, contrary to the management-informed industry-held belief that open plan offices enable easier and better worker communication and collaboration, architectural and interior design academic research indicates otherwise.

Research on open plan offices has largely focused on the effects of workstation scale and layout scale variables as elements of the physical environment that affect worker satisfaction. Spreckelmeyer (1993) lists the workstation variables as including factors of lighting, size of individual workspaces and privacy as the key determinants of worker happiness. Lee and Brand (2005) also identified workstation factors as the main contributors to worker satisfaction, especially the worker’s ability to personalise their workstation space. Danielsson and Bodin (2009) list the ambient factors of thermal comfort and air quality as key factors on staff contentedness, and these variables had a stronger influence that the preceding variables. Hua et al. (2010) points to the fact that office layout variables (such as distances from individual workstation to nearest meeting place and distances from individual workstations to the nearest copy/print area) determined staff perceptions about how supportive their work place environment is of nurturing and enabling collaboration. This literature therefore demonstrates that there are different variables that must be considered when examining the physical environment’s effects upon staff fulfilment, communication, collaboration and production.

While much of the above literature has identified negative and performance issues associated with open plan office environments, few authors have explored remedies to address these negative issues. One remedy that appears evident, and is subtly mentioned by several authors, is that to increase worker satisfaction is linked to good change management. If managers of an organisation can empower, engage and communicate successfully to employees about why and how the change to open plan offices is occurring, to enable the workers to participate in the design process towards their new work place environment, then staff may transition better and find themselves more satisfied with their new environment (O’Neill, 2010). To navigate this process and to survive in these new open plan office environments, Hedge (1982) has stated that it is essential for staff to learn new behaviours to assimilate with their new open plan work environment. Change management has been pointed to by management advocates as a key factor in achieving the successfullness of a move from enclosed/semi-enclosed environment to an open plan environment. Office interior design practitioners have produced many advice and guideline documents on how to best manage office change (O’Neill, 2008; O’Neill, 2010;
Johnson, 2009), but the impact of good change management has not been examined by this literature. Accordingly, there is a dearth of research and literature about change management strategies in relocating staff to open plan office environments, and little information exists to validate that change management strategies does in fact result in greater staff consumer satisfaction with their new work place environment.

3. Barwon Water

Barwon Water is a large regional water corporation that provides high quality and sustainable water, sewerage and recycling services to an area of over 8100 ²km in Victoria. The service catchment of Barwon Water includes parts of Victoria stretching from Little River and the Bellarine Peninsula in the east and from Meredith in the north to Apollo Bay on the southwest coast. The history of Barwon Water can be traced back to the establishment of the Geelong Municipal Waterworks Trust in 1908, and Barwon Water re-constituted as a statutory authority under the Victorian state *Water Act 1989* and continues under this legislation today. Barwon Water has an asset base of approximately $2.3 billion, including several reservoirs, treatment plants, pumping stations and an extensive pipe network. The organisation employs approximately 310 staff who perform roles in operational, strategic, engineering, planning, financial and administrative sectors.

Before a recent disruption to worker locations, due to the current commencement of the Ryrie Street refurbishment works, the Barwon Water workers in the Geelong region were split between three work sites; Ryrie Street, Mercer Street and Lonsdale Street (Figure 1).

![Figure 1: Locational map of Barwon Water offices.](image)

Barwon Water has been investigating office accommodation and office consolidation options since 2007 with the Ryrie and Lonsdale Street offices becoming increasingly aged, out-of-date and inefficient
for the workings of a modern corporation and a changing work environment dominated by computers (Begg 2015). Prior to the consideration of refurbishing the Ryrie Street Office, Barwon Water explored the feasibility of constructing a new building near the Geelong Railway Station in 2010 to replace the Ryrie Street and Lonsdale Street offices, but this project failed to gather funding support from internal and state government sources.

The need for the refurbishment and consolidation of Barwon Water’s premises is expressed in their current Corporate Plan (2014a). Barwon Water’s Strategic Intent (2014b, p. 1) to ‘provide water and sewerage services through efficiency, innovation and leadership’ as it’s mission for the period covered by the Plan. The lack of efficiency in the current Barwon Water workspaces was therefore a key driver for new accommodation.

Having identified that Barwon Water’s current office accommodation is not fit for purpose and does not support the organisation’s strategic direction, the decision was made to procure a new workplace … (Meinhardt & DEGW 2011, p. 11)

The stated objectives for the new Barwon Water accommodation are to:

- accommodate existing and future staff in accordance with contemporary accommodation principles;
- improve productivity, training and education; improve environmental performance; and to
- provide the means for Barwon Water to be a leader in sustainability (Meinhardt & DEGW 2011, p. 11).

GHD Woodhead, as project architects, have stated that consolidating Barwon Water’s operations under one roof in renewed accommodation would boost efficiency and productivity, and would save 45% on operational, maintenance and energy costs. Included in their design is; use of low VOC materials; 60% of floor area to have access to natural light and views in particular northern views to Corio Bay; bike storage for 40 bikes, showers and lockers provided; rainwater used for toilet flushing and irrigation; and, 90% of existing structure to be reused.

Images prepared by GHD Woodhead (Figures 2-4) depict the major external changes to the existing complex, including the provision of a new internal new atrium and an extensive open plan office environment.
Investigations into alternate and more cohesive office accommodations for Barwon Water’s employees commenced internally by Barwon Water in conjunction with consultants DEGW in 2007. In 2010, Barwon Water commissioned a detailed study by DEGW to investigate existing staff work patterns and staff perceptions about work environments generally and their existing environments (DEGW 2010). The aim of the DEGW (2010) study was to provide an information base to inform a brief for the 2010 new building project.

The study was conducted in three parts; manager interviews, staff workshops and an online workplace performance survey. The manager interviews focused upon understanding detailed requirements for specific functions. The staff workshops were conducted with representatives from all levels and departments to explore cultural variables and inter-relationships, current work styles and how these affect Barwon Water’s existing workplace. The online workplace performance survey was conducted to understand staff workplace priorities and was anonymously completed by 190 staff. A second staff workshop was also conducted to review and reflect upon the findings arising from the online survey and to explore ideal work environment scenarios.

The findings from the manager interviews and staff workshops largely informed the brief formulation for the new building in terms of functional requirements. In contrast, it is the findings from the online workplace performance survey that offered extensive information about work patterns, work culture and staff perceptions of existing workplaces, and these findings are summarised as follows.

The most important workplace variables, identified in the online survey, were those relating to being able to concentrate and perform tasks. The highest performing workplace variables were those relating to technological support systems and access to colleagues. The lowest performing variables were car parking, support facilities such as gyms, tearooms and social hubs, and building temperature(s). The largest gaps between performance and perceived importance were the availability of car parking and the ability to concentrate. In terms of the types of existing workstation scenarios that respondents worked at, the majority of respondents identified ‘their work area’ as comprising ‘their own desk’ in an open plan area. Only 5% of respondents had their own enclosed office. In terms of interactions with Barwon Water customers, the majority of staff had face-to-face interaction with customers as part of their daily roles and activities.
In regards to meetings, the respondents indicated the majority of their meetings remained planned as opposed to unplanned. Additionally, when asked about time spent in areas inside the existing office(s), respondents indicated that they spent the majority of their time in their individual workplace, as opposed to meeting spaces and other spaces in the building. These last two variables indicate that the majority of Barwon Water’s workforce was static in their movements in their workplace, and that such existing environments were not flexible and adjustable.

The recommendations of the DEGW study were parallel to those raised in the above literature review relating to the required functions and the feeling of new workplace environments. These recommendations include a variety of spaces for different functions (ie. quiet and private spaces for telephone calls, breakout areas for informal meetings, places for serendipitous encounters), flexibility of spaces to enable adaptability, visual transparency in the building to enhance connectedness, and adequate natural lighting, ventilation capabilities and views. The DEGW study did not avail the opportunity of open-ended responses thereby limiting the volume and quality of feedback provided on personal topics and perceptions. Additionally, the DEGW study did not directly ask Barwon Water staff about their perceptions of different types of workspaces, i.e. open plan office environments. This deficiency has resulted in a lack of comprehensive understanding as to how Barwon Water staff perceive the potential work environment to be constructed in the new open plan office environment embodied in the GHD Woodhead design. Additionally, there was also a lack of understanding of staff perceptions of open place offices as to whether this would limit management’s ability to plan and manage the change management process from the current to the new work environment.

4. Methodology

In 2015 a more inclusive and qualitative focused staff survey was conducted by the authors. 24 Barwon Water staff members from different levels, roles and locations at Barwon Water participated in the survey. Additionally, staff were also selected to represent a range of employment tenures at Barwon Water. This enabled a variety of responses to be collected from different staff members with vastly different experiences extant in the present Barwon Water work environment. The surveys were executed in February and March 2015, with the majority of employees who would normally be based at the Ryrie Street office having already been relocated or decanted to other offices while the Ryrie Street office was being prepared for construction and renovation. The result of this research was that some staff members had recently experienced changed work environments. In this instance, the employees were asked, where relevant, to provide responses based on both work environments at Barwon Water.

The surveys were administered face-to-face. The respondents completed the survey with clarifications and further detail with clarification from the researcher where necessary. The survey consisted of 17 structured and open-ended questions, with a variety of response types employed. These consisted of ranking options, selecting the most appropriate option, and written responses to open questions. The questions examined workspace type and time spent in different locations, meeting types, customer interactions, the importance and performance of different workplace aspects and perceptions towards open-plan offices. 43 staff were invited to participate. Of these, 29 responded in the positive, and of these 29, 24 were available at the time the study was conducted.

This study involved a much smaller sample group than the previous DEGW study, but with a confirmed and more comprehensive spread across locations, roles, levels, and lengths of employment at Barwon Water. In comparison to the previous DEGW study, it was conducted in person, rather than online. This executive strategy enabled the opportunity for the researcher to engage with a respondent
individually to enable them to complete every question comprehensively. While a cross-comparison of questions was included in the new study, additional open response questions were provided in the new survey that were not included in the DEGW survey to permit the respondents to provide more detailed feedback as to their perceptions about open plan offices. The aim of this second survey is to re-test the respondents on the same questions as the DEGW survey to directly compare the responses to determine if responses had largely remained the same, or if there had been noticeable differences since 2010.

The objective of conducting a second survey was to gain insights into the perceptions of Barwon Water staff to determine whether the time lapse since the first survey in 2010 had brought about changes in their perceptions. Additionally, the second survey, conducted immediately before the commencement of construction on the refurbishment, sought to provide a point of comparison for any future survey conducted following the completion and inhabitation of the new work environment. This collection of surveys, spread across a number of years, also enables a longitudinal study into workplace environment perceptions exploring if work patterns and employee values change due to changes in office environments.

5. Discussion

5.1. General findings

The discussion of general findings has been broken into four parts: work patterns, worker values, worker perceptions of open plan offices, and comparison to the 2010 survey.

5.1.1. Work patterns

In terms of allocated workspace, the vast majority of respondents had their own desk in an open plan area or their own desk in a multi-person enclosed area. Only 8% of respondents classified their work environment as an enclosed office. The majority of respondents spent all of their time working at their primary Barwon Water site, with few employees working across sites or in the field. Very little working time was from home. Within their primary Barwon Water site, respondents spent the vast majority of their time at their individual workstation, with a minority of time being spent in meeting spaces. Respondents indicated that most of their meetings were planned as opposed to unplanned. In regards to customer interaction, of those surveyed, approximately two thirds of respondents confirmed that they had direct interaction with customers at their Barwon Water office and/or the customer site. This indicates that most workers currently work in an enclosed form of open plan office, and that the workforce is static in its movements, without much flexibility in terms of spaces used.

5.2. Worker values

The respondents were asked to rate workplace variables firstly on how important they perceived they were, and secondly by how well they perceived the workplace variable performed. The most important variables were identified as being able to work comfortably at a desk, building temperature, access to natural light and good artificial light, and the ability to concentrate when necessary. The workplace variables with the biggest gap between how important they were and how they performed were building temperature and support spaces such as social hubs for eating and access to a gymnasium. The highest performing variables rated by the respondents were secure entry to the Barwon Water building
and the ability to work side-by-side with colleagues. The lowest performing factors were access to support facilities such as a gymnasium and a hub for socialising and eating. Building temperature was also rated as performing poorly by respondents.

In terms of productivity, respondents were split as to what impact the work environment had on both their individual productivity and on team productivity. Both were only slightly more than half of the respondents in both cases indicating that the work environment positively affected productivity.

5.3. Worker perceptions of open plan offices

The oral responses provided respondents with an opportunity to directly express their thoughts of open plan offices. The general consensus by respondents identified that open plan offices were acceptable, conditional that they were well designed. Respondents stated the need for a variety of spaces to cater for different personalities and job roles. Respondents were concerned about the potential noise levels and distractions in open plan offices, as well as a loss of privacy and confidentiality. Such respondents noted a main advantage as being access to other colleagues and work teams in Barwon Water.

5.4. Comparison to 2010 survey

In comparison to the 2010 DEGW survey, there were some significant differences in responses, but largely, the two surveys provided similar results. In terms of the workplace variables rated the most important, building temperature, working comfortably at a desk, being able to concentrate, and access to natural light were rated as being very important in both surveys. Building temperature was a workplace variable in both surveys that had a large gap between importance and performance, whereas car parking had a large gap in the 2010 DEGW survey, but not in the 2015 survey. The variables rated as the highest performing were quite different in the two surveys, whereas the lowest performing variables were very similar (Table 1).

| Table 1: Comparison of workplace factors in 2010 and 2015 surveys. |
|------------------|------------------|
| **2010 Survey**  | **2015 Survey**  |
| **Most Important** | **Most Important** |
| 1 Ability to concentrate | Ability to work comfortably at a desk |
| 2 Ability to conduct phone conversations | Building temperature during working hours |
| 3 Ability to work comfortably at a desk | Access to natural light |
| **Highest Performing** | **Highest Performing** |
| 1 Shared Utility Space | Secure entry to business |
| 2 Ability to have scheduled face-to-face meeting with colleagues | Ability to work side-by-side with colleagues |
| 3 An efficient and effective central booking system | Availability of car parking nearby |
| **Lowest Performing** | **Lowest Performing** |
| 1 Access to a gymnasium | Access to a gymnasium |
| 2 Availability of car parking onsite | Ability to work virtually using video-conferencing equipment |
| 3 Availability of car parking nearby | Building temperature during working hours |
| **Biggest Gap** | **Biggest Gap** |
| 1 Availability of car parking nearby | Building temperature during working hours |
| 2 Availability of car parking onsite | A hub for socialising/eating/meeting |
| 3 Building temperature during working hours | Access to a gymnasium |
5.2. Key findings

The most significant findings from the surveys were those related to the performance and importance of workplace variables (Table 2). For these questions, respondents were requested to rate both the performance and the importance of the variables out of 5, with 5 being that it is very important, and that it performs very well.

<table>
<thead>
<tr>
<th>Most important workplace factors</th>
<th>Average score</th>
<th>Workplace factors with biggest gap</th>
<th>Gap</th>
<th>Highest performing workplace factors</th>
<th>Average Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ability to work comfortably at desk</td>
<td>4.75</td>
<td>Building temperature during work hours</td>
<td>2.38</td>
<td>Secure entry to business</td>
<td>3.83</td>
</tr>
<tr>
<td>Building temperature during working hours</td>
<td>4.71</td>
<td>A hub for socialising / meeting / eating</td>
<td>1.67</td>
<td>Ability to work side-by-side with colleagues</td>
<td>3.79</td>
</tr>
<tr>
<td>Access to natural light</td>
<td>4.67</td>
<td>Access to a gymnasium</td>
<td>1.38</td>
<td>Availability of car parking nearby</td>
<td>3.78</td>
</tr>
<tr>
<td>Ability to concentrate</td>
<td>4.63</td>
<td>Ability to have confidential conversations with colleagues</td>
<td>1.38</td>
<td>Ability to access emails when off site</td>
<td>3.74</td>
</tr>
<tr>
<td>Quality of artificial light</td>
<td>4.58</td>
<td>Ability to concentrate</td>
<td>1.29</td>
<td>Quality of artificial light</td>
<td>3.63</td>
</tr>
</tbody>
</table>

The two most important workplace variables identified were being able to work comfortably at a desk, with an average rating of 4.75, and building temperature, with an average rating of 4.71. This implies that the arrangement of individual workspaces is the key variable to staff contentedness and productivity, with building temperature having a significant influence on the comfort of staff. The importance of the individual workspace to staff would suggest that staff are more concerned with variables on the scale of workstation design, than they were with overall office layout. The worded responses emphasised that this is because access to resources and immediate protection from noise and distraction are key variables to staff productivity.

The importance placed on air conditioning by staff is in contrast to its performance, with building temperature being the workplace variables with the greatest difference between perceived importance and performance. The difference between its importance rating (4.71) and performance rating (2.33) is 2.38 points. In the worded responses, some staff noted the inconsistency of the air conditioning, which is clearly a concern shared by many of the staff as reflected in its average rating. Thus, consistent air conditioning at a comfortable temperature variable is of key concern to many staff, and is currently having a significantly negative impact on their ability to work comfortably.

The worded responses demonstrated that many staff were concerned about noise and privacy. 45% of staff mentioned high noise levels as a key variable to how they perceived open plan offices. A third of respondents mentioned privacy concerns as a major variable in their perceptions of open plan layouts. On the positive side, 20% of staff perceived open plan offices as easily and quickly facilitating access to colleagues and other work teams.

6. Conclusion

The findings demonstrate that Barwon Water staff place high importance on both workstation scale variables and workplace scale variables. Being able to work comfortably at a desk with good lighting and building temperature are the most important variables to staff productivity and happiness. In terms of
staff perception of open plan offices, noise and privacy are key concerns, and the provision of a variety of different spaces is a key requirement. Easier collaboration and access to colleagues is the main perceived advantage of the open plan office layout. The surveys illustrated that staff are wary of open plan offices for these reasons, but are not opposed to them.

The differences between the 2010 DEGW and 2015 surveys demonstrate that the Barwon Water staff still place importance on similar variables over this time period, being the ability to work comfortably at a desk and the provision of well-being support facilities. The perceived performance of workplace variables differed between the two surveys, but this can likely be attributed to location change and technological development.

The recommendations for a work environment to suit the 2015 workforce are similar to those to suit the 2010 workforce, being a variety of spaces for different functions, comfortable temperature, well-designed individual workstations, and good natural lighting. This concludes that work environment matches Barwon Water’s objectives for the new office design. A final survey of staff upon the inhabitation of the new work environment will allow for analysis of how open plan offices have changed staff perceptions, values, and work patterns.

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References
Social participation in designing everyday spaces enabled by networked media: a case study of DIY rainbow crossing

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Abstract: Digital technologies have facilitated the process of sharing design patterns and spatial interventions in everyday settings. Influenced by the emerging culture of spontaneous actions and real-time expressions in virtual space, people participate in construction and reconstruction of the physical environment in a continuous process at small-scale. This paper explores the relationship between social media and temporary design of places by everyday users and investigates how the culture of participation, enhanced by new media, is reflected in architecture, design and use of places. This study is significant as it argues that architects can take advantage of new practices in design associated with active participation of people as they represent new ways to orchestrate individual parts and make a coherent whole. To indicate the interaction of media and design, the paper studies the case of DIY Rainbow Crossing, a community action creating rainbow pedestrian crossings in chalk. This not only advances our understanding on the role of social media in scaling up and speeding up the transmission of design ideas from person to person, but also leads us to model individual actions brought together in a singular process through social networks.

Keywords: Collective design; social networks; community architecture.

1. Introduction

The aim of this paper is to gain an insight into the collective nature of space interventions; this is the process in which a design pattern is shaped as ideas and their physical manifestations are propagated through online social networks; and it is located at the intersection of virtual space, social interactions, and the physical environment.

Over the last decade, the flow of information through digital platforms of sharing ideas and experiences has influenced the process of shaping patterns and themes of design. In the new forms of online social networks, all involved individuals play an active role in not only consuming but producing resources flowing in the network. In such an interactive digital environment, mostly known as Web 2.0, the capacity to create and share information is in more hands. The term Web 2.0 or the second version
of the World Wide Web treats the web as a platform which allows users to create content rather than being limited to consuming information on websites (O'Reilly, 2005). Allowing people to customize, filter and assess information, digital tools are leading to a new culture of participation (Rainie and Wellman, 2012). This has enabled users to participate in solving problems collaboratively and the diversity of perspectives has resulted in new insights and ideas and social creativity (Fischer, et al. 2006).

Having influenced the process of sharing information and feedback mechanisms, digital tools have opened new horizons to novel forms of civic engagement and community initiatives. The opportunities offered by Web 2.0 such as blogs and social networks have facilitated not only organizing different forms of civic activism such as protests and petitions but also collecting citizens’ remarks and suggestions (DeCindio and Peraboni, 2011). Applying the potential of new digital tools to engage people, transforms a single action to collective, and improves the process of design and planning to a collaborative and ongoing process.

Networked media is promoting not only online civic participation but also emerging themes of spatial interventions in public places. In parallel with the growth of employing digital media to facilitate engagement by city councils and local governments, there is a growing trend in spontaneous participation self-organized through online social networks associated with a physical activity and changing the place even though temporarily. In fact, the pervasive participation and the growth of collective behavior of users in the virtual public domain are translating into collective actions and interventions in physical urban places. This might indicate the correlation between the pervasive use of online social networks and the growth of spatial interventions in new forms of informal, pop-up, do it yourself (DIY), guerrilla, and handmade urbanism (Crawford and Speaks, 2005; Haydn and Temel, 2006; Burdett, 2011; Bishop, 2012; Oswalt and Philipp, 2013; Rosa and Weiland, 2013; Beekmans and Boer, 2014; Lydon and Garcia, 2015). While there is a growing interest in addressing the role of connectivity in civic engagement, it should be noted that, for this study, social participation is used as a point of departure to explore the properties of a collective process of design which takes shape in online social platforms.

One of the important consequences of the interconnection of online social networks and spatial interventions is the ongoing flows of design ideas in a crowd of interacting individuals and the global spread of ideas which leads to the replication of that idea. In fact, the transmission of a pattern takes place as an event repeats in different situations and places. In this process, the collective action of people makes a system similar to nature in morphological characteristic in which “there is endless variety; and yet at the same time there is endless sameness” (Alexander, 1979, pp. 145). In other words, the situation is different and unique because of the interaction of the difference of the contexts with the sameness of the patterns (Alexander, 1979). Given this, there is a need to move beyond the individual actions and consider the consequences of recurring ideas and how they make a system in the sense that Alexander (2011, pp. 59) proposes: “the word ‘system’ refers to a particular holistic view of a single thing”. A system view is concerned with the holistic property as a production of interaction among parts (Johnson, 2002; Salingaros, 2004; Alexander, 2011; Batty, 2013; Capra and Luisi, 2014). While there has been little discussion about the impacts of network relationships on this process, this paper, through a discussion of DIY Rainbow, proposes a model of how social media generates a common language of spatial interventions.

To establish the relationship between online social networks and citizen-based spatial interventions from a system perspective, a conceptual framework is proposed in the following section. This aims to model the interaction of networked social media and design. It is then used to analyse the case of DIY
Rainbow as a collective behaviour in a design context which spread globally through social networks and its physical manifestation got replicated in different real-world settings.

2. Collective design process through social media: a conceptual framework

The interactive landscape of new media allows large groups of people who share a common interest in spatial interventions to come together and form a crowd using mobile applications such as Twitter and connecting through a certain hashtag. The actions of such a coordinated crowd generate a coherent whole or a system. In other words, new media, facilitating and promoting collective behaviour, generates a coherent system of urban interventions with a common language of design. To elaborate the earlier discussion of collective interventions facilitated by networked media, three stages are explained. The process of dissemination, replication, and evolution of design ideas will be supported by a discussion of the case of DIY Rainbow in the following section.

Simple interventions in physical environment have the potential to instigate a collective action as they spread through social networks and get replicated in different geographical locations. This emerging process has introduced the globalization of “local bottom-up culture, events and ideas spread virally across the world and become branded products” (Beekmans, 2013). This process of spread and replication has been facilitated by new media as a platform to exchange information, ideas, and experiences. In fact, it is not only media content such as text, image and video which goes viral online, but urban interventions occurring in different real-world settings spread globally. Hence, it can be studied as a meme which is a cultural replicator or a unit of cultural transmission (Dawkins, 2006). In social media, this process of dissemination takes place through the use of hashtags to annotate ideas and discussions as internet memes (Kotsakos et al. 2014).

Replication of ideas and recurrence of activities in different real-world settings generate a system that grows from the bottom up. Although the physical manifestation of an idea is concerned with a specific locality, as internet meme, it is part of a global community through digital platforms consolidating individual actions of people around a shared topic of interest, urban interventions in this case. Such crowd-powered systems include many interconnected individuals. Furthermore, engagement of a large population replicating an idea in different contexts expands the space of design possibilities dramatically. This specifically makes sense when we consider the huge storing capacity of social media as a digital environment enabling the growth of ideas and access to relevant information. This enlarges the design space which is “the possible configurations that might be considered as solutions to a design problem” (Woodbury, 1993, pp. 216). Moreover, exposure to a diverse set of users and information results in generating new ideas and creative insights (Perry-Smith and Shalley, 2003).

The ongoing flows of ideas in a crowd of interacting individuals and the replication of ideas lead to the gradual transformation and adaptation to the local and physical conditions. This process of learning and evolving shapes a pattern of spatial interventions. This is alongside the ideas of Alexander (1979) on pattern language. He draws our attention to the patterns of events which are “merely anchored in space” (Alexander, 1979, pp. 92) and can be transmitted. Recently, this transmission of a pattern such as an innovative use of urban places takes place through virtual communities. Although this process is not new, it has been accelerated through the widespread use of social media. By following a common pattern language, groups of people conceive the physical environment almost as if they had a single mind (Alexander, 1979). This promises emerging human-inspired processes that create living structures
capable of forming a coherent and harmonious whole as Alexander (2002) explains but in the new context of digital communication.

3. Research method

To support the conceptual framework discussed above, the first step is to identify examples of recursive urban interventions spreading through social media. This usually includes a small-scale and short-term physical change reflecting a DIY culture. Moreover, there should be the engagement of highly interconnected individuals interacting with and learning from each other. ‘Parklet’ as an innovative way of transforming parking spaces into green and public spaces (Davidson, 2013), ‘yarn bombing’, referring to wrapping trees and urban furniture with colourful yarn (Wallace, 2012), and DIY Rainbow all represent interesting case studies to understand how a simple urban intervention as a shared topic of interest on social media turns into an internet meme, spreads globally and gets implemented locally. While each case represents different degrees of participation and different functionality, they all refer to recursive urban interventions which have been not only promoted but also aggregated and coordinated by social media. However, the process of spread and replication of idea in the case of DIY Rainbow took place in a few days following the day on which the first DIY rainbow crossing was created. This allows us to study the intensified process entirely. In addition, in the case of DIY Rainbow, Facebook functioned as the main platform to promote the movement as the physical manifestations were instantaneously reflected on the Facebook page. This has made it easier to capture the process by studying one specific type of social media rather than exploring all social media platforms to collect the required data.

To investigate the collective quality of urban interventions, primarily the whole process of the socio-spatial movement of DIY Rainbow in response to the removal of a temporary rainbow crossing on Oxford Street in Sydney is discussed. To indicate the dissemination and replication of ideas on Facebook, the frequency of creating a DIY rainbow crossing is analysed. Moreover, the argument of formation of a pattern through replication is supported by exploring the variations of rainbow crossings generated by people in different places. Finally through a discussion, the whole process of DIY Rainbow is located in the conceptual framework of how a coherent system is self-organized through social networks. This provides us with a big picture of how a digital swarm concerned with one shared interest which is a physical change in this case forms a system of small-scale interventions and moves forward a bottom-up urban process.

4. DIY Rainbow

DIY Rainbow Crossing, a community action creating rainbow pedestrian crossings in chalk, represents an interesting case study to support the suggested model which explains how a pattern language of design is shaped through social media as it brings the individual actions of people together in a bottom-up process. To indicate the importance of social media in the emergence and spread of this community movement, it is worth mentioning that DIY Rainbow was one of the 10 stories of Facebook in 2014 to celebrate a decade of activity since it was launched in 2004 (Facebook ten stories, 2014).

This social movement in the form of a temporary intervention in physical settings emerged in response to the removal of the temporary installation of a rainbow crossing on Oxford Street, Sydney as part of the annual event of Mardi Gras 2013 (Cugnetto, 2013). The initial idea for the protest was encouraging people to create their own rainbow crossing using chalk and share it on a Facebook page named ‘DIY Rainbow’. After only three days, the number of rainbows chalked by people on different streets and shared on Facebook page reached nearly 200 (Figure 1). This unpredictable engagement of
people in a spatial intervention in public spaces is interestingly reflected in the statement of James Brechney who started the movement by creating the first DIY rainbow in a laneway in Surry Hills, Sydney:

“We started taking photos of our ad hoc crossing and the images quickly spread on Facebook. Our quiet night of what I like to call “whimsical activism” really resonated with heaps of people who were also disappointed with the rainbow crossing removal. As the night progressed, there was a lot of chatter from people saying they’d love to make their own rainbow. At this point I wasn’t really convinced this would happen. It’s one thing to get people to like a photo, it’s another to get them outside making something” (Brechney, 2014).

Figure 1: An integrated image of the city, 59 photos of distinct chalked rainbow shared on the 13th April (source: Facebook).

Pop-up chalk rainbows in the request for a permanent rainbow eventually led to not only a permanent rainbow installation in Summer Hill, Sydney but also the exemption of rainbow chalk crossings from new graffiti laws in May 2014 (Busby, 2014). This community action provides a good example of how an informal intervention might go viral on social networks, Facebook in this case, and result in changing a planning policy as illustrated in a timeline in Figure 2.

Figure 2: Timeline of Rainbow Crossing Movement.
A temporal frequency analysis of DIY Rainbow, shown in Figure 3, illustrates the birth, growth, peak, and decline of the movement. Data is obtained from Facebook Page to visualise the rhythm of creating rainbow and posting photos of chalked rainbow. The vertical axis shows the number of distinct rainbow crossings according to photos shared on Facebook almost on the same day of creation in the physical place. On 12th of April, the first day of creating the facebook page of DIY Rainbow and one day after the first chalked rainbow, there have been 15 rainbow crossings. The graph shows a sharp growth in the number of DIY Rainbows at the beginning of the movement which represents how it changed to an Internet meme and went viral. However, the rate of making a rainbow crossing and sharing declined gradually in a non-steady fashion with some random peaks. Despite the temporary nature of intervention, there has been no certain end for DIY Rainbow as people in different locations and different times still get inspired through social networks to make their own rainbow.

![Graph showing temporal frequency analysis of DIY rainbows shared on the Facebook page.](image)

Figure 3: Temporal frequency analysis of DIY rainbows shared on the Facebook page.

While DIY Rainbow is significant in terms of understanding temporary nature of spatial interventions and the lasting impact of them, this paper specifically explores the collective nature of DIY Rainbow to address the interaction of media and design patterns. In fact, DIY Rainbow took place along with the growth of collective behavior of users in social media as we have been witnessing in recent years called as ‘media activism’ (Meikle, 2002) which has given rise to social movements such as ‘Occupy Wall Street’ and ‘Arab Spring’. However, in terms of a physical change in place, rainbow crossing movement represents an interesting example to investigate how people express their individualities while being part of a whole and make a system in the sense that discussed earlier, and what the contribution of social media is to fulfilling this process.

5. Discussion

DIY Rainbow exemplifies the emergence and growth of a community of numerous and diverse individuals in which online social networks are central in facilitating and promoting their interaction. In
the process of shaping a design system, as schematically illustrated in Figure 4, the first chalked rainbow crossing, as an initial idea of a physical intervention, was reflected in social media. It drove a change in the existing social networks, Facebook particularly, as the idea spread and captured the attention of people which led to the formation of sub-networks of people who shared that interest. Regardless of intention and motivation of people who participated in this movement, as the pattern of intervention, chalking rainbow in this case, spread in existing network, other physical changes took place inspired by the first action. This replication shaped a *pattern language* of temporary interventions under a certain name: DIY Rainbow. Tagging media content to the un-spaced phrase of ‘DIYRainbow’ united different actions of people around the world in media space and built a worldwide community supporting rainbow crossings.

![Diagram of Pattern Language](image)

**Figure 4:** Modelling the process of a pattern formation through social networks.

DIY Rainbow supports the idea that only simple patterns have the capacity of transmission in large populations. “Nothing which is not simple and direct can survive the slow transmission from person to person.” (Alexander, 1979, pp. 230) This could be identified in different rainbows chalked by people following the simple rule of drawing by chalk. However, every single rainbow had its own characteristics and the diversity of rainbows chalked on streets, stairs, front door space and bridges demonstrates the adaptability of design pattern to different places which enhanced the image and identity of places in different ways. It is not the first idea which got replicated identically, but as people *localised* and *personalised* the intervention, it transformed. In addition to adaptation of idea to local conditions and contexts, the *interaction* of ideas through network structure led to the transformation of the first action. In fact, the interactive environment of social media platforms allows people to learn from each other through the exchange of information and ideas.

By this case, we attempted to highlight the impact of online social networks on the *process* of transforming a temporary intervention from local to global and from individual to collective in which a dynamic system of design with a media-oriented growth is generated. It should be noted here that the primary goal of this paper, rather than an in-depth analysis of social participation through new media was to develop a conceptual framework through a discussion of DIY Rainbow to model emerging social design processes. As DIY Rainbow was a special case, considering the social motivation of participants and the community involved, there is a need to identify and study other examples of recursive spatial interventions such as ‘parklet’ and ‘yarn bombing’ as mentioned before. Future research might examine
the applicability of the model discussed here and expand it to other contexts to understand bottom up urban processes in relation to social media. On the other hand, as this study only included data available through Facebook, future studies could extend it by including other qualitative and quantitative methods of collecting data on DIY Rainbow such as interview with participants, in addition to an exploration of other social media platforms such as Twitter. Finally, a content analysis of images, nearly 1000 distinct rainbow crossings shared on the Facebook page in two months, and comments associated with them is needed to explore and categorise them. This will contribute to understanding the evolution of a pattern propagating through social networks.

6. Conclusion

This paper developed a model to describe a collective process in which a pattern language of spatial interventions takes shape in the context of online social networks. Primarily, it has been argued that the widespread use of social media in which interactivity is embedded has promoted citizen participation. A mass participation of interconnected individuals through social networks leads to a collective process in which the recurrence of a spatial intervention in virtual communities and its physical manifestation across different geographical locations create a coherent whole that exhibits characteristics of systems. This has been supported by the case of DIY Rainbow to argue how media not only facilitates the spread of ideas but also aggregates them from multiple sources and creates an accessible design database. This forms a coherent pattern which can be transmitted globally through social networks.

Addressing new practices of design and intervention governed by large groups of people, this study attempted to argue the shift in defining the role of architects and planners rather than “the authors of a finished work ... as facilitators whose job is to help people act more intelligently, in a more design-minded way” (Thackara, 2005, pp. 214) and capitalising on patterns as “a powerful tool for controlling complex processes” (Salingaros, 2000) within a hybrid context of design including digital and physical layers of interactions. While this paper provided some insights into the relationship of social media and design patterns, future research is needed to gain a deeper understanding of the dynamics of social networks in creating a crowd-powered system of design ideas around spatial interventions.

References

Stairway to health: an analysis for workplace stairs design and use

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Abstract: This paper reflects on a recent workplace design and physical activity study to argue for a radical rethinking of staircase design in office buildings. This paper deploys design analysis of three campus buildings alongside objective physical activity data and survey responses of study participants in these buildings (n=111) to identify limitations to past and current staircase design approaches. Working within a social ecological framework, this paper builds on observations of higher education office-based worker’s physical activity, attitudes to movement at work, and building design. The different approaches to staircase design from each of the three buildings from three different decades (1970s, 1980s, 1990s) within the study demonstrate shifts in architectural attitude to circulation design. Two key findings emerge. Firstly, that current health-focused design guides or staircase design audits do not go far enough in identifying the social-ecological environment which supports stair use. Secondly, that a radical rethinking during the design process of staircase design in office buildings may be needed to support at-work physical activity. This paper is significant in centring architectural design practice as a way of understanding physical activity behaviours within workplaces and finding ways of extending contemporary responses to population health dilemmas.

Keywords: Stairs; design; analysis; movement.

1. Introduction

Australia’s guidelines on physical activity, Australia’s Physical Activity and Sedentary Behaviour Guidelines (Aust. Dep. Health, 2014), have recently been updated to build on recommendations by the World Health Organisation. The new guidelines suggest that we ‘accumulate’ 2 ½ to 5 hours of moderate intensity physical activity each week and that this activity can be achieved in 10 to 20 minute
bouts during the workday. With the contemporary trend towards increased work hours, the idea of accumulating physical activity as part of a normalised workday activity is becoming increasingly important. Current research recognises that sitting for more than three to four hours per day is associated with an increase of health risks associated with sedentary behaviour (van der Ploeg et al., 2012; Chau et al., 2013). While these risks are reduced if a person is regularly engaging in moderate-to-vigorous physical activity (Chau et al., 2013), the risk accumulated by extended sitting is not fully overcome. Breaking up extended bouts of sitting with short spells of physical activity, even light activity such as slow walking or standing, has been shown to reduce the risk associated with sedentary behaviour (Dunstan et al., 2012).

The contemporary office is a site of extended sedentary behaviour. In Australian offices people working in administrative jobs are the most likely to spend over 80% of their time at work sitting (ABS 2011). In particular, workplace staircases have been identified as an opportunity to gain moderate-to-vigorous intensity physical activity within the workday and have been targeted in health promotion schemes such as Australia’s “Take the stairs instead” poster, part of the 2008-2010 “Find thirty every day” campaign. However, often the workplace promotion of stair-use fails to deal with the reality of staircase design within the building type where, often, its primary function is purely as a fire escape. Additionally, the idealised picture of active stairs in the health promotion posters is in stark contrast to the poor quality of workplace fire-exit stairs along with the off-putting requirements for safety signage used in reality (McGann et al., 2013).

In architecture practice, there are moves to explore the significance of staircase design in encouraging movement and the improvement of occupant health and wellbeing (for example, NAB workplace, Melbourne 2013), in supporting staff interaction and active movement (for example, Macquarie Group workplace, Sydney 2011), and in inter-floor connectivity and workplace activation (for example The GPT Group workplace, Sydney 2011). In the context of growing interest in active workplace design, this paper contributes to an growing body of research considering stair use in terms of stair location, accessibility and aesthetics (Bassett et al., 2013), with a particular focus on stair convenience and legibility (Nicol 2007; Jancey et al., forthcoming), stair convenience in relation to elevator availability (Olander and Eves 2011; Nicol and Zimring 2009) and the interventions around point of decision motivational signs (Bellicha et al., 2015; Dolan et al., 2006; Eves et al., 2012; Grimstvedt et al., 2010; Iversen et al., 2007; Ker et al., 2001; Lee et al., 2012; Ruff et al., 2014).

In this study, interpreting recordings of moderate-to-vigorous intensity physical activities looked to the quality of the workplace staircases, and how embedded these staircases were in the movement patterns of the staff. This research assesses the impact of difference in office design on the physical activity and sedentary behaviour of a cohort of office workers across three campus buildings at the same university. The three buildings studied were designed and built in three distinct time periods and reflect differing approaches to workplace design that is highlighted through the different emphasis put on the stairs within the design.

The purpose of the study is to:

• Compare physical activity behaviour (sitting, standing, walking, step counts) in different buildings of different design era’s with different design approaches to circulatory patterns.
• Determine employees’ perceptions of their workplace environment and their related mental and physical health.
Contribute to the body of knowledge on the identification of design elements that contribute to physical activity behaviour in workplace design.

2. The Study Buildings

While there is new debate on the design of healthy, productive, collaborative and space-saving workplace design, the vast majority of organisations do not have the opportunity to relocate to custom-designed premises. This research reflects the reality of such organisations occupying workplaces designed to an evolving set of design trends, philosophies, principles and regulations. In this study we engage with three existing, currently occupied and modified buildings across a range of ages and design approaches. In line with the dominant approach within the field, this paper takes a socio-ecological approach (see Zimring et al., 2005), to outline potential connections between the quality and design of building organisation and level of physical activity and sedentary behaviour.

2.1. Comparative Building Analysis

2.1.1. Building 1

Building 1 (Figure 1; top plan) contains approximately 81 academics and 19 administrative staff. The building was built during one of the most recent construction phases of the university, 1995-2005, and is in the north end of the campus. Building 1 is a four-story brick and concrete building built on a north-south axis, with its longest edges facing east and west. The building is organised with a double loaded spinal corridor that narrows at link sections with external views at three key points along its length. The building has three large fire stairs which connect all floors, each with external windows. These staircases are open and brightly lit. There is one lift adjacent to the central fire stairs. In addition, at the ground floor entry there is a grand curved open staircase that connects the foyer to the boardrooms on the next level only. Toilets are located in the middle of the building, on the eastern side. Nearly all rooms have external windows. Print stations are located centrally on the floors. The average floor area per level of the building is 1797m$^2$. The average width of the building is 14.3m. The length of the main corridor overall is 59m.

2.1.2. Building 2

Building 2 (Figure 1; middle plan) contains approximately 56 academics and 57 administrative staff. The building was built during one of the middle construction phases of the university, 1986-1985, and is located in the centre of the campus. Building 2 is a four-story brick and concrete building with two ‘wings’ of offices clustered around internal corridors. Between these two wings is an external fire stairs on the south side of the building which is used as the main vertical circulation route for the building and connects all four floors. In the east wing there are two additional internal staircases, one of which connects only the main entry level (second floor) to the next floor (third floor). The lift that runs between all floors is next to this entry staircase. A second fire stairs connects only the third and fourth floors to the outside of the second floor, and it is only possible to enter this staircase from the third and fourth floor. The majority of rooms in building 2 have external windows, although there are some large shared offices on the second and third floor that do not. Toilets are located in the eastern wing of the building on each level. The average floor area per floor of the building is 870m$^2$. The average width of the building is 20m. The length of the main corridor overall is 24m.
Building 3 (Figure 1: bottom plan) contains approximately 50 academic staff and 30 administrative staff. The building was built during one of the oldest construction phases of the university, 1966-1975, and is located in the south of the campus. Building 3 is a four story building constructed from off-form concrete. It is long and slim with the longer sides facing north and south. A narrow corridor runs through the building lengthways, and rooms are accessed from both sides of this corridor. Three internal concrete fire stairs and one external lift provide the vertical circulation. The three staircases are located on the north side of the building equidistant along its length. The lift is positioned adjacent to the main entry on the north side. Toilets are located at the centre of each floor. The average floor area per floor of the building is 1160m². The average width of the building is 12m. The length of the main corridor overall is 62m. The office fit-out is dated, and was scheduled for a new internal fit-out just prior to the time of the measurement. Most academic staff occupy individual offices, while the majority of
administrative staff are in open plan settings. Each floor has several narrow print rooms. On the second floor there is one larger staff kitchen with a large balcony overlooking a basketball court.

3. Methodology

3.1. Participants
A total of 111 university staff from three campus buildings were recruited at three time periods between October 2013 and April 2014. The times were selected for similarity in outside weather conditions and in work duties (such as semester weeks). Participants were required to be aged 18 years and older, working at least three days per week in an office-based role at the university campus and with the majority of that time spent in their allocated office building. A participant profile is provided in table 1. An invitation to participate was sent via internal email to all staff in the three selected buildings. All individuals participating in the study were coded to allow for individual and group comparison. More than three quarters of participants were female (76.6%), and the mean age was 45. Table 1 shows the demographics, employment status, and employment type by building.

<table>
<thead>
<tr>
<th>Table 1: Participant demographics.</th>
<th>Building 1 (n= 36)</th>
<th>Building 2 (n= 33)</th>
<th>Building 3 (n=30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean age</td>
<td>43</td>
<td>44</td>
<td>50</td>
</tr>
<tr>
<td>% female</td>
<td>77.8</td>
<td>78.8</td>
<td>75.9</td>
</tr>
<tr>
<td>% born in Australia</td>
<td>66.7</td>
<td>54.5</td>
<td>58.6</td>
</tr>
<tr>
<td>% university educated</td>
<td>86.1</td>
<td>90.9</td>
<td>65.6</td>
</tr>
<tr>
<td>Employment status</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>% full time</td>
<td>75.0</td>
<td>81.8</td>
<td>65.5</td>
</tr>
<tr>
<td>% part time</td>
<td>25.0</td>
<td>18.2</td>
<td>34.5</td>
</tr>
<tr>
<td>Employment type</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Professional</td>
<td>11.1</td>
<td>45.5</td>
<td>20.7</td>
</tr>
<tr>
<td>Admin support</td>
<td>38.9</td>
<td>27.3</td>
<td>41.4</td>
</tr>
<tr>
<td>Technical/other</td>
<td>5.6</td>
<td>6.1</td>
<td>3.4</td>
</tr>
<tr>
<td>Academic</td>
<td>44.4</td>
<td>21.1</td>
<td>34.5</td>
</tr>
</tbody>
</table>

3.2. Architectural Methods
Diagrammatic analysis of building plans were used to identify the current structural, interior component and organisational layouts of the interior. In addition, a new hybrid approach was used where participant data from the accelerometer was mapped onto the building plans. A photo survey was conducted of each of the buildings involved in the study. Circulation paths, view lines and spatial quality were a particular focus of the photographic recording.
3.3. Measuring instruments.

Both self-report (questionnaire) and objective (accelerometers) measures were used to determined sitting, standing and walking behaviours (Jancey et al., 2014). Self-reported mental and physical health and environment quality and demographic data was also collected. The questionnaire used was a combination of validated instruments; the Occupational Sitting & Physical Activity Questionnaire (OSPAQ) (Chau, Van der Ploeg, Dunn, Kurko, & Bauman, 2012) the SF-8 Health Survey (QualityMetric Incorporated, 2013) and the Indoor Environment Quality (IEQ) Survey (Zagreus, Huizenga, Arens, & Lehrer, 2004). Participants required approximately 10 minutes to complete the survey.

The ActiGraph GT3X+ accelerometer was used to objectively measure time spent in sedentary, light, moderate and vigorous activity. Accelerometers are a type of motion sensor used to quantify activity intensity and distinguish between low, moderate, and vigorous physical activity levels, and sedentary behaviour which can indicate sitting, standing, walking and stair climbing. Participants wore the accelerometers on their right hip during office hours for three to five consecutive workdays. Data was collected at one-minute intervals over the course of workday (Jancey et al., 2014).

3.4. Statistical analysis.

Descriptive statistics were used to summarise participants’ demographic, health characteristics, and the outcome variables (sedentary behaviour, physical activity intensity, step counts). Comparisons were made by building, floor, gender, and age. All data was analysed using SPSS version 22.0.

4. Findings

This paper aims to draw connections between aspects of workplace and building design, and movement in the workplace. Figure 2 highlights measured sedentary, light, moderate and vigorous activity. In a workplace setting moderate activity is generally associated with stair use.

![Figure 2: Accelerometer measured physical activity in three buildings by percentage of time in the workplace.](image)

On average the participants across the three campus buildings:

- spent less than 22 min per day in moderate to vigorous physical activity,
- spent less than 60 min per day in light physical activity,
- sat for more than 80% of their workday,
- sat for maximum bouts over 40 min in duration.
Recordings within the accelerometer and survey data compared to the building analysis suggests the four key findings as follows:

- **F1.** The physical activity and sedentary behaviour patterns of participants matches profiles of other Australian studies and compares poorly to the recommended physical activity and sedentary guidelines for health.
- **F2.** Territorial and unwelcoming corridors and stairs may contribute to workplace sedentary behaviour.
- **F3.** Well-designed and good quality circulation spaces (corridors and stairs) such as in building 1 may support moderate intensity physical activity.
- **F4.** Participant values (such as health-aware users in building 1) and building design influence the way people choose to move through a building.

### 4.1. Spatial Typology and Floor Plate Size

Building 2 offers a significant contrast in building organisation and floor plate dimension in comparison to buildings 3 and 1. Building 2 is clustered tightly into itself, with branched corridors leading from the main corridor which runs between the two sides of the building. This affects the path distance from the ends of the corridors to the middle. As, in all three buildings the toilets are located roughly in the centre, the maximum length of corridor end to centre correlates from workstation to toilet area. Building 1 has the longest main corridor length, and the higher end of distances to destinations such as print stations and kitchen/tea prep. While building 3 has the furthest typical distance to toilet areas from workstations.

### 4.2. Quality of Staircase

Building 1 has attractive, well lit and comfortable staircases (figure 3). Buildings 2 and 3 in contrast have stairs which are more problematic to use. All three staircases in building 1 have an excellent spatial quality and attractiveness. These are brightly lit by large windows and have views to the outside. The staircases are spacious and open feeling. Attractive fixtures and finishes have been used. The staircases are clean and well maintained. However, the doors from the central corridor which lead to the staircases are not immediately apparent. They are painted in the same colour as the hallway, and are not aggressively signed. The lift is far easier to locate as a new-comer to the building.

![Figure 3: Most used fire stairs in building 1.](image-url)
Building 2 has one main staircase; external to the building; and two secondary internal staircases (figure 4). One of these joins level two to level three. The second stair joins levels three and four to the outside of level two. This last staircase is somewhat hidden down one of many corridors rather than located on a major thoroughfare: as a result it is not much used. The main, external, staircase has some aesthetic quality, being open to views, fresh air (although also rain, cold or heat depending on the season). The stair treads are of a comfortable size. The two internal stairs are narrow and dark with no natural light or attractive quality. All three stairs are in reasonable condition and cleanliness.

![Figure 4: Staircases building 2: the main external stair (left) two internal stairs (centre and right).](image)

Building 3 staircases are accessed from narrow corridors which branch from the main corridors of the building (figure 5). The door to the staircase is painted the same emergency red as the door to the fire equipment cabinet. Inside the staircase is lit artificially as there are no windows. The aesthetic is in keeping with the ‘brutalist’ architectural style—which with its simple and raw materials and form (in combination in this case with a lack of windows) is unlikely to appeal to a lay audience. The inside of staircase doors have signs which explain what to do if you become locked in, suggesting that this has happened with some frequency.

![Figure 5: Typical concrete staircases building 3.](image)

5. **Discussion**

Participants in building 1 recorded the highest mean level of moderate physical activity, and the highest mean step count per day. Moderate physical activity is consistent with the exertion of walking quickly or going up and down stairs. Of the three buildings in this study building 1 has by far the best quality staircases and corridors; it also houses workers likely to have the most working knowledge of the risks of
sedentary behaviours. It seems likely that there is a link between the quality of these circulation spaces and the higher levels of moderate physical activity recorded for building 1 participants. One criticism of the staircases in building 1 was highlighted in a survey response. In building 1 not all staircases connect to level one—it is only possible to access level one from the central stair (adjacent to the lift).

In contrast the stairs in buildings 2 and 3 present several barriers to use and this may correlate with the lower total mean step count per day and lower recorded percentage of participant time in the workplace spent in moderate intensity physical activity. The two internal stairs in building 2 are limited in the number of floors they reach, they have no access to natural light or outlook and have few aesthetic qualities to recommend them. The external staircase also presents a deterrent to some, in particular a survey response by a participant in building 2 highlights the safety issues with building 2's main staircase, which is fully external and becomes wet when it rains. The brutalist architectural design style of building 3, of which the staircases are a particularly clear example, is not considered attractive by the study participants who described it as "pretty ugly". In particular the "grey concrete is not pleasant." In another survey response, a participant identifies that the poor lighting in the three identical stairwells in building 3 is a safety concern. In addition the doors to the stairwells are painted 'emergency red.' This forms a visual deterrent to opening these doors, especially to anyone who has ever accidentally set off a building fire alarm.

Nicoll (2006) identifies five factors of stair use: convenience, legibility, appeal, comfort and safety. All staircases in building 1 perform well against these categories, with the possible exception of legibility. Participants were asked to nominate the top five factors that affected their decisions regarding paths choices within the office building. For participants from all buildings, choosing the ‘fastest route’ was an important factor, as was the ‘preference to use the stairs,’ and a desire ‘not to wait for the lift.’ Participant response aligns with Nicoll’s (2007) identification of convenience and legibility being the key factors in workplace stair use.

6. Conclusion

This study opens avenues for future research and practice. Further exploration into movement behaviours of workers viewed through a lens combining both health and design perspectives is needed. Such a move would inform recommendations, for both office and building design and health promotion strategies, that support increased levels of physical activity within workplaces. In particular, multiple offices of different sizes and in different industries should be analysed in order to gain a better understanding of the impact of workplace design on staff physical activity. However, this initial study does provide an opportunity for reimagining workplaces as sites for increasing levels of physical activity as part of supporting healthy lifestyles.

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References


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Building and City Information Modelling
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BIM for procurement - procuring for BIM

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Abstract: Contractual frameworks currently applied in Australia predate the use of life-cycle Building Information Modelling (BIM) for the delivery of construction projects. To date, little has been done to align the various contractual procurement methods in Australia with the novel opportunities offered via BIM. It is the objective of this paper to position BIM under various contract procurement methods and to hint at the possibilities for adjustment of these procurement methods in the light of collaborative work-practices. The author does not claim to have extensive expertise in construction law and this paper does therefore not directly outline new forms of contractual arrangements. Instead, the author brings into perspective the opportunities and challenges of BIM under the contract procurement methods one by one.

Keywords: BIM; procurement; contract; collaboration.

1. Introduction

The adoption of Building Information Modelling (BIM) in parallel with the introduction of policies and national standards that govern its use progresses steadily in an ever growing number of developed countries (McGraw Hill, 2014). As much as BIM adoption is often market driven, regulatory frameworks and in particular contract procurement methods have a major impact on the success of BIM-use on medium-to-large construction projects. Contractual frameworks applied to govern design, construction and commissioning of projects typically predate the use of life-cycle BIM for the delivery of projects (Kuiper and Holzer, 2013). These frameworks may at times rather obstruct than support BIM use. Stakeholders from both project delivery as well as construction law (McAdam 2010, Chew 2010) have started to review the contract methods in the light of BIM. This paper adds to these efforts by scrutinising BIM-use under various contract procurement methods based on the common lines of reporting applied under these contracts. In particular the structure and sequence of reporting and sharing design and construction data will be analysed in the light of opportunities and challenges inherent to different BIM workflows.

The method applied for the research presented in this paper is as follows: After a brief problem definition, the author draws from literature to examine current international and Australian policies and
guidelines that relate to the adoption and procurement of BIM. Literature both relating to legal aspects of project procurement as well as practical aspects of project delivery has been reviewed in the light of BIM. The aim was to understand its impacts on the way stakeholders (can) engage under various Australian contract types. The author then compares the affordances of BIM to support collaboration among project stakeholders under these construction contracts. This overview is complemented by a reflection about the opportunities and constraints associated to BIM under these contract procurement methods. The author further discusses how considerations about contract procurement methods can be woven into BIM execution planning (as currently applied in practice). The paper will thereby consider the particular information requirements of each of the key parties who partake in the design, engineering, construction and operation of built assets along the way.

2. The BIM dilemma

As much as the focus of BIM development in its early days was put on technological advance, the legal and procurement aspect soon followed as an area of interest. By the mid-2000s, BIM proponents observed that the potential of information sharing and data interoperability offered via new technology can get constraint in practice by contractual frameworks or other legal considerations. Some key topics are listed here: Holzer (2007) describes how the use of BIM affects the distribution of roles and responsibilities of individual stakeholders and he hints at possible implications for planners who need to work towards specific BIM requirements by authorities. The US Associated General Contractors of America released a ConsensusDOCS 301 BIM Addendum (2008) for construction contracts with standardised BIM terminology for stakeholder and model type definition. Klimt (2011) highlights the need to resolve copyright and liability issues related to BIM models and Olatunji & Sher (2010) discuss model ownership and sharing of model data. Chew (2010) points out the limitations of BIM-use due to stakeholder focus on their individual part of the project with little consideration about process as a whole. In order to identify legal problems posed by the adoption of BIM, McAdam (2010) scrutinises UK contract procurement solutions. Further, Professional Indemnity Insurance in the context using BIM gets addressed by the UK Construction Industry Council CIC (2013). The above summary is a mere snapshot of a range of publications and industry papers on the legal aspect of BIM.

Considering a number of the topics listed here, the American AIA (California Council) published a document in 2007 where they promote a ‘radical’ new contract procurement method with the goal to maximise the potential BIM technology can offer with a more fitting legal framework: Integrated Project Delivery (IPD). IPD is based on the Australian ‘Alliancing’ contract model, complemented by an information management strategy that supports BIM collaboration. The AIA defines IPD as follows (2007):

Integrated Project Delivery (IPD) is a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction.

Whereas Integrated Project Delivery (IPD) was initially hailed as the ideal procurement method to allow teams to achieve ‘full BIM collaboration’ the industry is now viewing the idea of ‘full BIM’ more cautiously (Cleves & Dal Gallo, 2012). IPD as a delivery method is developing (mainly in the US); it is still the closest fit (contractually speaking) one could aspire to a contract method in the context of BIM. At the same time IPD in its pure form may well be too idealistic for common adoption throughout
construction projects globally. IPD currently gets applied under Integrated Forms of Agreement (IFOA) on a number of infrastructure projects, or by selected clients who have learned to fine-tune its use in order to manage the supply chain associated to procuring their projects (Alarcon et. al., 2011). It will require markets to mature in terms of BIM knowledge, and stakeholders to become more comfortable with novel ways of procurement. Sive and Hays (2009) assess that more and more projects are procured with reference to some elements of IPD, thereby applying impure IPD or ‘IPD lite’ as a closer fit between aspiration and current market dynamics.

With early excitement about IPD fading, researchers and practitioners alike increasingly turn to alternative contract types to be considered in the light of BIM. For each of those, BIM can play an important role in fostering collaboration and information transfer across participating parties.

3. BIM and procurement – the broader context

BIM in its ideal state affects the entire project life-cycle from procurement, feasibility studies through to design, engineering, construction, operation, and demolition. The importance procurement plays as part of this cycle has long been underrated. Even further, it is not only the effects of procurement on BIM one should consider, but ultimately also the opportunities BIM offers in revolutionising the way projects are procured in the first place. The below diagram (Figure 1) picks up on some typical processes associated to BIM that can be applied across different contract procurement methods. They include the use of BIM as template for generating tender documents, tight integration from Design BIM by consultants with Construction BIM by contractors and subcontracting parties, early involvement of contractors, lifecycle BIM (moving from BIM to Facilities Management - FM), and risk sharing of collaborating parties. The saturation of the dot suggests the potential to facilitate these processes under common varying contract types. The author accepts that variations to these occur depending on project-specific clauses in the contract.

![Figure 1: Matrix of delivery method and BIM characteristic.](image)

4. The impact of government policy and mandates

It appears that one key obstacle to the propagation of BIM is a lack of client demand (Goh et.al. 2014). Historically, there is truth to that. At the same time, one cannot ignore the ever growing list of
governments, or government departments that start to ask for BIM for publically commissioned work in one way or another. These requirements/mandates range from specific and well-defined (e.g. spatial programme validation) BIM requirements such as those brought forward in 2006 by the US General Services Administration (GSA), to the provision of major financial incentives, such as those by the Building & Construction Authority (BCA) in Singapore from 2010. Next to mandates in some Scandinavian countries, the most prominent example appears to be the UK with their step by step approach to achieving Level 2 BIM on Government projects by 2016. What sets the UK approach apart from others is its well-considered integration of policy across a number of industry and government stakeholders. In support of these developments, several industry frameworks are being established by the UK BIM taskforce (who produced the PAS 1192:2 and PAS 1192:3 frameworks in conjunction with the UK British Standards Institution BSI) that specifically address information requirements by various stakeholders across the building life-cycle. It is this life-cycle thinking and the inclusion of information-requirements by clients which may prove the key to success in the future (no matter if the 2016 deadline is ultimately achievable or not). The signals stemming from the UK have such an impact on a political level, that the European Union Parliament recently pushed through reforms for the EU Public Procurement Directive that include recommendations for the uptake of BIM on public works contracts by all its members (CM, 2014).

Next to guidelines and specifications for collaboration, a number of legal documents have been developed overseas. Most notably two strands of documents coming from the US: Firstly, the Consensusdocs 301 BIM addendum, released by the Associated General Contractors of America (AGC) back in 2008. The addendum highlights that there is no need to restructure contractual relationships; instead the BIM Addendum acts as a bolt-on document to a master contract. The key benefit of the document is its clear language and the clarity assigned to establishing BIM definitions that cut out ambiguity and increase clarity in terms of contract language. Secondly, the American Institute of Architects’ (AIA) 2013 suite of documents E203, G201, G202 (ex E202) and C106. These have been developed over time and they cover a range of BIM related policies from execution planning, data protocols, BIM project protocols and data licensing agreements.

At the point of writing this paper, the author’s research has not revealed any government-wide response to BIM by the Commonwealth of Australia. Despite advocacy from the industry group buildingSmart (2012) and their release of a National BIM Initiative document, no government-wide policy on BIM has been issued to date. In 2014, there has been an acknowledgement about the usefulness of BIM in the procurement of publically funded projects as part of a Productivity Commission’s inquiry into public infrastructure. Individual departments in various state governments start to request BIM for the delivery of their projects, but an encompassing guideline is missing.

5. **BIM – focus on contract procurement methods**

Following from the above comparison chart of contract procurement methods, this chapter analyses the characteristics of BIM-use for a number of distinct contract procurements methods as applied in Australia.

5.1. **Construct Only**

Still the most commonly applied form of contract to regulate construction projects in Australia, the ‘Construct Only’ method sees a separation between responsibilities and risk by the consulting and the contracting side. The ‘design-bid-build’ approach inherent to this form of contract procurement aims to
increase competitiveness in the bidding process, but at the same time does not necessarily guarantee the most integrated line of communication and reporting among consultants and contractors. Further, possibilities to interface BIM from the consultants and contractors to the Facility Management are limited, unless clients appoint those early on and push for dialogue across the entire project team. Such dialogue is often difficult due to the fact that project team members tend to get appointed sequentially with little opportunity for engagement when it counts most for life-cycle BIM.

Figure 2: Graphic representation of possible ‘Construct Only’ line of reporting.

Summary of typical opportunities and issues encountered under ‘Construct Only’ procurement:

- There exists a disconnect between Consultants and Contractor BIMs
- Separate BIM Management Plans for Design and Construction
- Consultants need to make assumptions on BIM requirements by Contractors
- Risk: Model handover for precision tendering is not guaranteed
- Consultants may be concerned about their professional indemnity if they hand over models
- Contractors are not likely to receive the information they need from BIM
- BIMs are likely to be set up with little consideration about operational needs.

5.2. Design and Construct (DnC)

The DnC project delivery method increasingly gets applied on medium and large projects where clients aim to reduce risk by having a Head Contractor oversee both the design and construction process. There are some variations of this delivery method, but often design consultants get novated to the contractor beyond the delivery of Level of Development (LOD) 300 BIM. DnC contracts benefit from transparency of information flow as consultants are aware that their BIM models will be handed over to subcontracting parties for high-precision tendering and for other knowledge-transfer purposes. Still, the DnC delivery method does not guarantee smooth transition of BIM from the consultants to the contractor and beyond.
Summary of typical opportunities and issues encountered under ‘DnC’ procurement:

- The DnC approach facilitates increased transparency in setting up & pricing tender packages
- Stakeholders can set up their models up with Construction BIM requirement in mind
- The DnC approach increases the potential for interfacing information between Consultants & Trade-contractors in Construction Documentation
- The risk lies with the Contractor to maximise BIM knowledge transfer
- BIM under DnC contracts Requires skilled Contractors who understands BIM workflows
- Input from client to help define operational requirements is not automatically guaranteed

5.3. Managing Contractor / ECI

Under the ‘Managing contractor/Early Contractor Involvement (ECI) method, there is an increased chance for BIM collaboration to unfold among the various project team members (Rahmani, et. al. 2010). In this two-stage process, clients involve Contractors early on to oversee the costing of early design proposals. In particular where contracting parties are involved at the outset of a project, BIM knowledge-transfer can occur early on, thereby benefitting common goals of BIM delivery. Under the Managing Contractor model, various stakeholders usually work side-by-side to advance solutions in an iterative process. The method also allows clients to voice their requirements and oversee the adherence to BIM lifecycle deliverables early on.
Summary of typical opportunities and issues encountered under ‘Managing Contractor’ procurement:

- The Managing Contractor model facilitates iterative information feedback with contractors
- It has the advantage of involving the Managing Contractor and the Suppliers during LoD 200
- The Managing Contractor, Designers, QS and Trade Contractors work side by side on BIM
- This procurement model helps to facilitate the BIM induction process for Trade-Contractors
- There exist increased opportunities for clients to communicate lifecycle BIM requirements.

5.4. Public Private Partnership (PPP)

PPPs don’t literally represent a delivery method; they refer in principle to the method of financing projects. Predominantly applied on large infrastructure projects, PPPs are principally run similar to DnC contracts with the advantage of a Joint Venture agreement between those providing design and construction services and Facility Management service provision. Tight collaboration is executed with a life-cycle view that encourages those using BIM to orient their efforts towards minimising lifecycle cost and maximising sustainability on the project.

![Figure 5: Graphic representation of possible PPP line of reporting.](image)

Summary of typical opportunities and issues encountered under ‘PPP’ procurement:

- In principle: PPPs are run with separate DnC & Operating Contracts
- Contractors & Consultants engage in a Joint Venture and work towards common BIM goals
- Unified BIM Management Plan, including post-delivery considerations as part of D&C
- There exist opportunities to share risk to achieve common goals

5.5. Alliancing / Integrated Project Delivery (example: Project Alliance)

Considered as a form of relationship contracting, Alliancing or IPD methods show most potential for intelligent sharing of digital project information across all stakeholders due to the non-litigious nature of collaboration. The relationship agreement is likely to be based on a shared project procurement
supported by equal gain & pain sharing among stakeholders. Information management is open and transparent with substantial knowledge-transfer across all stakeholders.

![Diagram of possible Alliancing/IPD line of reporting]

Figure 6: Graphic representation of possible Alliancing/IPD line of reporting.

Summary of typical opportunities and issues encountered under ‘Alliancing/IPD’ procurement:

- Relationship agreement: sharing pain & gain
- Alliancing/IPD contracts entail opportunities to include operational considerations by clients
- BIM collaboration can occur from very early stages
- Knowledge-transfer across entire project team (incl. Trade Contractors)
- A unified BIM Management Plan can be applied across the team from the start
- Data-capture for handover & FM already occurs during design & construction process
- Shared Risk – Activities undertaken within the Alliancing model are likely going to require project insurance (instead of individual stakeholder insurance)

6. Procurement: impact on BIM Execution Planning

Depending on the contract method, the focus in generating a BIM Execution Plan (BEP), also known as BIM Management Plan (BMP), should ideally be multi-layered. It can be about generating two separate plans, one covering BIM coordination for consultants, and one covering BIM coordination for contractors only. This will most likely the case on ‘Construct Only’ type contracts where planning by consultants happens with little consideration of the detailed processes undertaken by contractors (as these are yet unknown). An attempt to align consultants and contractor requirements makes little sense as stakeholders would need to base their modelling effort on assumptions that may be incorrect. On contracts that see the Head Contractor in control of the entire collaborative effort (such as DnC or Managing Contractor delivery), a BEP/BMP should consider BIM coordination all the way through from consultants, to the subcontractors, in particular tacking the issue of transition from Level of Development (LOD) 250-350. Modelling requirements by consultants should be defined precisely in sight of their models’ usefulness for tendering and coordination by subcontractors (but in clear consideration of the limited liability associated to ‘Design BIM’). Such approaches appear to make most sense under a ‘Design and Construct’ and ‘Managing Contractor’ procurement method, as well as a Design & Construct with ‘Early Contractor Involvement’.
Going further a ‘lifecycle’ BEP/BMP would help to address operational needs beyond design, planning and construction. It would be particular useful for facilitating projects with a vested interest for long-terms benefits of BIM by owner/operators. In order to facilitate such a framework for collaboration, one should include the Employer Information Requirements (EIR) for Facilities and Asset Management in the way the BEP/BMP is set up in the first place.

This requires an approach for conceiving BMP/BEP templates that can cater for teams that span entire consultant/sub-contractor/client stakeholder-groups. To achieve integrated information flow between those parties, an Asset Managers and Facility Managers (or even an Information Manager) should be involved in the setup of the BEP/BMP from day one. Despite the fact that key stakeholders are known, their key requirements may not be that certain in the earlier project stages. The latter approach to managing BIM collaboration facilitated via a BEP/BMP framework would most likely be suited for an Alliancing/IPD procurement method.

7. Conclusions

Contract Procurement methods in the construction industry have a major impact on the way BIM can be applied collaboratively throughout different stages of design, construction and operation. BIM becomes a powerful instrument to orchestrate information flow in a standardised fashion if the end goals are well defined and parties can start sharing building data with clear deliverables in mind. Currently applied project delivery methods and contract procurement methods do not always align with best practice BIM. Clients and their legal advisors can nevertheless counter-balance (to a degree) some known BIM roadblocks across any delivery method as long as they are aware of the implications of the line of reporting and the timing of stakeholder engagement. Whereas IPD as an idealistic framework for project delivery will still need to grow, more commonly applied methods of contract procurement have the potential to be revised and adjusted in order to synergise collaborative efforts and foster the uptake of BIM. Ultimately, BIM is set out to increase certainty and transparent information-sharing on construction projects. BIM is no silver-bullet to solve all problems across the construction industry but it is a means to increase communication and certainty. As a result, BIM can help stakeholders to reduce risk and increase productivity. Those engaged in the proliferation of BIM and those developing local policies and guidelines for its adoption need be aware of the interplay between contract procurement and the potential/willingness of the industry to respond to regulatory frameworks. Limitations of the (still predominantly conceptual) study presented here relate to the comparably recent adoption of BIM across the Australian construction industry. There are as yet no solid benchmarks available to measure BIM efficiency and no studies have been undertaken within our jurisdiction where its success is measured according to predefined metrics. In the future, once novel contract procurement documents get issued that consider the use of BIM, possibilities are likely to emerge to validate the benefits of BIM under various procurement models in a more quantitative fashion. More research is required to provide policy-makers with guidance about the right balance to adjust existing delivery methods whereby collaboration is fostered without the danger of over-constraining innovation across the construction industry with excessive layers of regulation.

Acknowledgements

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Density comparisons in New Zealand and European housing

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Abstract: This project combines existing statistical information on housing projects in Europe with a new comparison on a variety of apartment buildings in New Zealand. A housing review was first undertaken via a series of case studies on projects by Housing New Zealand, various councils and private developers. These case studies examined dwelling statistics such as FAR (floor area ratio), site coverage, dwelling units/hectare, and people/hectare. The research will provide important background data for the continued development of medium density housing projects in New Zealand, as a comparison with some traditional and more recent European medium density housing schemes.

Keywords: Density; housing; New Zealand.

1. Introduction

This research was undertaken to bring some clarity to data on New Zealand (NZ) medium-density housing. The research in this project was undertaken as part of a summer scholarship program being run at Victoria University, Wellington (VUW). The research aim was to analyse recent NZ attempts at medium-density housing and to directly compare them with more well-known medium-density housing schemes in Europe, as a means of better understanding and ultimately improving apartment design. A number of standard housing metrics were gathered for comparison, all relating to issues of density, so that the housing concerned could be examined across international borders on a ‘level playing field.’

2. NZ apartment housing

New Zealand’s history of housing is primarily in the semi-rural/suburban field, almost exclusively comprised of small, detached, suburban housing subdivisions with ensuing environmental damage from extensive suburban sprawl. Much has been written about the quality and style of the individual NZ home, ranging from Skinner’s The whare in the bush (2008) to Walsh and Reynold’s Big House Small House (2013). Little has been written about mass medium-density housing schemes in the mainstream press in NZ, but there is considerable current interest in the subject within academia and within the architectural profession. Gatley examines the history of NZ apartment housing in both Long live the modern (2008) and Vertical Living (2013), while Petrovic, in Your new house: Or would a flat suit you
better? (2003), argues that time has come for NZ to stop focusing inwards on small houses, and to look more seriously at the issues of apartment living. Over the past two decades, a push towards medium-density housing schemes has resulted in a variety of apartment types, some more successful than others. Recent work from the School of Architecture Masters program, has focused on innovative methods of medium-density housing, including Batchelor (2014), Shepherd (2014), and Robinson (2014). This paper gathers further information helping inform the debate over apartment living.

There have been a number of well-designed NZ medium-density housing schemes throughout the 20th century, starting predominantly in the inter-war and post WWII periods, achieving significant prominence not just because of their scarcity, but also because of their quality. These include, in Auckland: the Mayfair apartments, Courteville, and the Grey St and Symonds St flats, but these are in the minority. In Wellington, as a comparison, more efforts were put into large scale housing, with the Dixon St flats and the Douglas Maclean flats both notable examples, along with a considerable number of housing projects by the Wellington City Council, including the Central flats, the Berkeley Dallard flats, the Ara Hou medium-density housing scheme, Marshall St apartments, and more. Christchurch had significantly fewer apartment buildings, with many of the multi-story residential buildings being demolished post-quake in the Canterbury swathe of seismic-related destruction. The number of other medium-density housing schemes throughout the rest of NZ has traditionally been very small indeed, although in retirement markets such as Tauranga, recent growth in medium-density multi-unit apartment buildings is strong.

Petrovic (2003) notes that flats and apartments were still viewed by many mid-century émigrés as a symbol of the over-crowded and war-torn country they were trying to leave behind, although the better schemes were designed by émigré architects such as Ernst Plischke. Mitchell notes the desire for suburbia in the NZ psyche in The Half-Gallon Quarter-acre Pavlova Paradise (1972), the reality of which has long since passed on for most New Zealanders and especially for those living in NZ’s biggest city, Auckland. With the adoption of the Auckland Council’s new Unitary Plan, there is a gradual, albeit reluctant, acceptance by many that Auckland must concentrate itself more in the centre, and less expansion out on the edges. Housing quality of new apartment buildings and new medium-density housing schemes are mixed, with both some excellent housing schemes produced, along with some that have been widely derided for their lack of amenity.

3. European apartment housing

In the European architectural press there is not so much focus on the individual house as there is in NZ. Instead, the focus is on creating and highlighting good quality medium-density housing, suitable for the masses. While there may have been a stigma attached to apartment housing in NZ, as Petrovic notes, apartment housing is readily acceptable in Europe. Both between and after the two major World Wars, Europe was rebuilt with considerable effort towards a more egalitarian society, utilising architecture for the masses to smooth the way. Projects like Corbusier’s Unite d’Habitation (Marseilles, 1952), and Goldfinger’s Trellick Tower (London, 1972), are examples of mass housing schemes that have gone from popular, to deeply unpopular, and returned back to popularity again, but in countries like the densely populated Netherlands and the more sparsely populated Spain, medium-density housing continues to be a well-accepted way of living. Increasing world population and rising political unrest in Europe and the Middle East will put further pressure on Europe to house the masses, but there appears to be little appetite in Europe for more Asian-style high-density apartment projects.
Recent interest in density has been promoted heavily by A+T Publishing, with a series of publications all focusing around density. This includes *Why Density: Debunking the myth of the cubic watermelon; Density is Home; D-Book: Density, Data, Diagrams, Dwellings*, and a series of magazines and newsletters about Density. Elsewhere in Europe, Schneider has published several editions of their book on *Floor plan Housing Manual*, while in the USA, publications have also recently been focusing on issues of medium-density housing. A key aim of this research was to examine NZ housing on the same basis that the European and American examples were examined. Information on European examples of high-density and medium-density housing was drawn down directly from these European publications, while information on NZ housing was researched and data gathered from NZ raw data sources (LINZ, Koordinates) in the same format in order for direct comparisons to be made.

4. Data mining

4.1. Data sets

Units of measurement were not the same between different publications. While both NZ and Europe are metricated, the USA is still using imperial measurements (miles, acres and square feet), while the UK sits somewhere in-between, with most buildings being planned in metric units, but still largely reported by estate agents in square feet. Wikipedia publishes data for many USA and European cities in people(pp)/mile$^2$, as well as pp/km$^2$, but not in pp/ha. Data was given by different publications as dwellings per acre, per square kilometer, per square mile, or dwellings per hectare; it was unclear if these figures are inclusive or exclusive of public spaces such as roads, footpaths, and common garden areas. Other data was stored in the format of habitable rooms per kilometre, people per acre, or people per m$^2$. The overall results are unclear unless measurement systems are standardised and relatable. All of these data sets can be inter-related with some degree of intuition or accuracy, but a system of reporting with commonly used units of measurement was needed for any of the work to be comparable. Table 1 clarifies how standard area measurements relate to each other.

<table>
<thead>
<tr>
<th>hectare</th>
<th>acre</th>
<th>square mile</th>
<th>km$^2$</th>
<th>m$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.471</td>
<td>0.003861</td>
<td>0.01</td>
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</tr>
<tr>
<td>40</td>
<td>98.84</td>
<td>0.15444</td>
<td>0.4</td>
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<td>100</td>
<td>247.1</td>
<td>0.3861</td>
<td>1</td>
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<tr>
<td>259</td>
<td>640</td>
<td>1</td>
<td>2.59</td>
<td>2,590,000</td>
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</table>

It was resolved that for consistency, only the metric system would be used, and figures involving acres, square feet and square miles would be converted into hectares. Rather than looking at large neighbourhoods, which by necessity include a lot of open common areas such as roads (ie gross area), our research concentrated on actual built envelopes of projects where available (ie net area). There is a relationship between dwellings per area, habitable rooms per area, and people per area, but while some publications used one data type, another publication used a different type. While the amount of people/area can be presumed from the number of bedrooms, this figure is obviously the least reliable and least definite, while the amount of habitable rooms/area is widely used, but required a lot of access to internal apartment plans. As a result, this research publishes results in dwelling units per hectare, as the most reliable and commonly interchangeable unit of density. Table 2 shows the inter-relationship...
between all these units. Our final calculations of density include Site coverage, Floor to Area Ratios (FAR), etc. These are shown on the individual data sets produced (Figures 1-5 and table 3).

<table>
<thead>
<tr>
<th>pp/ha</th>
<th>pp/acre</th>
<th>pp/square mile</th>
<th>pp/km²</th>
<th>pp/m²</th>
</tr>
</thead>
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<td>4,000</td>
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<td>100</td>
<td>40.46945</td>
<td>25,900</td>
<td>10,000</td>
<td>0.01</td>
</tr>
</tbody>
</table>

4.2. Density data examination methods

Geographic information system (GIS) data was obtained through the Koordinates website (which includes data from various city councils and NZ government agencies) and City Council GIS mapping websites. This data related to legal boundaries for properties, building footprints and land contours, and was used in instances where case studies were not provided, or were not sufficiently detailed. This data extraction was also paired with the CAD programs Archicad and Sketchup to develop basic block models of the developments being researched, as a visual aid for further research. Issues relating to maximum and minimums of housing/apartment sizing have been examined previously, with the observation being made that while most developed countries have a minimum housing size standard, neither the UK nor NZ have such a standard, instead leaving this up to the market to self-regulate (Marriage, 2010). Whether or not the self-regulation is working is debatable. In the UK most developers work to the recommended minimum sizes from the 1961 ‘Parker-Morris’ report, while in NZ the more laissez-faire, hands-off style of regulation and government leads to some exceptionally small apartments being produced. This is unusual, given that in NZ there is not a shortage of readily-developable land.

Dependant on how many inhabitants per dwelling, how many habitable rooms per dwelling, and socio-economic factors, the amount of people per dwelling unit also can vary significantly from scheme to scheme. An indicative scale of effects is that a Studio or One-bedroom apartment contains, on average, 1.25 people; a Two-bedroom apartment contains 2.5 people; a Three-bedroom apartment contains 3.75 people; while Four (or more) bedroom apartments contain on average 5 people. In developing countries and in slum conditions, these occupation figures will all be much higher.

5. Case studies

The following set of case studies comprises data gathered on four prominent medium-density housing projects in NZ, the first known time that this data has been gathered in this format, in a comparison with the more well-known Unite d’Habitation in Marseilles. Further studies were made of several other housing schemes, but space permits only a small portion to be examined here in detail. The information gathered aligns with data collected by European agencies, allowing direct comparison to be made between NZ and European housing examples. The data is set out here individually, and then combined in a comparison (Tables 3 and 4) for further analysis.

5.1. Case study 1 – Dixon Street apartments - Wellington

NZ’s “first high-density [social] housing scheme”, the Dixon Street apartments were constructed by the Labour government towards the end of World War II (Gatley, 2014). The scheme was an attempt to alleviate the issues around returning servicemen post World War II, but also proved beneficial in the following baby-boom years. It proved to be a flexible and popular addition to social housing stock,
although is currently awaiting seismic strengthening (or demolition). The east-west single-loaded corridor arrangement means the living and bedroom spaces both have access to the private balcony, and thus an exterior wall, while the service areas on the western face border the various “ocean liner-like galleries providing access” (Gatley, 2008). The lack of green space is mitigated by proximity to the central city.

- **Date of Construction:** 1941-1944
- **Architects:** Ministry of Works (Gordon Wilson / Ernst Plischcke)
- **Number of units:** 115
- **Site Coverage:** 21%
- **Floor to Area ratio:** 2.09
- **People per hectare:** 332
- **Dwelling units per hectare:** 266
- **Floor area per person:** 63 m$^2$

5.2. Case study 2 – Freeman’s Bay Star housing (Phillips Street Block) — Auckland

The Phillip Street Block plan was the by-product of a housing shortage in New Zealand following World War II, the government’s “desire to limit suburban sprawl result[ing] in the introduction of various types of medium-density housing in the mid-1950s” (Gatley, 2008) and the desire of the Auckland City Council to rid the city of the slum housing existing on the site. The now iconic Star Blocks were named for their floor plan configuration. Four two-bedroom apartments are arranged around a central circulation core, this plan being repeated over three or four storeys. As a result, some apartments receive better sunlight ingress than others depending on their site orientation, however all liveable spaces are on exterior walls. There are no private open spaces, with a focus instead on shared green areas surrounding the blocks. Adding to this relaxed feel are the “meandering” roads running through the block, connecting the various peripheral streets and offering access to the open car parking. The various other buildings on site vary between single and four storeys, with differing levels of access and privacy, with the net result being a desirable and popular development close to the central city.

- **Date of Construction:** 1960-1967
- **Architects:** Ministry of Works (Neville Burren)
- **Number of units:** 200 (approx)
- **Site Coverage:** 21.7%
- **Floor to Area ratio:** 0.60
- **People per hectare:** 143
- **Dwelling units per hectare:** 57
- **Floor area per person:** 42 m$^2$

5.3. Case study 3 – Chester Court - Christchurch

The Chester Court development comprises 15x 2-3 bedroom units in two main terrace blocks, with garage and service buildings between them. These buildings form a perimeter to a central hard surfaced courtyard space to allow for vehicle maneuvering, with the primary access to the development through an archway. The blocks are oriented so that each unit faces north-south, meaning both living and bedroom spaces are on exterior walls. This allows for sunlight and daylight penetration to these spaces. The building itself attempts to reference various historically significant buildings from the area. The
central city is located close-by, offering a high level of amenity for potential occupiers. Chester Court is close to high-density, according to the Housing New Zealand requirements, whilst retaining character and a high level of quality.

- **Date of Construction:** 1995
- **Architects:** Phillip Kennedy Associates
- **Number of units:** 15
- **Site Coverage:** 21%
- **Floor to Area ratio:** 0.89
- **People per hectare:** 162
- **Dwelling units per hectare:** 65
- **Floor area per person:** 55 m²

### 5.4. Case study 4 – Courtyard townhouses, Seatoun - Wellington

The site for this development was surplus Defense Force land, known as Fort Dorset. The use of a varying scale of house has allowed privacy to be retained to courtyard spaces, with excellent sunlight and daylight ingress to the homes, whilst also offering a visual interest to the streetscape through the alternating forms. The single storey homes have two bedrooms and a single garage, with the two storey home allowing for an extra bedroom, as well as larger living and garaging spaces. This development has eschewed the typical suburban requirement for side yards, in favour of an intelligent design response that retains quality of life (Marriage, 2014).

- **Date of Construction:** 2005
- **Architects:** Studio Pacific Architecture (Nick Barratt-Boyce/Peter Mitchell)
- **Number of units:** 13
- **Site Coverage:** 49%
- **Floor to Area ratio:** 0.53
- **People per hectare:** 109
- **Dwelling units per hectare:** 34
- **Floor area per person:** 49 m²

### 5.5. Case study 5 – Unite d’Habitation – Marseilles, France

The model of a modernist housing block, this particular example proved inspirational to Le Corbusier’s contemporaries, with innumerable examples of the typology drawing on the “Radiant City” in the following decades, though not always as successfully. This example of housing retains its relevance through a variety of design decisions made that ensure a high quality of living. These include double height duplexes as the typical residence, ensuring natural light ingress from the balconies. The use of double-height units also allowed for the inclusion of the ‘streets’ that allow access to the residences. These streets occur every three floors, with pairs of homes interlocking around the central street corridor. Alongside the residential use, was that of levels dedicated to businesses and recreation. The seventh and eighth floors housed (and still do) a variety of professional services, with the roof space dedicated to pools, a running circuit and a nursery, though this has since shifted to an art space. The sculptural qualities of both the exposed concrete and *piloti* helps the building avoid the starkness of the later models of housing, and quite literally elevates it above them as one of Le Corbusier’s most well-respected works.
6. Conclusion

The results of the research work are summarized in Table 3 below. Analysis follows on the following page. Statistical information was derived from GIS and historical sources for NZ data, while published data exists for the European samples (Fernandez et al, 2011).

<table>
<thead>
<tr>
<th>Housing Name</th>
<th>Land (ha)</th>
<th>F.A.R.</th>
<th>Dwelling Units(DU)</th>
<th>People (pp/ha)</th>
<th>Area/person (m²)</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
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<td>2.09</td>
<td>115</td>
<td>332</td>
<td>63</td>
<td>LINZ / KOORD</td>
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<tr>
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<td>3.50</td>
<td>0.60</td>
<td>200</td>
<td>143</td>
<td>42</td>
<td>LINZ / KOORD</td>
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<tr>
<td>NZ-Chest Court</td>
<td>0.23</td>
<td>0.89</td>
<td>108</td>
<td>162</td>
<td>55</td>
<td>LINZ / KOORD</td>
</tr>
<tr>
<td>NZ-Scene One</td>
<td>0.37</td>
<td>9.93</td>
<td>120</td>
<td>728</td>
<td>63</td>
<td>LINZ / KOORD</td>
</tr>
<tr>
<td>NZ-Seatoun</td>
<td>0.38</td>
<td>0.53</td>
<td>13</td>
<td>109</td>
<td>49</td>
<td>LINZ / KOORD</td>
</tr>
<tr>
<td>NZ-Peak 1 (high-density)</td>
<td>0.04</td>
<td>9.56</td>
<td>108</td>
<td>3506</td>
<td>24.5</td>
<td>LINZ / KOORD</td>
</tr>
<tr>
<td>NZ-Elevat 1 (high-density)</td>
<td>0.07</td>
<td>14.71</td>
<td>82</td>
<td>2985</td>
<td>49.3</td>
<td>LINZ / KOORD</td>
</tr>
<tr>
<td>FRANCE-Unite d’H</td>
<td>4.84</td>
<td>1.44</td>
<td>337</td>
<td>320</td>
<td>48.6</td>
<td>DEZEEN</td>
</tr>
<tr>
<td>FRANCE-Druon</td>
<td>0.35</td>
<td>4.52</td>
<td>104</td>
<td>813</td>
<td>57.5</td>
<td>Fernandez p198</td>
</tr>
<tr>
<td>FRANCE-XTU</td>
<td>0.18</td>
<td>3.46</td>
<td>63</td>
<td>903</td>
<td>53</td>
<td>Fernandez p256</td>
</tr>
<tr>
<td>DEN-BIG 8</td>
<td>2.05</td>
<td>2.98</td>
<td>476</td>
<td>937</td>
<td>25.7</td>
<td>Fernandez p118</td>
</tr>
<tr>
<td>UK – S333 Block 3</td>
<td>0.18</td>
<td>2.55</td>
<td>32</td>
<td>606</td>
<td>40.9</td>
<td>Fernandez p160</td>
</tr>
<tr>
<td>UK – S333 Arch St</td>
<td>0.20</td>
<td>2.74</td>
<td>52</td>
<td>618</td>
<td>41.2</td>
<td>Fernandez p152</td>
</tr>
<tr>
<td>NED-Kempe T</td>
<td>0.25</td>
<td>2.28</td>
<td>64</td>
<td>550</td>
<td>46.5</td>
<td>Fernandez p166</td>
</tr>
</tbody>
</table>
Table 3 shows that while the European housing schemes are typically slightly more dense than

Table 3: Comparison analysis of European housing vs NZ housing.

<table>
<thead>
<tr>
<th>Country</th>
<th>Land (avg.)</th>
<th>F.A.R. (avg.)</th>
<th>D.U. (avg.)</th>
<th>pp/ha (avg.)</th>
<th>Area/person</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Europe</td>
<td>0.98 ha</td>
<td>2.63</td>
<td>152</td>
<td>605</td>
<td>51.2 m² each</td>
</tr>
<tr>
<td>NZ - medium</td>
<td>0.98 ha</td>
<td>2.81</td>
<td>111</td>
<td>295</td>
<td>54.4 m² each</td>
</tr>
<tr>
<td>NZ – high</td>
<td>0.06 ha</td>
<td>12.14</td>
<td>95</td>
<td>3245</td>
<td>36.9 m² each</td>
</tr>
<tr>
<td>All NZ</td>
<td>0.72 ha</td>
<td>5.47</td>
<td>107</td>
<td>1138</td>
<td>49.4 m² each</td>
</tr>
<tr>
<td>NZ med-dens to Euro</td>
<td>100% of site size</td>
<td>107% larger F.A.R.</td>
<td>73% of D.U.</td>
<td>49% density</td>
<td>106% size alloc.</td>
</tr>
<tr>
<td>NZ high-dens to Euro</td>
<td>6% of site size</td>
<td>461% larger F.A.R.</td>
<td>62% of D.U.</td>
<td>537% density</td>
<td>72% size allocation</td>
</tr>
<tr>
<td>Difference: all NZ to all Euro</td>
<td>73% of site size</td>
<td>208% larger F.A.R.</td>
<td>70% of D.U.</td>
<td>188% density</td>
<td>97% size allocation</td>
</tr>
</tbody>
</table>

Although this small survey is not statistically reliable (the sample size is too small), the analysis
indicates the direction being taken by certain recent housing projects. Apart from the two outlying
Density comparisons in New Zealand and European housing

examples, on the whole NZ’s examples compare well with European housing, being broadly similar on many of the statistical fronts. Physical area occupied per person is broadly similar (54.4 m² vs 51.2 m²), but traditional methods of density measurement still show NZ schemes as half the density of the Europeans (295 pp/ha vs 605 pp/ha). France’s much-lauded Unite has generated decades of interest as an architectural game-changer, as has NZ’s Dixon Street flats, but both of these schemes are significantly different from the housing schemes being promulgated in both countries today.

Over-population continues to be a serious concern throughout the world, far more serious an issue than was imagined at the time the Unite or the Dixon St buildings were being designed, and yet many recent medium density housing schemes appear to show no awareness of the pressures of housing requirements for the future. Housing schemes such as Elevate and the Peak in NZ, although designed for far greater density levels than NZ is used to, and far more dense than housing schemes in Europe indicate from the studied schemes, may yet become a regular part of the apartment housing scenario in NZ.

Acknowledgements

Grateful acknowledgements are given to Victoria University and First Light Studio for their sponsorship of the summer research scholarship.

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Investigating thermal comfort and occupants position impacts on building sustainability using CFD and BIM

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Abstract: Increasingly expensive and polluting sources of energy dictate the need of energy conservation in the society. The major energy consumption contribution in the operation phase of modern buildings is from their HVAC systems. Well planned HVAC systems may provide healthy and comfortable indoor environment, while poor design may result in wastage of energy. Traditionally the design of the systems is based on a constant number of occupants while the situational awareness of the system has been ignored. This paper focuses on the intelligence of the HVAC system in terms of its knowledge of the occupants of the facility in real time. Thermal comfort analysis is applied to study the indoor climate of buildings for efficient use of such HVAC systems. Computational Fluid Dynamics (CFD) is used to model and simulate the indoor conditions. Building Information Modelling (BIM) is used to be a platform to integrate all the data and apply spatial analysis and Green building standards are embedded in the BIM model to evaluate the building sustainability. Based on the results, more reasonable allocation of individual’s location in a room can be provided and an automatic control of lighting, air conditioning can be suggested to optimize energy consumption based on matching occupants’ comfort level.

Keywords: Intelligent HVAC; thermal comfort; CFD; BIM.

1. Introduction

About 90% life of an average individual is spent in the indoor environment (US, EPA, 2015). A major portion (40%) of the world’s energy is consumed in buildings; indoor thermal comfort accounts for 30–40% of that energy (European Union, 2015). The available sources of energy are becoming expensive, insecure and producing pollution therefore energy efficiency will play an ever-increasing role in ensuring sustainable energy use (EIA, 2014; Lombard, 2008). Therefore, well-designed building ventilation systems must be installed to optimize the use of energy while providing satisfaction to the building occupants (Redlich, et al., 1997).
Thermal comfort is an important aspect in representing human satisfaction, which is defined as “the condition of mind which expresses satisfaction with the thermal environment (ASHRAE, 2004; ISO 7730, 2005)”. A wide range of research has been carried out on residential and non-residential thermal comfort level. For instance, thermal comfort in 22 air-conditioned office buildings in different climates have been analyzed by Cena and Dear (1999), in which a relationship was observed between job satisfaction and thermal comfort level. In US, Canada and Finland, 61% of occupants were found not to be satisfied with the adjusted temperature in their office according to survey conducted in 215 building (Huizenga et al., 2006).

Thermal comfort analysis is one of the most useful methods of identifying thermal perceptions of occupants in a particular building space and of possible energy savings. Studies showed that the internal climate of a room is the strongest factor in maintaining thermal comfort. Direct manipulation of the internal climate is necessary to retain an acceptable level of thermal comfort (Nicol et al., 2002). Accurate modeling of the internal climate of buildings is essential if Building Energy Management Systems (BEMS) are to efficiently maintain adequate thermal comfort (Mullen et al., 2015). Fanger (1970) introduced a thermal comfort model based on six parameters that are determined by analyzing the whole body satisfaction and local discomfort. The Fanger equation depends on the physiological and environmental parameters such as air temperature, air relative humidity, air velocity, Mean radiant temperature, clothing thermal factor and activity level.

Traditionally the design of the HVAC systems is based on a constant number of occupants while the situational awareness of the system has been ignored. However, by automatically control the HVAC according to the number and the location of occupants’ may greatly reduce energy consumption in the life cycle of the building. The present research proposes a method to apply thermal comfort analysis based on the locations of HVAC system and the occupants location information collected in real time, so that an automated control of the HVAC system can be applied to save energy. Building Information Modeling (BIM) is acted as a platform to integrate real-time data and the spatial information of the built environment.

BIM is a new approach to design, construction, and facilities management in which a digital representation of the building process is used to facilitate the exchange and interoperability of information in a digital format (Eastman and Eastman, 2008). Kryegiel and Nies (2008) indicated that BIM can be applied in sustainability analysis widely while considering for example building orientation, building envelope, and construction materials. Recent research in the building construction industry reveals that Building Information Modeling (BIM) has not been popularly used to take the advantages of the new technology due to several reasons. Lack of knowledge and personnel that familiar with the technology are the major issues. With the introduction of BIM, different attributes of the building envelopes can be recorded in the digital database, for instance carbon dioxide emission, which facilitates the automatic sustainability assessments of buildings. Chen and Hsieh (2013) developed a BIM-assisted rule-based approach to automatically check of greenhouse gas emission of buildings. The normal carbon dioxide emission was calculated from the building and the area of green plants; and then the result would be checked with relevant rules. However, most of these applications are limited to the design stage. The present paper is a part of a research focusing on life cycle evaluation of building sustainability using BIM, RTLS, and integrating LEED standard into the system. Related research results can be found in Zhang et al., 2013; Zhang et al., 2014 and Zhang and Chen, 2015. The present paper proposes a methodology by simulating the wind velocity, distribution of air flow in a room using CFD, based on what thermal comfort is analyzed, the HVAC system is smartly controlled according to occupants’ number and location. In this way, energy can be used efficiently and waste can be reduced.
2. **Computational Fluid Dynamics (CFD) method**

Since 1950s Computational Fluid Dynamics (CFD) has been extensively used as a scientific tool in many applications and research projects. In 1974, Nielsen presented one of the earliest works where the airflow in rooms was simulated through CFD but due to limited computational resources CFD had to wait. The increase in computational resources has revitalized the use of CFD as a scientific tool and its usage continues to increase. Analysis of fluid flows is done through numerical algorithm in CFD which allows it to model and evaluate the indoor and outdoor airflow, heat transfer and contaminant transport. Therefore, CFD is a powerful tool to analyze thermal comfort and dissatisfied percentage in buildings. A surgery room in a hospital based on the CFD 3D model was analyzed for thermal comfort by Ho et al. (2009), which resulted in the identification of inefficient location of grilles of supply air. The impact of radiant cooling ceiling and mechanical ventilation systems on the thermal comfort using CFD modeling has been evaluated by Wei-Hwa et al. (2012), based on their results they provided a design guideline for installing a cooling ceiling system in terms of higher satisfaction of occupants. Evaluation of the thermal comfort level with the calibrated and non-calibrated CFD models has been done by Hajdukiewicz et al. (2013), which discussed about the calibrated CFD model in a highly-glazed meeting room with natural ventilation. The casual relationship between health symptoms and pollutant exposures in schools by collecting some parameters such as CO2 concentrations, ventilation rates and so on was evaluated by Daisey et al. (2003), indicating the poor ventilation implemented in many classrooms.

CFD compounded computer sciences, numerical techniques and physical sciences. CFD employs a series of finite discrete points to evaluate the original and continuous physical quantity field in space and time by adopting and a set of variable data. A field variable approximation is done by solving the algebraic equation set. Fluent, Airpak and Phoenics are the different platforms for performing for different applications. In this research, Airpak has been selected due to its capacity to model temperature, air velocity, Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD).

3. **CFD simulation in the present research**

In this paper, an office in a university campus is selected to analyze the performance of air conditioning system and the level of thermal comfort for occupants. Wind velocity and temperature have been simulated by using the CFD method. The Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD) are evaluated as well.

3.1 **Physical model of the office**

The physical model of the selected office is equipped with two central air conditions installed on the ceiling, as shown in Figure 1.

The parameters of model are as follows:

- Reference coordinate system: start point coordinates (0, 0, and 0) and ending points (8.5, 3, and 10.4);
- Room dimensions: 8.5 × 10.4 m;
• Indoor heating source: 7 sitting men (persons 1 to 7 with calorific value of 75 W; two sitting women (person 8 and 9) with calorific value of 60 W; nine LCDs with calorific value of 19.5 W; nine computer cases with calorific value of 220 W; and finally, nine florescent lamp sets with total power of 100 W for each set which are replaced by 0.4 m × 1.2 m blocks;
• Three external windows facing south with geometrical dimensions: 1.6 m × 3 m;
• Two ceiling HVAC air supply outlets: Dimensions: 0.9 × 0.9; air velocity: 2.5 m/s; air temperature: 18 °C; and
• Office door geometry dimensions: 2 m × 1.3 m, However, to simplify the calculation, the door is ignored in the simulation.

3.2 Setting of boundary conditions

The temperature buoyancy condition for the CFD simulation was provided by Arduino sensors. Indoor and outdoor temperatures are gathered by two DHT11 Arduino temperature and humidity sensors as well. The data for the CFD model were collected during the field measurement in the office on June 15th, 2015 as follows:

• The air was considered as an ideal gas with the reference buoyancy density of 1.173 kg/m³;
• (2) Outdoor measured parameters: Dry-bulb temperature at 32 °C;

Figure 1: The geometry of office with none occupants

Figure 2: Grid generation in Airpak software

• Indoor measured parameters: Dry-bulb temperature at 20 °C, relative humidity of 40%;
• The only external wall for this office is the south wall, with a constant heat flux boundary condition and 16.8 W/m² considered for heat transfer density;
• Outside windows: placed on the external wall with the heat transfer density of 16.8 /m²;
• Internal walls and floor: Front wall (south) with 21.8 °C, Left wall with 21 °C, Right wall with 20.2 °C and back wall with 20.4 °C, floor with 19 °C and ceiling with 20.2 °C;
• Air outlet: Air supply direction is along the Y axis with the dimension of 0.3 m × 0.3 m .The supply air velocity is 2.5 m/s and supply air temperature has an ambient value.
3.3 Mathematical model

The grid generation of the model is shown in Figure 2. To calculate the momentum conservation, mass conservation and energy conservation equations, low Reynolds number turbulence model (RNG $k - \varepsilon$ model) is implemented. Simultaneously, the influence of heat radiation of each heat source is also considered. In addition, five assumptions are taken into consideration for the physical model. First, indoor air flow is steady turbulent flow. Second, to conform the Boussinesq theory (1872), which says the buoyancy lift only influenced while changing the fluid density, the indoor air is chosen to be as incompressible. Next, the temperature of floor surface is well-distributed. Fourth, it is assumed good air tightness in the room. Hence, the leakage effect is not considered in the simulated room. Finally, the doors of the office are ignored from the calculation and all windows are assumed to be closed for simplification purpose. The modified mesh for simulation is set as the normal type and the coordinates of X, Y and Z were adjusted to 0.21, 0.1 and 0.07m, respectively.

4. Intelligent control system

The basic idea of this research is to provide thermal comfort and energy conservation by intelligently controlling the two HVAC air outlets installed in the ceiling of the office. The intelligence is based on its awareness of the occupants’ presence in the room and their location so as to decide which of the HVAC system should be kept on or off. The awareness is facilitated by a Real-time Location System based on RFID tags. A network of RFID receivers and tags are built to collect the locations of users in the building, as can be referred to Zhang et al. (2013). RFID tags are registered in the BIM model and the data written are transferred to the BIM model Properties associated with corresponding tags objects. The decision of which HVAC system should be turn on is taken by the main server at the Facility management office that is connected with a RFID receiver that is present inside the office room and the controller of the HVAC system. The details of this system are beyond the scope of this paper therefore not presented here.

5. LEED embedded BIM

A BIM model is created for the building to integrate energy consumption data with spatial areas, such as rooms. From the authors’ previous research result, requirements from the Leadership in Energy and Environmental Design (LEED) are embedded into the BIM model. Credits obtained from the design and the operation stage will be calculated and the performance of the building will be checked in terms of sustainability. Figure 3 shows the plug-in developed in a BIM software to integrate LEED requirements. More details can be found in Zhang et al, 2014 and Zhang and Chen, 2015.
In the present paper, the main focus is the Energy and Atmosphere, Credit 1: Optimize Energy Performance. Integrating the results derived from the CFD modeling into this BIM model enables the analysis of the building in terms of comfort and energy consumption. In this way an efficient and effective way to optimize energy consumption is presented which is based on the allocation of people’s places according to the requirement of lightning, air conditioning and other related systems. Data of energy consumption collected from the system after applying the automatic HVAC control will be evaluated and improvement will be calculated.

6. Analysis of model results

In order to establish the maximum benefits one common and two extreme scenarios (with respect to the number and location of the occupants) are developed. In the first scenario all the occupants are present in the room so it is decided by the server to keep both the HVAC systems on. For the second scenario the four occupants near the HVAC-1 happens to be present so the it is decided to turn on HVAC-1 and similarly in the third scenario five occupants near the HVAC-2 were present so the decision is to turn HVAC-2 on. For the aforementioned scenarios CFD model have been developed which simulated the Wind velocity and air distributions. Further, the Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD) are computed using the data acquired from the experimental measurements performed in the building.

6.1 Scenario 1:

The indoor air distribution of HVAC systems is related to the indoor temperature, energy consumption of air conditioning systems, human thermal comfort and health status. Therefore, it is essential to ensure the rationality of indoor air distribution. The location of the plane for analysis in the CFD model is depicted through the occupant’s position. It should be noted that the locations of occupants are separated by partitions in this office. Figure 4 illustrates the simulation of the office room with nine occupants. To analyze the distribution of airflow in this room, the airflow streamlines also are depicted in figure 4(a). The airflow streamlines were entered through the air conditions and exited through the outlet channel. The air from the air conditioning systems injected from four separate channels by the angle of 45 degree. Hence, the distribution of airflow, in terms of occupant’s location, is well-designed. Moreover, due to the location of air conditioning systems which are placed on the ceiling, there is not any side effect for utilizing the partitions in this office. Figure 4(b) illustrates the airflow distribution inside the modelled room. The result determines that the air flow inside the room is wind-driven. Figure 4(c) depicts a relatively high airflow between occupants 6 and 7 and from the air velocity of figure 4(d), it is concluded that airflow is extremely high for person 1 which again may result in local discomfort for this person. The average air speed in this room in the height of 1.077 meter is less than 0.5 m/s. In terms of the air velocity, there are two high speed airflow areas in the middle of the room. However, no occupants located in this area. Figures 4(e) and 4(f) illustrate the PMV and PPD models, respectively. Both images confirm that locations near windows are not suitable for occupants. Persons 5, 8 and 9 are located in a slightly hot area. Person 9 is located in the 25 percent dissatisfied area. Most of dissatisfied and slightly hot areas are identified near windows.
6.2. Scenario 2:

In this scenario only four occupants near the HVAC-1 are presented in the room. The intelligent system can recognize this situation and only turn the HVAC-1 on. Figure 5(a) illustrates the airflow streamlines in this condition. The left-south of the room has less air distribution. The air-velocity is depicted in figure 5(b) which confirms the area near the off HVAC system has lower air flow. In terms of PMV and PPD analysis, figures 5(c) and 5(d) show the south areas in this room is not suitable for sitting occupants in this scenario. However, in terms of energy management, 50% of the energy usage is saved as one of the HVAC systems is turned off by the intelligent system. According to the prepared questionnaire and experimental test based on hourly thermal comfort analysis, it was indicated that only during the first hour, occupants may feel discomfort. However, after the first hour, occupants feel much more comfortable. Hence, one HVAC outlet needs more time to adjust the temperature and prepare a comfort range.
6.3. Scenario 3:

Figure 6(a) shows the position of users and the airflow streamline in the third scenario when HVAC-2 is turned on. From the air velocity of figure 6(b), it is concluded that airflow is extremely high for person 6 which again may result in local discomfort for this person. Figure 6(d) shows the discomfort areas in this scenario. Although, the discomfort areas are increased in this scenario, the energy consumption is reduced by 50%. From the comparison between all scenarios, it is concluded that person 5 is located in the position where this is considered as a discomfort area in all scenarios. This simulation shows the possibility of an intelligent system in different scenarios to control HVAC systems and optimize energy usage by considering the thermal comfort of occupants in a big room. Same as scenario 2, during the first hour, occupants may feel discomfort. However, in the rest of working time, the condition has been changed to a comfort range. It is recommended to use passive performance of HVAC system before working hours to solve this situation. However, it needs more investigations.
7. Conclusion

An intelligent control system is designed to automate the decisions taken to provide thermal comfort in real time depending on the number and location of the occupants. The evaluation of the decisions taken by system in terms of thermal comfort based on wind velocity, distribution of air flow is done through CFD modeling. One common and two extreme scenarios in terms of location and number of occupants are tested. The results reveal up to 50% of energy saving under extreme scenarios and with thermal comfort parameters between acceptable ranges. These results are embedded in a BIM model along with the LEED standards which is capable of rule based automatic evaluation. This will provide an efficient way to assess different scenarios and perform spatial analysis during design to avoid re-work and improve green grade as well as enable the manager or the owner to forecast and diagnose energy consumption and achieve energy efficiency. Most importantly give the end-users a good awareness about how to properly use the designed features in the building and reduce energy wastage in daily life.

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Modeling the carbon footprint of urban development: a case study in Melbourne

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Abstract: It is estimated that urban areas account for 60-80% of global energy use and are responsible for the emission of more than 70% of global greenhouse gases. Since most future population growth is expected to be in urban areas, one main question regarding urban planning is how new urban communities should be developed in order to minimise resource consumption and greenhouse gas emissions. This research will develop a spatially explicit model to simulate the carbon footprint of urban growth under three different development scenarios: 1) the horizontal (the business as usual (BAU) scenario), 2) vertical (Le Corbusier’s ‘Radiant City’ scenario), and 3) the mixed scenario. The intention of the research is to 1) assist in identifying the ideal spatial composition and configuration of suburban communities with potential to consume less resources and produce less greenhouse gas emissions; 2) propose an alternative approach to greenhouse gas emission control at the neighbourhood level; and 3) inform planning and design actions aimed at realising low carbon development.

Keywords: Carbon footprint; sustainability; urban planning; Melbourne.

1. Introduction

In order to limit the increase of future global warming to 2° C, it is necessary to stabilise the atmospheric concentration of CO₂ equivalent at no more than 450 ppm. To achieve this, it is necessary for all countries to implement actions to contribute to the reduction of GHG emissions from 2010 to 2050 (Güereca et al., 2013). To cope with global climate change challenges, regional and local level environmental impact measurements are important in decision making for city and regional planning (Chen, 2014). Human activities superimposed on the natural environment have caused many important transitions in our society (Galli et al., 2012; The Royal Society, 2014). Consequently, numerous natural hazards—for example drought, flood, and urban heat island—cause social, economic, and environmental problems (Mezosi et al., 2014). In order to systematically measure the impacts of human activities on the natural environment, many tools and frameworks have been developed (Barnosky et al., 2012; Borucke et al., 2013; Galli et al., 2012; Steen-Olsen et al., 2012; Wackernagel, 2014) and many studies have been undertaken to better understand environmental pressures associated with the
material flows of energy, water and other goods and services used to satisfy human needs for water, energy, food, shelter and transportation (Chavez and Ramaswami, 2013; Jha et al., 2013; Ramaswami et al., 2012). Among all these tools and frameworks, the consumer responsibility approach uses footprints as indicators of the total direct and indirect effects of a product or consumption activity.

Carbon footprint is the environmental pressure from greenhouse gas (GHG) emissions, which is characterised by a consumption-based perspective able to track human pressure on the surrounding environment, where pressure is defined as appropriation of CO₂ uptake and GHG emissions. Conventional carbon footprint is the total CO₂ emitted directly or indirectly by a certain activity or the CO₂ accumulation during a product life cycle (Galli et al., 2011, 2012; Larsen and Hertwich, 2010; Wiedmann and Minx, 2008), where carbon footprint is used as a measure of greenhouse gas (GHG) emissions embodied in the consumption and is usually measured using CO₂ equivalent (tonne). However, this definition cannot be used to quantify CO₂ emissions for different land use types. In this study, carbon footprint is quantified as ‘CO₂ land’ by applying the carbon footprint concept used by Global Footprint Network (GFN), which is similar to ecological footprint as measured using Global Hectare (Chen, 2014). The aim of this study is to analyse the carbon footprint of three different urban development scenarios in order to identify the ideal spatial composition and configuration of suburban communities to reduce resources and greenhouse gas emissions.

2. Project site and methods

2.1. Project site – The Caroline Springs growth area

The Caroline Springs growth area is selected to analyse its carbon footprint under three development scenarios. This urban growth area includes four suburbs 25km west of Melbourne – Caroline Springs, Burnside, Burnside Heights and Taylors Hill, which were developed on greenfield land since the 1990s. At the 2011 Census, Caroline Springs had a population of 20,366. It is fast-growing and the anticipated population will exceed 25,000 people in 2015. Coupling the population growth is the rapid housing development. As one of the designated urban growth areas (UGAs) by Melbourne 2030 (DOI, 2002), today Caroline Springs is one of the major growth regions in Melbourne's western suburbs (Figure 1).

Figure 7: Caroline Springs is located at the urban growth boundary speculated in Melbourne 2030.
2.2. Methods

Time series of remote sensing imageries are collected for digital land use and cover change characterisation. GPS data and other higher resolution aerial photos are used for ground truth purposes. Statistical data and demographic data from the Australian Bureau of Statistics are collected for the analysis in the later stage, coupling the carbon footprint outputs from the GIS-based simulation model. The final stage of the study is to compare the carbon footprint of the 3 different scenarios and their carbon balance effect i.e. is the site a carbon source or sink and how large is it (Figure 2). The implications of the study are discussed in light of informing future urban planning practices aiming at realising low carbon city design. Given the data and tools used in the study, the method itself is innovative as it is the first attempt to create a spatially explicit account of carbon footprint at the neighbourhood level.

3. The three scenarios

As noted above, if Caroline Springs grows as projected by 2030, thousands of additional people will require housing over the course of the next two decades. If these people are to be housed in freestanding homes then 8,000 homes are required. As seen in Figure 1, there is land available for homes set out at an average density of 10 homes per hectare in the current western Melbourne metropolitan area.

3.1. Horizontal scenario (Business As Usual: BAU)

In this scenario, to accommodate most of the predicted population increase, Caroline Springs would simply continue to build low-density suburbs the way it currently does in the western metropolitan area.
Melbourne region. The BAU plan for Caroline Springs growth area is characterised by low to medium density single family housing development with a town centre built in the middle of the site (Figure 3a). The BAU scenario applies a set of design guidelines conceived to ensure that our suburbs are well crafted at the human scale but it doesn't, and nor can it be expected to, substantively challenge suburban orthodoxy. Supporting around 20,366 people (2011 census), the current urban footprint of Caroline Springs is 285,000 hectares. The average density is 10 dwellings per hectare (the average density in many European cities is 250 dwellings per hectare, often more).

![Figure 3: The three scenarios of urban development in Caroline Springs urban growth area: (a) BAU; (b) vertical scenario; and (c) mixed scenario.](image)

### 3.2. Vertical scenario

The vertical scenario uses a density 10 to 50 times that of conventional suburbia. The theoretical basis for the vertical scenario lies in Le Corbusier’s ‘Radiant City’. This utopian ideology of urban master plan using the ‘Towers in the park’ concept was perceived to have certain influence on the urban planning of many contemporary cities including New York City (Schulz, 2015). Though radical, strict and nearly totalitarian in its order, symmetry and standardisation, the Radiant City proposed principles had an extensive influence on modern urban planning and led to the development of new high-density housing typologies (Merin, 2013). The Radiant City was to emerge from a tabula rasa: it was to be built on nothing less than the grounds of demolished vernacular European cities. The new city would contain prefabricated and identical high-density skyscrapers, spread across a vast green area and arranged in a
Cartesian grid, allowing the city to function as a ‘living machine’ (Schulz, 2015). As mentioned above, the Caroline Springs growth areas have been developed on ‘greenfield’ land since the 1990s, thus providing an ideal opportunity to test the carbon footprint of the vertical scenario using the urban planning concept described in Le Corbusier’s ‘radiant city’ ideology. The plan under the vertical scenario for Caroline Springs growth area is characterised by high-density high rise development with vast landscape reserved as green space or parks (Figure 3b).

3.3. Mixed scenario
The mixed scenario combines the ideal ‘Towers in the Park’ concept with the typical existing growth pattern in Australian suburbs. Under this scenario, high rise residential development is scattered among the low or medium density developments. Some innovative ideas such as Food City (Weller, 2012), which involves increased density suggest that the remaining low-lying land on the site can be utilised for high-tech organic agricultural production (Figure 3c). This idea leads to a third, Car Free City, a system of public transport which can be built into greenfield areas and retrofitted through our existing suburbs. The mixed scenario represents the potential for low carbon city development as it provides more flexible housing choices (thus higher level of affordability). It is also a more environmentally friendly approach as well as economically progressive strategy because under this scenario environmental and ecological concerns are considered against other social and cultural issues such as economic desirability and associability of living in an urban region, which are detrimental to urban life. The carbon footprint of this scenario therefore will have profound influence on the planning of future cities.

4. Results

4.1. Spatially explicit modelling of carbon footprint
In this study, the carbon footprint is estimated by calculating the balance between the source and sink factors using land cover data based on each of the development scenarios. Carbon fluxes and emissions of each land use type are mapped using GIS-based spatially explicit modelling. A literature survey reveals that no previous spatially explicit study at suburb scales has been made. Therefore this study is the first attempt to quantify carbon footprint at the neighbourhood scale in an explicit manner. The carbon footprint per person was calculated as:

\[ CF = \sum_{i=1}^{n} CF_i \]  (1)

Where: \( CF \) is the total carbon footprint of the site; \( i \) is individual land use category; \( n \) is the total number of land use categories (\( n = 8 \) in this study - 1) Residential, 2) Industrial and commercial, 3) Civic and institutional, 4) Agricultural, 5) Forest, 6) Grassland, 7) Wetland, and 8) Transport); \( CF_i \) is the individual land use type on the site.

Considering the fact that there are different sub-types in each land use category (e.g. different housing densities under the residential category, or different tree densities under the forest category), \( CF_i \) is calculated as:

\[ CF_i = \sum_{j=1}^{k} CF_j \times E_j \pm A_j \]  (2)
Where: \( j \) is individual land use sub-type; \( k \) is the total number of sub-types in one land use category; \( CF_j \) is the carbon footprint of the land use sub-type \( j \) for the land use type \( I \); \( E_j \) is the equivalence factor for cross site comparisons, which deals with situations where the carbon sequestration or emission rate for the same sub-type of land use may be different for different project sites; \( A_j \) is the adjustment factor considering local ad hoc events (such as a local bushfire) that may affect the carbon sequestration or emission of the site.

Integrating Equations (1) and (2), \( CF \) is calculated using Equation (3) as follows:

\[
CF = \sum_{i=1}^{n} \sum_{j=1}^{k} CF_{ij} \times E_{ij} \pm A_{ij}
\]

In this study, carbon footprint information is adapted from published average carbon flux (see Table 1 for details).

<table>
<thead>
<tr>
<th>Land use type</th>
<th>Carbon Footprint (± t C ha(^{-1}) yr(^{-1}))</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential</td>
<td>+ 120</td>
<td>Floyd, 2012</td>
</tr>
<tr>
<td>Commercial and industrial</td>
<td>+ 894.9</td>
<td>Rothberg, 2011</td>
</tr>
<tr>
<td>Civic and institutional</td>
<td>+ 60.4</td>
<td>Alvarez et al., 2014</td>
</tr>
<tr>
<td>Agriculture(^{c})</td>
<td>- (1.5-2.4)</td>
<td>IPCC, 2000</td>
</tr>
<tr>
<td>Forest</td>
<td>- (2.5-7)</td>
<td>Valentini et al., 2000</td>
</tr>
<tr>
<td>Water</td>
<td>- (0.2-0.4)</td>
<td>IPCC, 2000</td>
</tr>
<tr>
<td>Grassland, park, open space</td>
<td>- (0.7) - (+0.2)</td>
<td>Parton et al., 1995; Chen et al., 1999</td>
</tr>
<tr>
<td>Wetland, riparian lowland</td>
<td>- (0.4-0.8)</td>
<td>IPCC, 2000</td>
</tr>
<tr>
<td>Transport</td>
<td>+ 29.3</td>
<td>Zhang et al., 2014</td>
</tr>
</tbody>
</table>

\(^{a}\) Assuming no leakage outside the project boundaries and no emissions from carbon stocks in the soil; 
\(^{b}\) + denotes carbon source, and – denotes carbon sink; 
\(^{c}\) CO\(_2\) fertilisation effect in agriculture land is considered (at current rates of increase of CO\(_2\) in the atmosphere) to be 0.036 t C ha\(^{-1}\) yr\(^{-1}\) (van Ginkel et al., 1999)

4.2. Carbon footprint of the three urban development scenarios

The plans for the three development scenarios were digitised in GIS and used as input data for Equation (3) to simulate the carbon footprint under each scenario. Ancillary data such as remote sensing imagery and GPS readings are used to improve accuracy in digitising site-specific land use types such as industrial and commercial land use, and civic and institutional land use. Model outputs are presented in terms of spatial distribution patterns and annual carbon footprint for the entire suburb and for dwelling units.

4.2.1. Spatial pattern of carbon footprint

The carbon footprint for each scenario is simulated and mapped using ESRI ArcGIS package. Results show that for all three scenarios, carbon footprint along the Kororoit Creek area is lower, due to the fact that the water area, wetland, and vegetated riparian zones are net carbon sinks. However, activity centres and high-density residential areas have the higher carbon footprint due to intensive consumption of energy and resources. Based on the simulation results, the vertical scenario has the
lowest carbon footprint (526,167 t C per ha per year), while the BAU scenario has the highest carbon footprint (603,533 t C per ha per year).

4.2.2. Total carbon footprint and average carbon footprint per dwelling unit

In terms of average carbon footprint per dwelling unit, the vertical scenario has the lowest value, while the BAU scenario again has the highest footprint, indicating the BAU scenario’s carbon and environmental performance leaves considerable scope for improving sustainable urban growth and management. Total carbon footprint for the suburb, number of dwelling units, and carbon footprint per dwelling units under the three scenarios are summarised in Table 2.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Total net carbon footprint (t C per ha per yr)</th>
<th>Total dwellings</th>
<th>Average carbon footprint per dwelling (t C per ha per yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAU</td>
<td>603,533</td>
<td>17,150</td>
<td>35.2</td>
</tr>
<tr>
<td>Vertical</td>
<td>526,167</td>
<td>17,496</td>
<td>30.1</td>
</tr>
<tr>
<td>Mixed</td>
<td>587,126</td>
<td>18,010</td>
<td>32.6</td>
</tr>
</tbody>
</table>

As evidenced by this study, the vertical scenario, in which high-density housing development consumes less land with a larger portion of land on the site used for agricultural or other productive land uses, has the lowest footprint. The agricultural and productive land uses can assimilate carbon in the atmosphere. The removal of carbon dioxide from the atmosphere by forests and other vegetation also provides an important carbon sink. Thus, development based on land clearing (such as greenfield development) must be carefully considered in order to minimise the carbon footprint of urbanisation. However, the validity of the vertical scenario is yet to be tested on unique sites integrating and balancing the value of the people in the place, design culture, and public affordance.
5. Discussion

5.1. Development scenarios and the flavour of urban culture

In Australian cities like Melbourne, which is a quintessential suburban city, the liveability and life style is largely “radicalised” around the low density suburb. Although climate change, global warming and other pressing issues have been affecting citizens’ lifestyles, it is not likely that Australian citizens will soon accept the urban lifestyle similar to those of the Asian cities – where the majority of the population live in high rise apartments. Therefore, the priority in the next few decades is to promote and facilitate the mixed scenario. In the second phase, the high density vertical scenario may be considered and tested in some pilot study cities. Considering its potential to decrease the carbon footprint of cities, the mixed scenario and vertical scenario have been planned or built at small-medium scales around the activity centres in established suburbs or have been planned to be built around new town centres in Melbourne (Figure 5). In the future, this practice could be adopted and used widely in Melbourne’s urban growth frontier given other urban issues - such as social problems generally associated with high-density residential land use in areas of relatively low natural and cultural amenity - are sufficiently tackled and well-integrated in design and planning. To a certain degree, development following all the three scenarios will co-exist in Melbourne.

Figure 5: Mixed-use residential, retail and office development for North Melbourne (source: buchan.com.au).

5.2. Data quality and modelling techniques

Since the simulation is based on geocoded spatial data in GIS, the quality of input data has considerable influence on the outcomes of the study. The carbon footprint data were sourced from a literature survey from various sources and for different time frames, which may contribute to errors and increase discrepancy. Data with high quality in terms of both spatial and temporal resolutions is highly desired in order to maximise the reliability of the findings. In this study, basic land use information is the primary data used to drive the model. Details and further disaggregation of sub-types within each major land use type will improve the reliability of the model outputs. Unfortunately, many of these datasets are currently not available at neighbourhood scale, which probably explains why studies alike are rare.
Modeling the carbon footprint of urban development: a case study in Melbourne

At national or regional scales, carbon accounting studies heavily rely on statistical data, which are generally useful to guide national policy making aimed at emission reduction. However, national reduction goals are to be realised through local actions such as urban planning, design and development, which are always taken at much finer (e.g. city suburb or neighbourhood) scales. Additionally, national level carbon footprint accounts ignore spatial heterogeneity, which leads to ecological fallacy in analysis. Therefore, spatially explicit carbon footprint accounting at finer scales is critical to the realisation of the ambitions of carbon-neutral cities and the implementation of low carbon development. Unfortunately there are few efforts being made in this regard so far, although similar studies have been made in water and land use footprint (Phisher and Bayer, 2014; Norman, et al, 2012). We expect this paper to fill the gap in the carbon footprint literature by applying a novel approach to account carbon footprint at the suburban neighbourhood scale.

5.3. Further improvements to carbon footprint accounting

The model demonstrated in this paper would benefit greatly from improvements to the data used in determining the carbon footprint of urban areas/development scenarios. Data typically used in life cycle assessment (LCA) can be used to provide a more detailed, and potentially reliable, analysis of carbon footprint. This may include both spatially disaggregated national average environmentally-extended input-output data (Wiedmann et al., 2014) and industry sourced process data, providing information on carbon emissions for materials, transport modes and building typologies used in the different urban development scenarios. GIS-based carbon accounting at broad scale can be integrated with LCA assessment at building or block level to construct city-wide carbon footprint assessment in a spatially explicit manner. The implication of such studies on city and regional planning is profound and priorities should be given to these emerging interdisciplinary fields in the future.

6. Conclusion

Understanding the relationship between urban density and carbon emissions is essential for low carbon development. This paper has demonstrated a model for analysing the carbon footprint of urban developments based on land use. A suburban area located in Melbourne, Australia, was used as a case study for which three development scenarios were analysed in order to identify the type of development resulting in the lowest carbon footprint. It was shown that the vertical development scenario offers the best opportunity to reduce greenhouse gas emissions in urban areas. This analysis and the findings provide useful evidence and guidance for the planning and design of low carbon communities, which collectively will help to make the dream of low carbon cities a reality.

Acknowledgements

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References


Neighbourhood Information Models: 3D digital tools supporting surveyor-architect-planner workflows

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Abstract: The City of Melbourne lacks affordable, quality and sustainable housing choices. Addressing these complex needs, professionals are currently performing information discovery, design and planning assessments with outdated tools and processes. What would be the impact of integrating disciplinary technologies of land surveyors, architects and planners into a 3D virtual place called a Neighbourhood Information Model (NIM) to assist their work leading to statutory planning approval? As NIM did not exist, qualitative and quantitative approaches were employed by the writer to explore emerging 3D sharable tools and processes. Surveys of land surveyors and architects in Victoria were conducted and professionals, researchers and software providers were interviewed. Tools explored included: 3D laser scanning, photogrammetry, Building Information Models, parametric scripting, 3D city models and Electronic Development Approval. Result themes included: tool engagement, efficiency gains, adoption drivers and limiting factors. Results show a growing professional engagement with sharable 3D digital information tools, especially for central Melbourne apartment developments. Their use was found to increase overall workflow efficiency and increase communicative and decision-making power. This paper proposes that NIM tools and associated integrated Knowledge Management processes improve practice efficiency and efficacy of built outcomes. There remains a need for further research, tool development and testing.

Keywords: 3D; BIM; eDA; NIM.

1. Introduction

This research looked specifically at apartments in central Melbourne, Australia identifying three problem areas: 1) the quantity and affordability of housing; 2) the quality, diversity and sustainability of housing; and 3) the complexities of simultaneously addressing city, neighbourhood and building concerns. The research aim was to explore how sharable 3D digital information tools and associated processes can assist with addressing these issues. The research question was: What are the impacts of emerging sharable 3D digital information tools for surveyor-architect-planner workflows in the Melbourne apartment sector? The objectives were to explore emerging tools and associated processes in terms of:
Neighbourhood Information Models: Neighbourhood Information Models: 3D digital tools supporting surveyor-architect-planner workflows

a) user engagement, b) efficiency gains, c) adoption drivers, and d) limiting factors. Following these studies, ideal tools and processes are recommended for further research, tool development and testing.

This research focuses on land surveying, architectural design and statutory planning from project inception until planning permit determination. Surveying tools explored included: 3D laser scanning and photogrammetry. Architectural tools included: Building Information Models (BIM) and parametric scripting. Planning tools included: 3D city models and Electronic Development Approval (eDA) systems. Two main concepts proposed here that bring these tools and associate processes together are: Neighbourhood Information Models (NIM) and Neighbourhood Knowledge Management (NKM).

Neighbourhood Information Models (NIM) are multi-disciplinary, multi-dimensional, object-oriented, database-driven, web-delivered, digital representations of specific functional, built and natural environment. ‘Neighbourhood’ extends beyond the subject site as required for planning permit determination (multi-site BIM). ‘Information’ is explicit enriched data that can be learned. ‘Model’ refers the instructional representations: self-navigable 3D, static 2.5D images, 2D drawings, numeric and text. Successful NIM provides information that is comprehensive, accurate, relevant, reliable and usable, thus enhancing workflow efficiency.

Neighbourhood Knowledge Management (NKM) systems effectively administer the collection, production and transmission of discovery, design and planning processes within specific, knowable socio-spatial contexts. Successful NKM is the accepted embodiment and optimal embedding of coordinated professional processes effectively.

Firstly, Melbourne, like other cities, is rapidly growing which is putting pressure on housing availability and affordability. The City of Melbourne needs to double dwelling numbers within 20 years (2011 to 2031), i.e. an additional 62,000 dwellings (City in Future 2014). Moreover, Greater Melbourne’s home ownership has become unaffordable: average home loan repayments are 32% of average household incomes (Plan Melbourne 2013). Furthermore, planning permit assessments take around 4 months (Victorian planning statistics 2013-2014): double the statutory two month limits. There are also inefficiencies in surveyor-architect-planner workflows. These delay costs ultimately get passed on to housing consumers.

Secondly, housing quality, diversity and sustainability are important issues. There is a lack of diversity in city dwellings. For example, housing for groups and a dwelling mix to cater for all ages in the neighbourhood, etcetera (Plan Melbourne 2013). Resilience issues associated with increasing extreme weather events and water, energy, storage and waste costs cannot be ignored. Moreover, the City of Melbourne’s study Understanding the Quality of Housing Design (2013) assessed 36% of their 25 built case studies of inner city apartments as having poor design outcomes.

Thirdly, simultaneously addressing city, neighbourhood and building concerns is complex. City concerns are many: economic, environmental, social, heritage, functional, infrastructure, mobility, legal, and so on. Building concerns are also many: feasibility, timing, circulation, massing, aesthetics, interiors, landscaping, sustainability, structure, services, vistas, noise, operational costs, and sale-ability to name a few. Built-environment professionals must deal with these concerns within adversarial, disciplinary silos, communicating in 2D and written descriptions, while addressing a 3D world and intuitively understanding 3D proposals better than 2D.

Meanwhile, digital tools and associated processes that can assist are expanding in reach and sophistication. However, interrelated service providers are not integrating their disciplinary tools in order to efficiently and effectively address these problems.
Following is a brief review of literature and identification of the research gap addressed. The methodology section explains how and why the research was carried out, the results sections summarises some of the key findings, and recommendations are discussed in more detail.

2. Literature review

The literature reviewed prioritised qualitative human impacts resulting from architectural technology; disciplinary technology; integration issues associated with blending Building Information Models (BIM) with Geospatial Information Systems (GIS); and Knowledge Management (KM) theory, particularly the relationship of information with knowledge. As an area not covered in the literature reviewed, this research sought to combine these fields and have particular applicability to current Melbourne residential projects.

In the literature, technology was considered as requiring technical veracity as well as cultural palatability if it was to be adopted (Loukissas 2012). Digital tools in the literature reviewed included: Virtual globes in particular ethics and benefits of use (Sheppard et al. 2007); and comparisons of 3D laser scanning and photogrammetry (Oniga 2011). Survey Information Models were proposed to integrate 3D land surveys into architectural models (Houghton et al. 2013); the rising importance of BIM (BEDMWG 2010) was evident; 3D city models used for Melbourne statutory planning (Crisafi and Guy 2013) were examined; and the problems with communication between BIM and GIS software (Randolph et al. 2010) raised. Knowledge Management (KM) theory reviewed included: the Socialisation-Externalisation-Combination-Internalisation cycle where knowledge is produced, converted to information, linked to other information, then learned. Decision-making and workflow theory (Zeleny 2005) was also explored. The value of integrating technologies and KM theory for the whole surveyor-architect-planner workflow for residential planning approvals in Melbourne is uniquely explored in this paper. Information Models (IM) for professional information delivery and Knowledge Management (KM) for process execution are described further in the Recommendations section below.

3. Methodology

The research methodology was tailored to explore emerging tools and practices across multiple fields. As such it was cross-sectional looking at cutting-edge contemporary surveyor-architect-planner practice. The research was exploratory to find trends and best practice and to make recommendations for future practice. Qualitative techniques were employed to analyse processes and get a sense of user perceptions. Quantitative techniques were used to assess user engagement and perceptions of efficiency. For future research it would be useful to set up controlled tests to get empirical efficiency data.

The research methods were project examples, interviews and surveys. Project examples established current best practice processes and offered a context for interview responses. Two projects examples of apartment towers in Melbourne were selected based on interviews and availability of data. The major statutory planners in Melbourne currently using 3D city modelling for permit assessments suggested architects and projects that best leveraged 3D models. A cross-section of 21 contributors including land surveyors, architects, statutory planning officers, researchers, digital tool providers, and property developers were interviewed. Interviews were semi-structured and purposeful with interviewees selected as field leaders or status-quo indicators for comparison. Interviews provided stakeholder tool experiences and perceptions. Surveys were conducted from a total population of 417 registered land surveyors and 3660 architects in Victoria. A sample of 31 registered land surveyors responded out of 50
randomly invited and 51 architects responded out of 96 randomly invited, with a general response rate of 62% and 53% respectively. Using a confidence level of 95%, this equated to a confidence interval of 16.9 for land surveyors and 13.6 for architects. Surveys highlighted engagement with tools and process efficiencies. The results provide a value case for NIM.

4. Results

Results suggest Victorian land surveyors all collect 3D data, 61% of architects use 3D digital models for the majority of early stage projects, while very few statutory planners use 3D. Total stations collected data by 81% of surveyors for a majority of their projects, while only 4% use 3D laser scanners for the majority of their projects. Object-oriented (BIM) modelling is used by 38% of architects for most of their schematic design and planning approval projects, with 25% using 3D surface modelling. Victorian State statutory planners (DELWP) require 3D city models for all planning permit applications. Although best practice surveyors, architects and planners use sharable 3D digital tools, sharing 3D information is generally infrequent and only one way. Only 5% of architects get 3D surface models and 5% get object-oriented models from land surveyors. Outside the City of Melbourne, other authorities in Greater Melbourne do not accept 3D digital models for statutory planning. However, there are movements towards higher 3D tool engagement and 3D information sharing by all stakeholders.

Tool capacity identified does or could handle most planning concerns. Architects interviewed used 3D parametric modelling to test built form and internal amenity. 3D models were used by planners to assess materials, sunlight to public spaces and vistas to key monuments. 3D simulations tested impacts of natural light, ventilation and noise. External amenity, public realm, storage, parking, utilities and waste could all productively use 3D. Effectively NIM could address all planning compliance requirements, exception for a few specialist fields like physical model wind tunnel tests.

Overall efficiency was improved with shared 3D digital information for surveyor-architect-planner processes. Surveyors laser scan 3D onsite quicker than total stations and collect more data preventing multiple site visits. Architects bring 3D point clouds from laser scans directly into their tools and use parametric processes to test alternatives rapidly. Shared 3D digital information brings effort forward in time for more impactful decisions. 3D is easier to understand than 2D and text, allowing quicker feedback. Automation and digital interoperability improve efficiency. Users controlling navigation of models in real time is more efficient than requesting views. A 3D collaborative approach speeds up performance-based planning and evaluation of alternatives. Web-portals for lodgement, referrals, progress tracking, notifications and electronic stamping is more efficient than hardcopies and post.

From the research it is clear that more work needs to be done to make the tools more relevant, usable, accurate, comprehensive, reliable, inclusive, and integrated. The interviews highlighted legitimate limitations: personal preference, recruitment, 3D enabled staff availability, training, cultural, communication, political, legal, financial, project deadline pressures, computer processing power, software functionality, file sizes, internet speeds and other factors that need to be overcome for NIM-type technology to be widely adopted.

5. Recommendations

From the results it is likely that NIM adoption would improve: the quantity and affordability of housing by making professional practice more efficient; the quality, diversity and sustainability of housing by making practice more effective; and mediating practice complexities by being more integrated. For
successful NIM implementation the above limiting factors should be addressed. The Cooperative Research Centre for Construction Innovation suggests that technology advancement requires: “digital communication”, a “single platform” and “trust” (BEDMWG 2010). 3D digital information must be shared both ways between land surveyors and architects, architects and planners, through a single 3D information model that integrates workflow partners’ inputs and outputs - NIM. It is important for people to trust in the abilities and progressive improvement of professionals and technology overtime.

5.1. Recommendation 1: trust in professional and technological advancement

Trust entails getting over legal and risk related fears that people might steal Intellectual Property (IP), invade privacy or sue over errors. As Information Models become more sophisticated, legal rights, responsibilities and restrictions become easier to define. People’s ability to steal IP lessens when meta-data proves authorship. Meta-data also makes errors traceable. By only allowing registered land surveyors to submit surveys, architects to submit designs, and statutory planning to do the endorsing, Professional Indemnity insurance can cover errors, thus mediating risk. Privacy is protected through secured access portals and model partitioning. Moreover, 3D requires the same legal standing as 2D. Standards can also change to meet the added sophistication enabled by these advanced simulation tools – such as shadows incorporating lux levels in planning controls – thus leading to better built outcomes.

Technology advancement requires a bottom-up and top-down commitment to 3D integrative practice, commitment to infrastructure and skills investment, and staff and workflow partners recruited based on demonstrated knowledge of these integrative 3D tools. Short, medium and long-term commitment with strong leadership, pilot projects, research, protocols and staff buy-in is required so immediate project pressures do not derail NIM implementation. Financial burdens of knowledge-based, organisational, and technological capital should depreciate and return on investment overtime.

Figure 1: Levels of Accuracy versus Levels of Usability (Author).

Figure 2: Discretion versus originality to establish human or computer roles (Author)
5.2. Recommendation 2: develop and adopt appropriate accuracy and usability

File sizes of 3D models constrained by hardware performance can be improved by making software applicable to the task at hand; low Level of Accuracy (LoA) when broad urban scope, and high LoA when detailed building scope. Models can be very detailed, but if they are not accurate then they cannot be relied upon. The other side of this coin is usability; if high LoA then file size is also high, slowing computer processing, making software unusable – low Level of Usability (LoU). Upgrading systems to cope with high LoA while still having high LoU is too expensive. Figure 1 combines these concepts of LoA versus LoU, with the ‘sweet spot’ where technology is sufficiently affordable, fast, usable and accurate.

5.3. Recommendation 3: prescriptive controls automated and performance discretion

Planning permit applications assessed against prescriptive controls should be automated leaving original or controversial applications to be assessed manually with performance controls. Planners should implement 3D online planning support (eDA) for lodgement, referrals and notifications speeding up document management with repetitive, deemed-to-satisfy code checking automated. Digital tools cannot replace the human empathy and creativity required to design and administer city plans, however
they can reduce administrative work so people can focus on the empathetic and creative work required. Figure 2 shows human involvement limited to high checker discretion situations where the proposal is outside standards.

5.4. Recommendation 4: single discipline platform with NKM and NIM workflow cycles

Figure 3 shows Specialists and Generalists employing their wisdom to direct professional processes, using their digital tools (applications) executed with Knowledge Management (KM) techniques, producing Information Models (IM) that are relevant and communicable through the workflow. This system merges: Nonaka’s Socialisation-Externalisation-Combination-Internalisation cycle; Zeleny’s taxonomy of knowledge (Zeleny 2005); and observations of workflow generalists and specialists. The cycle entails: actors sharing experiences – socialisation; KM tools output to IM – externalisation; IMs join – combination; IMs can input into others’ KM systems – internalisation. Generalist feedback goes to previous stages or associated Specialist or is sent forward to the next stage once ready. The process requires human input for: training, pragmatism, creativity and empathy. There is two-way communication with planning and design feedback from: third parties, workflow contributors, other workflow stages and other projects. Integration of catenary actors appreciates and influences prior and subsequent work.

5.5. Recommendation 5: integrated approach with more effort in strategy

Long-term processes are transformed by NIM and NKM, thus contributing to easing of service delivery complexities. This is about being holistic, where strategic processes produce greater outcome harmony for stakeholders. Figure 3 shows new process stages as: 0) **planning strategy** (pre-project) – strategic planners and stakeholders model preferred neighbourhoods, 1) **project discovery** – developers and surveyors compile project information and formulate briefs, 2) **project design** – architects approve building designs, propose alternatives or make adjustments, and 3) **planning approval** – statutory planners endorse designs that deviate from pre-approved deemed-to-satisfy standards only. The majority of planning resources go into strategic planning instead of statutory. More efficient and effectual design and planning processes result from work and agreements made prior to architecture projects thus integrating all neighbourhood projects, not just integrating disciplines. Continuous strategic effort by all stakeholders is input into a single web-hosted platform where all stakeholders can access a single point of truth – NIM – or move towards this end. Figure 4 shows that NIM-enabled integrated Generalist effort is less during the project cycle but about the same as traditional project effort overall. This is due to continuous effort during the strategic planning phases. Where strategic input increases, so does the chance for all stakeholders of getting better built outcomes than might result from a condensed effort during a project under traditional fragmented processes.
The tool and process recommendations above are preliminary and have not been tested in practice. They are based on studying trends from a recent literature review, project examples, interviews and surveys. Therefore, further research, technology development and testing should occur. Action research could document recommended NIM implementation and their effect longitudinally within practices. Case studies can look at practice processes in more depth. Technology testing could be done in controlled environments like universities. There could also be further research into the tools used by and desired by strategic planners, property developers, referral authorities and third parties. The integration of NIM and ecological sustainability could explore energy, heat, light, ventilation and water systems as well as flora and fauna. The extension of NIM (know-what) and NKM (know-how) is Wisdom Strategy (know-why) that is about ethics and a holistic approach could be further explored.

6. Conclusion

In Melbourne, Australia, amidst the professional service delivery complexities of addressing rapid population growth and shortages of affordable, appropriate, sustainable housing choices, there pervades sluggish project turnarounds, fragmented dispositions with out-dated tool use and processes. Governments, academia and industry are investigating ways to overcome these problems using integrated 3D digital information tools and processes.

Other researchers have looked into: the impact of technology on people; the capacity and benefits of surveying, architecture and planning technology; technology interoperability; the theory of Knowledge Management (KM); and barriers to IT adoption. This research proposes a NIM tool approach using KM with applicability to Melbourne residential towers. A qualitative and quantitative approach was employed to a cross-section of actors. A project example was used to establish current practice and give context to interview results. Interviews gave professionals’ opinions of applications. Land surveyor and architect surveys highlighted engagement with 3D digital tools and perceived efficiency gains. Professional engagement with sharable 3D digital information tools is growing and their use has increased workflow efficiency. The results of this study showed tools relevant to NIM increased decision-making and communicative power. There are solutions to overcome limiting factors of NIM adoption.
Further research, tool development and testing could develop a stronger case for a NIM approach which will likely improve the following problems: 1) quantity and affordability of housing by making professional processes more efficient; 2) quality, diversity and sustainability of housing by being more effective; and 3) service delivery complexities by being more integrated. With ‘trust’, industry could adopt a NIM approach in the following steps: 1) automational – the ‘know-what’, quantitative, prescriptive, current processes automated; 2) informational – the ‘know-how’, qualitative, performance-based, decision-making processes streamlined; and 3) transformational – the ‘know-why’, holistic, strategic processes harmonised. In conclusion, NIM has the potential to: establish a reliable basis for decision-making; increase efficiency and streamline professional and bureaucratic processes; bring decision-making forward in time for greater design impact; make automation possible freeing time for more creativity and empathy; and to be more pro-active and strategic.

References

Abstract: This paper describes those principles of the new UK construction-sector classification system, Uniclass 2015, which are specifically intended to serve built-environment information modelling (BIM). Though only seven tables have been officially published at the time of writing, others have been published in draft for comment, and others have been drafted. This paper cuts across them all. Basic requirements for the classification system were spelled out in a ‘functional specification’, which was developed some time after the first ten tables had been published in draft. Uniclass 2015 at that point already met all but one of these requirements, and had developed a number of other principles not identified in the functional specification.

Keywords: Classification; Uniclass 2015.

1. Introduction

If all construction project information is to be held centrally, for access by all along the entire project timeline, as it is in built-environment information modelling (BIM), then this information should be organised using a classification system that supports these needs. Existing classification systems, such as Uniclass 1997 (CPI, 1997) and the North American OmniClass (CSI/CSC, 2006 to 2013), do not fully support them, though they could be bent to this purpose. Critiques on the two have been published (Gelder, 2011 and 2013 respectively).

The framework for such a classification system is described in ISO 12006-2:2015 Building construction – Organization of information about construction works – Framework for classification, for which the author was the UK expert. By 2006 the author had begun to devise a classification system that would eventually implement and extend this standard. The author developed this system, now known as Uniclass 2015, with input from colleagues at RIBA Enterprises, and others, in the UK to mid-2014. For an outline of its development, see Table 1 (and Gelder, 2015). Unlike Uniclass 1997 and OmniClass, it is unified, and aligns to the ISO.

At that point the UK government commissioned a competition for the development of a classification system, using a ‘functional specification’ to brief the work (SBRI/TSB, 2014). The team
proposing to run with Uniclass 2015, led by RIBA Enterprises, for which the author was working at the time, won the competition.

Table 1: The development of Uniclass 2015.

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<td>Development of ISO 12006-2:2015</td>
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</table>

This team developed it further, particularly to better deal with transport and utilities infrastructure, and the first official tables were published in 2015 (RIBA Enterprises, 2015). Uniclass 2015 is now the UK Government’s official construction sector classification system, and is a part of its BIM Level 2 resource set. It is being used already in a several UK BIM tools, and a number of Australian organisations have expressed an interest in it.

For this paper, which explores some of the principles of Uniclass 2015 relevant to BIM, the author has used mostly published material in the public domain, but brought up-to-date, rather than unpublished documents internal to NBS, as the basis for discussion.

As a classification system, Uniclass 2015 comprises a number of tables, each dealing with a different object class. Seven of those tables have been published for use, but others have been published in draft, and others have been developed to varying degrees. This paper refers to them all, but readers should be aware that some of the published tables are quite different to the published drafts for which the author was primarily responsible. This paper describes the author’s own views. Table 2 shows these tables, against those identified in ISO 12006-2, and those in OmniClass. It can be seen that Uniclass 2015 extends both in scope (on Work results, see 9.2).

The largely after-the-fact ‘functional specification’ had seven main requirements for the classification system, discussed in order:

- Digital, quick to use, and free.
- Unified.
- Cross-sector (e.g. buildings, geography, infrastructure), cross-discipline, cross-role and cross-purpose.
- Full asset lifecycle (e.g. development, use, FM, demolition).
Consider legacy classification systems.
Integration with barcoding.

### Table 2: The classification tables in Uniclass 2015.

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>A.2 Construction information</td>
<td>Form of information</td>
<td>Table 36 Information</td>
</tr>
<tr>
<td>A.3 Construction products</td>
<td>Products (published)</td>
<td>Table 23 Products</td>
</tr>
<tr>
<td>A.4 Construction agents</td>
<td>Agents</td>
<td>Table 41 Materials</td>
</tr>
<tr>
<td>A.5 Construction aids</td>
<td>Construction aids</td>
<td>Table 33 Disciplines</td>
</tr>
<tr>
<td>A.6 Management</td>
<td>Project management (draft)</td>
<td>Table 34 Organizational roles</td>
</tr>
<tr>
<td>A.7 Construction process</td>
<td>Project phases (draft for comment)</td>
<td>Table 32 Services</td>
</tr>
<tr>
<td>A.8 Construction complexes</td>
<td>Complexes (published)</td>
<td>-</td>
</tr>
<tr>
<td>A.9 Construction entities</td>
<td>Entities (published)</td>
<td>Table 11 Construction entities by function</td>
</tr>
<tr>
<td></td>
<td>Activities (published)</td>
<td>Table 12 Construction entities by form</td>
</tr>
<tr>
<td>A.10 Built spaces</td>
<td>Spaces (published)</td>
<td>Table 13 Spaces by function</td>
</tr>
<tr>
<td>A.11 Construction elements</td>
<td>Elements (published)</td>
<td>Table 14 Spaces by form</td>
</tr>
<tr>
<td></td>
<td>Systems (published)</td>
<td>Table 21 Elements (includes Designed elements) (UniFormat)</td>
</tr>
<tr>
<td>A.12 Work results</td>
<td>-</td>
<td>Table 22 Work results (MasterFormat)</td>
</tr>
<tr>
<td>A.13 Construction properties</td>
<td>Properties</td>
<td>Table 49 Properties</td>
</tr>
<tr>
<td></td>
<td>Modelling (draft for comment)</td>
<td>-</td>
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</tbody>
</table>

### 2. Digital

Uniclass 1997 was only available in book form, and had to be paid for. CPI did not consider that it needed to be maintained. OmniClass tables are delivered online in PDF and Excel formats, with irregular updates, and are free, which is an improvement. But neither are delivered in an online digital format which would allow rapid searching across all the tables simultaneously. Uniclass 2015 has been published in such a format. The format is also designed to support search by synonym, which could be an alternative English-language term for the object in question, or a foreign-language term. This was also a requirement of the functional specification.

The functional specification recognized that a working classification system will never settle. Uniclass 2015 is dynamic. It can only realistically be published, and maintained, in an online digital format.

### 3. Unified

Existing classification systems such as Uniclass 1997 and OmniClass are not unified. Many of their tables were developed independently and do not align where they could. This is perhaps acceptable in a pre-BIM environment in which each table has just one main silo user (e.g. quantity surveyors conventionally use Elements, specifiers use Work results, manufacturers use Products). But where use of many tables is
needed by a collaborating user, as it is for BIM, this is problematic. A unified classification system, in which similar principles are used in every table, is preferred.

### 3.1. Congruence

Uniquely, the Uniclass 2015 tables are congruent. They have similar terminology, sequencing, grouping (bracketing) and coding as far as practicable. This principle is intended to make it as simple as possible to use the classification system along the timeline, i.e. for object classes along the hierarchy. This is essential for the compositional view of modelling, in which parent objects are mapped to smaller ‘part-of’ objects, in turn mapped to their smaller ‘part-of’ objects. Once a user has learned the classification mode for one table, the chances are that it will also have been used in other tables of interest.

High-level objects are classified using the same terms and codes for functions. For example, the system has Co-30 for *Industrial complexes*, Ee-30 for *Industrial entities*, and Ac-30 for *Industrial activities*. At the lower level of Systems, we have Ss-40-30 for *Industrial FF&E systems* (i.e. 30 indicates *Industrial*). Other congruences in Uniclass 2015 include the concepts of structure, openings and coverings being applied to both fabric sub-Elements and fabric Products and, on the services side, the concepts of sources, distribution and outlets being likewise shared by sub-Elements and Products. The Project phases table and the Project management table share the concepts of phases (e.g. briefing followed by concept design) and standard activities within each phase (e.g. execution followed by verification). The Modelling framework uses the same performance requirements for high-level object classes, and another set for Entities down to Systems. The services groupings are the same from Regions down to Systems. The Elements and Systems tables align at group level. Temporary work systems align with permanent work systems. And so on.

There are no such congruences in Uniclass 1997 or OmniClass. Every table is a one-off. The critiques already mentioned give examples.

Applying this principle requires some discipline. Because of congruence, if the content of one table is changed, it is likely that the content of others will need to be changed too. This is a good check on whether the proposed change makes sense.

### 3.2. Coding

All the tables are coded numerically, with each level having two digits, with only the table identifiers being alphabetical (and meaningful, e.g. Ee for Elements). This is better than Uniclass 1997, in which tables are variously alpha-numeric, numeric or alphabetical, and the table identifiers are alphabetical with no meaning (e.g. Table J). It is a small improvement on OmniClass, in which table identifiers are numerical with no meaning (e.g. Table 22).

Within each table the object of interest (the System or the Product, for example) is always at the bottom level. This is not the case in either Uniclass 1997 (except for Tables J and K) or OmniClass. The number of levels in the various tables in Uniclass 2015 is also fairly consistent (most have 3 or 4), again unlike its predecessors: OmniClass ranges from 2 to 8, Uniclass 1997 from 2 to 7.

The code 00 is not used at all – the coding stops at the level being studied (e.g. Pr-45 rather than Pr-45-00-00-00) to indicate a collection of objects, i.e. that the user is not at the lowest level in a table’s hierarchy. This is unambiguous, unlike OmniClass where the 00 code could be a collection or an object.
3.3. One object class and one classification mode per table

Uniclass 2015 has one object class, and one classification mode, per table. Uniclass 1997 and OmniClass do not always do this. For example, in OmniClass the Spaces (by function) table also includes classification by planning type. The Spaces (by form) table includes a legal and geopolitical classification. Similarly, Uniclass 1997 Table E Construction entities offers alternative approaches to classification for buildings and bridges. Table D Facilities describes three object classes (Complexes, Entities, Spaces), but none of them completely.

4. Cross sector

A key requirement of the functional specification was that the classification system serve all sectors and so be sector-neutral. Work towards this objective had been underway since 2006, starting with a proposal for mergers of the separate building and civil tables for Elements and for Work sections in Uniclass 1997. This idea has been extended so that all tables must serve buildings and landscape, transport and utilities infrastructure, and process engineering. The first ten tables published in draft for comment had reasonable content for building and landscape, reflecting the author’s expertise, but left room for objects serving other sectors. Transport infrastructure has since been added to the seven tables that are now officially published – Complexes, Entities, Activities, Spaces, Elements, Systems and Products.

The tables in Uniclass 1997 and in OmniClass do not serve all sectors evenly (Gelder, 2011; 2013). OmniClass, for example, is skewed in the Spaces (by function) and Products tables towards healthcare. Uniclass 2015 aims to be more balanced.

A good example of sector-neutrality is the way that Products have been classified. They are not classified by sector: there are no tables, or parts of tables, for landscape products, or transport infrastructure products, for example. Nor are they classified by the Systems they serve: there are no tables for Air-conditioning products, or Walling products. Rather, Products are classified pragmatically by their function (e.g. Metal primers), material (e.g. Clay bricks), form (e.g. Centrifugal fans), or a mix of the three – generally whatever seems to make sense to manufacturers, suppliers and specifiers.

The classification system also had to serve all disciplines, roles and purposes, and so be discipline-, role- and purpose-neutral. For example, the Project phases and Project management tables recognise that procurement is not just about the construction phase, but occurs in all phases of the project. Uniclass 2015 is not an object library, a plan of work, a method of measurement, a manufacturer catalogue, or a specification. But it has to be able to be used equally easily for all these applications, and others besides.

5. Full asset lifecycle

The functional specification required the classification system to serve the entire project life cycle. This requirement has been met in a number of ways.

5.1. Object hierarchy

Uniclass 2015 sets out a continuous hierarchy of mutually-exclusive physical object classes, from Regions down to Products. This aligns roughly to the timeline: when designing, a designer starts with high level objects, such as Complexes, and ends with low-level objects, such as Products. When
constructing, one works the other way round. Builders start with Products, assemble them into Systems, which assemble into Elements, and so on.

This hierarchy is very similar to the hierarchy in ISO 12006-2:2015, and so will be found in many classification systems around the world (eventually). However it includes Regions, Districts, Complexes, Activities and Systems, unlike Uniclass 1997 and OmniClass – they do not have complete continuous mutually-exclusive hierarchies. See Table 2.

5.2. Project phases and Project management tables

The Project phases and Project management tables embody the entire project timeline, from before inception to after deconstruction, and give all phases equal status. The construction phase does not rule the classification system.

5.3. Specification

A key insight in the development of Uniclass 2015 was that the specification serves the entire time line (Gelder, 2014a). And so, the brief is a type of specification, as can be seen in ISO 9699 and its predecessor (O’Reilly, 1987). At the other end of the timeline, the operation and maintenance (O&M) manual might be better viewed as an O&M specification.

The written description for a project is not just of Systems and Products (the conventional construction specification), but also of all other object classes relevant to the project. It evolves along the timeline, with new information being added, about lower object classes, and older information, about higher object classes, becoming redundant. In traditional IT this redundant information is discarded, but in BIM it is retained in the model for future reference and back-checking.

This insight suggests that introducing a standard structure to specifications all through the timeline, based on Uniclass 2015, would be very beneficial in a BIM environment. Currently briefs, construction specifications and O&M manuals have quite different structures, creating time silos, but for no good reason. The Modeling framework provides this structure.

6. Legacy considered

The functional specification required the classification system to draw upon precursor classification systems where relevant. Uniclass 2015 drew upon ideas and concepts in a number of existing classification systems, including Uniclass 1997 and OmniClass.

The idea that the object of interest should always be at the lowest level was borrowed from Uniclass 1997 Table J, as were the groupings for services (e.g. 70 Electrical), used from Regions down to Systems. The idea of two digits per level was borrowed from OmniClass. Uniclass 1997 Table D Facilities was used as the basis for the Regions, Districts, Complexes, Entities, Activities and Spaces tables, and for FF&E Systems, in Uniclass 2015. This was key for the development of congruence.

The concepts implemented for fabric Elements were borrowed from Uniclass 1997 Table G, which has a simple set of technically-neutral fabric elements (e.g. External walls), all made up of standard technically-neutral sub-elements, e.g. Core fabric and External finishes. These ideas were extended to Elements of other kinds.

Compliance with ISO 12006-2:2015 (not actually published at the time) was a key requirement of the functional specification. The advantage of compliance is that a complying classification system from one jurisdiction should be able to have its various tables relatively easily mapped to those of another. Both will have implemented Elements, for example, using the same definition for this object class.

This standard sets out an internationally-accepted framework for classification. The author was the UK expert on the working group for the 2015 edition. This work began in 2011, before the functional specification was published. Compliance with the standard (and vice versa), which is based on the 2001 edition, was always the intention in the development of Uniclass 2015.

Uniclass 2015 was one of the first classification systems to work to the new ISO definitions. These differ from the old. For example, an Element was defined in the 2001 edition as a ‘construction entity part which, in itself or in combination with other such parts, fulfils a predominating function of the construction entity’, but is now defined as a ‘constituent of a construction entity with a characteristic function, form, or position’ – the function of an Element is no longer the only way it can be classified. OmniClass is geared to the definitions in the 2001 edition. Uniclass 1997 is aligned to older definitions, given in a precursor document to the 2001 edition.

8. Integration with bar coding

This requirement in the functional specification was wrong-headed. Bar codes are developed by manufacturers on an ad hoc basis, apart from the first few digits which represent the country in which the coding was applied. No universal classification system is used. Some individual manufacturers might have their own, but these will only be used by them. There is nothing for the Uniclass 2015 codes to map to, in other words – this would have to be done for every individual product. Furthermore, barcodes must be scanned visually by the reader. Most objects in a building or other entity are hidden, remote, or both. Barcodes cannot be overwritten, or updated, along the timeline.

However, it is possible for the classification to integrate with radio-frequency identification (RFID) tags, quite easily. This does not need mapping between Uniclass 2015 and whatever classification is used in the RFID tag. Depending on the type of tags, they can be written with data from the BIM, using the open-BIM IFC file format if desired. The Uniclass 2015 code can be held directly in the RFID tag. Furthermore, RFID tags don’t have to be visible to be accessed, and can be accessed remotely, depending on the size of the tag (or aerial). They are much better suited to ID labelling of objects in a building than barcodes. They can also be overwritten, or updated, along the timeline. At deconstruction it is therefore possible for the RFID tag to hold a potted history of that object. This idea has been demonstrated live (Swift et al., 2015).

9. Other principles

At this point the paper examines some minor requirements of the functional specification, and looks at some other principles developed for Uniclass 2105 (Gelder, 2014b).

9.1. Procurement neutrality

Uniclass 2015 takes the view that a clay brick is a clay brick. It does not have separate classifications for the various routes by which a clay brick (or a classroom, or any other object) might be procured. This
means that concepts such as imported, locally-sourced, second-hand, off-the-shelf, factory fabricated, hand-made and site-made are treated as properties of the object (along with colour, density and so on).

Likewise the Project phases table is neutral in terms of whether the project is of the traditional construct-only kind, design-and-construct, construct-and-Soft-Landings (BSRIA, 2014), design-construct-operate-transfer, or any other permutation of procurement. The table accommodates them all. This applies also to the Modelling framework, and the Project management table.

Uniclass 2015 is also scale-neutral. Products can be tiny (a staple) or huge (a tree), as can Entities (a garden shed, or The Pentagon). A rigid approach to granularity is not driving the classification system.

9.2. Work results and Modelling

Uniclass 2015 is perhaps unique among construction-sector classification systems in that it does not have a Work results table. This traditionally describes the work of the building trades, by describing Systems and their Component products in the one section, and so is a basic component in construction specifications. It is replaced in Uniclass 2015 by the separate tables for Systems and Products, where Systems are typically executed by trades. Because all the object classes are mapped formally, and digitally, to their children, using the Modelling framework, the traditional Work sections table, which combines Systems and Products in an informal way, is redundant.

However, NBS Create (a BIM-ready specification library produced by RIBA Enterprises), which implements the Modelling framework, allows the specifier the choice of views: separate Systems and Products sections (with no repetition of Products common to several Systems), or combined Systems and Products sections, the traditional ‘work sections’ view, with repetition of Products common to several Systems. These are simply alternative views of the same BIM-ready database.

The ISO recognizes that ‘work’ is much broader than the business of the construction trades. For a given project, it includes pre-design work, design work and maintenance work too. Design work starts with Regions, in principle, and drills down the object class hierarchy, as has been noted. Construction work doesn’t stop with trades (Systems and their component Products). After all, the combined trades efforts result in Entities such as buildings and bridges, and built collections of these, with all the interstitial landscape, aggregate to Complexes, and so on all the way up to Regions. So specification sections for all these object classes, along with associated geometry, describe ‘work’. The ISO recognizes this. The traditional trades view of a project – Work results (as implemented in the 2001 edition of the ISO, in OmniClass, and in Uniclass 1997) – doesn’t cut it for BIM.

The Modelling framework deals with part-of relationships (children are ‘part of’ their parents) so, strictly speaking, is not a classification table, classification being about type-of relationships, as the ISO makes clear. The framework is, properly, outside the scope of the ISO. However, the concept of a Modelling framework is not an unusual idea. For specifications it equates to the widespread idea of a standard section structure for construction specifications, seen in implementations of the North American SectionFormat (not a part of OmniClass – CSI/CSC, 2009), in NBS Create (this standard section structure is embedded in the Modelling framework), and in other specification libraries such as NATSPEC in Australia.

9.3. Migration and mapping

The functional specification required legacy classification systems complying with the ISO to be mapped, and in due course migrated, to Uniclass 2015. Facetiously one could argue that none of the legacy
systems comply with the ISO, but this is unhelpful. However, mapping between even compliant classifications is not easy. Many-to-many correspondences (e.g. one system has classifies adhesives by function, another by materials) are inevitable, and render such mappings near to useless in terms of exchange of information.

The nub of this is that, sooner or later, tools in the UK such as plans of work, manufacturer catalogues, solid object modelling software, specifications, and methods of measurement must be reclassified to Uniclass 2015. Accordingly RIBA Enterprises has begun this work for NBS Create, the NBS National BIM Library, the IHS Construction Information Service, and RIBA Product Selector.

9.4. Unambiguous classification

The functional specification required that there be no ambiguity in Uniclass 2015. A good example is that of windows. They cannot simultaneously be an Element, a System and a Product (as estimators, specifiers and manufacturers would conventionally have). Objects can only be of one class – there can be no inbuilt silos. In Uniclass 2015, windows are classed as a System. Their components (frames, glass, sealant, handles) are Products. They correspond to the technically-neutral sub-Element, External wall operable openings, in turn a part of a technically-neutral Element, an External wall.

An example of ambiguity in Uniclass 1997 is the Element ‘external lighting’ which is found in two tables (G and H) at least five times. It occurs just once in Uniclass 2015 (in the June 2013 draft – the published version does not include services)

Uniclass 2015 avoids the use of ‘other’ or ‘miscellaneous’ or ‘mixed-use’. These are useful for filing perhaps, but not for classifying (Borges, 1952; Banks, 2007). Uniclass 2015 also only classifies an object in one way in a given table. For example, it has PVA adhesives (classified by material), but not also Tiling adhesives (classified by application or parent System). Compare this with glass sheets in Uniclass 1997, for example – classified by manufacture (e.g. toughened), function (e.g. safety) and finish (e.g. coloured) in Table L.

9.5. Human and machine readable

This was a requirement of the functional specification. Annotations in Uniclass 2015 use both words (human-readable) and codes (machine readable), both standardized. Both are needed. Typos in the code wouldn’t otherwise be detected or corrected, and the codes by themselves convey no information to human readers. On the other hand, the words alone wouldn’t tell users where to find the object in the classification system, and hence in the model – codes are needed for this.

The codes can be extended to deal with types and instances (project-specific, and beyond the role of Uniclass 2015), as well as classes.

9.6. Numbering

Numbering in Uniclass 2015 is not consecutive – gaps are left to allow for some future additions to the classification. Each level in a table can have up to 99 members, though in practice around 20 members is considered ‘full’. At the bottom levels in each table, objects are set out in alphabetical sequence (rather than random, or first-in-first-listed, or ‘technical logic’). This means that Brass widgets are followed by Steel widgets (under B and S), rather than Widgets, brass being followed by Widgets, steel (under W).
The numbering takes account of letter usage in English as far as possible, e.g. more room is left for words beginning with ‘S’ than for words beginning with ‘Z’.

9.7. Schema

There are many other principles, but the Uniclass 2015 schema seems a good one to end on. It maps to the schema in ISO 12006-2:2015, and is fairly simple. The most complicated idea is that an Entity can have three classes of children – Activities (client view), Spaces (designer view) and Elements (constructor view). Space data sheets are used to model Spaces to their component Activities and Systems.

A final note is that it is possible in the schema for an object of one class to have just one child object in another. A good example is a dry stone wall. It is an Element (External free-standing wall), with just one sub-Element (External free-standing wall structure) comprising just one system (Dry stone walling system), executed by a specialist trade using just one Product (Site-found stones)!

10. Conclusion

Uniclass 2015 has been developed as a classification system for building information modelling. Existing classification systems, such as Uniclass 1997 and OmniClass, were not suitable. In order to serve this sophisticated need, the classification system has been kept as simple as possible. The principles described in this paper indicate how this has been achieved.

Uniclass 2015 came out of its public beta stage on 9 October 2015 and, with the rest of the NBS BIM Toolkit, ‘is ready for full project use’. It will continue to develop as the UK’s official classification system for the construction industry, with the expectation that it will find its way overseas, e.g. through international adaptions of NBS (and other) tools using Uniclass 2015, such as the NBS BIM Object Standard (NBS, 2015), or though projects carried out by British organizations overseas, using the various UK BIM standards such as PAS 1192-2:2013 Specification for information management for the capital/delivery phase of construction projects using building information modelling, the Toolkit and Uniclass 2015.

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Buildings and Energy
A life cycle assessment approach to improving the energy performance of housing: a case study

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Abstract: The aim of this study was to conduct a streamlined life cycle assessment (LCA) to identify the global warming potential (GWP) of a single-storey residential house (283 m² floor area) located in Melbourne, Australia. Evaluation of the initial design through a life cycle assessment approach was used to inform further improvements to the house across its initial construction, operation and maintenance stages with the aim of reducing its global warming impact. An input-output-based hybrid approach was used to calculate embodied energy of building materials and components based on a bill of quantities. IES-VE software was used to estimate operational energy demands of the house. Energy demand was converted into carbon dioxide equivalent (CO$_2$-e) using emissions factors to determine global warming potential. Based on the initial design, the total life cycle energy demand of the house was 18,758 GJ (66 GJ/m²) and the initial global warming potential a significant 1,474 t CO$_2$-e (5.2 t CO$_2$-e/m²). The operational stage contributed 83% to the total global warming potential of the house. The redesign of the house focused on improving passive thermal performance using materials and systems readily available in the construction industry. Total life cycle energy demand was reduced by 29% to 13,238 GJ (47 GJ/m²). The initial global warming potential decreased by 29%, down to 1,039 t CO$_2$-e (3.67 t CO$_2$-e/m²) for the redesigned house. The study highlights the potential for further improvements and the need for alternative construction materials and technologies in the local construction industry.

Keywords: Life cycle assessment; embodied energy; housing.

1. Introduction

Residential energy use in Australia is significant and continues to increase due to an expanding population. According to EPA Victoria (2008), housing and residential energy use represents 5% and 16% of Victoria’s ecological footprint, respectively. Therefore, selection of building materials and systems must consider how they affect the embodied energy and operational energy demands of a building. The aim of this study was to assess the global warming potential of a typical new detached residential building across its initial construction, operation and maintenance stages using a streamlined life cycle assessment approach. Life cycle assessment (LCA) is a tool used to identify and evaluate the loads and
impacts imposed on the environment by a particular product. This includes effects linked with processes upstream in the supply chain (Curran, 1993). LCA includes every stage of a product’s life cycle, from raw material extraction to its final demolition and disposal. Operational functions and building elements with the most significant energy demands were then identified and redesigned to minimise global warming potential using construction materials and systems readily available in the local market.

2. Case study house

The study analyses a single-storey, detached residential building located in Melbourne, Australia. The floor area is 283 m², similar to the national average size of 248 m² (ABS, 2010). The house has three bedrooms, a pergola and detached garage and is typical of new housing constructed in Australia.

Figure 1 shows a 3D visualisation of the house. Construction materials used are listed in Table 1.

3. Research Method

3.1. System boundary

Figure 2 indicates the stages included within the system boundary of the study. Energy demands for all stages of the building life cycle are included except for demolition as this has been shown to be an insignificant component of a building’s life cycle energy demand and most difficult to accurately determine. The operation stage includes energy for heating, cooling, lighting and appliances. Excluded from this study are the landscaping elements and fitout items such as cabinetry, sinks and plumbing.
3.2. Life cycle embodied energy and emissions

An input-output-based hybrid approach developed by Treloar (1997) was used in this study to achieve a more comprehensive assessment of embodied energy as it accounts for data gaps that tend to exist in a traditional process analysis (Crawford, 2011).

Embodied energy was calculated based on a bill of quantities established from the set of working drawings. Published embodied energy coefficients from Crawford (2011) and Hammond and Jones (2011) were then multiplied by the quantity of materials to determine initial embodied and recurrent embodied energy. Recurrent embodied energy was calculated based on the average service life data for the materials contained within the house. The initial embodied energy of each material was multiplied by the number of replacements required during the 50 year period of the study. The sum of initial and recurrent embodied energy then results in total life cycle embodied energy over 50 years.

Direct energy for the construction process and a remainder value to account for data gaps associated with sideways truncation of the system boundary were then added to the above embodied energy values. Using input-output analysis, direct energy was calculated based on the cost of the house and the direct energy intensity of the Residential Building sector (ABS, 2001). A direct energy figure of 64 GJ was calculated.

The remainder value was determined by subtracting the total energy intensity of all pathways from the input-output model covered by the embodied energy coefficients from the total energy intensity of the Residential Building sector (10.633 GJ/A$1000) and multiplying the sum of remaining pathways by the estimated cost of the house ($183,950).

Total life cycle embodied energy was converted into greenhouse gas emissions to determine global warming potential. A conversion factor of 60 kg CO₂-e/GJ of embodied energy was used as per previous studies (e.g. Treloar, 2000), based on the average fuel mix and emissions intensity of Australian energy supply.

3.3. Operational energy and emissions

The IES-VE plug-in for SketchUp was used to determine the amount of energy required during the operational stage of the house over a period of 50 years. Primary energy values (GJ) were calculated using a conversion factor of 3.4 for electricity and 1.4 for natural gas (Treloar, 2008). As recommended for Victorian households (AGO, 1999), constraint factors of 0.45 and 0.4 were then applied to predicted heating and cooling energy loads, respectively, to reflect occupancy levels and zoning. Operational primary energy was then multiplied by emission factors (Department of Climate Change, 2008) and global warming potential factors (IPCC, 2007) to determine the total operational energy-related emissions and global warming potential.

3.4. House redesign

The findings of the initial life cycle energy analysis were used to inform the redesign of the house. An iterative design process was used to inform the redesign process in order to reduce the life cycle energy and global warming potential of the original house. A focus was placed on optimising passive thermal performance in conjunction with life cycle embodied energy. The redesign was based on the use of currently available materials and construction technology with consideration of a typical client’s demands and budget.
4. Results

4.1. Embodied energy and emissions of initial house

For a 50 year period, the initial house was found to have a life cycle embodied energy demand of 4,219 GJ resulting in an estimated 253 t CO₂-e emissions. Table 1 shows a breakdown of the embodied energy and related emissions of the house, by element.

<table>
<thead>
<tr>
<th>Element</th>
<th>Materials</th>
<th>Life cycle embodied energy (GJ)</th>
<th>Life cycle embodied emissions (t CO₂-e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finishes</td>
<td>Wool carpet, paint, plasterboard</td>
<td>964.90</td>
<td>57.89</td>
</tr>
<tr>
<td>Substructure</td>
<td>Reinforced concrete</td>
<td>842.00</td>
<td>50.52</td>
</tr>
<tr>
<td>Roof</td>
<td>Colourbond, softwood structure</td>
<td>828.70</td>
<td>49.72</td>
</tr>
<tr>
<td>Wall</td>
<td>Brick veneer</td>
<td>361.89</td>
<td>21.71</td>
</tr>
<tr>
<td>Windows</td>
<td>Single glazing</td>
<td>103.70</td>
<td>6.22</td>
</tr>
<tr>
<td>Doors</td>
<td>MDF, aluminium</td>
<td>91.74</td>
<td>5.50</td>
</tr>
<tr>
<td>Electrical equipment</td>
<td>Heating: Gas ducted system</td>
<td>123.60</td>
<td>7.41</td>
</tr>
<tr>
<td>Direct energy</td>
<td></td>
<td>64.00</td>
<td>3.80</td>
</tr>
<tr>
<td>Remainder value</td>
<td></td>
<td>838.44</td>
<td>50.00</td>
</tr>
<tr>
<td><strong>Life cycle embodied energy (GJ)/Emissions (t CO₂-e)</strong></td>
<td></td>
<td><strong>4,219.01</strong></td>
<td><strong>252.77</strong></td>
</tr>
</tbody>
</table>

A further breakdown of the embodied energy of the house by material (Figure 3), indicates that the steel roof sheeting, steel reinforcement in the concrete slab and the carpet are the three most significant contributors to the life cycle embodied energy. Attempts to reduce the embodied energy of the house should therefore focus initially on these materials.
4.2 Operational energy and emissions of initial house

Throughout the 50 year life cycle of the house, an estimated 14,539 GJ of primary energy is required for its operation (Table 2), resulting in and estimated 1,221 t CO₂-e emissions (Table 3).

<table>
<thead>
<tr>
<th>Use</th>
<th>Delivered energy (GJ)</th>
<th>Primary energy (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating (22%)</td>
<td>2,332.8</td>
<td>3,265.92</td>
</tr>
<tr>
<td>Ducted system (gas)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Cooling (0%)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Air conditioning (electricity)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Equipment (34%)</td>
<td>1,445.4</td>
<td>4,914.36</td>
</tr>
<tr>
<td>Various (electricity)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lighting (44%)</td>
<td>1,870.2</td>
<td>6,358.68</td>
</tr>
<tr>
<td>Fluorescent (electricity)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5,648</strong></td>
<td><strong>14,539</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Primary energy (GJ)</th>
<th>GHG</th>
<th>Emissions factor (kg/GJ)</th>
<th>Global Warming Potential</th>
<th>GWP (kg CO₂-e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity</td>
<td>11,273.04</td>
<td>CO₂ 92.7</td>
<td>1</td>
<td>1,045,011</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH₄ 0.0048</td>
<td>25</td>
<td>1,353</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>N₂O 0.0013</td>
<td>298</td>
<td>4,367</td>
<td></td>
</tr>
<tr>
<td>Natural gas</td>
<td>3265.92</td>
<td>CO₂ 51.2</td>
<td>1</td>
<td>167,215</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>CH₄ 0.0048</td>
<td>25</td>
<td>392</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>N₂O 0.0029</td>
<td>298</td>
<td>2822</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1,221,160</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.3. Life cycle global warming potential of initial house

The life cycle global warming potential of the initial house over a period of 50 years was found to be 1,474 t CO₂-e (5.21 t CO₂-e/m²) with operational energy-related emissions accounting for 83% of this. Heating accounts for the largest share of operational energy demand, but the smallest share of operational energy-related emissions due to the use of natural gas, characterised by a smaller primary energy conversion factor and emissions intensity than brown coal-fired electricity.

Based on the assessment of the initial house design and the fact that the overwhelming majority of the global warming impact associated with the house is due to operational energy demands, the chosen improvement strategies focus on reducing operational energy demand whilst at the same time ensuring that embodied energy is not considerably increased.
4.4. Redesigned house

As operational energy demand was identified as the most significant contributor to energy demand and greenhouse gas emissions, the redesign of the house focuses on passive thermal strategies while also considering strategies for reducing embodied energy via alternative construction materials and systems.

The redesign of the house used the LCA approach described in Section 3 to select construction materials and systems that would help to minimise life cycle energy demand and emissions through an iterative design and assessment process. Several design iterations were compared to select a proposal resulting in the lowest life cycle energy. To ensure an objective comparison of embodied energy and operational energy between iterative design strategies, operational energy was simulated in IES-VE by incorporating a single iteration at a time using the initial house design energy data as a base case. To save time, the operational energy shown in this comparison is in the form of delivered energy. A sample of this exploration is demonstrated below for alternative wall designs (Figure 4). Although a reverse brick veneer construction system has a higher embodied energy due to additional fibre cement cladding, the R-value improves significantly, thus reducing operational energy by a greater amount than the increase in embodied energy.

![Figure 4: Comparison of life cycle energy for external wall design options.](image-url)

The redesigned house used reverse brick veneer construction for the external walls; roof tiles in place of Colourbond steel sheeting; increased insulation levels in the floor, roof and walls; fluorescent lighting replaced with LEDs; single glazing replaced with double glazing; and carpet, steel and aluminium with a higher recycled content. All changes to the original house design are highlighted in Table 4, showing the breakdown of life cycle embodied energy and emissions for the redesigned house.
Table 4: Life cycle embodied energy and emissions of the redesigned house, by element.

<table>
<thead>
<tr>
<th>Element</th>
<th>Materials</th>
<th>Life cycle embodied energy (GJ)</th>
<th>Life cycle embodied emissions (t CO₂-e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finishes</td>
<td>Recycled nylon carpet, paint, plasterboard, ceramic tiles</td>
<td>794.80</td>
<td>47.69</td>
</tr>
<tr>
<td>Substructure</td>
<td>Reinforced concrete, (50% recycled steel), R3.0 insulation</td>
<td>906.40</td>
<td>54.38</td>
</tr>
<tr>
<td>Roof</td>
<td>Concrete tiles, softwood structure, R4.0 insulation</td>
<td>678.4</td>
<td>40.70</td>
</tr>
<tr>
<td>Wall</td>
<td>Reverse brick veneer with fibre cement sheet and R2.5 insulation</td>
<td>521.85</td>
<td>31.31</td>
</tr>
<tr>
<td>Windows</td>
<td>Double glazing</td>
<td>202.70</td>
<td>12.16</td>
</tr>
<tr>
<td>Doors</td>
<td>MDF core, aluminum-recycled</td>
<td>76.62</td>
<td>4.60</td>
</tr>
<tr>
<td>Electrical</td>
<td>Heating: Gas ducted system</td>
<td>123.60</td>
<td>7.41</td>
</tr>
<tr>
<td>Direct energy</td>
<td></td>
<td>64.00</td>
<td>3.80</td>
</tr>
<tr>
<td>Remainder value</td>
<td></td>
<td>838.44</td>
<td>50.00</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td><strong>4,206.81</strong></td>
<td><strong>252.05</strong></td>
</tr>
</tbody>
</table>

Table 5: Life cycle operational energy of the redesigned house, by use.

<table>
<thead>
<tr>
<th>Use</th>
<th>Delivered Energy (GJ)</th>
<th>Primary Energy (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating (15%)</td>
<td>948.06</td>
<td>1,327.28</td>
</tr>
<tr>
<td>Ducted system (gas)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cooling (8%)</td>
<td>205.99</td>
<td>700.37</td>
</tr>
<tr>
<td>Air conditioning (electricity)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment (70%)</td>
<td>1,872.72</td>
<td>6,367.25</td>
</tr>
<tr>
<td>Various (electricity)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting (7%)</td>
<td>187.27</td>
<td>636.72</td>
</tr>
<tr>
<td>LED (electricity)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3,214.04</strong></td>
<td><strong>9,031.62</strong></td>
</tr>
</tbody>
</table>

Improvements to the thermal performance of the building fabric reduced operational energy demand by a significant 38% and resulted in a reduction in life cycle embodied energy by 0.3%. Using the same approach for calculating the GWP associated with operational energy as in Table 3, the total life cycle greenhouse gas emissions/GWP of the redesigned house over 50 years is 1,039 t CO₂-e (3.67 t CO₂-e/m²). This is a 29% reduction compared to the initial house and enough emissions to fill the house 775 times. Figure 5 compares the life cycle GWP of the initial and redesigned house.
5. Discussion and Conclusion

This study has shown that the appropriate selection of construction materials and systems can result in a significant reduction in energy demand and global warming potential for a residential building. The life cycle analysis approach used enables a holistic assessment of the potential benefits of implementing a solution for improving building performance across every stage of the building life cycle. Both embodied and operational energy demand have been reduced through an iterative design approach. Simple strategies such as using building materials with higher recycled content (and thus lower embodied energy), improving the R-value of the building fabric and integrating more efficient lighting reduced the energy demand and GWP of the original house. These strategies are increasingly available with minimal cost implications as they are growing in popularity and are readily available in the market.
The results of this study can be benchmarked against similar previous studies. Crawford (2011) calculated an initial embodied energy figure for a similar detached house of 13 GJ/m², which compares closely with the 11 GJ/m² in this study. The operational energy-related emissions from previous studies, such as 3.4 t CO₂-e/m² over 50 years from AGO (1999) also compare closely with the figures from this study. A figure of 1.57 t CO₂-e/m² for 50 years from Crawford (2011) is lower again, but for a much more operationally efficient house, indicating that even the redesigned house has potential for further reductions to operational energy (Figure 6).

As this study was conducted based on strategies that incorporate readily available alternatives in the construction industry, it is suggested that in order to achieve the ambitious goal of net zero energy and emissions buildings, alternate construction materials and technologies not commonly used currently, and a greater proportion of renewable energy in the national fuel mix are needed.

Based on this study, it can be deduced that alternative building materials with lower embodied energy must be explored to compensate for increased embodied energy as a result of the additional insulation and glazing required to reduce operational energy demands. Traditional building products with minimal heat and chemical processing are key to minimising embodied energy in a residential design. In many cases a dying trade, it is crucial for the industry to bring these products back into the market. For instance, lime wash and lime plasters are effective substitutes for paint and cement. Another popular product is compressed stabilized earth blocks (CSEB) with interlocking shapes, discarding the need for mortar. According to Auroville Earth Institute (2015), they are estimated to require four times less embodied energy compared to standard bricks. Compared to bricks which are strengthened by heat, compressed earth blocks contain less embodied energy as they are air dried.

Natural building techniques using resources from the site itself are an effective construction method to minimise energy for logistics and raw material extraction processes. Earth excavated from the site can be used to create adobe flooring and rammed earth walls. An adobe floor is estimated to contain up to 90% less embodied energy compared to a standard concrete slab (Racusin and McArleton, 2012). Rammed earth walls on the other hand have a lower R-value compared to brick veneer and therefore still require additional insulation materials in the Melbourne climate. Rammed earth walls are estimated to contain 16% less embodied energy in comparison to standard brick veneer (Treloar et al., 2001). Consideration must also be given to the longevity of these materials and their practicality for use in modern houses.

This study highlights the considerable potential that still exists to reduce the environmental effect of buildings on the natural environment. While considerable improvements have been made over recent years, there is still a long way to go to get close to the ambitious target of net zero, or even net positive, energy and emissions housing.

References


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Hammond, G. and Jones, C. (2011) Inventory of carbon and energy (ICE) version 2.0, Sustainable Energy Research Team (SERT), Department of Mechanical Engineering, University of Bath, UK.
Adapting Malaysian housing for smart grid deployment based on the first nationwide energy consumption survey of terrace houses

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Abstract: Malaysia will pursue the smart grid transformation plan led by Tenaga Nasional Berhad to establish a reliable, secure and sustainable electricity delivery system. Increasing demand for energy and issues linked to the traditional grid makes the smart grid transition more attractive and efficient. As residential sector energy demand is a fifth of national energy consumption in Malaysia, the features of surrounding construction and the performance of present and future houses will have a significant impact on electricity grid support requirement. Hence, analysis of the existing housing stock and its occupants’ energy consumption profile are fundamental to inform the development of the Malaysian smart grid, especially by defining characteristics and energy generation potentials of its domestic consumers. This paper analyses the current state of the Malaysian terrace houses, the most common residential type in the country, using results of the first nationwide energy consumption survey on samples across peninsular Malaysia. The study discovered scope for substantial improvements of both current and future housing stock, to achieve higher indoor comfort levels with considerable energy demand reductions for cooling. It clearly identifies and shows that this particular housing type can well exploit advantages engendered by the smart grid through an informed design approach.

Keywords: Energy consumption; residential building design; smart grid; postal survey.

1. Introduction

Electricity has become an indispensable element of modern society, with most nations depending on it as a mechanism of development. While it has been valued as a necessity in Malaysian households (Bekhet and Othman, 2011), local electricity generation has always relied on non-renewable sources. This dependence is neither sustainable nor feasible for the economy and the environment. Following the economic expansion and improvement of living standards in recent decades, energy demand
intensification threatens current supply capacity, with an indirect detrimental impact on the environment. The smart grid has been identified as a possible way out by the Malaysian government, which recently has initiated a transformation plan led by Tenaga Nasional Berhad (TNB), the major national energy supplier. Several studies have claimed multiple benefits of the smart grid as an efficient, reliable and secure electricity distribution system (Nair and Zhang, 2009). The smart grid allows for the integration of renewable energy sources (Byrd et al., 2013), energy efficiency increase through grid operation & energy demand management (Qureshi et al., 2011) and other related energy conservation strategies realised at the consumer end (Paget et al., 2011; Rakob, 2010).

Implementation of the smart grid requires the adaptation of the housing stock to fit alternative energy generation, distribution and storage. Are Malaysian residential buildings suitable for this change? To answer this question, a study was initiated at the University of Auckland in 2012 with the aim of developing fit-for-purpose house types. This paper presents the results of the first research phase. It focuses on terrace housing — the most common Malaysian building type — occupancy profiles and typical energy usage.

2. Future Malaysian Smart Grid

As the Malaysian national grid is part of the Association of Southeast Asian Nations (ASEAN) electricity network, upgrading the current infrastructure is imperative to keep pace with regional development. Technological advances in the energy supply grid make possible the integration of renewables, decentralized generation and energy efficiency. The smart grid concept will transform the power industry, introducing intelligent bi-directional communication, ubiquitous metering with real-time evaluation, and management of energy generation and consumption. The smart grid makes the power supply infrastructure robust, reliable and secure, and serves as a backbone for smart appliances that promote energy saving through energy efficiency practice. It allows new services to emerge, especially those that could enable consumers to manage and control their energy consumption: smart meters allow real-time access to the energy market, current usage and costs. The United States, Germany, Italy, New Zealand, Australia and Japan have already adopted the system; many other countries will follow.

Malaysia’s Smart Grid Initiative Plan was started in 2011. It has three phases: setting up a smart grid information centre, providing a test bed for future smart grid applications, and identifying issues pertaining to renewable energies integration, electric vehicle charging solutions and the establishment of an intelligent micro grid. TNB Research is conducting the smart grid study phase. This project’s aim is to collect sufficient data to evaluate cost effectiveness, formulate time-of-use tariff schemes, study consumers’ behaviour and plan for nationwide implementation. A thousand smart meters will be installed, at an estimated cost of MYR 9 billion, in two locations: Bandar Melaka International Trade Centre in Melaka (800 units) and Putrajaya (200 units). Subsequently, 200,000 smart meters are expected to be installed in Kuala Lumpur and Selangor across all sectors. TNB had earlier replaced four million electro-magnetic meters with digital meters. The smart grid transformation program however, will require a nationwide smart meter replacement, at an estimated cost of MYR 1000 each, thus requiring TNB to invest MYR4 billion as an initial investment (Noordin and Mokhtar, 2014).
2.1. Malaysian residential energy demand

The Malaysian residential sector consumed 14,365 GWh in 2006, 19% of the electricity used in the Malay Peninsula (Saidur et al., 2006). Based on the latest information from Energy Commission (2014), last year residential energy was 2,853 ktoe, 6.1% of national energy consumption. This figure is even more relevant when considering the forecast 3.1% annual growth of energy usage (APERC, 2006) and makes the implementation of effective energy conservation strategies in the housing construction sector an urgent matter.

Kubota et al. (2011) broke down energy use in a typical terrace house, one of the most common types in the country, into five categories: cooking (45%), cooling (29%), others (11%), lighting (8%) and laundry/cleaning (7%). This included both electricity (major usage) and fossil fuel energy (cooking usage). Considering the significant cooling load (17% air conditioning, 10% ceiling fan, and 2% others), there is large scope for the development and implementation of strategies to improve the overall building thermal performance, and of innovative technologies for higher efficiency and clean energy generation. The activation of houses as positive energy generation nodes in the smart grid may have a significant impact on the Malaysian electricity sector, so future terrace houses must be designed and constructed accordingly to take full advantage of the grid’s potential. Technologies that communicate with the smart grid through smart meters will enable consumers to participate in energy saving efforts, while energy generation and distribution made possible by the smart grid can become a solution to peak load issues.

2.2 Malaysian terrace house type

Malaysian housing in urban areas is made up of uniform and large scale developments encompassing various residential types, of which terrace houses represent the most substantial cohort: 1.8 million units, equal to 41% of the total housing stock (NAPIC, 2013). Since the early 1990s, it has become the most common residential type, driven by the growing number of middle class buyers (Rahim and Hashim, 2012), and developers’ liking of the type for its quick construction methods (Khan, 2012). The origins of the Malaysian terrace house are in foreign roots, mainly Chinese, Dutch and British. Its predecessors are the Melakan townhouse and the Chinese shop house. Both types exemplify the diverse assimilation of cross cultural building traditions, including construction methods, building materials and ornament. The Melakan type was the earliest townhouse in Malaysia, present since the end of the 17th century (Fee, 1998). Longitudinally, it is separated into sections: a recessed porch with adjacent side archways leading to a reception hall, private spaces connected by covered passages and interior courtyards to allow air and light into the long and narrow volume of the house. Typically double storeyed, its internal layout comprises sitting rooms, bedrooms, an ancestral room, a dining room, a kitchen and bathrooms (both at the back). The Chinese shop house was introduced to Malaya by Chinese immigrants in the 19th century. This type includes a commercial unit integrated with private quarters. Typically six to seven metres wide and 30 to 60 metres deep, it is double storeyed with an internal layout of a business area on the street front, an air well/courtyard, living areas on the upper storey, with kitchen and bathrooms at the back. Both Melakan townhouses and Chinese shop houses were climatically responsive and thermally comfortable. However, modern terrace houses are the result of market-driven adaptations that pose serious issues of thermal discomfort and excessive energy use, with alien construction methods and materials as the main reasons.
3. Nationwide terrace house survey

Malaysian terrace house design for the smart grid, research that has been carried out at the University of Auckland since 2012, revealed a gap in knowledge about performance of the current stock, the demographic profile of occupants and their energy consumption. For this reason, a postal questionnaire survey of randomly selected participants across the Malay Peninsula, was organised. Participants were urban terrace house occupants from the twelve states in West Malaysia, including the Federal Territory. The study area was limited to West Malaysia because it is TNB’s electricity supply jurisdiction, and the respondents were randomly selected from a list of terrace house occupants, obtained from the Department of Valuation (Assessment) and Property Management under each selected Municipality Council. Random selection was considered the best method to represent the whole terrace house population, for its capability of eliminating conscious and unconscious bias from the researcher, while offering to each individual equal probability of being selected from the population. Given time and resource constraints, a self-administered questionnaire survey method was chosen and, considering the whole terrace house stock, the sampling size was ascertained through the Krejcie and Morgan table equal to 384 sampling units, representing the population with a confidence level of 95% (Krejcie and Morgan, 1970). As the typical postal survey response rate in Malaysia is between 20% and 30% (Osman et al., 2006), thirteen hundred questionnaire survey forms (QSF) were distributed. The QSF contains four sections; Part 1: general information, Part 2: energy use information, Part 3: house typology and Part 4: thermal comfort. Considering the time limitation, this study adopted a two-prong response method that allowed the respondents to complete the survey either by hand or online.

3.1. Survey outcomes

The survey process took approximately ten weeks to complete with 342 useable forms received, constituting 26.5% of the total QSFs distributed and thus matching the expected response size. General information about the respondents is presented in Error! Reference source not found. below, which shows data about household size, income and employed family members, comparing survey results with data from literature and statistical records. The average household size from the survey is higher than the national figure, yet lower than an earlier study by Kubota et al. (2011). In addition, respondents also earn relatively high salaries, with higher average household income compared to the national value, and at least two employed household members.

<table>
<thead>
<tr>
<th>Item</th>
<th>Surveyed data (mean; n=342)</th>
<th>Mean data from Malaysian census or other sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household size</td>
<td>4.57</td>
<td>4.4, 4.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Department Planning Unit (2012) ( ()</td>
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<td></td>
<td></td>
<td>Department of Statistics Malaysia (2013)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Kubota et al. (2011)</td>
</tr>
<tr>
<td>Household income</td>
<td>MYR 6,859.62</td>
<td>MYR 5,000 (overall) ( ()</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MYR 5,742 (urban)</td>
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<tr>
<td></td>
<td></td>
<td>MYR 3,080 (rural)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Department of Statistics Malaysia (2013)</td>
</tr>
<tr>
<td>Employed household size</td>
<td>2.178</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NA</td>
</tr>
</tbody>
</table>
High household income implies better purchasing ability and aspiration to better living standards. This is supported by various studies — (Toe, 2013; Kubota et al., 2011; Isa et al., 2010) — that recorded an increasing number of air conditioning (AC) systems in terrace houses, previously considered luxury items. A cascade effect drives the energy demand increase (Endut and Jajri, 2010).

Figure 1 below describes three variables of energy use in a typical terrace house. Occupancy rate and AC use pattern obtained from the survey were analysed against earlier daily load data published by Ponniran et al. (2007). The graph shows a similar pattern for the three, with spikes in the early morning and evening. The discrepancy between energy load (which drops after 9 pm), and occupancy and AC usage (constant overnight) can be attributed to the sample taken by Ponniran, where fans were preferred over AC. Furthermore, with two AC units per household recorded through the survey, the power consumption pattern of the selected sample is expected not only to deviate but be higher. These observations are also typical of patterns in New Zealand homes (Qureshi et al., 2011), which provides opportunities for designing demand-side management by electricity utility. If this behaviour can be captured, benefits can be realized not only by consumers who will gain price benefits if real-time pricing of electricity is available, but also ensures energy efficiency, helping reduce grid losses by flattening usage peaks. Thus, with regards to the smart grid, the survey’s results highlight intervals when energy needs can be potentially covered by on-site renewable sources and others when additional energy shall be required and could be sourced from local storage or supplied by the grid. Such occurrences, though, can be mitigated via decentralised energy generation and distribution, but require innovative design strategies to reduce energy consumption and maximise energy outputs. Even though solar energy can be an alternative source to cushion daily energy spikes, the usage pattern identified through the survey suggests that storage capability is required to cater for morning and evening peaks. As this has been argued to be costly, especially for individual use, the collective nature of terrace house developments might provide an economically feasible answer though decentralised energy storage facilities. These would allow for daytime collection of solar energy from PV panels installed on the roof of each residential unit, to be employed during peak time, in form of electricity (electrochemical storage) or directly as chilled load (chilled water / ice energy storage). Stored energy could be used during grid peak loads to avoid high charges due to Time of Use (ToU) mechanism. Further cost-benefit studies are required in this field comparing on-site storage options with feed-in mechanisms.

![Figure 1. Average power consumption (kW) (Ponniran et al., 2007), daily occupancy rate and daily AC usage pattern.](image-url)
Comparing occupancy rate and AC usage pattern data with typical daily Malaysian dry and wet bulb temperatures (Tang et al., 2013) allows verification of the temperature range requiring mechanical ventilation. The graph depicts a negative relationship between the main grouped variables of temperature and respondents. During the time when surrounding temperature increases, occupancy rate and AC usage decreases as dwellers leave the house for work or school. Although at least 35% of the occupants remain at home, AC units are used in the early morning (continued from the night before), in the mid-day and again just before sunset, when the outdoor temperature rises above 30°C (to reach its peak around 2pm), and the family is home during lunchtime.

Various studies on thermal comfort ranges for the tropical climate, indicated that a temperature between 25°C and 30°C is deemed comfortable, and published data consistently agreed on 28°C (with air velocities between 0.15 and 0.5 m/s) as the reference value for thermal neutrality. Based on the graphical depiction below (Figure 2), there is a distinct difference between the outside temperature and AC usage pattern. Typical terrace house construction, of brick walls and a concrete frame, performs like latent heat storage, releasing heat inside the building after its surrounding temperature drops and leading to thermal discomfort. Besides, in a country of high humidity, water vapour carries latent heat, causing thermal discomfort and requiring extra load to reduce temperature. The typical terrace house indoor temperature of 28.6°C measured by Mohd Zaki et al. (2011) lies above the agreed thermal comfort level, confirming the need for both design and technological improvements to achieve better thermal performance.

Figure 2. Average daily temperature (Tang et al., 2013), daily occupancy rate and AC usage pattern.

Despite the numerous type variants, the majority of Malaysian terrace houses are either single or double storey buildings - respectively 57% and 43% of the surveyed sample. Typically, they are built in specific sizes, with their width ranging from 16’ (5.48m) to 30’ (7.32m) and length ranging from 50’ (19.8m) to 85’ (24.4m). Respondents were asked to select from a list of width and length options that best represent their home’s dimensions. Based on the responses received, average terrace house dimensions are 24’ (6.85m) wide and 70’ (20.79m) long. Their perimeter walls and internal partitions are typically made of bricks and strengthened by the concrete structure. Roofs are pitched and built using
Adapting Malaysian housing for smart grid deployment based on the first nationwide energy consumption survey of terrace houses

clay or concrete tiles. The envelope is completed with either casement or louvered aluminium windows fitted with single glazing.

Using earlier findings by Toe (2013), this study investigated the internal layout of the variants for both single storey and double storey types. The aim was to identify the most prominent layout to be adopted in the succeeding research stage. Figure 3 below shows the most common floor plan layout of both single (Type 6 = 21.5%) and double storey (Type 2, ground floor = 19.1% and Type 2, first floor = 43.83%).

The typical internal layout of a single storey unit comprises a living area and a master bedroom with tandem bathroom at the front, dining area and a room in the middle, a kitchen and another room at the back. A shared toilet is located either in the middle or the back of the house. The double storey type has a living area at the front, dining area in the middle, and another room, the kitchen and a shared toilet at the back. The internal arrangement of the first floor includes a master bedroom with a tandem bathroom on the front, a family room in the middle, and two bedrooms at the back with a shared toilet.

Figure 3. Typical internal layouts for single and double storey terrace house based on the survey.

Table 2. Responses about courtyard/air well presence in the TH design section, segregated by the year of construction

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</thead>
<tbody>
<tr>
<td>Response</td>
<td>2.92%</td>
<td>9.36%</td>
<td>11.11%</td>
<td>15.20%</td>
<td>2.63%</td>
<td>1.46%</td>
<td>3.80%</td>
</tr>
</tbody>
</table>

A significant design feature of the earlier type is the internal courtyard or air well, which, unfortunately, has become less common in modern terrace houses (Toe, 2013; Sadafi et al., 2012). Indeed, results of the survey (Table 2) confirm that the majority of courtyards and air wells are found in units built between the early 80s and the end of the 90s. Overall, only 46.5% of the respondents reported the presence of internal courtyards and air wells, with 86.16% of these still maintaining their original function.

The study also considered the impact of orientation on indoor thermal comfort, already investigated in a study by Al-Obaidi and Woods (2006). Given that Malaysia is located slightly north of the equator, exposed walls should be perpendicular to the North-South axis as to minimize solar heat gain.
Fortunately this is easily achievable as terrace houses only have front and rear façade exposed. Roof exposure and orientation are instead significant for PV integration in order to achieve optimum energy output. Unfortunately though, according to the survey’s results (Figure 4), only about 30% of existing terrace houses are aligned to the North-South axis, thus increasing the risk of overheating due to excessive solar gains as well as the cooling load.

![Figure 4. TH entrance façade orientation.](image)

Another significant aspect investigated in the survey concerns occupants’ ventilation preferences and habits (Figure 5). Questions were structured to investigate (a) window usage and natural ventilation, (b) preference for fan or air conditioning use and (c) factors affecting air conditioning usage. Response analysis found that almost half of the sample population considers natural ventilation a sufficient diurnal cooling strategy. However, occupancy rate data (Figure 1 and Figure 2) shows that less than half of the occupants are at home during the day. Nonetheless, daytime natural ventilation is perceived as more important than nocturnal ventilation. This is explained by a similar study (Kubota et al., 2009) that, while stating the significance of night purge as a passive means to achieve indoor thermal comfort, identifies security concerns and insect disturbance among the reasons for not opening windows during the night. The scrutiny of responses about fan and AC use revealed the importance of fans in both diurnal and nocturnal cooling to support natural ventilation. The scrutiny of responses about fan and AC use revealed the importance of fans in both diurnal and nocturnal cooling to support natural ventilation.
Adapting Malaysian housing for smart grid deployment based on the first nationwide energy consumption survey of terrace houses

Figure 5. Seven point scale responses about natural and mechanical ventilation habits.

Mixed responses were received on the use of AC coupled with fan to achieve thermal comfort at day and night. Survey outcomes acknowledge night-time as more important than daytime AC usage. This supports the AC usage pattern discussed earlier (Figure 2) as most occupants are affected by latent heat release. Despite more than 40% stating they are willing to pay more to achieve comfort, this study disclosed that limiting AC usage outweighs it. Nonetheless, this finding supports the notion of higher purchasing ability and aspiration to better living standards.

4. Conclusion

This paper presented the findings of a nationwide survey limited to terrace house occupants in the Malay Peninsula, investigating possible adaptations of this common type to the future Malaysian smart grid deployment. Results of the study confirm the great potential of terrace houses in terms of energy savings and on-site generation, providing valuable indications for design improvements of both existing and future housing stock. Higher household income, compared to previous census data, reveals the ability of terrace house occupants to achieve better living standards, while cautious when spending on AC usage. Such behavioural patterns can be further enhanced through the installation of smart meters, to better inform occupants about their energy usage. Nevertheless, thermal discomfort issues linked to design deficiencies of the existing stock have become barriers to the occupants’ energy conservation efforts. While there is ample scope for the improvement of the envelope’s performance, fewer upgrade opportunities are provided by the existing stock in terms of PV installation, as less than 30% of the units offer suitable orientation, even though their built form is optimal for PV placement. Considering the above, further research is required to enhance the design of future generations of terrace houses, reducing energy cooling demand and developing individual units as energy generation nodes integrated in the upcoming Malaysian smart grid.
Acknowledgement

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APERC (2006), "APEC Energy Demand & Supply Outlook 2006: Malaysia".


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Bridging the gap: energy efficiency improvements for rental properties

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Abstract: World leaders have acknowledged that climate change is one of the biggest challenges we face in the 21st century and have committed to limit warming to within two degrees Celsius. To do this, energy efficiency needs to be improved across all sectors. However, researchers have identified that there is a large gap between what is occurring and what can be done in regards to energy efficiency. Rental properties, in particular, have seen very few improvements in energy efficiency due to a range of barriers including misinformation, split incentives and an uneven power dynamic between renters and landlords. This is important because not only do rental properties account for 25 percent of the Australian housing stock, the high proportion of low income households in rental properties are particularly vulnerable to rising energy prices. This research aimed to identify feasible solutions for overcoming the barriers to energy efficiency improvements in rental properties in Victoria, Australia.

Keywords: Energy efficiency; rental properties; barriers; solutions.

1. Introduction

In 2009, 114 world leaders at the Copenhagen Climate Change Conference created the Copenhagen Accord which recognised “climate change [as] one of the greatest challenges of our time” (UNFCCC, 2014, p 1). The Copenhagen Accord also stated that “to prevent dangerous anthropogenic interference with the climate system the scientific view is that the increase in global temperature should be below two degrees Celsius” (UNFCCC, 2014, p. 1). The global community therefore faces the ongoing challenge of meeting future energy needs and maintaining current qualities of life, while reducing greenhouse gas (GHG) emissions produced by human activity.

Improving energy efficiency is key to mitigating climate change. However, despite the proven benefits of energy efficiency there is a significant gap in the uptake of energy efficiency improvements, particularly in rental situations (de T’Serclaes and Jollands, 2007). In Australia, rental properties represent 25 percent of the property market. The low uptake of energy efficiency improvements in the private rental sector not only undermines Australia’s attempts to reduce GHG emissions, it jeopardises equitable access to energy for low income households.
Previous studies on the barriers to energy efficiency improvements in rental properties confirm that there are several market failures occurring in the private rental market. Empirical studies reveal that these market failures are exacerbated by low vacancy rates, short term rental leases, and a fiscal and regulatory system that preferences landlords. There is also a significant gap in the literature of empirical research into possible solutions to overcoming these barriers.

This is the first study to test solutions to overcoming the barriers to energy efficiency improvements with a sample of landlords, renters and real estate agents, for the state of Victoria, Australia. The aim of the study is to identify the most feasible solutions to overcoming the barriers to energy efficiency improvements in rental properties.

2. Background

Despite a slowdown in residential sector energy consumption (BREE, 2014), researchers agree that there is a gap between the potential energy savings offered by energy efficient technology and the savings realised (Allcott and Greenstone, 2012 and de T’Serclaes and Jollands, 2007). In 2007, de T’Serclaes and Jollands attempted to quantify the amount of energy not saved due to barriers to energy efficiency in rental situations worldwide. They estimated that each year over 3,800 PJ of potential savings, equivalent to roughly 85 percent of Spain’s total energy use, were lost (de T’Serclaes and Jollands, 2007).

Energy costs have increased significantly in the last decade. The average household electricity bill in Australia increased 83 percent between 2007 and 2013 (Chester, 2013). Gas prices have already risen 66 percent since 2008, and are predicted to increase up to 24 percent more by the end of 2015 (Redrup, 2014). Approximately 28 percent of Australian private rental households suffer utility stress (Sullivan, 2007), and “electricity and gas bills [are] the greatest cause of rental arrears (63 percent) in Victorian low income households” (Chester, 2013, p. 7). As energy prices continue to rise, disparity is occurring between those who can afford to improve the energy efficiency of their property and those who cannot. Paradoxically, those who are most vulnerable to price increases are the people with the least capacity to improve the energy efficiency of their property. The relationship between lower incomes and the private rental market reveals that improving the energy efficiency of rental properties would not only reduce GHG emissions, but could also reduce economic stress for low income households.

2.1. Current barriers to energy efficiency improvements in rental properties

There is a broad range of factors that act as barriers to energy efficiency improvements, universally and particularly in the Australian context. De T’Serclaes and Jollands (2007) identify a range of market barriers and failures that inhibit energy efficiency improvements. Market barriers are circumstances that discourage entry into a market, while market failures occur when “one or more of the conditions necessary for markets to operate efficiently are not met” (de T’Serclaes and Jollands, 2007, p. 24).

Ungar et al. (2012) name imperfect information as the most prominent barrier to energy efficiency improvements. Examples of imperfect information include limited knowledge of the energy performance of different equipment, unpriced health and environmental costs of fuel types, energy savings being difficult to measure, uncertain future energy prices and that specific energy uses are not quantified in utility bills. De T’Serclaes and Jollands (2007) categorise imperfect information as a market failure because consumers do not have enough information to make the most rational choice.

Burford et al. (2012) point out that most of the literature on barriers to energy efficiency in rental properties focuses on the split-incentives between landlords and renters. Williams (2008) and de
T’Serclaes and Jollands (2007) agree that the split incentives between landlord and renter are a classic example of the Principle Agent (PA) problem. De T’serclaes and Jollands (2007, p. 27) define PA problems as “potential difficulties that arise when two parties engaged in a contract have different goals and different levels of information”. According to this theory, the result is adverse selection and moral hazard, for example, a renter choosing a property with poor thermal performance (adverse selection), and a landlord acting opportunistically by purchasing the cheapest appliances that cost the renters more to run (moral hazard) (de T’Serclaes and Jollands, 2007). Sorrell et al. (2004) criticise the PA theory as reductionist and argue it does not hold true in complex world scenarios. The following Australian studies support the existence of split incentives but also expose a range of externalities which exacerbate the market failure.

Dillon et al. (2010, p. 8) in their evaluation report found “most, if not all, renters displayed some degree of anxiety about the relationship with their property managers or landlord”. This mistrust results in misinformation about the energy performance and thermal comfort of rental properties, and can therefore be classified as a market failure (de T’Serclaes and Jollands, 2007).

Further investigation into the causes of this fear reveals another market failure: distortionary fiscal and regulatory policies. According to Sullivan (2007), renters in Victoria experience limited security of tenure, with short term rental leases and limited rights to make changes to properties. The Victorian Residential Tenancies Act requires renters to ‘make good’ properties at the end of their lease. This means even willing renters are discouraged from improving properties themselves, or asking for permission to engage in energy efficiency programmes offered by external parties (Dillon et al., 2010).

Fear of eviction is fuelled by very low vacancy rates in many Australian cities, particularly inner Melbourne where the vacancy rate is under one percent (DSE, 2009). According to Williams (2008), “vacancy rates can have a critical impact on the balance of power between renters and landlord and therefore upon the renters’ ability to demand energy efficiency” (Williams, 2008, p. 17). Low vacancy rates of under five percent exacerbate the split incentive problem as owners are under little pressure to improve rental properties and renters know that if they demand improvements they can be easily replaced. Sullivan (2007) points out that the current tax system in Australia also provides greater assistance to established home owners and investors than to renters, exacerbating the power dynamic.

There is a large pool of funding available in Australia to support energy efficiency activities in households according to Dillon et al. (2010). Riedy et al. (2004) and Chester (2013) agree however that existing rebates, grants and other schemes are complicated and time consuming which has inhibited their uptake. Johnson and Sullivan (2012) found that a lack of capital is a substantial barrier to renters engaging in such schemes. Low income households were much more likely to engage in free energy efficiency schemes than those that required financial contribution.

Previous studies suggest possible policies or scenarios that could overcome the barriers to energy efficiency improvements in rental properties. However, there is a lack of evidence-based studies into what solutions would improve the energy efficiency of rental properties in Victoria and be supported by landlords, renters and agents. This research aimed to fill this gap and contribute to the shift towards a more equitable, informed and successful energy efficient market for rental properties.

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1 Make good refers to ensuring the rental property is in the same condition as when it was leased. This means under the Tenancy Act residents do not have the rights to make permanent energy efficiency improvements.
3. Research Method

In order to identify the most feasible solutions to overcoming the barriers to energy efficiency improvements in Victorian rental properties, five possible solutions were tested with a sample of landlords, renters and real estate agents.

Recognising the difficulties of sourcing solutions from a population with insufficient knowledge of energy markets and efficiency, it was decided to instead test several solutions that have been suggested by experts or trialled in other countries (participants were however always given the opportunity to put forward their own suggestions). Given their complex nature, the solutions (Table 1) were presented as scenarios that illustrate the intended effect and interaction between stakeholders, rather than the exact policy, law or contract that would be implemented.

<table>
<thead>
<tr>
<th>Solution</th>
<th>Description</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Amending the Residential Tenancies Act to allow renters greater rights to improve rental properties.</td>
<td>Tenants Union of Vic., (Dillon et al., 2010), (Strempel et al., 2010)</td>
</tr>
<tr>
<td>2</td>
<td>Classifying energy efficiency improvements as repairs in the rental properties tax classifications so landlords can tax offset the entire cost of the improvement in the same financial year.</td>
<td>Moreland Energy Foundation, (Williams, 2008)</td>
</tr>
<tr>
<td>3</td>
<td>A residential ‘Green Lease‘- Landlords recouping the cost of energy efficiency improvements by increasing the rent for a fixed period e.g. 80% of the cost the renter saves.</td>
<td>(Williams, 2008), (Blundell, 2013)</td>
</tr>
<tr>
<td>4</td>
<td>Pay as you save system - no upfront costs for the improvement and the contract can be transferred to new renters or owners.</td>
<td>(Williams, 2008), (GEMenergy, 2014)</td>
</tr>
<tr>
<td>5</td>
<td>Mandatory minimum energy efficiency standards for rental properties.</td>
<td>(Riedy et al., 2004), (Dillon et al., 2010), (Strempel et al., 2010)</td>
</tr>
</tbody>
</table>

A mixed-method research approach was used to gauge the reactions, attitudes and support of landlords, renters and real estate agents towards the suggested solutions. The key challenge to engaging landlords and renters is that they are geographically dispersed. Web surveys were considered the most effective tool for engaging both landlords and renters under these conditions.

Although landlords and renters are the core stakeholders in energy efficiency improvements for rental properties, real estate agents manage two thirds of rental properties in Australia (DSE, 2009) and therefore play a critical role in the rental market. Semi-structured interviews (30 mins.) were conducted with five agents, providing a triangulated view of the perceptions and viability of the solutions.

3.1. Data Collection

A snowball sampling technique was adopted to disseminate the survey. Individuals and groups were contacted via social media, email and phone, and asked to support the research by sharing the survey with supporters, friends and family. Attempts were made to bridge geographical and political divides such as contacting all 79 Victorian councils, 125 Victorian State Members of Parliament (MPs) and 29 Victorian Federal MPs. All responses were collected by the online survey program eSurv.org. Agents were approached by phoning and emailing real estate agencies.
3.2. Data Analysis

The research approach required both quantitative and qualitative analysis. The quantitative responses to the scenario questions, which were answered along a Likert Scale, were split up into landlords and renters. For the sake of comparison the numbers were converted into proportions of each stakeholder group. The proportions were then represented as a diverging stacked bar chart.

The qualitative comments and agent interview transcripts were analysed using thematic coding. The codes were inductive codes; codes derived from the comments provided. Inductive coding was chosen because as far as the authors know, there is no previous empirical research investigating the particular solutions being tested in this study, and therefore responses cannot be predetermined. The codes were kept consistent across all the questions and stakeholders so that responses and/or attitudes that were not only common to each scenario but across the research, could be identified.

3.3. Limitations

There were some limitations to this study, including a small sample of landlords, a bias towards respondents with a greater concern for reducing GHG emissions, and a limited geographical scope. Everything was done to avoid and reduce the effect of these limitations but factors including time restrictions and limited monetary resources restricted the capacity for this research to reach a larger number of people.

4. Results

Altogether 230 people responded to the survey - 194 renters and 36 landlords, which is considered a representative sample using the Cochran Equation (Israel, 1992), of the estimated 1.25 – 1.5\(^2\) million landlords and renters in Victoria. This section presents the findings of the 230 survey responses and five interviews with agents. Respondents provided 365 qualitative comments throughout the survey.

4.1. The main motivations and barriers for energy efficiency improvements

Cost and lack of rights were the two most common barriers identified from the survey. This is supported by the findings of the previous studies discussed in the background. However, the qualitative information revealed for many respondents it was not the cost alone that was the barrier, but the lack of assurance that renters would see return for their investment due to short insecure leases. This is a distortionary regulatory policy and therefore a market failure (de T’Serclaes and Jollands, 2007).

There were a lot of contradicting comments on the question of what improvements renters can and can’t make to a rental property. The agents interviewed were adamant that renters could make any changes they wanted with permission from the landlord, and landlords believed they should be asked before potential improvements are made. In contrast, renters not only indicated that agents and landlords had discouraged them from making improvements, but 82 percent of the renters who had

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\(^2\) The 2011 there were 515,586 rented dwellings in Victoria (ABS, 2013), with publicly rented dwellings representing approximately a quarter of these. For an average household size of 2.6 people (ABS, 2013) the total number of renters in Victoria can be estimated at just over 1 million. Assuming that each landlord owns 1-2 properties (ATO National data indicates 70% of landlords own just one investment property (Collyer, 2011)) the total number of renters and landlords in Victoria can be estimated at 1.25-1.5 million.
made improvements made them without permission from the landlord. This misinformation and mistrust aligns with the Principle Agent Theory, whereby two parties in a contract have different goals and different levels of information (de T’Serclaes and Jollands, 2007), more commonly described as split incentives. The presence of this market failure creates a case for more education and awareness about what energy efficiency improvements can be made to rental properties.

In addition to barriers, the study also asked what the main motivations were for landlords and renters who made energy efficiency improvements. The most consistent motivations cited were a desire to reduce gas, water and electricity bills, conserve water and reduce GHG emissions, and to improve the heating, cooling and comfort of the property. Other common motivators cited were that energy efficiency improvements are a smart investment and it made the respondent feel good. Landlords listed government schemes as motivators more often, which is unsurprising given they are eligible for more schemes than renters.

The finding that renters and landlords are motivated by multiple factors is evidence that any promotion of energy efficiency improvements (technology, schemes or policy), should always provide information on the broad range of benefits associated with the improvement.

4.2. Responses and reactions to the proposed solutions from landlords, renters and agents

Figure 1 presents the responses to the question for each solution relating to the level of support. The quantitative responses in this figure were analysed along with the qualitative responses to each solution, which ranged from 24 to 57 comments per solution.
No consensus emerged in the literature as to what constitutes an adequate level of support for a policy or financial solution. A nuanced approach was applied to the analysis of levels of support for the solutions that considered the qualitative responses, took into account the number of unsure answers and placed a high value on the proportion of respondents who outright disagreed. Of the five solutions put forward two of them were clearly supported by all three stakeholders:

- Solution 2 - Classifying energy efficiency improvements as repairs in the rental properties tax classifications so landlords can tax offset the entire cost of the improvement.
- Solution 5 - Mandatory minimum energy efficiency standards for rental properties.

Solution 2 had the greatest level of support - over 90 percent from both landlords and renters, less than 7 percent unsure and only one renter who disagreed with the solution. Agents were also convinced that the solution would be effective, with no negative repercussions for the renter. The only concern expressed in the qualitative data was whether the single incentive was enough to encourage landlords to make energy efficiency improvements, suggesting that Solution 2 would work well with Solution 5.

Solution 5, a mandatory energy efficiency standard, was the next most supported – by over 90 percent of renters and over 70 percent of landlords. A total of 10 percent of landlords did not support the solution and 19 percent were unsure. However, the number of landlords who strongly disagreed reduced if the mandatory standard was combined with other solutions, such as tax offsetting energy efficiency improvements (Solution 2). Agents agreed that this solution could be effective and provided some additional ideas for financial incentives. The biggest concern raised in the comments was whether a minimum energy efficiency standard would result in rent increases unfairly disadvantaging low income renters. If this solution was to be implemented, the qualitative responses suggest a lead time of less than five years, phasing in the minimum standard and putting in place protective mechanisms against unfair rent increases.

Solutions 1 and 3 were not sufficiently supported by all stakeholders. More than 15 percent of respondents disagreed with the solutions, a high number of respondents were unsure, and there was little support from agents as well as strong consistent negative reactions in the comments.

Solution 4, a pay as you save system for improvements where renters use energy savings to pay off the loan, received a reasonable degree of support. Over 58 percent of landlords and renters agreed that the solution could result in increased energy efficiency improvements and no more than 13 percent disagreed. However, there was a high number of respondents unsure about the solution and there were mixed reactions in the comments and from agents.

Finally, landlords, renters and agents all agreed that there is a need for greater government involvement, in both setting standards for energy efficiency in rental properties and rewarding energy efficiency improvements.

5. Discussion and conclusion

This section discusses how the proposed solutions to overcoming the barriers to energy efficiency improvements in rental properties would be implemented and what additional barriers might arise.

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3 Solution 3, a residential green lease, was least supported despite them being widely used in commercial rentals. This suggests a greater perceived power imbalance between stakeholders in residential than commercial properties.
Bridging the gap: energy efficiency improvements for rental properties

The implementation of Solution 2, tax offsetting the entire cost of energy efficiency improvements, would require a change to national tax law, the Income Tax Assessment Act 1997 (ATO, 2015). This could happen through either a tax amendment bill which would need to be passed through both Federal Houses of Parliament or via a Public Ruling by the Commissioner of Taxation (Scolaro, 2006). Currently, the most significant national policy in regards to energy efficiency in residential properties is the Council of Australian Governments National Strategy on Energy Efficiency (COAG, 2008). Despite all the states and territories signing the Strategy, many of the agreed measures and policies have not come to fruition (e.g. a mandatory disclosure of energy and water performance for all residential properties and a phase out of electric hot water systems). Given the current lack of political will for national energy efficiency policy, Solution 2 is ambitious, but the likelihood of the change occurring would increase with national public support. This makes the case for further testing of Solution 2 with a wider Australian audience.

If Solution 5, a mandatory energy efficiency standard, were to be implemented it would also increase the likelihood of Solution 2 being implemented (ATO, 2015). Currently anything classed as repairs are entirely deductible against a landlords income in the same financial year. Expenditure required to make a property satisfy regulatory requirements falls into the repairs classification (ATO, 2015).

Rental standards are managed by state governments therefore to implement Solution 5 a bill would be required to pass through the Victorian Parliament. However, there are currently no minimum standards for rental properties, energy efficiency or otherwise, and an attempt by the Australian Greens Party in 2013 to pass minimum requirements failed to pass through the parliament (Greens, 2014). The support for this solution by all the stakeholders in this study presents a case for the implementation of a minimum energy efficiency standard to be revisited by policy makers.

A consistent theme that arose throughout this study was that renters could not afford rent increases to cover the cost of energy efficiency improvements. This fear is not unfounded. An annual study conducted by Anglicare Australia found that in Victoria less than one percent of advertised rental properties in 2015 were affordable for low income families (Anglicare, 2015). Rental affordability must be considered in the implementation of any of the solutions discussed. Support for Solution 2 and Solution 5, will rapidly decline if they result in significant rent increases.

Finally, another consistent theme that arose was the desire from renters for longer rental leases which in turn would encourage renters to invest in more energy efficiency improvements. In Victoria the maximum lease contract is 12 months, and irrespective of the length of time a renter has been in a property a landlord is only required to give 90 days’ notice for eviction or less in some circumstances (Hulse et al., 2010). This is not the standard internationally. Ireland, Denmark, The Netherlands, Sweden and Germany all offer either multi-year or unlimited rental leases, and have much tighter restrictions on eviction of renters (Hulse et al., 2010). Anecdotal evidence from this study suggests that longer more secure rental leases would result in greater uptake of energy efficiency improvements.

5.1. Key recommendations

Below is a series of key recommendations for solutions to overcome the barriers to improving the energy efficiency of rental properties. This study confirms the findings of de T'Serclaes in his review of existing policy responses to the financial barriers of energy efficiency, that “capital availability is not the

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4 Rental housing is classified as unaffordable if rent payments are more than 30% of the households total income per month (Anglicare, 2015).
most important tool in overcoming energy efficiency’s financial barrier. Instead, the solution lies in carefully designed policy packages, and strong political will.” (de T’Serclaes, 2007, p. 6). Victoria and Australia will see a greater uptake of energy efficiency improvements in rental properties with a multi-faceted approach.

Solutions that could be readily implemented:

- Increased education and awareness of what changes renters can make to rental properties.
- Increased promotion of the VEET scheme, aimed at landlords and renters.
- Informing renters of the ability to negotiate energy efficiency improvements when agents or landlords request a rent increase.
- Ensure communication and promotion of energy efficiency improvements advertise their multiple benefits, including: financial savings, comfort, smart investment, the feel good factor, reduced emissions and conservation of resources.

Solutions that require legislative change:

- Making a change to the Tax Assessment Act 1997 to include energy efficiency improvements under repairs to a rental property, so that the full cost of the repair is tax deductible.
- Minimum energy efficiency standards for rental properties. A phased in approach, combined with financial incentives for landlords to get their property to standard, is recommended.
- Provide the opportunity for longer rental leases with greater security from eviction.

This study provides an important foundation for building a more effective and equitable energy efficiency market for the rental sector. With further research, consultation and communication with landlords, renters and agents, the solutions identified as supported in this study have a greater chance of gaining broader acceptance and being implemented. It is recommended that for future research more landlords and real estate agents be engaged from rural areas, information on different locations be recorded and further attempts at overcoming the sustainability bias be made. Altogether the results and recommendations from this study provide direction for community, business and political leaders to create a well-designed package of solutions for improving the energy efficiency of rental properties in Victoria.

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Does current policy on building energy efficiency reduce a building’s life cycle energy demand?

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Abstract: Building energy efficiency regulations often focus solely on thermal energy demands. Increasing the thermal performance of the building envelope through additional insulation and efficient windows is the typical approach to increasing building thermal energy efficiency. This can result in a significant increase in embodied energy which is currently not considered in building energy regulations. A case study house in Melbourne and Brisbane, Australia is used to investigate the life cycle primary energy repercussions of increasing building energy efficiency levels over 50 years. Embodied and operational energy are quantified using the comprehensive hybrid approach and a dynamic software tool, respectively. Energy efficiency is improved by material or design changes as well as a combination of both. Results show that while increasing the envelope thermal energy performance yields thermal operational energy savings, these can be offset by the additional embodied energy required for additional insulation materials and more efficient windows. The point at which increasing the thermal performance of the envelope does not yield life cycle energy benefits is just above current minimum energy efficiency standards in Australia. In order to reduce a building’s life cycle energy demand, a more comprehensive approach that includes embodied energy and emphasises design changes is needed.

Keywords: Building energy efficiency regulations; life cycle energy analysis; residential; Australia.

1. Introduction

The operation of buildings alone represents 30-40% of the primary energy demand in most developed economies (IEA, 2014). In 2012, buildings represented 20% of the final energy demand in Australia, of which 60% was associated with residential buildings (BREE, 2012). This makes buildings one of the most important areas to target in order to reduce energy use and greenhouse gas emissions (IPCC, 2014).

The considerable energy use associated with the operation of buildings has led to the development of building energy efficiency regulations. These regulations impose a minimum level of energy efficiency for all new buildings and in some cases retrofitted buildings. An example of such regulations is the Australian 6 Star Standard (ABCB, 2011). These regulations focus on thermal operational energy requirements of buildings since these typically represent the largest contribution to their delivered
Does current policy on building energy efficiency reduce a building’s life cycle energy demand? (Perez-Lombard et al., 2008). In Australia, maximum levels of annual heating and cooling final energy demand per m² must be met, e.g. 114 MJ/m²·a for Melbourne, Australia (NatHERS, 2003). While such regulations can lead to a reduction in thermal energy use, improved thermal comfort and healthier buildings, it is critical to ensure that they do not result in an increased energy demand at other stages of a building’s life cycle, notably for the production and manufacture of building materials.

The need to integrate embodied energy requirements into building energy efficiency regulations has been advocated for in many previous studies such as Garcia-Casals (2006). This is because energy efficiency measures often require additional materials to be installed which leads to an increase in embodied energy demands (Stephan et al., 2012). It is therefore essential to ensure that reducing thermal energy requirements results in net life cycle energy benefits. For instance, Stephan et al. (2013) have shown that a Passive house, meeting one of the most stringent thermal energy efficiency certifications in the world, can have the same life cycle energy use as a house built to minimum requirements in Belgium, over 100 years.

Over time, building energy efficiency regulations tend to become more stringent. However, very few studies have evaluated the life cycle repercussions of increasing thermal energy efficiency levels in buildings. Those that do, often focus on life cycle cost, such as Morrissey and Horne (2011) and Hasan (1999). Almost all of those that focus on life cycle energy demand underestimate embodied energy by relying on a process analysis approach (e.g. Sartori and Hestnes (2007) and Dahlstrøm (2011)). There is therefore a need to quantify the life cycle energy benefits of increasing thermal energy efficiency in buildings in order to inform effective building energy efficiency regulations.

The aim of this study is to quantify the life cycle energy repercussions of an increasing stringency in building energy efficiency policy in Australia. The study uses a representative case study house in Melbourne and Brisbane.

Section 2 describes the case study house and the approach used to quantify the embodied and operational energy. Section 3 presents the results, which are discussed in Section 4.

2. Method

This section describes the research approach and the case study building and its characteristics. The input-output-based hybrid analysis technique used to quantify embodied energy is described as well as FirsRate5, the dynamic software tool used to quantify heating and cooling energy requirements.

2.1. Research approach

In order to evaluate the net life cycle energy benefits of the current building energy efficiency regulation in Australia, different energy efficiency levels were investigated. A case study house (described in Section 2.2) was modified from a base case scenario (meeting the compulsory 6 Star standard out of a possible 10 Stars (equivalent to zero or near zero energy demand for heating and cooling)) to meet increasing energy efficiency levels and higher associated star ratings. These modifications were performed using two approaches: improvement by material and improvement by design. The first follows a business as usual approach and gradually increases the amount of insulation and the glazing thermal performance. The second uses design changes to achieve a higher star rating. These include exposing the thermal mass of the house (by removing carpets, using reverse brick veneer outer walls and installing shading devices). Lastly, for each location, a single scenario that combines both
improvements by material and design was investigated. This scenario meets the highest star rating possible, considering the range of modifications investigated in this study.

The net life cycle energy difference between each of the aforementioned scenarios and the base case house was calculated. This reveals the net benefits of increasing thermal energy efficiency by material, by design and by a combination of both.

2.2. Case study house

A three-bedroom single family house was chosen as the case study (Figure 1). This house was developed by the Housing Industry Association (HIA) as a representative sample of new Australian houses for costing purposes. The brick veneer house has a net conditioned floor area of 135.4 m² (when modelled according to the Australian Nationwide House Energy Rating Scheme technical guidelines and zoning protocols) and a gross floor area of 202 m². This house is representative of housing in Australia, where more than 74% of all dwellings are detached houses (ABS, 2013).

Figure 1: Floor plan of the case study house.
As described in Section 2.1, the base case house meets the minimum 6 Star energy efficiency standard for Melbourne. For Brisbane, some minor modifications were made to the envelope assemblies in order to achieve the minimum 6 Star requirement. Table 1 summarises the characteristics of the base case house, for Melbourne and Brisbane.

Table 1: Main characteristics of the case study house for Melbourne and Brisbane.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Melbourne</th>
<th>Brisbane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period of analysis</td>
<td>50 years</td>
<td></td>
</tr>
<tr>
<td>Number of occupants</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Climate zone</td>
<td>Maritime temperate</td>
<td>Warm temperate</td>
</tr>
<tr>
<td></td>
<td><em>Cfb</em> in the Köppen classification</td>
<td><em>Cfa</em> in the Köppen classification</td>
</tr>
<tr>
<td></td>
<td>Zone 21 in the FirstRate5 tool</td>
<td>Zone 10 in the FirstRate5 tool</td>
</tr>
<tr>
<td>Orientation</td>
<td>Kitchen / Family to North (see Figure 1)</td>
<td></td>
</tr>
<tr>
<td>Site</td>
<td>Suburban terrain</td>
<td></td>
</tr>
<tr>
<td>Areas</td>
<td>135.4 m² net conditioned floor area (NCFA), 38.9 m² unconditioned Garage, 9.8 m² unconditioned utilities (bathroom and laundry), 36.68 m² glazing</td>
<td></td>
</tr>
<tr>
<td>Roof</td>
<td>Concrete tile attic-type roof with 160 mm fibreglass insulation batts (U-value=0.29 W/(m²·K)) and a 60 mm reflective blanket (U-value=0.77 W/(m²·K))</td>
<td>Metal deck roof to garage, no insulation</td>
</tr>
<tr>
<td>External walls</td>
<td>Brick veneer walls with 90 mm fibreglass insulation batts (U-value=0.5 W/(m²·K)) plus single sided reflective foil, single brick walls to garage and no insulation</td>
<td></td>
</tr>
<tr>
<td>Internal walls</td>
<td>Plasterboard on stud frame, 90 mm fibreglass insulation batts (U-value=0.5 W/(m²·K)) to unconditioned spaces</td>
<td></td>
</tr>
<tr>
<td>Floors</td>
<td>Concrete slab on ground, no insulation, tiles in wet areas, carpet in other living spaces, concrete finish in garage</td>
<td></td>
</tr>
<tr>
<td>Windows</td>
<td>Timber framed, clear single glazing</td>
<td>Timber framed, toned single glazing</td>
</tr>
<tr>
<td></td>
<td>U-value = 5.75 W/(m²·K), g-value: 0.69</td>
<td>U-value = 5.7 W/(m²·K), g-value: 0.52</td>
</tr>
<tr>
<td>Heating energy demand (MJ/m²·a)</td>
<td>87&lt;sup&gt;b&lt;/sup&gt;</td>
<td>8&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Cooling energy demand (MJ/m²·a)</td>
<td>25&lt;sup&gt;b&lt;/sup&gt;</td>
<td>33.9&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Total final thermal energy (MJ/m²·a)</td>
<td>112&lt;sup&gt;b&lt;/sup&gt;</td>
<td>41.9&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Star rating</td>
<td>6&lt;sup&gt;b&lt;/sup&gt;</td>
<td>6&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Constraint factor heating</td>
<td>0.45&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.25&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Constraint factor cooling</td>
<td>0.4&lt;sup&gt;c&lt;/sup&gt;</td>
<td>0.4&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>Gas heater efficiency</td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td>Electrical cooling COP</td>
<td></td>
<td>2.5</td>
</tr>
</tbody>
</table>

Note: <sup>a</sup>FirstRate5 is a certified dynamic software tool used to calculate the thermal energy efficiency of buildings in Australia (see Section 2.4); <sup>b</sup>As calculated with FirstRate5; <sup>c</sup>Constraint factors correct estimated heating and cooling demands to account for actual occupancy (see Section 2.4).

2.3. Quantifying embodied energy

The embodied energy of a construction material is the sum of all energy inputs across its supply chain, including raw material extraction, material manufacture, processing, transport to site and construction,
as well as the energy associated with the provision of services required to support each of these processes, such as banking and insurance. Embodied energy was quantified using the comprehensive input-output-based hybrid analysis technique developed by Treloar (1997) and validated by Crawford (2008). This technique combines industrial data with average economic data to produce comprehensive embodied energy coefficients for building materials. Most existing studies rely on the so-called ‘process analysis’ which underestimates embodied energy due to truncation of the supply chain.

The initial embodied energy of the house and the recurrent embodied energy associated with material replacement over 50 years were calculated. Average material service life values were used to calculate recurrent embodied energy. These are based on NAHB and Bank of America (2007). The sum of initial and recurrent embodied energy is the life cycle embodied energy and is given by Equation 1.

\[
LCEE_h = \sum_{m=1}^{M} (Q_m \times EC_m) + \left( TERRrb - \sum_{m=1}^{M} TERRm \right) \times C_h + \sum_{m=1}^{M} \left[ \left( \frac{POA}{SLm} - 1 \right) \times \left( Q_m \times EC_m \right) + \left( TERRrb - TERRm - TERRi\ne m \right) \times C_m \right]
\]

Where: \( Q_m \) = Quantity of material \( m \) in the house (e.g. t of steel); \( EC_m \) = Hybrid energy coefficient of material \( m \) in GJ per functional unit; \( TERRrb \) = Total energy requirement of the Residential Building sector \( rb \) in GJ/AUD; \( TERRm \) = Total energy requirement of the input-output pathway representing material \( m \) in GJ/AUD; \( C_h \) = Cost of the house in AUD; \( POA \) = Period of analysis in years; \( SLm \) = service life of the material \( m \) in years; \( TERRi\ne m \) = Total energy requirement of all input-output pathways not associated with the installation or production process of material \( m \) being replaced in GJ/AUD; and \( C_m \) = Cost of the material \( m \) in AUD.

2.4. Quantifying operational energy

Operational energy requirements comprise only heating and cooling demands in this study as these are the only demands considered by the Building Code of Australia (except for lighting which is considered only in a basic manner). They are also the focus of most similar regulations, globally. Annual specific final heating and cooling requirements are computed using FirstRate5 (FR5), one of the three accredited software tools that are used to evaluate the thermal energy efficiency of buildings in Australia. FR5 relies on the CHEENATH simulation engine which is a multi-zone dynamic energy simulation. It takes into account solar radiation, thermal mass and natural ventilation and uses a time step of one hour. The final heating and cooling demands are used in conjunction with the climate zone to determine the star rating of a building (see Table 1 for those of the base case house).

However, while dynamic energy simulation software can model building physics, the estimated energy demand still depends significantly on building users. A study by the Australian Greenhouse Office (AGO, 1999) has shown that simulated energy demands often overestimate the actual energy use in real-life buildings. This is confirmed in a study by Williamson et al. (2010) that showed that the heating and cooling energy demand estimated with FR5 was higher than measured energy use in 3 out of 4 houses. In order to correct for this overestimation, the AGO (1999) recommended the use of ‘constraint factors’ to account for occupancy patterns and zoning. The factors used in this study are 0.45 and 0.25 for heating in Melbourne and Brisbane, respectively, and 0.4 for cooling in both locations (AGO, 1999). These factors do not account for any other user-driven variability in operational energy use which can significantly affect the results. This is further discussed in Section 4.
The final heating and cooling energy requirements were converted to primary energy terms in order to account for all losses associated with energy production and distribution. This was done by dividing final energy figures by the efficiency of the heating/cooling system and multiplying the resulting delivered energy by a primary energy factor depending on the energy source. A factor of 3.4 and 3.1 were used for electricity in Melbourne and Brisbane, respectively, based on Treloar (1998). The primary energy conversion factor for gas was 1.4 based on the same source. The primary operational energy use of one house in a given location over the period of analysis is calculated as per Equation 2.

\[
\text{LCTOPE}_h = \text{POA} \times \left( \frac{\text{PEF}_{s=H} \times \text{FHE}_{FR5} \times \text{CFH}}{\eta_H} + \frac{\text{PEF}_{s=C} \times \text{FCE}_{FR5} \times \text{CFC}}{\eta_C} \right)
\]  

(2)

Where: \( \text{LCTOPE}_h \) = Life cycle primary thermal operational energy of the house \( h \) in GJ; \( \text{POA} \) = Period of analysis in years; \( \text{PEF}_{s=H} \) and \( \text{PEF}_{s=C} \) = Primary energy conversion factors for the source \( s \) used for heating \( H \) and cooling \( C \) in GJ/GJ; \( \text{FHE}_{FR5} \) and \( \text{FCE}_{FR5} \) = Final annual heating and cooling energy demands as calculated by FirstRate5 in GJ; \( \text{CFH} \) and \( \text{CFC} \) = Heating and cooling constraint factors; and \( \eta_H \) and \( \eta_C \) = Heating and cooling system efficiency.

2.5. Quantifying life cycle energy

The life cycle energy demand of a house (\( \text{LCE}_h \)) is simply the sum of its life cycle embodied energy (\( \text{LCEE}_h \)) and of its life cycle thermal operational energy (\( \text{LCTOPE}_h \)). The difference between the life cycle energy demand of a house scenario \( h \) and that of the relevant base case house (BC) in Melbourne or Brisbane (\( \Delta \text{LCE}_{h,BC} \)) is the difference between the life cycle energy demand of a house scenario (\( \text{LCE}_h \)) and that of the base case house (\( \text{LCE}_{BC} \)), i.e. \( \text{LCE}_h - \text{LCE}_{BC} \).

3. Results

Figure 2 compares all houses with an improved star rating to the base case 6 Star house, in Melbourne (top) and Brisbane (bottom), respectively. The embodied energy demand related to materials and assemblies associated with the thermal performance of the building envelope, namely insulation and windows, are grouped into the thermal embodied energy category. Non-thermal-related embodied energy covers all other materials in the buildings such as timber or carpet. Note that only a maximum of 7 Stars could be achieved for Melbourne with the chosen design changes.

Results show that simply increasing the thermal energy performance of the envelope can paradoxically result in an increased life cycle energy demand in Brisbane and negligible life cycle energy benefits in Melbourne. This is due to the increase in thermal-related life cycle embodied energy (+572 GJ and +422 GJ for the 9★M houses in Melbourne and Brisbane, respectively). This is a very significant result as current building energy efficiency regulations tend to focus solely on improving the thermal energy efficiency of the envelope, notably by specifying maximum heat transfer values for envelope elements, e.g. in different European regulations (Rodríguez-Soria et al., 2014). This result is in line with the findings of Stephan (2013) and Crawford and Stephan (2013) who have shown that current building energy efficiency regulations, which do not consider embodied energy, can paradoxically lead to an increased energy demand over the life of a building.
Figure 2: Difference between life cycle energy demand of improved scenarios and base case house in Melbourne and Brisbane over 50 years. Note: Δ = difference, IEE = initial embodied energy, REE = recurrent embodied energy, M = improvement by material, D = improvement by design, M&D = improvement by material and design.
In parallel, improvements by design tend to result in net reductions of both thermal operational energy and embodied energy. The 7★D house in Melbourne and the 9★D house in Brisbane save 145 GJ and 303 GJ over 50 years, respectively. Design changes such as exposing the concrete slab by removing the carpet (in the two aforementioned scenarios) can significantly reduce the cooling demand (see Figure 2) while simultaneously reducing the life cycle embodied energy requirements associated with installing and replacing the carpet. Current building energy efficiency regulations do not encourage changes by design.

In addition to the above, Figure 2 shows the star rating is not correlated with life cycle energy requirements. For instance, the 10★M&D house in Brisbane and the 9★M in Melbourne have a higher life cycle energy demand than the 7★D house in Brisbane and the 7★M house in Melbourne, respectively. This is because star ratings do not consider embodied energy at all even though it can be as significant as thermal operational energy. More inclusive building energy efficiency regulations that consider embodied energy in their ratings should be used to better measure and ensure net life cycle energy benefits.

4. Discussion
This section discusses the results and limitations of the study and proposes potential pathways to ensure that building energy efficiency regulations result in net reductions in life cycle energy.

4.1. Building energy efficiency regulations and life cycle energy
This study has demonstrated that current building energy efficiency regulations in Australia do not always result in net life cycle energy reductions over 50 years. Whether in Melbourne’s marine temperate climate or Brisbane’s warm temperate climate, increasing the thermal energy performance of the house by solely increasing the amount of insulation and using efficient windows does not result in notable life cycle energy savings and can even significantly increase them for Brisbane. This is because the embodied energy of the additional materials counterbalances the net reductions in thermal operational energy. The business as usual approach of increasing the thermal performance of the envelope seems to have reached its limits: star ratings higher than 6 and 7 in Melbourne and Brisbane, respectively, result in insignificant savings or dramatically increase life cycle energy demand. Conversely, houses with an improved thermal energy performance by design had the lowest life cycle energy demands. This is because design changes can reduce both operational and embodied energy requirements simultaneously, yielding significant savings.

If building energy regulations are to yield life cycle energy savings these should firstly take embodied energy into account, as advocated by a number of previous studies (García-Casals, 2006; Crawford and Stephan, 2013; Stephan et al., 2013). However, this would require a significant amount of work before it can be implemented. Indeed, a common quantification technique for embodied energy should first be agreed upon in order to obtain consistent results, as advocated by Dixit et al. (2012). This technique should ideally rely on hybrid analysis in order to ensure that embodied energy is not underestimated.

Secondly, building energy efficiency regulations should encourage a design approach to energy performance as this is shown to yield significant benefits. Potentially, the benefits of particular design decisions for each climate could be evaluated and encouraged. For example, using reverse brick veneer walls significantly reduced thermal operational energy for the same embodied energy requirement as typical brick veneer walls. Such design measures could be explicitly favoured by the regulation.
4.2. Limitations

This study suffers from a number of limitations. Firstly, it considers only thermal operational energy and does take into account non-thermal operational energy requirements which can be very significant. Stephan and Crawford (2014) have shown that non-thermal operational energy can represent up to 67% of the total primary operational energy of an Australian house over 50 years. In addition, while care has been taken to choose a representative case study house, results are specific to this building only and variations to the type or design of the house may result in different findings. Thermal operational energy can vary widely based on user behaviour, the occupancy pattern of the building, orientation, nearby shading and other factors. It can also vary in time due to improved thermal performance, the installation of more energy efficient systems or a reliance on renewable energy sources (when considered in primary energy terms). Gram-Hanssen (2010) has shown that this variability can be up to 365% between two households living in identical dwellings in Copenhagen, Denmark. In addition, embodied energy figures can vary by up to 40% when hybrid analysis is used for its quantification (Crawford, 2011). Results therefore suffer from significant uncertainty and variability. A sensitivity analysis targeting individual variables should be undertaken to evaluate the robustness of the results. Despite these limitations, this study provides one of the most detailed life cycle energy analyses of building energy efficiency regulations to date.

5. Conclusion

Improving the energy efficiency of buildings should not only focus on thermal performance but should also include their embodied energy. The significant contribution of embodied energy to the life cycle energy demand of buildings emphasises the need for more comprehensive energy efficiency regulations. These will better ensure that net energy reductions do occur and that savings in thermal operational energy are not offset by an increase in embodied energy, as is currently the case in Australia. More comprehensive building energy efficiency policies will ultimately help reduce energy use and greenhouse gas emissions.

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House size and future building energy efficiency regulations in Australia

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Abstract: The size of houses in Australia has significantly increased over the last decades. New houses have higher embodied and operational energy requirements due to their increased use of materials and larger area. Yet, current building energy efficiency regulations fail to adequately capture the effect of house size because of their omission of embodied energy and their sole use of a spatial functional unit for operational energy (e.g. MJ/m²). This study quantifies the effect of house size on life cycle energy demand in order to inform future building energy efficiency regulations. It uses a parametric model of a typical suburban house in Melbourne, Australia and varies its floor area from 100 to 392 m² for different household sizes. Both initial and recurrent embodied energy requirements are quantified using hybrid analysis and all operational energy end-uses (thermal and non-thermal) are calculated in primary energy terms over 50 years. Results show that larger houses appear to be more energy efficient per m² than smaller houses while actually having a much higher life cycle energy demand. Also, embodied energy represents 49-70% of the energy demand across all 360 variations. Guidelines are provided to improve current building energy efficiency regulations.

Keywords: House size; life cycle energy analysis; embodied energy; functional unit.

1. Introduction

There is an urgent need to reduce greenhouse gas emissions from human activities in order to prevent major disruptions to the Earth’s ecosystems and climate. Reducing energy use in buildings is a key to reducing greenhouse gas emissions (IPCC, 2014). However, most existing building energy efficiency regulations focus on reducing operational energy only (ABCB, 2011), not considering embodied energy requirements. This narrow focus fails to capture the significant amount of additional materials needed in the ever larger new Australian houses (ABS, 2013b). Also, the use of a spatial functional unit to express energy efficiency (e.g. MJ/m²) does not systematically capture house size in the assessment. In the Australian case, an area adjustment factor is introduced to penalise houses with a conditioned floor area larger than 200 m² and favour smaller houses.
Clune et al. (2012) and Wilson and Boehland (2005) evaluated the relationship between house size and operational energy use and greenhouse gas emissions in Australia and the USA, respectively. They both found that large energy efficient houses can use more energy than smaller conventional houses and result in a more significant effect on the environment.

The lack of consideration of embodied energy in current building energy efficiency regulations has been widely discussed (García-Casals, 2006; Anderson et al., 2015). Excluding embodied energy could be due to the fact that many previous studies found that it represents only 10-20% of the life cycle energy demand over 50 years, e.g. Chau et al. (2015). However, this low figure comes from the systematic underestimation of embodied energy due to the use of process analysis for its quantification (Majeau-Bettez et al., 2011). Embodied energy can actually represent 30-70% of the life cycle energy demand of houses over 50 years (Stephan and Crawford, 2014a), depending on a range of factors, such as energy efficiency and size.

These flaws in energy efficiency regulations are particularly important in Australia where houses are among the largest in the world with an average of 241.1 m² of gross floor area (ABS, 2013a). Given that the average household size has also been declining in Australia over the last few decades (ABS, 2007), the floor area per capita has risen dramatically from ~57 m²/capita in 1984 to ~94 m²/capita in 2012. Since larger houses require more materials and associated embodied energy, as demonstrated by Fuller and Treloar (2004) and Fuller and Crawford (2011), the increase in floor area per capita results in a very high energy intensity per capita for housing. Considering an average initial embodied energy intensity of 14.1 GJ/m² as in Fay et al. (2000), this increase in floor area results in ~522 GJ of extra primary energy per capita. This is enough to drive around Australia ~11 times (in a car with a fuel efficiency of 10 L/100 km, considering that the energy content of gasoline is 32.4 MJ/L and based on 14 500 km per roundtrip).

House size is therefore a determinant variable that significantly affects the life cycle energy demand of dwellings but is not accounted for in most existing building energy efficiency regulations. Existing studies that have evaluated the effect of house size on its life cycle energy demand either use a small sample of house sizes (e.g. Fuller and Treloar (2004) and Fuller and Crawford (2011)) or focus on operational energy only (e.g. Wilson and Boehland (2005) and Clune et al. (2012)). It is therefore critical to better understand how size affects the overall life cycle energy profile of a house.

1.1. Aim and scope

The aim of this paper is to quantify the effect of house size on the life cycle energy demand in order to inform future building energy efficiency regulations that can effectively reduce total energy use. The focus is on energy because it is a good proxy for building environmental impacts (Oregi et al., 2015).

The life cycle stages taken into account comprise raw material extraction, material manufacture, processing and transport, construction and operation and maintenance. The end-of-life stage is not taken into account because of the huge uncertainties regarding the fate of the building many decades into the future. This study quantifies the embodied energy of all building materials as well as the operational energy used for heating, cooling, lighting, hot water, appliances and cooking. All results are expressed in primary energy terms.

2. Method

This section describes the modelling approach and the quantification algorithms used. These are based on Stephan and Crawford (2014b) and quantify embodied and operational energy over the building’s life
cycle. The user-transport energy demand which is also considered in Stephan and Crawford (2014b) is not taken into consideration in this study.

2.1. Modelling approach

In order to evaluate the effect of house size on life cycle energy demand, a large sample of house and household sizes is needed. Collecting detailed data on existing houses (e.g. bill of material quantities) can be a prohibitive and time consuming task. Using a computer model can streamline the process.

A hypothetical house is modelled using the advanced software tool developed by Stephan (2013) and described in Stephan and Crawford (2014b). The tool modifies the house size, generates the associated bill of material quantities and calculates its life cycle energy demand over 50 years for different occupancy levels. While the tool is able to model multi-storey houses and apartment buildings, this was considered to be outside the scope of this paper. The total number of variations includes 9 widths × 10 depths × 4 household sizes (=360 variations). These are based on typical dimensions of houses built by major developers in Australia. The household sizes are representative of the most common households living in detached houses according to the last census (ABS, 2013b). Lone person households were not considered as these typically reside in apartments based on the same census data.

Certain combinations of width and depth result in the same floor area (e.g. 12 × 10 m and 10 × 12 m). These pairs of combinations have both been evaluated because they result in different material quantities. The characteristics of the house are listed in Table 1. Note that the thermal performance of the house in terms of envelope heat transfer as well as the efficiency of building systems is kept constant across all sizes. This allows a better comparability of results and negates the effect of particular variables on the outcome (e.g. the ventilation rate).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Width (m)</strong></td>
<td>10, 10.5, 11, 11.5, 12, 12.5, 13, 13.5, 14</td>
</tr>
<tr>
<td><strong>Depth (m)</strong></td>
<td>10, 12, 14, 16, 18, 20, 22, 24, 26, 28</td>
</tr>
<tr>
<td><strong>Household size (number of occupants)</strong></td>
<td>2, 3, 4, 5</td>
</tr>
<tr>
<td>Location</td>
<td>Melbourne, Victoria, Australia</td>
</tr>
<tr>
<td>Period of analysis (years)</td>
<td>50</td>
</tr>
<tr>
<td>Structure type</td>
<td>Timber-framed</td>
</tr>
<tr>
<td>Façade</td>
<td>Brick veneer wall; 100 mm of fibreglass insulation; Double glazed aluminium-framed windows (30% window to wall ratio)</td>
</tr>
<tr>
<td>Roof</td>
<td>Concrete tiles; 200 mm of fibreglass insulation</td>
</tr>
<tr>
<td>Flooring</td>
<td>Carpet in bedrooms and living rooms; ceramic tiles in wet areas</td>
</tr>
<tr>
<td>Internal walls</td>
<td>10 mm painted plasterboard</td>
</tr>
<tr>
<td><strong>Average U-value of the building (W/(m²·K))</strong></td>
<td>~0.58</td>
</tr>
<tr>
<td>Ventilation (ach⁻¹)</td>
<td>3</td>
</tr>
<tr>
<td>Operational energy sources</td>
<td>Gas heating (eff.: 70%) and cooking (eff.: 90%), Electrical cooling (COP: 2.5)</td>
</tr>
</tbody>
</table>

Note: characteristics in *italic* are varied, eff = efficiency, COP = coefficient of performance.

The study uses the climate of Melbourne, Victoria for which the assemblies used are designed (notably in terms of thermal performance). This is not only because Victoria has the largest houses in
Australia (and therefore in the world) but also because Melbourne is the fastest growing city in Australia in terms of population, with an estimated population of 10 million by 2051. It is therefore set to increase its housing stock in the coming decades (Victorian Government, 2014). This section has described the modeling approach. The next two sections describe the quantification of embodied and operational energy, respectively.

2.2. Quantifying embodied energy

Embodied energy represents the sum of all energy inputs for the production of building materials across their supply chains. Initial embodied energy represents the embodied energy of the building as-built while recurrent embodied energy is the energy required to produce and replace building materials throughout the period of analysis. This paper relies on the comprehensive input-output-based hybrid analysis developed by Treloar (1997) to quantify embodied energy. This approach takes into account entire supply chains and does not underestimate embodied energy, as is commonly the case in existing building life cycle energy analysis studies (Crawford and Stephan, 2013). The quantities of materials in each size variation are multiplied by embodied energy coefficients compiled by Treloar and Crawford (2010). An additional amount of energy is then added to the total to account for non-material processes, such as insurance and advertising. The replacement rates of building materials, which determine recurrent embodied energy, are based on Ding (2004). The life cycle embodied energy for each house size is quantified as per Equation 1.

$$LCEE_h = \sum_{m=1}^{M} (Q_m \times EC_m) + \left( \sum_{m=1}^{M} TER_{rb} - TER_m \right) \times C_h$$

$$+ \sum_{m=1}^{M} \left[ \frac{POA}{SL_m} - 1 \right] \times \left[ (Q_m \times EC_m) + \left( TER_{rb} - TER_m - \sum_{i \neq m} TER_{i \neq m} \right) \times C_m \right]$$

Where: $LCEE_h =$ Life cycle embodied energy of house $h$, in GJ; $Q_m =$ Quantity of material $m$ in the house, in t, m³, m or another functional unit; $EC_m =$ Hybrid energy coefficient of material $m$, in GJ per functional unit; $TER_{rb} =$ Total energy requirements of the residential building sector $rb$, in GJ per AUD; $TER_m =$ Total energy requirements of the input-output pathways representing the material production processes for which process data is available, in GJ per AUD; $C_h =$ Cost of the house $h$ in AUD; $POA =$ Period of analysis, in years; $SL_m =$ Average service life of the material $m$, in years; $TER_{i \neq m} =$ Total energy requirements of all input-output pathways not associated with the installation or production process of material $m$, in GJ per AUD; and $C_m =$ Cost of the material $m$ in AUD.

2.3. Quantifying operational energy

Operational energy can be divided into thermal and non-thermal energy. Thermal energy is quantified using the heat transfer coefficient of envelope elements, ventilation rates and heating degree hours. The steady-state thermodynamic equations used rely on indoor comfort temperatures of 20°C and 26°C for heating and cooling, respectively. The degree hours calculated factor in solar gains and free internal gains by adapting the balance temperature. While using dynamic thermal modelling through a third party software tool (e.g. EnergyPlus) could generate more accurate results, the steady-state approach is sufficient within the scope of this study. Indeed, since this paper aims to compare houses with different
sizes, the consistency of the quantification approach for all variations is the most important aspect (rather than the accuracy of the energy demand estimation). In addition, using a dynamic simulation software does not systematically result in a more accurate estimation of energy use, as demonstrated by a number of studies, such as Williamson *et al.* (2010).

Non-thermal energy is modelled using average intensities that are derived from DEWHA (2008). Lighting is calculated based on the floor area of the house while hot water, appliances and cooking are calculated based on the number of occupants.

The annual operational energy demand is assumed constant over time. The life cycle operational energy demand is calculated as per Equation 2, by converting each energy use to primary energy terms, summing all operational energy demands and multiplying the total by the period of analysis. Primary energy conversion factors of 3.4 for electricity and 1.4 for gas are used and are based on Treloar (1998).

\[
LCOPE_h = POA \sum_{e=1}^{E} \left( \frac{OPE_e}{\eta_e} \times PEF_e \right)
\]

Where:\[LCOPE_h = \text{Life cycle primary operational energy of the house } h \text{ in GJ}; POA = \text{Period of analysis in years}; OPE_e = \text{Annual final operational energy demand of the end-use } e \text{ in GJ}; \eta_e = \text{Average efficiency of the system used for end-use } e; \text{ and } PEF_e = \text{Primary energy conversion factor of the end-use } e \text{ based on the energy source.}
\]

2.4. Quantifying life cycle energy

The life cycle energy demand of each house \([LCE_h]\) is simply the sum of its life cycle embodied energy \([LCEE_h]\) and its life cycle operational energy \([LCOPE_h]\) over the period of analysis (50 years).

3. Results

This section presents the results of the study. The significance of current issues in building energy efficiency regulations is first evaluated. This is followed by a detailed analysis of the influence of size on the life cycle energy demand of the studied house.

3.1. The significance of the functional unit

Figure shows the total life cycle energy demand per capita (upper part) and per m² (lower part) for all studied house sizes. Two main observations can be made.

Firstly, while the life cycle energy demand per capita increases with house size, it decreases when expressed on a per m² basis. For any household size, the largest house always has the lowest energy intensity per m². Using a spatial functional unit not only fails to consider the size of the house but also favours larger houses. This is because the life cycle energy demand is sublinearly correlated with house size, meaning that the percentage increase in house size is larger than the associated increase in energy use (see Section 3.3. for more details). This means that building energy efficiency regulations need to correct energy use for house size in order to avoid artificially decreasing the energy intensity per m² of larger houses and making them look efficient while they result in a higher life cycle energy demand.

Secondly, Figure reveals the importance of lifestyle. Indeed, two occupants living in a 160 m² house (point A) use a similar amount of energy over 50 years as three occupants living in a 260 m² house (point
B) or four occupants living in a 392 m² house (point C). Expressing results on a per capita basis relates energy use back to the occupants and enables a comparison of different lifestyles by capturing the floor area per capita.

Figure 1: Effect of gross floor area and occupancy on the life cycle energy demand of the house over 50 years, per capita and per square metre.

3.2. The significance of embodied energy

Regardless of the house or household size, embodied energy represents a significant share of the life cycle energy demand over 50 years. As shown in Figure 2, even in the case of a 100 m² house with 5 occupants, embodied energy represents 49% of the total. On average, initial embodied energy represented 61.6% of the life cycle embodied energy over 50 years (across all 90 house sizes).

More importantly, for the largest house size, embodied energy dominates the life cycle energy demand, representing up to 70% of the total for a household size of two occupants. Even if five occupants live in that same house, the share of embodied energy is still 63%. This high contribution of embodied energy is due to the use of the comprehensive input-output-based hybrid analysis for the quantification of embodied energy and the relatively higher than usual thermal energy efficiency of the house (achieving a 7 Star rating under the current Australian building energy efficiency regulation). Since new houses have a reduced operational energy demand, enforced by current building energy efficiency regulations, embodied energy becomes more significant and should be considered. It is also important to underline that in this study, operational energy includes all non-thermal end-uses and is expressed in primary energy terms, capturing all losses across the energy supply chain. A more detailed analysis of the influence of size on the life cycle energy demand is provided in the following section.
3.3. The influence of size on the life cycle energy profile of houses

Figure 3 depicts the life cycle embodied and operational energy demand of all studied house sizes, by floor area and reveals a more significant increase in embodied energy with house size compared to the operational energy demand. It intentionally omits hot water, appliances and cooking energy demands as these are assumed to be affected solely by the number of occupants in this study.

For the largest house (392 m²), the life cycle energy demand (excluding hot water, appliances and cooking energy) is 15 443 GJ compared to 5 156 GJ for the 100 m² house. That is an increase of 200% compared to the 292% increase in house size. The life cycle energy demand seems to be sublinearly correlated with house size. This is why using a per m² functional unit tends to favour larger houses.

The embodied energy of assemblies varies differently with house size depending on the assembly type. As a general observation, the embodied energy of horizontal assemblies increases to a similar extent, e.g. flooring (+293%), the roof (+292%) and the slab (+206%). In comparison, the embodied energy of vertical assemblies, such as outer walls, interior walls and windows increases by ~110% (note that the window to wall ratio has been kept constant at 30% in all variations). This is because the amount of walls needed per m² is not the same for all house sizes. Horizontal assemblies are therefore likely to contribute more to the life cycle energy demand of large houses compared to smaller ones. The ‘other finishes’, ‘construction’ and ‘other’ are calculated on a per m² basis and are therefore directly correlated with floor area. Overall, the life cycle embodied energy increases by 193% and is therefore sublinearly correlated with house size as well.

The heating and cooling demands increase by 166% and 165%, respectively. This is because the heat exchange area is not a direct function of the floor area but also depends on the level of compactness of the building. In other words, heating and cooling increase at around 57% the rate of the floor area of the case study house. The Australian building energy efficiency scheme takes this into account and uses an area adjustment factor of ~40% between a 100 and a 400 m² house (Delsante, 2005). This factor seems to be slightly underestimating the effect of size. However, regulations or certifications that do not correct for house size could be systemically allowing larger houses to achieve a better rating because they have a lower heating and cooling demand per m². This is the case of the passive house certification. This study shows that in reality larger houses result in significantly higher embodied and operational energy use and associated environmental impacts.
Figure 3: Effect of gross floor area on the life cycle energy demand of the house over 50 years, by use.

4. Discussion

This section describes the contribution of this study and provides guidelines regarding the improvement of current building energy efficiency regulations. Limitations of this study are then highlighted.

4.1. Contribution

This study has quantified for the first time the relationship between house size and life cycle energy demand while using a comprehensive embodied energy quantification approach. Results show that larger house sizes result in a higher life cycle energy demand, notably through the increase in embodied energy. Also, it was found that both operational and embodied energy are sublinearly correlated with house size. Hence, the use of a spatial functional unit (e.g. MJ/m²) to express energy efficiency tends to favour larger houses, even for embodied energy. These results can inform future building energy efficiency regulations in Australia and in other countries. The USA is particularly relevant because it also has a residential building stock with a high share of large houses (U.S. Census Bureau, 2013).

In order to actually reduce the overall energy use, current building energy efficiency regulations need to be revised. The main amendments proposed include:

- Incorporating embodied energy into the energy efficiency assessment;
- Developing standards for measuring embodied energy using the most comprehensive forms of analysis;
- Using overall and per capita energy use in addition to the current per m² measure; and
- Including efficiency requirements for primary energy and not only final thermal energy.
Implementing these changes in current building energy efficiency regulations would help ensure that net energy reductions are achieved and that additional environmental effects associated with larger houses are considered.

4.2. Limitations

This study suffers from a number of limitations. Firstly, using a computer model to estimate bills of material quantities and operational energy demand can result in a significant level of uncertainty. Collecting actual bills of material quantities and post-occupancy operational energy figures would significantly improve the robustness of the results. This however would require a significant amount of resources. Secondly, the operational energy use of a particular household can differ significantly from that of another. There is therefore a significant amount of variability in operational energy use and presented values should be considered as averages. Similarly, there can be a large level of uncertainty in embodied energy figures (±~40%). Because all houses in this study have the same materials, the uncertainty affects all houses equally and does not therefore influence the findings. However, the contributions of each of the embodied and operational energy can be significantly altered by uncertainty and variability. Finally, this paper uses a case study house and results are valid only for the studied house. Other house types and building materials might result in different findings.

5. Conclusion

With a forecasted increase in the global population and notably in urban population, it is essential that large houses with small households are avoided in order to minimise effects on the environment. This study has quantified the life cycle energy demand associated with house and household size. It shows that future building energy efficiency regulations should take embodied energy and house size into account in order to ensure actual reductions in the life cycle energy demand. Failing to incorporate embodied energy and house size into building energy efficiency regulations can lead to a paradoxical increase in life cycle energy use when building so-called ‘energy efficient’ large suburban houses.

Acknowledgements

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Household energy use in Uganda: existing sources, consumption, and future challenges

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Abstract: This paper details patterns of energy consumption for domestic buildings in urban areas of Uganda. The paper shows the range of energy sources employed by households, the level of consumption of energy, as well as common appliances and equipment in use. The findings suggest strong demand for energy, but largely from solid fuel sources, with most households making use of firewood or charcoal for cooking. While currently low by world standards, electrical energy use was largely for lighting and entertainment. Efforts at increasing access to electricity to reduce pressures on dwindling forest resources, although a noble goal, has significant challenges, linked to limited and erratic availability of electricity, approaches to building design, as well as lifestyle transformations that contribute to a growth in energy demand. The study itself contributes to discourse on energy use and energy efficiency in buildings, filling the gap in the availability of information and geared to informing future policy and interventions.

Keywords: Household energy use; household energy consumption; electricity; Uganda.

1. Introduction

Over the past decade Improving access to ‘modern’ sources of energy has been a key goal of governments across sub-Saharan Africa. This was largely a result of growing concerns for the heavy reliance on wood fuel, accounting for over 80% of domestic energy consumption, but regarded as an inefficient and unsustainable means of meeting energy needs. Across eastern Africa, countries have thus embarked on ambitious rural electrification programmes, with Tanzania, seeking to achieve 30% connectivity by 2015, up from 9% in 2012 (Bloomfield, 2014). Regardless, a move towards increased electricity use in domestic buildings has raised concerns related to its impact on somewhat limited and often erratic electricity supplies, as presented by Pérez-Lombard, et al. (2008). Constant electricity blackouts and brownouts across East Africa, highlight deficiencies in generation capacity, vis-à-vis the fast growing demand for electrical energy. Growth in demand for energy has been from rapid economic
growth, as well as electrification drives that have seen a large increase in the number of households connected to mains electricity over the last two decades. This has not been matched by any ‘real’ increase in generation capacity, and while Uganda has seen an increase in its electrical generation capacity, from 0.766 Billion kWh in 1990 to 2.406 billion kWh in 2010 and largely from hydro, this has barely kept up with the exponential growth in demand, which increased from 0.602 Billion kWh to 2.192 Billion kWh over the same period (not accounting for transmission loses of about 25%). On a per capita basis, generation capacity of 70.8kWh for 2007, was significantly lower than the average for sub-Saharan Africa at 451kWh, and far below the G7 average of 9,837kWh for same year (NationMaster, 2003-2015). This does indicate significant disparity between the available electrical energy supply, and growing demand.

While growth in electricity connectivity is welcome, serving to meet the aspirational desires of the population, and reducing the negative effect of the current heavy reliance on wood fuel, this comes with significant challenges related to the nature of electrical energy generation and distribution. The inevitability of increased demand from domestic connections (currently 26%), thus presents a hurdle for both current, and future energy transitions, particularly given current consumption patterns are largely unknown. Knowledge of current household energy consumption patterns is generally anecdotal, but does suggest growth patterns akin to those seen across the globe, increasing steadily as economies grow. Nevertheless, lack of fine grain data on which to base future energy efficiency measures, emerges as a hindrance to future planning. With blackouts and brownouts showing no sign of abating, increased connectivity without an appreciation of current household electricity consumption patterns may serve to exacerbate the already precarious energy problem. Further, with the exponential increase in residential developments, with more than 60% of planning applications for residential developments in 2013 (Uganda Bureau of Statistics, 2014), understanding the nature of energy consumption in domestic buildings becomes critical, given a general absence of energy related building standards in East Africa, and indeed across much of sub-Saharan Africa (Iwaro and Mwasha; 2010).

According to UMEME (2014), Uganda’s energy distributor, the total number of formal grid connections in 2014 stood at 650,573, of which 91% were domestic, accounting for the largest proportion of grid connections (Adeyemi and Asere, 2014). Households are also the fastest growth market for electrical connections, growing at 13% per annum, significant given only 20% of urban households and 1% of rural households were officially connected to the electrical grid in 2001 (Sebbit et al., 2001; 237). Household energy demand thus presents as an important area for investigation, given the total number of households in 2014 stood at 7,353,427 (Uganda Bureau of Statistics, 2014), suggesting a tremendous potential for growth in energy demand. Indeed, it is often cited that for most African countries south of the Sahara, building construction over the next few decades will surpass the number of buildings in existence today, a consequence of a large housing backlog, and a rapidly increasing population (Tipple, 1994).

Understanding demand and consumption of energy, presents an opportunity to better address the needs of users, but requires information about current energy use patterns. This paper investigates the state of domestic energy consumption across Uganda, seeking to gain an appreciation of current energy use. Previous household energy studies, by Sebbit et al. (2001), and Lee (2013), were directed at ascertaining the energy mix in households, but did not investigate the breakdown of energy consumption. The studies did confirm that households were heavily reliant on fuel-wood as the primary source of energy, prompting activities directed at introducing appliances to reduce consumption of wood fuel. Such activities did not address electrical energy use, generally considered to be negligible in
relation to total household energy demand. Nevertheless, the disparity between electricity generation capacity (and growth) and growth in consumption of electricity, does call for greater attention to this area, more so in light of recent discoveries of viable oil reserves in Uganda, which have scuttled discourse on energy conservation, skewing it back towards a ‘business-as-usual’ approach.

2. Methodology

Although the wider project from which this study relates took in over 300 buildings and a variety of building types, as reported by Kazoora, et al. (2015), the focus of this paper is specific for residential buildings. The paper only reports on residential buildings in urban centres, with data from 79 households presented. Data was collected through a walkthrough energy audit, making use of a questionnaire based on the Energy Audit Manual for use in the Operation of Buildings developed by UNHABITAT (1988). The study had two components: the first looking at general elements of the siting and operation of the buildings, and included; site description, nature of the building envelope, nature of lighting, ventilation and use of shading devices. With regard to energy, the second component reviewed electrical bills, documented electrical equipment used within dwellings, as well as the time and duration of use. Buildings studied were sampled from across the three sub-climate zones of Uganda: Hot and Wet – Savannah; the Cool Wet Highland Climate Zone; and, the Hot-Humid Climate Zone – Lakeside. Consideration was made to sample dwellings from different income groups, dwelling sizes, and typologies, although it was acknowledged that access to buildings was a key-determining factor in the selection of buildings surveyed, given overt security concerns across the country. In all, each walk through audit took approximately 60 minutes to complete. Data was analysed using IBM SPSS, Apple Numbers and Microsoft Excel, with two key areas of focus for this paper: the sources of energy used by households; and, energy consumption within the dwellings.

3. Findings

Buildings included in the study showcased a diverse array of housing types built over the past 70-years. A substantial proportion of buildings (over 60%) were constructed after 1990, highlighting the rapid growth in construction after the protracted civil war in Uganda during the 1980s. Dwellings ranged in size, from a tiny 9sq.m., for a single room tenement dwelling (known locally as a Mizigo), to over 600sq.m for some large detached dwellings (See Figure 1), giving an average area of 137sq.m. Buildings sat on lot sizes ranging from 120sq.m., to over 16,000sq.m. for some old style company estates that housed junior employees. This gave an average plot ratio of about 0.28, suggesting that most buildings did have access to significant open space around them. Single storey detached housing were predominant in the study, with only a few apartments recorded. The dominance of detached dwellings in urban areas could be linked to the perception of what these represented: upward mobility, wealth and status, somewhat cultivated by the legacy of colonial style bungalows found in wealthy urban neighbourhoods, but also linked to a strong traditional attachment to the land, significant as many living in urban centres are first generation urban residents. The small single or double room Mizigo dwellings, predominant for low-income urban housing, emerged as a consequence of pre-independence housing policies. Mizigo were originally intended to house temporary workers (generally male), who were expected to return to their main (rural) place of residences on weekends, holidays, and on completion of their employment. These dwellings generally had shared washrooms, and no cooking facilities, and continue to be built to this day, as a cheap means of accommodating the burgeoning number of urban dwellers.
3.1. Sources of energy

Energy used in households included in the study was largely from two fuels: charcoal (89% of households) and electricity (85% of households). Most households used charcoal for cooking, burning through an average of 71kg of charcoal each month. Less prominent, was the use of kerosene (24% of households), and LPG (22% of households), with an average of 6.7litres, and 14kg per month for each fuel type (See Table 1).

<table>
<thead>
<tr>
<th>Source (Per cent of Households)</th>
<th>High</th>
<th>Low</th>
<th>Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>Firewood (7.6%)</td>
<td>450.0kg</td>
<td>25.0kg</td>
<td>285.0kg</td>
</tr>
<tr>
<td>Charcoal (88.6%)</td>
<td>240.0kg</td>
<td>10.0kg</td>
<td>60.0kg</td>
</tr>
<tr>
<td>LPG (21.5%)</td>
<td>50.0kg</td>
<td>3.0kg</td>
<td>7.5kg</td>
</tr>
<tr>
<td>Kerosene (24.1%)</td>
<td>50.0litres</td>
<td>0.5litres</td>
<td>2.5litres</td>
</tr>
<tr>
<td>Electricity (86.1%)</td>
<td>472.0kWh</td>
<td>7.0kWh</td>
<td>78.3kWh</td>
</tr>
</tbody>
</table>

While black-outs (locally referred to as load shedding) were a regular occurrence across the country, the low penetration of generators, and solar PV systems was surprising, with only two households having generators, one having a small PV collector, and none with solar hot-water systems. Lack of solar PV and solar hot water systems could in part be attributed to the high upfront investment associated with these systems, as well as an enduring belief that solar systems were expensive and unreliable.
(Karekezi, and Kithyoma, 2003; Kulabako, 2013). This view persists in spite of a marked fall internationally in the cost of PV systems, and significant improvements in solar technologies in recent years, not to mention the tax-free status for imported solar PV and solar hot-water systems in Uganda, making these considerably cheaper than ever before. Most households made use of a mixed energy regime as a means of mitigating against energy shortages and cost increases, and as a means of ensuring household activities were not affected by the unavailability of one fuel source. The energy mix indicated that households steered clear of formal energy sources (gas and electricity) for cooking.

While a large percentage of urban households were connected to mains electricity, use of charcoal as the predominant fuel for cooking was a significant revelation. This could be linked to three key factors: first, a perception that electricity tariffs are high (relative to income); second, the unreliable electricity supply, compelling households to seek out alternatives due in order to maintain regular meal times; and third, a large percentage of rural-urban migrants comfortable with ‘traditional’ fuels as a source of energy. This heavy reliance on charcoal, may suggest that moves to change how people consume energy may be far more difficult than imagined, and linked not only to ideas of energy cost and reliability, but to socio-cultural factors, as expressed in through claims that ‘food cooked on charcoal stoves tasted better than food cooked on electricity or gas’. Anecdotal evidence also suggested that for many households, fuel for day to day activities was purchased on a ‘need-to’ basis, a key factor in the introduction of pre-paid metering, giving householders access to electricity, when they needed it, and could afford to pay for it. The low penetration of solar PV and solar hot water systems, despite more than two decades of irregular electricity supplies, suggests deeper factors influencing the choice of fuel for household use beyond merely cost and availability, more so as charcoal is used across all households and not linked to household status. Indeed, the findings of a similar study conducted in Nigeria by Chidebell-Emordi (2015), found the penetration of generators at 72% of households, a consequence of a highly irregular electricity supply. That study however did not report on the uptake of solar PV or solar hot water systems, although it could be speculated that this was negligible. Tillmans and Schweizer-Ries (2011) suggest that the low uptake of these new technologies, despite their relevance, could be linked to a lack of familiarity or limited exposure, restricting their uptake.

3.2. Energy consumption

Reviewing energy consumption within households, overall consumption considering all sources, and based on conversion rates derived from Myles et al. (2007), was calculated to be about 698kWh per month per household or average; seven times the average monthly household consumption rate for electricity at 96.3kWh per month (1,155kWh per annum). This is a clear indication of the large proportion of energy used for cooking. Looking specifically at electrical energy, 1,155kWh per annum is far below average annual electricity use in different parts of the world: Australia – 7,227kWh; South Africa 4,389kWh, and the global average of 3,471kWh (Wilson, 2012). This imbalance is often cited as justification for a business-as-usual approach to energy use, with developing countries playing ‘catch-up’.

Household energy use in itself is misleading, not accounting for dwelling sizes that vary considerably. Taking dwelling size into account was necessary to correlate energy use with building area to give an idea of comparative energy use across different dwellings and dwelling types. On average, households used 86kWh of energy per square metre per annum, however, with charcoal, LPG, and firewood used almost exclusively for cooking, in terms of square metre consumption, they were excluded in subsequent comparisons. Considering only electricity consumption relative to dwelling size, this was
found to be 9.4 kWh per square metre per annum on average, with higher per square meter consumption in smaller dwellings, as presented in Figure 2. Seeking to contextualise this figure was through comparison with studies undertaken in other parts of the world. Chaiiwatworakul et al. (2015) found electricity consumption to be 23.6 kWh per square metre per annum in northern Thailand. In the UK, Yohanis et al. (2007) determined electricity consumption to be between 30 and 60 kWh per square metre per annum (depending on the dwelling type), but acknowledging that most households made use of gas or oil for cooking and space heating respectively. For a hot arid climate, Aldossary et al. (2014), found electricity consumption to be 163 kWh per square metre per annum for houses, and 203 kWh per square metre per annum for flats in Riyadh, Saudi Arabia, most used for space cooling.

![Figure 1: Household electrical energy consumption per square metre (Authors).](image)

The inverse relationship between consumption of electrical energy and building area is indicative of the households not using electricity for space heating or cooling. This however did raise questions about what household appliances were installed in the various households. Major appliances in use in the different households are presented in Table 2. Dwellings has at least one light fitting in each habitable room, most being compact fluorescent bulbs or fluorescent tubes. A few households did make use of incandescent light bulbs, as these considerably cheaper to buy than fluorescents. Of households reporting appliances used, all indicated having at least one mobile phone within the dwelling, with more than 82% of households reporting more than three devices, and some reporting more than eight. While ubiquitous, lighting and mobile phones are generally not large consumers of energy, however use patterns and efficiency are raised as being of particular interest. Besides mobile phones, the most predominant appliances were those related to entertainment: televisions, DVD players and radios/hifi systems, found in about 80% of households. Electric irons were the most common high-energy appliance and found in 82% of dwellings, followed by electric kettles at 57%. Modern kitchen appliances were less common, reflecting the predominance of traditional ways of food preparation, but also a
consequence of the poor electricity supply, which affected performance of such equipment. These findings are in line with a similar study conducted in Nigeria by Chidebell-Emordi (2015), who found a high percentage of entertainment equipment in dwellings (100%). A key difference in Nigeria was the use of fans (89%); and the use of AC units (18%), an indicator of the markedly different climate of southern Nigeria relative to Uganda.

Table 2: Household electrical appliances (Authors).

<table>
<thead>
<tr>
<th>Item</th>
<th>Per cent of Households</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mobile Phone/PDA</td>
<td>100.0%</td>
</tr>
<tr>
<td>Computer (Desktop)</td>
<td>17.6%</td>
</tr>
<tr>
<td>Computer (Laptop)</td>
<td>60.8%</td>
</tr>
<tr>
<td>DVD Player/Games Console</td>
<td>56.9%</td>
</tr>
<tr>
<td>Iron</td>
<td>82.4%</td>
</tr>
<tr>
<td>Kettle (Electric)</td>
<td>56.9%</td>
</tr>
<tr>
<td>Microwave Oven</td>
<td>23.5%</td>
</tr>
<tr>
<td>Radio / Hifi</td>
<td>78.4%</td>
</tr>
<tr>
<td>Refrigerator/Freezer</td>
<td>54.9%</td>
</tr>
<tr>
<td>Television</td>
<td>82.4%</td>
</tr>
<tr>
<td>Washing Machine</td>
<td>11.8%</td>
</tr>
</tbody>
</table>

Kwong et al. (2014) suggested that provision of comfort for building occupants is increasingly a key consumer of energy across the tropics. However, the current study did not find many households seeking to achieve comfort through the use of mechanical means, with only two households making use of portable fans. This low penetration of climate modification equipment may be linked to the moderate upland tropical climate of Uganda, with a large diurnal range of 9.0 Deg.C (Griffiths, 1972), aiding in reducing the impact of high daytime temperatures. While climate related behavioural adaptations were not explicitly investigated in the current study, they nevertheless emerge as an important consideration in the evaluation of current and future trends in energy consumption. In this case, although achieving thermal comfort through mechanical means was not a major contributor to energy consumption, it was nevertheless evident that building performance was a factor in energy use, with building design, siting and layout already influencing use of artificial lighting. The convenience of flicking a switch, making it more likely that lights would be used during the day, influenced by window sizes, which were generally small, and in a number of cases below the minimum required by planning regulations of 10% of the floor area for habitable rooms, with some living rooms having window to wall ratios as low as 4%. A further aspect of the contextual zeitgeist is a preoccupation with security, with many builders and householders alike, going to great lengths to install burglar proofing in the already limited window area, further affecting indoor light levels. In addition, with only a small proportion of buildings having their main façades facing North (5%) or South (14%) which are relatively easy to shade, but over 21% facing East, and 14% West, it is evident that building design may play a significant role in climate change related energy demand.

4. Discussion

A high proportion of energy used in the surveyed buildings was found to come from solid fuel sources, a dependency linked to, and perpetuated by an erratic electricity supply, as well as poor availability of modern fuel sources such as LPG. A key challenge linked to the household energy mix, relates to how any transformation or change can be effected, given entrenched attitudes associating formal energy
sources with high cost. The view of modern fuel sources as expensive is in the context of the immediate cost, and not the wider social and environmental impacts associated with these fuels. It is here that the somewhat convoluted nature of energy related discourse in the context of Uganda, and for many countries in sub-Saharan Africa. While energy use is low by world standards, the potential for growth is immense, linked not only to an increase in the number of households, but also to increased consumer related practices and modern appliances. While inroads have been made in some areas: seen in the introduction of energy efficient light fittings and the promotion of energy efficient charcoal stoves, these are only a small contributors to energy savings, relative to the exponential growth in overall energy demand. More significantly, this does not address the socio-cultural factors that drive this demand, neither does it link to current and future global CO$_2$ emission targets, a key challenge for energy transitions in sub-Saharan Africa (Sokona, et al.; 2012).

In relation to future CO$_2$ emissions link back to architectural design, and the contribution this has to a building’s lifetime energy use, with siting and layout potentially contributing to increased demand for energy to cool (or heat) buildings. It is acknowledged that it was not possible to ascertain the extent to which this could contribute to future energy demand without an appreciation of thermal comfort requirements, and the extent to which buildings meet these requirements. What is evident however, are buildings that seemingly ignored some basic tenets of climatic design, with many buildings having their predominant facades facing East and West, and inadequate provision for natural lighting and cross ventilation. While significant for climatic design, a key part of achieving energy efficiency and sustainability goals is evidently linked to the users and their ideals and preferences. This is evident in the use of artificial lighting during the day, a consequence of buildings not being designed for daytime use. Further, facing a building toward the East evokes spiritual beliefs, related to the breaking of a new day, while a tradition of facing the main road, relates to a basic human need for communication, as encompassed in the following passage by Kingsolver (1998; 35):

In a long row the dirt huts all kneel facing east ... east towards the village’s one road and the river and behind all that, the pink sunrise surprise. ... But no one here stays under a roof. It is in the front-yards - all the world’s a stage of hard red dirt under bare foot ...

Any move to influence future energy demand therefore needs to acknowledge occupancy patterns, as well as attitudes and behaviour nuances as a key factor in current energy use, and its potential impact on future trends. In the context of future demand for energy, these factors take on added impetus, particular given the different motivational factors that drive people to make decisions related to their consumption patterns, as was noted by Fischer (2008). In the context of lighting, the drive to use energy efficient luminaires for instance, was never fully elaborated, and while these may have provided energy saving to householders, this was not immediately evident, and the cost of the new luminaires, is a challenge many failed to account for. Relating this to whole buildings, the disassociation of building design from building performance has also failed to acknowledge the realities of power blackouts and brownouts as a factor to be considered. This does suggest that diffusion of ideas is currently not as evident, ironic given the proliferation of the Mizigo as an appropriate answer to housing demand despite its apparent limitations and inadequacies. Inadequate supplies of mains electricity has in itself been insufficient to prompt social or political change in Uganda, while in Zimbabwe, the country is set to make solar hot water systems compulsory for new houses as a consequence of power generation being less that 50% of peak demand (Zimbabwe to ban electric water heaters to save power, 2015).
5. Conclusions

The energy mix found in different households was a consequence of what could best be described as ‘hedging’, with households seeking to ensure access to energy resources regardless of changes in availability and cost. These use patterns while key in appreciating the challenges, and opportunities presented for energy saving, the concentration on ‘low-hanging fruit’ in changes in the use of energy efficient charcoal stoves, or more challenging, the lack of discourse related to energy conservation due to prospects of an oil boom, may serve to present a blind side in regard to a growing but potentially larger challenge. While current energy consumption in Uganda is low by global standards, the potential for it to grow is immense; from new grid connections, as well as from households making use of more electrical equipment and appliances, and not forgetting potential demand driven by climate change. Consequently, understanding the current demand for energy, providing a benchmark from which to plot future patterns and trends is crucial: the 9.4kWh per square metre per annum, giving a point of reference for future changes to energy consumption patterns.

The challenge of transforming attitudes and belief systems is a key hurdle, and linked to broader global systems, whereby societal aspirations are intrinsically tied to ‘the other’, which for energy could result in a massive growth in consumption from the business-as-usual paradigm. The low penetration of alternative energy sources, and the high percentage of households making use of solid fuel sources, presents a challenge given an inherent slow growth in electricity generation capacity, the difficulty in building traditional distribution networks, and the need to balance economic growth with environmental consciousness. Nevertheless, this scenario could present an opportunity to propose alternative design paradigms that could propagate good practices by example, through what Rogers termed diffusion of innovation, described as “the process in which an innovation is communicated through certain channels over time among the members of a social system” (Rogers, 1995: 5). Such an approach is however difficult to imagine in the current milieu, more out of circumstance, than necessity. Nevertheless, the challenge in terms of energy transitions in overtly evident, and expressed through a pertinent question for architects in the region and asks: ‘can we design and build better Mizigo from which this diffusion can spring?’

Acknowledgements

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References


Influence of four outdoor complex fenestration systems on the solar heat gains of an office space in a semiarid climate

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Abstract: Semiarid regions, such as Central Chile, are characterized by high solar radiation and temperature. In this climate, current architecture of fully glazed façade office buildings might cause high cooling energy consumption due to high solar heat gains (SHG), even in winter periods. In Chile’s Central region, the implementation of outdoor complex fenestration systems (CFS) is a common practice. However, the impact of CFS on the building thermal performance is usually unknown. The main objective of this paper is to evaluate the impact of four outdoor CFS in terms of their capability to control SHG through a window oriented northwest of an office space located in Santiago of Chile. An integrated thermal-lighting analysis tool is used to evaluate the performance of these CFS. The CFS evaluated are undulated horizontal louvers spaced 120 or 240 mm with 0 or 20\% of perforations. The main results show that the CFS evaluated significantly reduce SHG over the whole-year compared with SHG through an unshaded clear double glazing window; perforations and spacing of louvers increase SHG substantially in comparison with the CFS without transparency, but they allow outdoor visibility; and the CFS 3, with slats spaced 120 mm and 20\% perforations, provides a good balance between the control of SHG and outdoor visibility.

Keywords: Complex fenestration systems; solar heat gains; integrated thermal and daylighting analysis tool; \textit{mkSchedule}.

1. Introduction
The building sector accounts for 40\% of the total energy consumption and one-third of the green gas house emissions (UNEP, 2009). In Chile, a developing country, the building sector consumes 28.8\% of the total energy consumption (MinEnergía, 2013). Chile’s Central region, where Santiago is located (S33°
Influence of four outdoor complex fenestration systems on the solar heat gains of an office space in a semiarid climate

22° 46' W, is a cooling dominated climate, thus office buildings usually present high cooling energy consumption due to high internal and solar heat gains (SHG).

The SHG might be significant due to the climate characteristics of Santiago of Chile and the current architecture of fully glazed buildings’ façades. Figures 1a and 1c show the average daily temperature and hourly beam solar radiation in January, March, July and October, while Figure 1b shows the monthly average global horizontal radiation (ASHRAE, 2013). It is observed that Santiago’s climate is characterized by high temperatures and solar irradiance for around 8 months of the year. This climatic condition exposes office building to large heat gains due to solar radiation and heat conduction.

Figure 1: Weather data of Santiago of Chile. a) Daily temperature. b) Monthly average global horizontal solar radiation. c) Hourly beam solar radiation.

Different architectural design strategies could be implemented to achieve high thermal and energy performance of office buildings in climates like that of Santiago (i.e. reduce window-to-wall ratio, windows with very low solar heat gain coefficient or SHGC, high efficient lighting with very low heat gains). However, most of the buildings are designed with fully glazed façades as the ones shown in Figure 2, following a global architectural tendency. In Santiago’s climate, these types of buildings are affected by excessive SHG, which turns in high cooling energy consumption and visual discomfort. For instance, it is observed in Figure 2b that internal rollers of the north oriented façade are down in Titanium Tower, the second tallest building in Chile. This fact may be the user’s response to high SHG or excessive daylighting. The glazing installed on this building has a low SHGC of 0.30, thus the fact of observing rollers down evidences that the control of SHG in this climate cannot be fully performed by the glazing system.

Solar heat gains through windows highly impact on the building energy performance and occupant’s comfort. Several authors have reported the large contribution of SHG through fenestration to cooling loads in warm climates (Reilly and Hawthorne, 1998; Li and Lam, 2000; Winkelmann, 2001; Kuhn, 2006). Exterior shading devices are effective architectural building skins to reduce SHG through glazed façades because they intercept solar radiation before it reaches the glass. Fully shaded glazing façades can reduce SHG up to 80% according to ASHRAE (2013), while Bustamante et al. (2014) have reported reduction of short wave solar transmissions above 90% due to outdoor shading devices such as rollers and undulated and perforated metallic screens.
In Santiago of Chile, it is a common architectural practice to incorporate exterior shading devices to control SHG. There is a large variety of exterior shading devices such as louvers (fixed and movable), venetian blinds, and perforated screens. However, most of these devices correspond to a non-specularly transmitting layer, thus they are defined as complex fenestration systems or CFS (Laouadi and Parekh, 2007). The problem arises because the thermal and optical properties of CFS are commonly unknown and most of building energy simulation tools consider them in simplified ways. As consequence, this situation makes difficult to evaluate the impact of CFS on the thermal performance of buildings, especially during the early design stages. For this reason, the aim of this paper is to evaluate the influence of four outdoor CFS in terms of their capability to control SHG through fenestrations of an office building located in Santiago of Chile. The simulations are carried out with a recently developed daylighting and energy performance simulation tool, which is briefly described in Section 2.2.

2. Research methodology

2.1. CFS evaluated and office space description

This paper evaluates, via simulations, the influence of four outdoor CFS on the solar heat gains through the fenestration system of an office space oriented northwest. The CFS evaluated are:
Influence of four outdoor complex fenestration systems on the solar heat gains of an office space in a semiarid climate

- CFS 1 - undulated slats/louvers installed with slats spacing of 120 mm and slope of 60°,
- CFS 2 - undulated slats/louvers installed with slats spacing of 240 mm and slope of 60°,
- CFS 3 - same as CFS 1 but 20% of perforations; and
- CFS 4 - same as CFS 2 but with 20% of perforations

Figure 3 shows the arrangement and characteristics of the evaluated CFS. As can be seen, the slats of all CFS are highly undulated, while CFS 3 and 4 are perforated. Figure 3d also shows a zooming detail of the perforation pattern of CFS 3 and CFS 4. The four evaluated CFS correspond to the commercial products named Celoscreen of HunterDouglas Company Chile. Additionally, a double clear glazing system (without CFS) is also evaluated. The SGHC of this system is 0.83.

The tested office space was an experimental facility that consists of a highly insulated mobile module of 2.4 m x 4.0 m x 3.0 m (exterior dimensions) with a floor-to-ceiling double clear glazing façade oriented northwest (Figure 4).
2.2. Simulation tool

The evaluation of the CFS described above was performed using an integrated thermal and lighting analysis tool that integrates Sketchup, for creating the CFS and building models and properly exporting it to Radiance for calculating the bidirectional scattering distribution function (BSDF) of each CFS and the building lighting simulations, and Energy Plus for thermal and energy simulations. A detailed description of the whole simulation tool and parts of it can be found in (Molina, 2014; Molina et al., 2014c; Vera et al., 2015). This tool was developed to allow the thermal and lighting evaluation of spaces with controlled CFS and artificial lighting, thus the core of this tool is a program that generates the schedule of the position of the CFS and power fraction of luminaries, called mkSchedule. The schedule is generated to be used in detailed lighting and energy simulations (Vera et al., 2015). Although this paper includes the evaluation of fixed CFS and no artificial lighting, the same tool was used to perform thermal simulation.

The BSDF describes the bidirectional optical properties of the CFS; BSDF is needed for each CFS to properly evaluate their impact on the SHG through the fenestration system. This is done, first, by creating the CFS geometry in Groundhog, a Sketchup extension that allows exporting the model to Radiance (Molina et al., 2014b). Once the CFS model is transferred to Radiance using Groundhog, the BSDF of each CFS was obtained via ray-tracing simulations performed with a Radiance’s program called genBSDF, which has been validated by McNeil et al. (2013) and Molina et al. (2014a). The BSDF of each CFS obtained with genBSDF needs to be assembled to the optical properties of the double clear glazing by means of WINDOW 7.3 (LBNL, 2014), thus the BSDF of the whole fenestration system is generated.
EnergyPlus can read, as input, the BSDF of the whole fenestration system (CFS + double clear glazing), thus the thermal simulations take into account more precisely the optical properties of each CFS.

Using this tool, the office space model is created and incorporates the CFS and double clear glazing window as shown in Figure 5. Then, the office space is thermally simulated over the whole year for four different CFS. The climate data of the EnergyPlus weather data file for Santiago of Chile is used in these simulations.

3. Results

Since this paper focuses on evaluating the influence of four CFS in terms of their capability to control SHG, temporal maps of SHG and accumulative distribution of SHG are presented below for each CFS. Additionally, results for the case of the double clear glazing window without CFS are also presented to have the same base case to compare the results obtained for the CFS evaluated.

Figure 6 shows the temporal maps of annual SHG for the four CFS and double clear glazing window without CFS. This temporal maps show the SHG during the whole year. The x-axis corresponds to the day of the year while the y-axis is the hour of the day. Dark-blue zones show the periods of the year with no solar radiation. It should be noted that the scale of SHG was limited to 133 W/m², which is the maximum SHG found for the cases with CFS. However, the clear double glazing window has SHG up to 542 W/m².
Figure 7 presents accumulative curves of the percentage of time when SHG are lower than the value shown in x-axis. This information allows better comparison of the CFS’s performance with the performance of unshaded double clear glazing window. For a certain SHG and CFS, the y-axis provides the percentage of time of the whole year, excluding the periods with no solar radiation, when SHG are lower than the value of the x-axis.

![Temporal maps of annual solar heat gains of different CFS and clear double glazing.](image)

**Legend**

- **0 W/m²**
- **133 W/m²**

**CFS 1**
- Maximum SHG: 30 W/m²

**CFS 2**
- Maximum SHG: 101 W/m²

**CFS 3**
- Maximum SHG: 71 W/m²

**CFS 4**
- Maximum SHG: 133 W/m²

**Clear double glazing system**
- Maximum SHG: 542 W/m²

Finally, Figure 8 shows the outdoor visibility at 2 PM of the CFS evaluated. The images were obtained from inside the experimental office space module using a fisheye lens in a summer clear sky day. Since
outdoor visibility is important for human comfort, it is necessary to reduce SHG in balance with providing proper outdoor visibility. Although this paper presents this very simplistic approach to evaluate the outdoor visibility, it can provide useful qualitative information about the impact of the different CFS on visibility.

![CFS images](image1.png)

Figure 8: Outdoor visibility of the different CFS at 2 PM of fenestration façade oriented northwest.

4. Discussion

Figures 6 and 7 clearly show the significant reduction of SHG caused by the evaluated CFS in comparison with the clear double glass window. Figure 6 shows that the window without CFS allows high SHG during large portion of the year, which is represented by extensive red zones in this Figure. Otherwise, the four CFS evaluated presents none or few hours with excessive solar radiation. Moreover, CFS 4 reaches the highest annual peak of SHG among the CFS evaluated, with a peak of 133 W/m². Figure 7 shows this value of SHG is exceeded 37% of time by the unshaded clear double glazing window, which also presents a peak of SHG of 542 W/m². Comparing the windows without CFS and CFS 1, the CFS evaluated with the lowest SHG and peak of SHG of only 30 W/m², it is observed in Figure 7 that the SHG are above this value 82% of time for the clear double glazing window without CFS. These results reflect that outdoor CFS are highly efficient to control SHG over the whole year.

Comparing the results of SHG among the CFS assessed, it is observed that the most effective CFS for controlling SHG is CFS 1 due to it fully covers the window and has no perforations. However, it completely eliminates outdoor visibility as shown in Figure 8, which is an undesired effect for human comfort. For this reason, larger spacing between the slats of the CFS and perforations that allows larger visibility are interesting aspects to be evaluated:

- First, the increase in spacing of slats for 120 mm to 240 mm can be seen comparing the SHG of pairs CFS 1 with CFS 2 and CFS 3 with CFS 4 in Figures 6 and 7. As expected, larger spacing causes higher SHG, and the increment of SHG is similar for slats with 0 (CFS 1 versus CFS 2) or 20% (CFS 3 versus CFS 4) perforations. Figure 6 shows that the larger spacing mostly increases SHG during winter time, which makes sense because the sun altitude is lower causing higher irradiance on the northwest fenestration system after midday.
- Second, the effect of perforations of 0 or 20% can be analysed comparing the resulting SHG of CFS 3 with CFS 1 and CFS 4 with CFS 2. In both cases, SHG are higher for CFS with perforations. Also, Figure 7 shows that the increment of SHG is 36.7% and 31.7% with CFS 3 (in comparison
with CFS 1) and CFS 4 (in comparison with CFS 2), respectively. Notoriously, these results evidences that a low percentage of perforations (20%) increases the SHG significantly in comparison with the CFS without perforations.

- Thirds, comparing the SHG results of CFS 1, CFS 2 and CFS 3 allows analysing the relative impact of 20% perforations versus doubling the slats' spacing with 0% perforations. Figure 7 shows that the SHG of CFS 3 are much lower than that for the CFS 2. It means that larger spacing between slats allows much larger SHG than only increasing perforation to 20%.

Regarding the results of outdoor visibility of Figure 8, the approach used in this paper allow to qualitatively conclude that perforations and larger spacing between slats allow significant improvements of outdoor visibility in comparison with CFS 1 that has no transparency and fully covers the window. However, unshaded regions of the window due to perforations and larger slats’ spacing increase the SHG. In consequence, a trade-off between reducing the SHG and allowing outdoor visibility is a key factor for the overall performance of CFS. In this sense, CFS 3 seems to be the only CFS arrangement that allow low SHG and significant outdoor visibility. As shown in Figure 8, the outdoor visibility of CFS 3 is as good as CFS 2 and 4 even though it has no spacing between slats and only has 20% of perforations.

5. Conclusions

This paper evaluated the influence of four outdoor CFS on the SHG through a northwest fenestration façade of an office space in Santiago of Chile. The CFS evaluated correspond to undulated horizontal slats or louvers that were spaced at 120 or 240 mm with 0 or 20% of perforations. Simulations were performed using a simulation tool developed for integrated thermal and lighting analysis. Optical properties of each CFS, represented by the Bidirectional Scattering Distribution Function or BSDF, were obtained using genSHGC of Radiance to properly take into account the solar radiation transmission of the CFS evaluated. The main conclusions that can be drawn from this study are:

- Outdoor CFS can significantly control SHG over the whole year. SHG are significantly reduced by the CFS evaluated in comparison with the clear double glazing system without CFS.
- Increasing louver spacing causes higher solar heat transmission through the fenestration system compared to perforations. However, a low percentage of perforations (20%) also increases the SHG significantly compared to the CFS without perforations.
- The most effective CFS to control SHG is CFS 1, which fully covers the window and has no perforations. The SHG are very low with peaks of 30 W/m². However, CFS 1 does not provide outdoor visibility which might significantly diminishes visual comfort.
- CFS 3 represents a good balance of controlling the SHG and allowing outdoor visibility. The peak of the SHG of CFS 3 is 71 W/m², but 80% of the time SHGs are lower than 40 W/m², which is reasonable for fully glazed office building in Santiago of Chile. On the other hand, outdoor visibility of CFS 3 is comparable to the outdoor visibly observed in CFS with larger spacing between slats as CFS 2 and CFS 4.

This paper demonstrates the importance of slats’ spacing and perforations on the thermal performance of outdoor CFS. Further studies are needed to optimise their design in CFS to obtain a balanced performance in terms of office energy use and occupant’s visual comfort.
Influence of four outdoor complex fenestration systems on the solar heat gains of an office space in a semiarid climate

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Life cycle energy and large and small housing in New Zealand

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Abstract: Overcrowding in houses is a known problem but in some developed countries like New Zealand a new phenomenon, here called “large housing” has appeared. From 1974 to 2011 the average new New Zealand house almost doubled in size while occupancy reduced in the same period. First studies indicate large houses include several bathrooms, double/triple garaging, extra bedrooms/living areas, specialized rooms, more fixed and moveable furniture and more appliances, and that people only spend 11% of daily time in these spaces, suggesting the resources associated with them are underused. This study aims to discover the energy embodied in these extra spaces and their fittings for couples living in different sized houses. The energy people use of living in different sized houses is also estimated over a life-cycle. The results indicate that house size is highly correlated with more embodied energy and people living in large houses use several times the life cycle energy of those in small houses. In addition, a great part of this energy is used in spaces correlated with 11% of a daily life. It seems housing decisions highly affect energy consumption. Indeed, for sustainable housing, human behaviour is as if not more, important than technical features.

Keywords: Large housing; embodied energy; New Zealand; house size.

1. Introduction

An initial study of New Zealand houses shows that new houses have almost doubled in size from 1974 (108.7 m$^2$) to 2011 (191.6 m$^2$) (Statistics New Zealand, 2014a). At the same time average household size has decreased from 3.7 in 1951 to 2.6 in 2011 meaning fewer people are living in larger houses (Statistics New Zealand, 2008). Fuller and Crawford (2011) reported the same living pattern in Australia. Because of the lack of studies on large houses there is little knowledge about their features, although a preliminary unpublished study as part of this research showed these houses have extra bedrooms, extra living rooms, en-suite bathrooms, double and triple garaging and more rooms with specialized functions.

Large houses use more embodied energy through more use of building materials and those associated with bathroom and kitchen fittings (Vale and Vale, 2009). Over the life cycle of a house, operational energy is also required for heating, cooling, and lighting and larger houses use more operating energy (Mithraratne et al., 2007). Apart from this, the energy associated with maintenance, which will be greater for larger houses, will also be added to the life-cycle energy consumption. In
addition, large houses need more furniture and appliances to fill rooms. Though the embodied energy of these is not very big, having a relatively short life means furniture and appliances will be replaced several times within the life cycle of house (Treloar, 1999). Consequently, the energy associated with these will make up a significant part of the life cycle energy of the house (Mithraratne et al., 2007).

Although most people living in large houses believe these give them more flexibility, results of an unpublished part of this study shows extra rooms are rarely used in large houses. If large houses are associated with increased energy consumption over their life cycle this will have environmental impacts, such as creating higher levels of CO$_2$ emissions (Crawford, 2011). Accepting the fact that large houses are more flexible for occupants, this study aimed to develop a method to show the impact of selecting different sized houses and how sustainable each size of house could be for different sized households.

2. Methodology

As a part of a PhD study on the effects of large housing on occupant behaviour and resource use in New Zealand an online survey was undertaken from February to April 2015. The questionnaire used the web-based service Qualtrics (Qualtrics, 2015). To limit the scope of the study the questionnaire targeted three household types: single person households, couples and couples with 1 or 2 children as statistics show that large housing mostly accommodates small families (Statistics New Zealand, 2011). Assuming furniture in rental houses does not necessarily belong to the tenants, the survey was also limited to owner-occupied houses.

The questionnaire first asked for general information about family members. It went on to ask about the type and number of spaces in their home, furniture and its location and the time spent in each room of the house, outdoors, and out of home by each occupant over one day. This method is popular in time-use microenvironment studies (Wu et al., 2011) although it has not been used in architectural studies before. The survey was anonymous and a snowball sampling technique was used for recruitment. Overall, 445 households took part in the survey. While 212 (47.6%) households finished the whole survey, 285 (64.0%) households only finished the house and furniture parts. Considering the number of people in each household, the survey provided a data set for time-use of 538 individuals and 212 houses/households. This paper will discuss energy effects of houses (including bathroom, toilet and kitchen fittings but excluding furniture) only occupied by couples, while time-use and furniture studies will be presented in separate papers. In total 96 couples successfully entered data regarding their house and furniture. Garages are also excluded from this study and will be analyzed and presented in future publications.

Initial embodied energy and life cycle energy per square metre has been taken from the available literature for New Zealand for a typical timber frame house with timber or other lightweight cladding. All houses are assumed to be of this particular type to provide comparable results according to the house size.

3. Analysis

3.1. Large housing

Large and small are relative terms which need be defined according to user characteristics. For instance, a large or small shirt for an adult male means the size is compared to a normal male adult body. This
approach can be used for house size. Large housing in this study is defined as living in houses with extra rooms relative to the number of normal occupants.

Each household needs a living room, dining room, kitchen (either separate or combined), and bathroom with toilet. In addition, all family members also need a bedroom although this could be shared for couples. All crowding indices working with number of bedrooms also allow shared bedrooms for children of the same and opposite genders up to a specific age, which varies between different crowding indices (Goodyear et al., 2011). This study considers one bedroom for each family member and assumes couples share a bedroom.

The number of rooms follows Statistics New Zealand (2014b) definitions. It includes all habitable spaces (with floor area more than 4 m²) enclosed by walls, floor and ceiling/roof excluding all service areas (bathroom, laundry etc.). The kitchen, living room and dining room are counted separately even where these are combined. A six room house is thus the standard three bedroom model, even where a ‘bedroom’ might be in use as a study or playroom. Based on this definition, Table 1 summarizes the number and type of rooms necessary for each household type. Regardless of type of room, having any room other than these will be considered extras in this study. So a couple with 5 rooms is considered to have 1 extra room.

<table>
<thead>
<tr>
<th>Household type</th>
<th>Type of rooms needed</th>
<th>Number of rooms needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single person</td>
<td>1 Kitchen + 1 Living room + 1 Dining room + 1 Bedroom</td>
<td>4</td>
</tr>
<tr>
<td>Couple</td>
<td>1 Kitchen + 1 Living room + 1 Dining room + 1 Bedroom</td>
<td>4</td>
</tr>
<tr>
<td>Couple with 1 child</td>
<td>1 Kitchen + 1 Living room + 1 Dining room + 2 Bedrooms</td>
<td>5</td>
</tr>
<tr>
<td>Couple with 2 children</td>
<td>1 Kitchen + 1 Living room + 1 Dining room + 3 Bedrooms</td>
<td>6</td>
</tr>
</tbody>
</table>

Large housing is a complicated term as couples living in 5 room and 10 room houses are both in large housing although the first household has 1 and second 6 extra rooms. As a result this study looks at the energy embodied in these large houses with extra rooms above the basic requirements in Table 1, to give a comparison for different sized houses occupied by couples. Analysis of the survey data shows of 96 couples, 4 (4.2%) were living in houses with 0 extra rooms, 10 (10.4%) in houses with 1, 25 (26.0%) in houses with 2, 22 (22.9%) in houses with 3, 13 (13.5%) in houses with 4, 12 (12.5%) in houses with 5, and 10 (10.4%) in houses with 6 and 6+ extra rooms.

### 3.2. Floor plan area study

The on-line survey asked participants for the floor area of their house and garage(s) and to send an electronic or hard copy of their house floor plan using a prepaid envelope. Many participants provided data for the floor area although very few sent floor plans. For those who did, a comparison was made between given floor area and measured floor area through an AutoCAD 2015 analysis. This showed significant differences for some cases. Additionally, with so few plans it was difficult to find average areas of rooms and NZ databanks could not be used as the survey was anonymous and postal addresses were not supplied. A search failed to find a similar study of New Zealand houses, and those of other countries could not be used because New Zealand houses differ in size and their features. However, the survey had information about number and type of rooms. Consequently, a floor plan study of New Zealand houses was undertaken. As a first step 30 published plans of New Zealand houses with differing numbers of rooms were selected and analyzed in AutoCAD 2015 to find room and whole house areas.
Overall floor area was measured inside the external walls and to take account of internal partitions half the area of each shared wall and the whole area of non-shared walls were allotted to the relevant room. Data for all houses were gathered in an Excel spreadsheet and an average floor area was produced for each room type. The study showed that by using 30 cases a stable average for each room was achieved.

However, the average floor area for each room type did not reflect what happened in different sized houses. For instance, the average floor area for main bedrooms was too small for large houses and too big for small houses. This led to a different strategy. It was decided to select 30 houses each of 4, 5, 6, 7, 8, 9, 10, 11 and 12+ room houses and do the same analysis for each house size separately. The average room sized for four room houses is only used to represent four room houses in the survey and so on. In addition, circulation spaces also varied considerably according to the overall floor area. Calculating circulation space area as a percentage of the overall floor area gave a more precise estimation of the area for circulation. It should be noted that as this part of the research is still under way, the results here are based on analysis of 103 houses (an average 11 houses of each size).

3.3. Embodied Energy

Alcorn investigated the embodied energy of New Zealand building materials and published and updated relevant data in 1996, 1998 and 2003. He updated data and developed an input-output method (Baird and Chan, 1983) into a process analysis method (Alcorn, 1996) and finally hybrid analysis (Alcorn, 2003). The results culminated in his PhD thesis (Alcorn, 2010) in which he tried to develop a method for measuring the sustainability of samples of New Zealand houses from the 1970s, 2000s, 2010s, and 2020s, using the embodied energy of construction and operating energy for each house of type. The lower levels of overall energy and associated CO₂ emissions were considered to be more sustainable (Alcorn, 2010). It should be noted that Alcorn’s work did not include plumbing and electrical works (Alcorn, 2010).

Based on Alcorn’s embodied energy of materials data two more studies have looked at the embodied energy of New Zealand houses. Mithraratne et al. (2007) calculated the embodied energy of a typical 94 m² New Zealand house for three different types of construction: light construction, heavy construction and super-insulated construction, using the data set provided by Alcorn and Wood (1998). Unlike Alcorn (2010) this study includes plumbing and electrical works based on a similar study in Australia by Fay (1999). Mithraratne et al. (2007) also considered the embodied energy of furniture and expanded their calculations for two different sized houses (146 m² and 194 m²) and compared the results. Their comparison showed the embodied energy of the building materials per square metre decreased for larger houses because there were fewer interior walls. Mithraratne et al. (2007) also considered the useful life of building components and operating energy and compared the life-cycle energy consumption of each house for 0, 25, 50, 75 and 100 years. The second study by Vale and Vale (2009) compared the embodied energy of materials in typical 100 m² and 200 m² New Zealand houses with walls of timber frame with brick veneer, straw bale, and straw stabilized adobe block. Vale and Vale (2009) also considered maintenance and operating energies to give life cycle energy for a period of 50 years. Like Mithraratne et al. (2007), Vale and Vale (2009) considered the embodied energy of plumbing, electrical works, and kitchen fittings and large appliances in detailed calculations of these spaces. Table 2 summarizes total initial embodied energy of houses by area as first constructed, excluding furniture, fittings and appliances according to Mithraratne et al. (2007), Vale and Vale (2009) and Alcorn (2010).

This study aims to compare the embodied energy of different sized houses, so the data from Mithraratne et al. (2007) was used as this covers a range of small (94 m²), medium (146 m²) and large
(192 m$^2$) houses. To control the effects of different technologies and materials, in this first analysis all houses were assumed to be timber frame with timber or other lightweight cladding, as these are the most popular house types in New Zealand. As houses in this study are not necessarily the same size as those investigated by Mithraratne et al. (2007), a graph was constructed of house size/embodied energy per square metre (Figure 1). The numbers in boxes show the initial embodied energy per square metre for the three Mithraratne et al. (2007) case study houses. These values were joined and the lines created extrapolated so an approximate embodied energy could be read off for any size of house. Mithraratne et al. (2007, p. 171) also calculated the life cycle energy of the three case study houses for 25, 50, 75 and 100 years. Life cycle energy for each stage includes initial embodied energy and maintenance and operating energies over the period but excludes fittings and furniture. The annual space conditioning energy consumption is 2,123 kWh for the 94 m$^2$, 3,016 kWh for the 146 m$^2$, and 3862 kWh for the 146 m$^2$ light construction houses based on an all-day heating pattern (Mithraratne et al., 2007, p. 157, 168, 171). Though an all-day heating pattern seems unrealistic for NZ houses (in New Zealand people usually do not heat the house overnight), this pattern was used for comparison of light and heavy weight constructions, to avoid the energy required to heat up the mass diurnally. The same heating values were used in this preliminary study. The maintenance schedules for the building fabric, plumbing and electrics were also taken from Mithraratne et al. (2007). Structural elements are replaced every 100 years, wall cladding 30-60 years, roof covering 40 years, electrical works 50 years, joinery 60 years, plumbing 16-50 years, flooring finishes 17-50 years, repainting finishes 8-10 years, and kitchen upgrade in every 30 years. Following the same method for the initial embodied energy, life cycle energy per square metre was created for different stages of building life cycle (Figure 1). The second, third, fourth, and fifth lines respectively represent trend lines after 25, 50, 75 and 100 years. It should be noted that figures in boxes are those of the Mithraratne et al. (2007) data set while other figures are extrapolations based on these.

<table>
<thead>
<tr>
<th>House type</th>
<th>Floor area (m$^2$)</th>
<th>Total EE (GJ)</th>
<th>EE per m$^2$ (GJ/m$^2$)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light construction</td>
<td>94</td>
<td>179.3</td>
<td>1.91</td>
<td>Mithraratne et al. (2007, p. 164)</td>
</tr>
<tr>
<td>Heavy construction</td>
<td>94</td>
<td>262.5</td>
<td>2.79</td>
<td>Mithraratne et al. (2007, p. 164)</td>
</tr>
<tr>
<td>Super-insulated construction</td>
<td>94</td>
<td>230.1</td>
<td>2.45</td>
<td>Mithraratne et al. (2007, p. 171)</td>
</tr>
<tr>
<td>Timber frame, brick veneer</td>
<td>100</td>
<td>264.0</td>
<td>2.64</td>
<td>Vale and Vale (2009, p. 146)</td>
</tr>
<tr>
<td>Straw bale</td>
<td>100</td>
<td>185.0</td>
<td>1.85</td>
<td>Vale and Vale (2009, p. 146)</td>
</tr>
<tr>
<td>Straw stabilized adobe block</td>
<td>100</td>
<td>234.0</td>
<td>2.34</td>
<td>Vale and Vale (2009, p. 146)</td>
</tr>
<tr>
<td>Light construction</td>
<td>146</td>
<td>236.3</td>
<td>1.62</td>
<td>Mithraratne et al. (2007, p. 171)</td>
</tr>
<tr>
<td>Super-insulated construction</td>
<td>146</td>
<td>315.7</td>
<td>2.16</td>
<td>Mithraratne et al. (2007, p. 171)</td>
</tr>
<tr>
<td>Light construction</td>
<td>192</td>
<td>305.0</td>
<td>1.59</td>
<td>Mithraratne et al. (2007, p. 171)</td>
</tr>
<tr>
<td>Super-insulated construction</td>
<td>192</td>
<td>395.0</td>
<td>2.06</td>
<td>Mithraratne et al. (2007, p. 171)</td>
</tr>
<tr>
<td>Timber frame, brick veneer</td>
<td>200</td>
<td>461.0</td>
<td>2.31</td>
<td>Vale and Vale (2009, p. 146)</td>
</tr>
<tr>
<td>Straw bale</td>
<td>200</td>
<td>349.0</td>
<td>1.75</td>
<td>Vale and Vale (2009, p. 146)</td>
</tr>
<tr>
<td>Straw stabilized adobe block</td>
<td>200</td>
<td>418.0</td>
<td>2.09</td>
<td>Vale and Vale (2009, p. 146)</td>
</tr>
<tr>
<td>Light weight 1970s-slab</td>
<td>200</td>
<td>331.7</td>
<td>1.66</td>
<td>Alcorn (2010, p. 267)</td>
</tr>
<tr>
<td>Light weight 2000s-slab</td>
<td>200</td>
<td>352.3</td>
<td>1.76</td>
<td>Alcorn (2010, p. 267)</td>
</tr>
<tr>
<td>Light weight 2000s-suspended</td>
<td>200</td>
<td>354.7</td>
<td>1.77</td>
<td>Alcorn (2010, p. 261, 267)</td>
</tr>
<tr>
<td>Light weight 2010s-slab</td>
<td>200</td>
<td>412.9</td>
<td>2.06</td>
<td>Alcorn (2010, p. 267)</td>
</tr>
</tbody>
</table>
3.4. Embodied energy of bathroom and kitchen fittings

As mentioned above, bathroom and kitchen fittings are excluded in the calculations of the initial embodied energy and life cycle energy of the New Zealand houses studies. Vale and Vale (2009) give a detailed table of the initial embodied energy of bathroom fittings. In this study houses have separate bathrooms, separate toilets, and combined bathroom/toilets, so the initial embodied energy of each has been calculated separately using the data from Vale and Vale (2009) by excluding or including appropriate fittings and associated plumbing and taps and valves in each scenario (Table 3). Using the useful life of each element from Mithraratne et al. (2007, p. 132) life cycle energies were calculated for 25, 50, 75 and 100 years and are presented in Table 3. This shows the life cycle energy of a separate bathroom fittings after 50 years is nearly four times initial embodied energy because of the relatively short replacement cycle of fixtures and fittings (15-20 years).

Vale and Vale (2009) also calculated the initial embodied energy of kitchen components. Their table includes major appliances like a cooker, refrigerator and dishwasher and finishes for walls and floor. As figures by Mithraratne et al. (2007) include finishing materials and this study does not cover appliances, these were excluded to give the results presented in Table 3 (initial embodied energy). Using the useful life of each component from Mithraratne et al. (2007, p. 132) total life cycle energies per square metre were also calculated for 25, 50, 75 and 100 years and these are presented in Table 3.
Table 2 Initial embodied energy and life cycle energy of combined bathroom/toilet, separate bathroom, separate toilet and kitchen fittings and components (based on dataset by Vale and Vale (2009, p. 150, 188) and Mithraratne et al. (2007, p. 132))

<table>
<thead>
<tr>
<th></th>
<th>Combined bathroom/toilet</th>
<th>Separate bathroom</th>
<th>Separate toilet</th>
<th>Kitchen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial embodied energy (MJ)</td>
<td>3753.0</td>
<td>3356.0</td>
<td>712.0</td>
<td>1429.0</td>
</tr>
<tr>
<td>Total life cycle after 25 years (MJ)</td>
<td>8712.2</td>
<td>7817.7</td>
<td>2171.5</td>
<td>2965.0</td>
</tr>
<tr>
<td>Total life cycle after 50 years (MJ)</td>
<td>13671.3</td>
<td>12279.3</td>
<td>3414.1</td>
<td>4501.0</td>
</tr>
<tr>
<td>Total life cycle after 75 years (MJ)</td>
<td>18630.5</td>
<td>16741.0</td>
<td>4656.6</td>
<td>6037.0</td>
</tr>
<tr>
<td>Total life cycle after 100 years (MJ)</td>
<td>23589.7</td>
<td>21202.7</td>
<td>5899.0</td>
<td>7573.0</td>
</tr>
</tbody>
</table>

3.5. Large housing and energy consumption

This part compares the initial embodied energy of houses occupied by couples, including bathroom and kitchen fittings. For each participant the total floor area was estimated based on the number of rooms and the method outlined in 3.2. The nearest initial embodied energy per m² was extracted from Figure 1 and multiplied by the total calculated floor area of each house. Initial embodied energies of bathroom and kitchen fittings were extracted from Table 3 and multiplied by the number of bathrooms and kitchens reported and the results added to the initial embodied energy of the building materials. Figure 2 presents the results of this comparison for couples living in houses with 0-6+ extra rooms.

Figure 2 Initial embodied energy of building materials including bathroom/kitchen fittings for houses with 0-6+ extra rooms occupied by couples (furniture and appliances excluded)

The same method was used to calculate total energy use at 25, 50, 75 and 100 years. Life cycle energy per m² in Figure 1, includes initial embodied energy and maintenance and operating energies over the period. Appropriate values from Figure 1 were multiplied by the calculated floor area of each house to find total energy consumption (excluding bathroom and kitchen fittings) for that particular stage of life. Life cycle energies of bathroom and kitchen fittings for the relevant life stage were extracted from Table 3, multiplied by the number of bathrooms and kitchens for each house, and the
Life cycle energy and large and small housing in New Zealand

results added. The final total life cycle energy for each stage for houses with 0-6+ extra rooms occupied by couples is presented in Figure 3.

![Figure 3: Comparison of total life cycle energy for houses with 1-6+ extra rooms occupied by couples (furniture and appliances excluded)](image)

4. Discussion

As could be predicted, this study shows that larger houses need more energy for construction, maintenance and operation over their life cycle. According to Figure 2, the initial embodied energy to build a house with three extra rooms for a couple is almost double (86.6% more) that of a house with no extra rooms. A house with 3 extra rooms is a very popular type in recent developments in New Zealand, typically with a combined living room/dining room/kitchen, 3 bedrooms and a study (subtotal 7 rooms) while a house of a similar type with no extra rooms for a couple would only have a combined living room/dining room/kitchen and a bedroom. The initial embodied energy is even more for a couple in a house with 6 or 6+ extra rooms as in this case the initial embodied energy of the house and fittings is more than 2.5 times that of houses with no extra rooms (150.3% more). A house with 6 extra rooms for a couple could include a combined living room/dining room/kitchen, a formal living/dining room, 4 bedrooms and a study, again a popular house type in New Zealand. These results mean that the initial embodied energy required to build a house with 3 and 6 extra rooms for couples is equal to that needed to build 1.9 and 2.5 houses with no extra rooms for couples. A study by Fuller et al. (2009) in Melbourne also found the embodied energy of a typical 2009 house (233.5 m^2) is more than 215% that of a 1950 house (95 m^2). Another study by Fuller and Crawford (2011) compared energy consumption per capita in 7 houses representing a house per decade from 1950s-2000s and a 2008 house, with an increase in size in each decade. The results showed an increase in embodied energy per capita with increase in house
size. However, in both studies houses used different materials and technologies and it is not clear what part of the increase in the total embodied energy was really rooted in house size differences.

The discussion above only reflects the initial embodied energy of different sized houses, which is not the whole story. Over the life cycle of a house, annual operating and regular maintenance energies need to be included. Figure 3 shows the total life cycle energy of a house increases over its life cycle with the increase rate higher for larger houses than small ones. Figure 3 shows the ratio of total life cycle energy in year 100 to initial embodied energy (Year 0) is respectively 8.65, 8.77, 8.94, 9.27, 9.31, 9.39 and 9.45 for houses with 0, 1, 2, 3, 4, 5, and 6-6+ extra rooms. This shows the resources consumption of larger houses increases more than small houses over the life cycle. Assuming a couple lives 75 years in the same house, at the end of this period the energy consumption of a couple in a house with 3 extra rooms is more than double (105.7% more) that of a couple in a house with no extra rooms. For a couple living in a house with 6 or 6+ extra rooms for 75 years the life cycle energy is more than 2.8 times that of a house with no extra rooms (181.2% more). These mean that using the energy equivalent of a house with 3 and 6 extra rooms over 75 years, it would be possible to make and operate 2.1 and 2.8 houses of the same materials and technology with no extra rooms for couples.

Large housing needs more furniture and appliances to fill the extra rooms in the house. Though the initial embodied energy of furniture and appliances is not large, the fact these items need to be replaced several times over the life cycle of a house will make their associated life cycle energy more significant (Treloar, 1999). Though data to investigate this has been collected through this survey, its analysis will be presented in a separate paper. In addition, large houses normally have more space for parking cars and so have larger garages. The floor area of garages was not included in this study and so relevant embodied energy is omitted from the analysis. This investigation will also be presented in a separate paper. From this it seems this analysis of the energy impact of living in large houses will be an underestimate.

People who choose to live in large houses usually argue these are more flexible. Accepting this, the question arises as to how much these extra rooms are used. Results of an unpublished part of this survey regarding time spent in different rooms of the house shows that depending on the house layout people spend 76.4%-85.8% of their time at home indoors in the living room, dining room, kitchen and sleeping bedroom. Considering the brief time spent in bathroom, this is 79%-88% of the average time spent at home indoors. This clearly shows that extra rooms, if they exist, are used in total for 12%-21% (16.5% on average) of time at home indoors, or 2.5 hours/day. In addition, the results of the same study show that people living in 4 and 4+ room houses spend less time at home indoors, which could relate to being too busy at work to earn money to pay for the large house.

Results of previous studies by Alcorn (2010), Vale and Vale (2009) and Mithraratne et al. (2007) show that the building technology and materials used in New Zealand houses all have high effects on both initial and life cycle energies of a house. Accepting this, the results of this study suggest that human behaviour regarding house size selection has a high impact on both the initial and life cycle energy of a house. Living in suitable sized houses could significantly reduce energy and resource consumption. So establishing public trends for living in suitable sized houses and even revising housing regulations to help this will be useful (Crawford, 2011). Considering the fact that large housing mostly happens in developed countries with access to high levels of natural resources because of their economies raises the question of the extent to which people should be able to use natural resources, a great part of which belongs to future generations (Dresner, 2008). As Crawford (2011) says there is no penalty/incentive for building larger/ smaller houses so maybe it is time for developed countries to consider regulations like those of
the UK with its social housing extra ‘bedroom tax’ (National Housing Federation, 2013) to limit large housing.

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Massive timber as effective thermal mass in Australian contemporary housing

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Abstract: Since 2003, in an attempt to reduce the use of energy and subsequent greenhouse gas emissions in Australia, the Building Code of Australia has gradually increased thermal performance requirements for residential and non-residential buildings. To meet these requirements has included the selection improved glazing systems, increased insulation levels to subfloor, walls, ceiling and roofing, and a reduction of infiltration losses. However, these measures do have limitations and in many cases the inclusion of appropriately sized and placed thermal mass may provide a more efficient and effective thermal performance outcome. This study comparatively explored, through the use of a NatHERS approved house energy simulation program, the use of massive timber elements within the built fabric of a selected group of contemporary house designs. The simulations required the establishment of a base built fabric model for each case study house. Each house was then simulated with different built fabric systems in flooring, external wall lining, internal partition walls and ceilings. The built fabric systems included standard lightweight insulated timber framing, clay brick, concrete block and solid softwood and solid hardwood systems. Additionally, the study also included the assessment of these interventions in cool temperate, temperate, hot and dry, and hot and humid Australian climates. The results and analysis of the simulations reveal that the use of massive timber elements, as thermal mass, provides a comparative thermal performance improvement of up to 24% in all houses in all climate types. Additionally, the research identified benefits from the different types of thermal mass relative to the location within the built fabric of each house. Furthermore, the research has started to inform a thermal mass diagram for Australia, which indicates a climate-based delineation for the use of softwood or hardwood massive timber systems as thermal mass.

Keywords: Thermal mass; building simulation; massive timber; house energy rating.

1. Introduction

This research has resulted from an ongoing exploration of the built fabric benefits that may be obtained by using mass-timber construction in Australian buildings. This interest has been developed through the combination of right sizing thermal mass in professional practice and deeper research questions about
what sustainable materials may provide effective thermal mass (Dewsbury, 2012a). This paper focuses on the simulated thermal performance effectiveness of massive-timber construction as a form of thermal capacitance in Australian houses. For comparative purposes this research has also simulated the comparative thermal performance from other conventional thermal mass materials, such as clay brick and concrete block (Galloway, 2004). Theoretically, the selection of materials with a high thermal capacity provides ‘good thermal mass’. However, the correct application of thermal mass within the built fabric is paramount if it is to assist in the effective balancing of indoor temperatures within accepted bandwidths for human comfort (Slee et al., 2013). It is generally accepted that the provision of a higher level of thermal comfort can enable a reduction in heating and cooling demands and consequent energy requirements. Furthermore, it is generally accepted that thermal mass works best in climates that have a large diurnal range, which makes it a suitable intervention for many parts of Australia (Szokolay and Brisbin, 2004).

The last decade has seen increasingly stringent regulation within the Building Code of Australia, (now the National Construction Code), aimed at reducing the amount energy that buildings use for heating and cooling (ABCB, 2004; 2007; 2010). This has been in response to the Australian governments desire to reduce greenhouse gas emissions in line with its international commitments (COAG, 2009; Pitt & Sherry, 2010). To meet these requirements, in most instances, has required the selection of improved glazing systems, increased insulation to subfloor, walls, ceiling and roofing, and a reduction of infiltration losses (Iskra, 2004; Dewsbury and Nolan, 2015). Whether it is the need to further improve energy efficiency or the exploration of other means to improve human thermal comfort within buildings, the effective application of thermal capacitance can play a significant role (Slee and Hyde, 2015).

Previous building simulation based research, which explored the use of massive-timber construction, demonstrated potential thermal performance benefits in two Australian climates, namely Melbourne and Launceston. The research examined a large group of typical residential house designs in order to study the potential benefits of massive-timber as thermal mass and its impact on thermal performance, relative amounts of embodied energy, and benefits from carbon sequestration (Dewsbury, 2012b; 2013a; b). Similar research has been completed in New Zealand, but only focussed on 40mm mass-timber elements (Bellamy and Mackenzie, 2007). However, in the 1970’s and 1980’s the United States Bureau of Standards conducted extensive thermal performance research within test buildings, where it was recognised that solid log walls provided both insulation and thermal capacitance (Burch, 1982). That research, like this research, compared standard framed construction, clay brick and concrete block systems as thermal mass. All of these previous activities recommended that further research on the potential of timber and other thermal mass types, and their placement, relative to climates, was required. Additionally, previous researchers have tried to develop ‘rules of thumb’ for thermal mass placement. One task suggested locating thermal storage into ceilings as more effective than placing the same thermal mass within flooring, such as a concrete slab-on-ground (Slee and Hyde, 2011; Slee et al., 2014b). It is not clear if solid timber construction would work effectively within the same scenarios that were tested in Slee’s research but it became a point of leverage to enable a broader testing of thermal mass placement (Slee et al., 2014a). Another positive aspect to the use of mass timber construction is its effect on indoor environmental quality, where it has provided a large moisture buffering value (MBV), by effectively reducing the relative humidity of a space (Hameury, 2006). The MBV aspect of mass timber was not considered in this paper, as current NatHERS building simulation programs do not consider this phase change aspect of material properties.
The intent of this research was to establish, through the use of built fabric thermal simulation and its impact on conditioning energy, what benefits the use of massive-timber elements may provide for thermal performance. This included different Australian climate typologies, (cool temperate, temperate, hot and dry, hot and humid) and different types of massive timber (softwood and hardwood).

2. Methodology

This research required several stages to provide appropriate data and analysis. The set of typical house plans that had been previously used was to be reviewed. The climates for simulation purposes were to be selected. The thermal mass systems were to be reviewed. The software selection was to be re-assessed. A suitable method of analysis was to be selected which could enable a visual presentation of the data. All these tasks were completed and critiqued to ensure there were no unintentional biases.

In the previous research by Dewsbury (2012b; 2013b), mentioned above, the house designs were a mix of architect and volume builder designed detached houses, with a single two-storey residence. To better represent contemporary trends in this task, some of the architect-designed houses were deleted and additional volume builder designs were added. This included two two-storey volume builder designs typical of new housing in Victoria and New South Wales. The houses were all quite modest in size, with floor areas ranging from 73m$^2$ to 176m$^2$, which is slightly smaller than Australia’s average house size of 214m$^2$ (Reneweconomy, 2015). Key data for the houses is shown below in Table 1. Eleven houses were selected, which had a range of initial house energy ratings from 5 stars to over 9 stars. The orientation that was adopted for simulation purposes was identical to what was shown on the original council approved documentation. To establish an initial benchmark, all houses were subject to a base set of construction parameters, which were used to establish a controlled scenario for analysis.

<table>
<thead>
<tr>
<th>House</th>
<th>1 / 2 Storey</th>
<th>Area (m$^2$)</th>
<th>Conditioned area (m$^2$)</th>
<th>Glazed area (m$^2$)</th>
<th>Percentage of glass to floor area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Volume builder)</td>
<td>1</td>
<td>176</td>
<td>126.5</td>
<td>39.0</td>
<td>22.2%</td>
</tr>
<tr>
<td>H2 (Volume builder)</td>
<td>1</td>
<td>142</td>
<td>125.0</td>
<td>38.0</td>
<td>26.8%</td>
</tr>
<tr>
<td>H3 (Volume builder)</td>
<td>2</td>
<td>130</td>
<td>118.0</td>
<td>25.0</td>
<td>19.2%</td>
</tr>
<tr>
<td>H4 (Volume builder)</td>
<td>2</td>
<td>109</td>
<td>96.0</td>
<td>23.0</td>
<td>21.1%</td>
</tr>
<tr>
<td>H5 (Volume builder)</td>
<td>2</td>
<td>113</td>
<td>86.0</td>
<td>21.0</td>
<td>18.6%</td>
</tr>
<tr>
<td>H6 (Architect)</td>
<td>1</td>
<td>73</td>
<td>54.5</td>
<td>23.0</td>
<td>31.5%</td>
</tr>
<tr>
<td>H7 (Architect)</td>
<td>1</td>
<td>132</td>
<td>87.5</td>
<td>52.0</td>
<td>39.4%</td>
</tr>
<tr>
<td>H8 (Volume builder)</td>
<td>1</td>
<td>83</td>
<td>72.5</td>
<td>34.5</td>
<td>41.6%</td>
</tr>
<tr>
<td>H9 (Volume builder)</td>
<td>1</td>
<td>136</td>
<td>126.0</td>
<td>25.5</td>
<td>18.8%</td>
</tr>
<tr>
<td>H10 (Architect)</td>
<td>1</td>
<td>173</td>
<td>150.0</td>
<td>64.0</td>
<td>37.0%</td>
</tr>
<tr>
<td>H11 (Volume builder)</td>
<td>1</td>
<td>110</td>
<td>76.0</td>
<td>31.0</td>
<td>28.2%</td>
</tr>
</tbody>
</table>
A review of typical Australian climates was undertaken to establish suitable locations for simulation by the NatHERS approved software. These locations and climates were derived from the Australian Building Code Board’s Australian climate definitions (ABCB, 2009). The selection of appropriate postcodes focused on locations that are on fringes of major cities, to produce realistic suburban climatic conditions for the simulations, namely:

- Oatlands, Tasmania (the coolest climate)
- Outer suburban Melbourne, Victoria (mild temperate)
- Outer suburban Adelaide, SA (warm temperate)
- South western Sydney, NSW (warm temperate)
- Alice Springs, NT (hot and dry)
- South western Brisbane, Queensland (warm humid)

To ascertain the thermal mass interventions, a review of typical materials that are identified for use as thermal mass in Australia and an exploration of systems that are evolving in other nations were undertaken. This led to the list of variables for external walls, internal walls, ceiling and floors, as shown in Table 2. Based on advice from industry collaborators, wall thicknesses were kept to the traditional values of 90 and 110. However, future research will explore a greater range of timber thicknesses.

<table>
<thead>
<tr>
<th>Area</th>
<th>Code</th>
<th>Variation - Internal skin to external skin (all dimensions in mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>External walls</td>
<td>Base</td>
<td>10 plasterboard / R2.5 batt in frame / 20 cavity / weatherboard</td>
</tr>
<tr>
<td></td>
<td>W1</td>
<td>10 plasterboard / 90 solid softwood / 20 cavity / weatherboards</td>
</tr>
<tr>
<td></td>
<td>W2</td>
<td>10 plasterboard / 90 solid softwood / 80 insulation / 20 cavity / weatherboards</td>
</tr>
<tr>
<td></td>
<td>W3</td>
<td>10 plasterboard / 90 solid hardwood / 20 cavity / weatherboards</td>
</tr>
<tr>
<td></td>
<td>W4</td>
<td>10 plasterboard / 90 solid hardwood / 80 insulation / 20 cavity / weatherboards</td>
</tr>
<tr>
<td></td>
<td>W5</td>
<td>110 solid clay brick / 80 insulation / 20 cavity / weatherboards</td>
</tr>
<tr>
<td></td>
<td>W6</td>
<td>10 plasterboard / 90 filled concrete block / 80 insulation / 20 cavity / weatherboards</td>
</tr>
<tr>
<td>Internal walls</td>
<td>Base</td>
<td>10 plasterboard / 90 air space / 10 plasterboard</td>
</tr>
<tr>
<td></td>
<td>W7</td>
<td>10 plasterboard / 90 filled concrete block / 10 plasterboard</td>
</tr>
<tr>
<td></td>
<td>W8</td>
<td>10 plasterboard / 90 solid softwood / 10 plasterboard</td>
</tr>
<tr>
<td></td>
<td>W9</td>
<td>10 plasterboard / 90 solid hardwood / 10 plasterboard</td>
</tr>
<tr>
<td></td>
<td>W10</td>
<td>110 solid softwood</td>
</tr>
<tr>
<td></td>
<td>W11</td>
<td>110 solid hardwood</td>
</tr>
<tr>
<td></td>
<td>W12</td>
<td>110 solid clay brick</td>
</tr>
<tr>
<td>Ceiling</td>
<td>Base</td>
<td>10 plasterboard / R3.5 batt insulation</td>
</tr>
<tr>
<td></td>
<td>C1</td>
<td>10 plasterboard / 110 solid softwood</td>
</tr>
<tr>
<td></td>
<td>C2</td>
<td>10 plasterboard / 110 solid softwood / R3.5 bulk insulation</td>
</tr>
<tr>
<td></td>
<td>C3</td>
<td>10 plasterboard / 110 solid hardwood</td>
</tr>
<tr>
<td></td>
<td>C4</td>
<td>10 plasterboard / 110 solid hardwood / R3.5 bulk insulation</td>
</tr>
<tr>
<td>Floors</td>
<td>Base</td>
<td>Carpet with underlay / 100 concrete slab / R2.0 insulation</td>
</tr>
<tr>
<td></td>
<td>F1</td>
<td>Carpet with underlay / 110 solid softwood / R2.0 rigid insulation</td>
</tr>
<tr>
<td></td>
<td>F2</td>
<td>Carpet with underlay / 110 solid hardwood / R2.0 rigid insulation</td>
</tr>
<tr>
<td></td>
<td>F3</td>
<td>110 solid softwood / R2.0 rigid insulation</td>
</tr>
<tr>
<td></td>
<td>F4</td>
<td>110 solid hardwood / R2.0 rigid insulation</td>
</tr>
<tr>
<td>Glazing</td>
<td>Base</td>
<td>Aluminium framed 4/12/4</td>
</tr>
</tbody>
</table>
The software used for all thermal performance simulations was AccuRate Sustainability (version 2.3.3.13 SP1) developed by the CSIRO. AccuRate is the most comprehensive of the three NatHERS approved software tools. The three accredited software tools are traditionally used by house energy rating assessors to simulate heating and cooling loads, (in MJ/m²perA.), of house designs. As mentioned above, each house plan was initially simulated in a ‘base’ form to establish a reference point for all further analyses. Each of the built fabric variables were applied through front-end modifications to each AccuRate file and each simulation used the specified location-based climate zones, to provide the total energy value for heating and cooling. The simulated heating and cooling energy data was collated and entered into Excel spread sheets. The resultant raw data was analysed to establish minimum, maximum and average increases and/or decreases in simulated energy use. Box plot graphs were developed within Excel, to allow for easy viewing of the relative thermal performance benefit of each built fabric variable. After the initial simulations were completed, it became evident that a hot and humid climate should also be investigated and a limited number of simulations were completed for one house post-coded as Cairns, and included the softwood, hardwood, and concrete construction system variables.

3. Results

The results are discussed in the following paragraphs. For each location a box plot graph illustrates the data and a short paragraph summarises the key findings. At the end of this section there is a summary box plot graph for general information only, as key design decisions should adopt climate specific findings. In each case the calculated heating and cooling energy from the thermal mass systems are compared to the base design simulation data. The amount of improvement is given as a percentage, where (thermal mass scenario – base simulation result)/base simulation result. The order of the discussion will commence with the coolest climate and finish with the warmest climate.

3.1. Oatlands (Tasmania)

The box plot graph for this climate is shown below, in Figure . The placement of thermal mass on the floor showed the lowest average thermal performance improvements of 5% and 7% for the softwood and hardwood variations respectively. Of the external wall systems, the insulated softwood massive timber walls provided the greatest improvement, with an average thermal performance improvement of 17%. The traditional materials for inside-out construction, clay brick and concrete block provided an average improvement of 15%. When massive timber was simulated as partition walls it out-performed the traditional mass systems by 3%, with an average thermal performance improvement of 12%. However, the greatest surprise was from the simulation of mass in the ceiling, where the simulations revealed a 13% improvement from the insulated hardwood variation.
3.2. Melbourne

The box plot graph for this climate is shown above, in Figure 2. In the mild temperate climate of suburban Melbourne the simulations showed the following results. When the thermal mass was simulated in the floors, the hardwood system provided the greatest benefit with an average 8% improvement in thermal performance. The use of massive timber in the external walls had a very similar result to the clay brick and concrete variations with average improvements of 18%, 19% and 19% respectively. The placement of thermal mass in the partition walls resulted in average thermal performance improvement of 16% for hardwood, 13% for softwood, and 12% for clay brick and concrete block. Locating the massive timber thermal mass in the ceilings provided an average thermal performance improvement of 15% for both the softwood and hardwood variations.

3.3. Adelaide

The box plot graph for this climate is shown below, in Figure 3. The building simulations for the warm temperate climate of Adelaide showed the greatest benefit when the thermal mass was located within the external wall system. In this scenario the dense mass systems of clay brick and concrete block provided an average thermal performance improvement of 24%, whilst the massive timber systems provided an average improvement of 20%. The massive timber insulated floor systems provided a simulated thermal performance improvement of 3% and 10% for the softwood and hardwood systems respectively. The simulation of the partition wall systems provided an average thermal performance improvement of 15% for softwood, 17% for hardwood, 16% for concrete block and 17% for clay brick. When thermal mass was simulated for the ceiling system, the average thermal performance improvements were 17% and 19% for the insulated softwood and insulated hardwood systems respectively.
3.4. Sydney

The box plot graph for this climate is shown above, in Figure 4. Further up the east coast of Australia, in the warm temperate climate of Sydney, the simulated use of massive timber has provided an average thermal performance improvement of 5% for the exposed softwood system and 14% for the exposed hardwood system. In both cases, the carpeted scenario reduced the thermal performance outcome. Similar in nature to the Melbourne data, the use of inside-out clay brick and concrete block construction systems provided an average thermal performance improvement of 32%, whilst the massive timber systems provided an average improvement of 24% for the softwood and 27% for the hardwood scenarios. The simulation of the insulated massive timber ceilings provided an average thermal performance improvement of 21% for softwood and 24% for hardwood.

3.5. Alice Springs

The box plot graph for this climate is shown below, in Figure 5. The results show significant thermal performance benefits when thermal mass is included in the hot and dry climate of Alice Springs. The use of exposed massive timber as flooring provided an average thermal performance improvement of 4% for the softwood and 12% for the hardwood variations. The inside out construction systems provided thermal performance improvements of 21% for the softwood, 24% for the hardwood, 30% for the clay brick and 29% for the concrete block variations. The simulation of thermal mass in partition walls provided a thermal performance improvement of 18% for the softwood, 22% for the hardwood, 24% for the clay brick and 22% for the concrete block wall systems. The simulations, which explored the use of, insulated massive timber for ceilings show improvements of 19% for softwood and 22% for hardwood.
3.6. Brisbane

The box plot graph for this climate is shown above, in Figure 6. This warm temperate climate has a much smaller diurnal range than Alice Springs or Sydney. The exposed massive timber flooring systems provided a thermal performance improvement of 6% and 14% from the softwood and hardwood systems respectively. The inside-out wall systems provided improvements of 19% for softwood, 20% for hardwood, 24% for clay brick and 25% for concrete block. The use of thermal mass in the partition wall systems provided average thermal performance improvements of 12% for the softwood, 15% for the hardwood, 19% for clay brick and 17% for the concrete block scenarios. The simulated use of insulated massive timber as a ceiling system provided an improved thermal performance of 17% for the softwood and 19% for the hardwood variations.

3.7. Softwood, Hardwood or Concrete

Based on the findings from the above data, a simplified model of House 3 was established. In the research above, House 3 often provided the best fit to the average data. The house was simulated as ‘all softwood’, ‘all hardwood, and ‘all concrete’. The design was simulated in the Oatlands, Alice Springs, Brisbane and Cairns climates. A Summary of the simulation results is shown in Table 3, below. Aside from showing some benefit from using softwood as thermal mass in Cairns, the data from these simulations, when combined with the entire simulation data set shows a distinct pattern of heavy mass benefits in some climate types and the lighter softwood thermal mass other climate types. The softwood systems seem to provide a better thermal performance result in climates where the temperatures spend a greater amount of time outside the standard human comfort bandwidths.

<table>
<thead>
<tr>
<th>Location</th>
<th>Base (MJ/m²A)</th>
<th>All softwood</th>
<th>All hardwood</th>
<th>All concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oatlands</td>
<td>162</td>
<td>106</td>
<td>34.6%</td>
<td>112</td>
</tr>
<tr>
<td>Alice Springs</td>
<td>197</td>
<td>105</td>
<td>46.7%</td>
<td>94</td>
</tr>
<tr>
<td>Brisbane</td>
<td>79</td>
<td>57</td>
<td>27.8%</td>
<td>55</td>
</tr>
<tr>
<td>Cairns</td>
<td>200</td>
<td>185</td>
<td>7.5%</td>
<td>189</td>
</tr>
</tbody>
</table>
3.8. Averaged results

This amalgamation of data was conducted to establish if there were any general trends that could be identified. The box plot graph shown below, in Figure 7, does present some interesting information. Firstly, that the use of thermal mass in flooring appears to provide the least effective improvement. The insulated massive timber softwood (C2) and hardwood (C4) ceiling system provide a significant thermal performance improvement. The hardwood massive timber inside out constructed external wall system (W4) provides a very similar thermal performance benefit as the clay brick (W5) and concrete block (W6) external walls. All of the internal partition wall systems, massive timber, clay brick and concrete block walls, provide comparable thermal performance improvements.

![Box plot graph showing averaged results](image)

Figure 7: Average of all simulation results

4. Discussion

Generally, the simulation results show here, the massive timber systems provide a very comparable and at times, a better thermal performance result. However, there are some distinct trends that appear to exist. The 110mm solid hardwood ceiling system generally provided the best thermal performance improvement of 19.1%, which is very evident when compared to floor systems with an average improvement of 11.1%. Nonetheless, a massive ceiling system requires a significant change in construction practices. The hardwood partition wall system shows an average thermal performance benefit of 17.7% and could be readily applied to existing building designs with a much smaller structural requirement than the clay brick or concrete block alternatives. Previous research has discussed the use of a 100mm concrete slab ceiling system which found up to a 39% reduction in simulated energy needs for heating and cooling in the Melbourne climate (Slee et al., 2014b). However, the building modelled had an unrealistically small glass to floor area ratio. In this research the simulated use of the 110mm massive timber ceiling system provided up to a 27% reduction in heating and cooling energy needs in the Melbourne climate, from standard volume builder house plans. The results in this research correlates with previous published simulation results, where the 110mm solid softwood partition had an average improvement of 12.3% in the cool temperate Tasmanian climate (Dewsbury, 2012b; 2013b). Similarly research in New Zealand has found potential energy improvements with the use of 90mm solid wood internal partition walls in Auckland and Christchurch (Bellamy and Mackenzie, 2007). Furthermore, the data hints at distinct thermal type patterns that may exist relative to particular climates. But this may be more about the right sizing of thermal mass relative to the energy inputs. This
is best shown by the improved thermal performance of the softwood systems, when compared to the hardwood systems in Oatlands, Brisbane and Cairns.

This research has focused on six climate types. To gain a deeper understanding and allow for an informed discussion with the wood products and the design and construction industries, these concepts need to be tested in many more climates within Australia. Additionally, one must be wary, as the simulation tool is simulating an indirect gain system. If a house is operated as an active gain solar passive system, the results may differ. However, many researchers have discussed that passive solar houses are often not managed as designed, resulting in a significantly different outcome. Finally, these findings need to be investigated and validated empirically.

5. Conclusion

The thermal performance simulations in this research demonstrated the benefits that may be achieved when massive timber systems are used as effective thermal mass. The hardwood timber variations provided comparable or better thermal performance results than conventional thermal mass materials in the internal walls, ceiling and floor systems across most climates. While the traditional mass materials of clay brick and concrete block did record higher improvements when used as the lining on external walls, the timber variants provided very comparable results. However, the benefits of massive timber while not yet fully understood cannot be forgotten; light in weight when compared with concrete, easier to recycle, retrofitting potential, a complete structural system, only requires simple tools for construction, environmentally responsible (FSC approved timber sources and high carbon capacity), opportunities for a new industry within regional Australia, and as this research has shown, its capacity to provide effective thermal mass in a range of Australian climates. However, more research needs to occur, which would include the simulation of a larger sample of house types and climates within Australia and elsewhere, the use of thicker massive timber systems and the empirical validation of an improved thermal performance.

6. Acknowledgements

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Operational energy consumption in Chilean social housing: exploring the impacts of household changes

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Abstract: Recent initiatives towards the reduction of domestic energy consumption largely depend upon the availability of thorough information to enable focalised interventions and a posteriori impact assessment. This is a significant issue in developing countries, as informality of fuel markets and lack of intelligent technologies can undermine the capacity of policy makers to effectively target consumer behaviour. This study explores an alternative approach to inform such measures using energy forecasting before occupancy. Accordingly, a secondary analysis of publicly available datasets was conducted to assess general patterns of operational energy consumption in Chilean social housing and to develop a set of forecasting models which accuracy was later evaluated with the results of an on-site survey. Although the forecasting capabilities of the proposed models is not yet conclusive, the results of this study suggest that discrete socio-demographic factors can predict general patterns of operational energy consumption and therefore increase the accuracy of future energy efficiency measures.

Keywords: Operational energy; forecasting; social housing; Chile.

1. Introduction

Developing countries are currently facing a major energy challenge. In order to achieve sustainable growth, most emerging economies may need to reduce their dependence on fossil fuels whilst meeting an increasing demand for energy services that can be essential for economic development and improved living standards (TWAS, 2008). According to UN-Habitat, over the next 25 years about 2 billion people will need to be provided with shelter and basic services. While most of this unprecedented growth is expected to happen in countries that still struggle with inadequate infrastructure, environmental problems, urban poverty, and high energy prices (Golubchikov and Badyina, 2012), according to the
International Energy Agency buildings already account for more than one third of the total energy that is consumed globally (IEA, 2013).

In Latin America, Chile has pioneered the implementation of measures to reduce operational energy consumption in residential buildings. Since the incorporation of Thermal Regulation to the law, a number of initiatives have progressively been introduced including building retrofit programs, labelling schemes for appliances, educational campaigns, and financial incentives for adoption of clean technologies (see MINVU-IC, 2006; UTEC, 2010). Nonetheless, there is still room for substantial improvement. Solving major energy problems may require a shift towards more sustainable ways of living; hence the need for a better understanding of the conditions that surround energy consumption at the household level. This problem is even more significant in developing countries where lack of reliable information can compromise initiatives to assist households living in fuel poverty (Coady et al., 2006).

In this context, there is a growing body of research focused on the predictive capabilities of discrete socio-demographic factors that may increase the accuracy of future interventions (Frederik et al., 2015). General household attributes such as mean income and number of members have been shown to be strong predictors of domestic energy consumption (Abrahamse and Steg, 2011), hence their potential capacity to inform energy efficiency measures in technologically lagging contexts. This study uses the Chilean social housing program as research context to explore the energy consumption forecasting capabilities of socio-economic factors that change over the dwelling’s life cycle towards informing initiatives to assist households at risk of fuel poverty.

2. Methods

Secondary analysis of three publicly available datasets was used to assess general patterns of domestic energy use in Chilean social housing. The results were then used to develop a number of forecasting models which predictive capabilities were later evaluated by contrasting their results with observations obtained through an energy consumption survey. Secondary analysis involves the use of information collected for the purposes of a previous study to assess a phenomenon that often involves a different research question (Goodwin, 2012). This technique is extensively used in social research and the public sector, where has informed the implementation of energy efficiency measures through e.g. customer baseline assessment (Hakim, 1982; ECW, 2009). In this context, regression and cluster analysis can be used to assess the strength of existing relationships between energy consumption patterns and different socio-demographic factors (Swan and Ugursal, 2009; McLoughlin et al., 2015).

Accordingly, the regression models of this study were developed using pooled data from the a) Encuesta Panel de Vivienda (EPV) (MINVI, 2010), which was used to assess monthly gas and electricity consumption based on energy bills, the b) Estudio de usos finales y curva de oferta de la conservación de la energía en el sector residencial (EUF) (CDT-CCHC, 2010) for disaggregated energy consumption by fuel type and end use in kilowatts hour per month (kWh/m), and the longitudinal c) Encuesta Panel CASEN 4R 1996-2001-2006 (EPC) (MIDEPLAN, 2006) for analysis of household changes over a 10 year time period. Before statistical analysis, a preliminary step consisted in the identification of households whose demographic characteristics resembled those targeted by the Chilean social housing policy (MINVU, 2014). In the EUF dataset this was done by removing any case with a socio-economic score different than 4 and any dwelling with a surface area below 38 m² or above 60 m² resulting in a total of 675 cases. In the EPC dataset only houses and apartments with a tax assessment below CL$8,171,982 obtained through subsidies were included in the analyses resulting in a total sample of 1,060 cases.
Then, in the EPC dataset only cases belonging to the first and second income deciles living in dwellings acquired through public subsidies were included in the analyses for a total of 325 cases.

The resulting forecasting models were evaluated with the results of a domestic energy consumption survey that was conducted between the months of August and October 2014 in Concepcion, the largest metropolitan area of central-southern Chile, which is characterized by its temperate maritime climate with warm summers and mild winters (means of 17°C and 8°C respectively, with 70% of relative humidity). The survey consisted of 2 main modules: household characteristics and energy use. The household characteristics module gathered demographic information of the households including their total autonomous income, the number, age, gender, occupation and educational level of the residents as well as type of dwelling (i.e. detached, semi-detached or terraced house, or apartment). The energy consumption module gathered mean monthly electricity and gas consumption through energy bills (30 cases, i.e., test population 1), while 12 months of electricity consumption were accessed through energy providers (34 cases, i.e., test population 2).

After defining the target population, a first stage of analysis focused on the identification of the best predictors of operational energy consumption. Accordingly, Pearson’s product-moment correlation coefficient $r$ was used to evaluate existing relationships between demographic and consumption variables, where $r=0.00$ to 0.19 was considered negligible, $r=0.20$ to 0.29 as weak, $r=0.30$ to 0.39 as moderate, $r=0.40$ to 0.59 as strong, and $r=0.60$ to 1.00 as very strong correlations. Different household, dwelling and location variables where tested against energy consumption per fuel type and end use, including household size, household structure, age and gender of all members, number of nuclei, socio-economic segment, educational level, occupation type, and both autonomous and total household income (i.e. household variables), dwelling type (apartment, terraced, semi-detached, and detached house), material, size, year of construction, main orientation, and number of rooms (i.e. dwelling variables), region, climatic zone, and urbanisation (i.e. location variables). The energy consumption variables analysed included kWh/m of firewood, electricity, paraffin, liquefied gas and natural gas, and their use for space or water heating, cooking, illumination, appliances and electronics.

After identification of the strongest predictors, Automatic Linear Modelling was used for the development of forecasting models. Multi-variable regression was used when the contribution of all variables was statistically significant ($p<.05$), and non-linear regression when visual analysis of scatter plots and $r$-square values evidenced non-linear relationships. $R$-square values and visual analysis of residuals against results was used to assess accuracy in the regression models, and k-means cluster analysis was used to automate exploratory socio-demographic segmentation procedures. Any case with a $z$-score higher than 3.0 or lower than -3.0 was considered an outlier and therefore excluded from the analyses. All the analyses were conducted in IBM SPSS Statistics v22.

### 3. Results and discussion

#### 3.1. Energy consumption by fuel type

Figure 1 summarizes the mean domestic energy consumption by fuel type in Chilean social housing as found in the EUF target population. The largest consumer of household energy was firewood with 67.89% of the total, while electricity and gas accounted for 10.82% and 20.27% respectively. Despite differences in total kWh/m between the EPV and EUF datasets, the ratio of gas to electricity consumption was similar with 65.89% to 34.11% and 65.18% to 34.82% respectively. Total energy
consumption in kWh/m was sorted by dwelling type, climatic zone, and household size. Preliminary visual analyses suggested that the size of the household may be the strongest indicator of overall energy consumption in the EPV dataset, while in the EUF dataset the influence of this variable was unclear. These relationships were confirmed by Pearson correlation analysis, which showed strong correlations between total kWh/m and climatic zone in the EUF dataset ($r=0.725$, $n=665$, $p<.001$), while moderate ones for total kWh/m and number of users in the EPV dataset ($r=0.340$, $n=1,018$, $p<.001$). Only weak correlations were found between total kWh/m and dwelling type ($r=-0.253$, $n=665$, $p<.001$) in the EUF dataset, whilst other correlation results were negligible. Kruskal-Wallis H test confirmed significant differences in total energy consumption among number of users per household (EPV) ($H=140.54$, $p<.001$), climatic zones (EUF) ($H=72.14$, $p<.001$), and dwelling types (EUF) ($H=279.6$, $p<.001$).

Disaggregation of total kWh/m by fuel type (Fig. 1) evidenced that firewood consumption was strongly correlated to climatic zone ($r=0.533$, $n=664$, $p<.001$) and moderately correlated to dwelling type ($r=-0.304$, $n=664$, $p<.001$), while no significant correlations were found with the number of users per household. Also in the EUF dataset, moderate correlations were found between climatic zone and both natural ($r=0.308$, $n=650$, $p<.001$) and liquefied gas ($r=-0.306$, $n=670$, $p<.001$), whilst only weak correlations between climatic zone and electricity usage ($r=-0.242$, $n=666$, $p<.001$). In contrast, in the EPV dataset household size evidenced moderate correlations with electricity consumption ($r=0.372$, $n=1,023$, $p<.001$) and weak correlations with gas consumption ($r=0.246$, $n=1,032$, $p<.001$). No correlations were found between firewood usage and household size.

The regression analysis results are shown in Table 1. Climatic zone was the strongest predictor of total energy ($R^2=0.526$), firewood ($R^2=0.319$) and gas ($R^2=0.220$) consumption in the EUF dataset, while number of users was the best predictor for electricity ($R^2=0.141$) and total energy ($R^2=0.120$) in the EPV dataset. Paraffin consumption and total gas showed the lowest rates of covariance in the EPV dataset.
Table 1: Results of regression analysis by fuel type on the EUF and EPV datasets.

<table>
<thead>
<tr>
<th></th>
<th>r square</th>
<th>F</th>
<th>std. err</th>
<th>sig</th>
<th>var1</th>
<th>var2</th>
<th>model</th>
</tr>
</thead>
<tbody>
<tr>
<td>EUF total</td>
<td>0.526</td>
<td>735.60</td>
<td>781.21</td>
<td>&lt;.001</td>
<td>c zone</td>
<td>-</td>
<td>linear</td>
</tr>
<tr>
<td>total (no firewood)</td>
<td>0.134</td>
<td>51.91</td>
<td>767.92</td>
<td>&lt;.001</td>
<td>c zone</td>
<td>n users</td>
<td>linear</td>
</tr>
<tr>
<td>electricity</td>
<td>0.095</td>
<td>69.72</td>
<td>0.41</td>
<td>&lt;.001</td>
<td>n users</td>
<td>-</td>
<td>power</td>
</tr>
<tr>
<td>gas</td>
<td>0.220</td>
<td>60.83</td>
<td>369.28</td>
<td>&lt;.001</td>
<td>c zone</td>
<td>-</td>
<td>cubic</td>
</tr>
<tr>
<td>firewood</td>
<td>0.319</td>
<td>155.01</td>
<td>803.75</td>
<td>&lt;.001</td>
<td>c zone</td>
<td>d type</td>
<td>linear</td>
</tr>
<tr>
<td>liquefied gas</td>
<td>0.161</td>
<td>42.70</td>
<td>98.78</td>
<td>&lt;.001</td>
<td>c zone</td>
<td>-</td>
<td>cubic</td>
</tr>
<tr>
<td>natural gas</td>
<td>0.259</td>
<td>75.16</td>
<td>348.36</td>
<td>&lt;.001</td>
<td>c zone</td>
<td>-</td>
<td>cubic</td>
</tr>
<tr>
<td>paraffin</td>
<td>0.019</td>
<td>6.27</td>
<td>35.43</td>
<td>=.002</td>
<td>n users</td>
<td>c zone</td>
<td>linear</td>
</tr>
<tr>
<td>EPV total</td>
<td>0.120</td>
<td>69.18</td>
<td>164.86</td>
<td>&lt;.001</td>
<td>n users</td>
<td>c zone</td>
<td>linear</td>
</tr>
<tr>
<td>electricity</td>
<td>0.141</td>
<td>83.75</td>
<td>65.93</td>
<td>&lt;.001</td>
<td>n users</td>
<td>c zone</td>
<td>linear</td>
</tr>
<tr>
<td>gas</td>
<td>0.075</td>
<td>27.89</td>
<td>132.12</td>
<td>&lt;.001</td>
<td>n users</td>
<td>-</td>
<td>cubic</td>
</tr>
</tbody>
</table>

3.2. Energy consumption by end use

Figure 2 summarizes mean kWh/m of domestic energy by end use in Chilean social housing as found in the EUF dataset target population. Space heating was the largest consumer with 74.35% of the total, while water heating and cooking accounted for 9.39% and 7.67% respectively. Appliances and electronics including stand-by use were responsible for 6.93% of the total, while illumination was the lowest consumer with 1.67%. Sorting of end uses by dwelling type, climatic zone, and household size confirmed significant increases in space heating consumption in colder climatic zones (significantly in zone 7) and in both semi-detached and detached dwellings. Although space heating was not clearly linked to number of household users, disaggregation by end use suggested linear relationships between this variable and energy consumption in electronics, appliances, and water heating (Fig. 2).

Figure 2: Mean energy consumption in kWh/m by end use and dwelling type (left), climatic zone (centre) and household size (right) according to the EUF survey.
Pearson correlation analysis confirmed a strong positive correlation between climatic zone and space heating \((r=0.646, n=675, p<.001)\) and with cooking activities \((r=0.439, n=675, p<.001)\), while only weak ones with both water heating \((r=0.248, n=675, p<.001)\) and illumination \((r=0.239, n=671, p<.001)\). Number of users per household showed moderate correlations with consumption in electronics \((r=0.248, n=675, p<.001)\), similar to the ones found between dwelling type and water heating \((r=0.248, n=675, p<.001)\). No significant differences were found in energy consumption for space heating among dwelling types or household sizes. However, when disaggregated by fuel type, climatic zone 7 evidenced strong correlations between household size and liquefied gas consumption \((r=0.462, n=104, p<.001)\).

The results of the regression analyses are shown in Table 2. Climatic zone confirmed to be the strongest predictor for energy consumption for space heating \((R^2=0.417)\) and cooking purposes \((R^2=0.376)\), while number of users was a strong predictor for consumption in both electronics \((R^2=0.149)\) and water heating \((R^2=0.114)\).

### Table 2: Results of regression analysis by end use on the EUF dataset.

<table>
<thead>
<tr>
<th>End Use</th>
<th>r square</th>
<th>F</th>
<th>std. err</th>
<th>sig.</th>
<th>var1</th>
<th>var2</th>
<th>model</th>
</tr>
</thead>
<tbody>
<tr>
<td>space heating</td>
<td>0.417</td>
<td>481.85</td>
<td>955.45</td>
<td>&lt;.001</td>
<td>c zone</td>
<td>-</td>
<td>linear</td>
</tr>
<tr>
<td>water heating</td>
<td>0.114</td>
<td>43.04</td>
<td>182.16</td>
<td>&lt;.001</td>
<td>c zone</td>
<td>n users</td>
<td>linear</td>
</tr>
<tr>
<td>cooking</td>
<td>0.376</td>
<td>134.59</td>
<td>68.60</td>
<td>&lt;.001</td>
<td>c zone</td>
<td>-</td>
<td>cubic</td>
</tr>
<tr>
<td>appliances</td>
<td>0.033</td>
<td>11.27</td>
<td>23.73</td>
<td>&lt;.001</td>
<td>c zone</td>
<td>n users</td>
<td>linear</td>
</tr>
<tr>
<td>electronics</td>
<td>0.149</td>
<td>118.02</td>
<td>21.38</td>
<td>&lt;.001</td>
<td>n users</td>
<td>-</td>
<td>linear</td>
</tr>
<tr>
<td>illumination</td>
<td>0.079</td>
<td>28.73</td>
<td>14.85</td>
<td>&lt;.001</td>
<td>c zone</td>
<td>n users</td>
<td>linear</td>
</tr>
</tbody>
</table>

### 3.3. Household evolution

Household size was strongly correlated from 1996 to 2001 \((r=0.674, n=185, p<.001)\), from 2001 to 2006 \((r=0.626, n=185, p<.001)\), and from 1996 to 2006 \((r=0.499, n=185, p<.001)\). Household size in 1996 strongly predicted household size in 2001 \((F(1,183)=152.407, p<.001)\) with an \(R^2\) of 0.454, while household size in 2001 was also a strong predictor of household size in 2006 \((F(1,183)=117.662, p<.001)\) with an \(R^2\) of 0.391. However, number of users in 1996 showed lower predictive capabilities over the 10 year time series \((F(1,183)=60.776, p<.001)\) with an \(R^2\) of 0.249. Different clustering options were evaluated aiming to extend these predictive capabilities over the complete time period (i.e. from 1996 to 2006) (Fig. 3). K-means clustering of households based on age of the oldest female and total autonomous income retrieved the strongest predictions, where the mean age of the oldest female was 30 years with CL$2,824 of normalised autonomous income for cluster 1; 32 years with CL$62,026 for cluster 2; 55 years with CL$5,335 for cluster 3; and 60 years with CL$105,090 for cluster 4 (Fig. 3). Pearson correlation analysis showed strong relationships between number of users in 1996 and 2006 for cluster 1 \((r=0.692, n=34, p<.001)\), cluster 3 \((r=0.550, n=44, p<.001)\), and cluster 4 \((r=0.668, n=12, p=0.018)\), while moderate ones for cluster 2 \((r=0.340, n=93, p<.001)\). The results of regression analyses conducted over these 4 clusters are shown in Table 3. Although the predictive capabilities of cluster 2 for the period 1996-2006 was lower than the non-clustered group \((R^2 = 0.249)\), the predictive capabilities of clusters 1, 3 and 4 were significantly increased. Neither household size, age of the oldest female nor initial autonomous income predicted autonomous income
at the end of the studied period. Nevertheless, autonomous income in 1996 was strongly correlated to total income in 2006 ($r=0.431$, $n=182$, $p<.001$), which in turn was strongly correlated to autonomous income in 2006 ($r=0.995$, $n=184$, $p<.001$), enabling predictions of total household ($F(1,180)=40.97$, $p<.001$, $R^2=0.185$) and estimations of autonomous income ($F(1,182)=17,635.33$, $p<.001$, $R^2=0.995$) for cluster-based projections over the studied time period (section 3.5).

![Figure 3](image)

Figure 3. Evolution of household size and total autonomous income grouped by age segments over the studied time period (left), and results of k-means cluster analysis based on age of the oldest female and total autonomous income (right).

| Table 3: Results of regression analysis by cluster over the studied time period (log10). |
|---|---|---|---|---|---|---|
| **cluster** | **$r$ square** | **$F$** | **std. err** | **sig.** | **const.** | **n users** | **age** |
| 1996 – 2006 |
| cluster 1 | 0.488 | 14.79 | 1.628 | <.001 | +1.304 | +0.911 | -0.021 |
| cluster 2 | 0.207 | 11.77 | 1.397 | <.001 | +5.053 | +0.351 | -0.066 |
| cluster 3 | 0.312 | 9.28 | 1.907 | <.001 | -0.470 | +0.562 | +0.028 |
| cluster 4 | 0.551 | 5.52 | 1.187 | =.027 | +5.290 | +0.470 | -0.640 |
| 1996-2001 |
| cluster 1 | 0.503 | 28.31 | 1.645 | <.001 | +1.417 | -0.120 | +0.770 |
| cluster 2 | 0.383 | 23.61 | 1.342 | <.001 | +0.504 | +0.041 | +0.666 |
| cluster 3 | 0.529 | 16.87 | 1.575 | <.001 | -0.291 | +0.021 | +0.932 |
| cluster 4 | 0.525 | 4.97 | 1.028 | =.035 | +5.621 | -0.063 | +0.305 |
| 2001-2006 |
| cluster 1 | 0.498 | 27.81 | 1.452 | <.001 | -0.189 | +0.634 | +0.022 |
| cluster 2 | 0.290 | 15.53 | 1.370 | <.001 | +5.365 | +0.436 | -0.092 |
| cluster 3 | 0.544 | 17.91 | 1.550 | <.001 | +2.199 | +0.754 | -0.030 |
| cluster 4 | 0.859 | 27.45 | 0.665 | <.001 | +0.755 | +1.045 | -0.011 |

3.4. Partial comparative assessment

In order to assess the accuracy of the regression models presented in the previous sections, their predictive capabilities were contrasted to the results of an on-site survey. Household size was strongly
correlated to both total and mean monthly electricity consumption in test population 2 (\(r=0.589, n=29, p=.001\)), while only weakly correlated in test population 1 (\(r=0.229, n=31, p=.021\)). No significant correlations were found between gas consumption and household size. Mean autonomous income showed strong correlations with household size in both test population 1 (\(r=0.426, n=31, p=.017\)) and test population 2 (\(r=0.604, n=35, p<.001\)), but no statistically significant correlations were found with total energy consumption. Changes in household size in the 2004 to 2014 period displayed strong correlations in test population 1 (\(r=0.704, n=32, p<.001\)) whilst only moderate ones in test population 2 (\(r=0.309, n=36, p=.067\)).

Observed and predicted values for electricity consumption and household evolution based on EUF and EPV models are shown in Figure 4. Predicted and observed results were strongly correlated for electricity consumption (\(r=0.568, n=29, p=.001\)) and household size evolution (\(r=0.559, n=29, p=.002\)) using the EUF models, while regression analysis confirmed that the predictions were statistically significant for both electricity (\(F(1,27)=12.85, p<.001, R^2=0.322\)) and household size changes (\(F(27,1)=12.85, p=.002, R^2=0.313\)). In contrast, the results obtained through EPV models were less conclusive. Although predicted and observed household size changes were strongly correlated (\(r=0.404, n=36, p=.015\)), correlations for electricity outputs were only moderate (\(r=0.304, n=35, p=.046\)). Regression analysis confirmed the moderate predictive capabilities of EPV models in both household size (\(F(1,34)=6.62, p=.015, R^2=0.163\)) and electricity (\(F(1,33)=3.34, p=.076, R^2=0.092\)).

![Figure 4](image)

**Figure 4.** Comparative analysis of predictions (x axis) versus observations (y axis) for electricity consumption in kWh/m (left) and household changes (right) over a 10 year time period in test population 1 (upper row) and test population 2 (lower row).

### 3.5. Time Projections

In order to illustrate the possibilities of the forecasting models developed by previous sections, they were used to estimate the evolution of operational energy use in an example household over a 50 year
time period. The chosen household characteristics were close to the mean with 4 members and $32,000 of autonomous income, where the oldest female had 30 years of age at the beginning of the series. According to the household evolution forecasting formulas, household size changes can be predicted as:

\[
\begin{align*}
    h_{10}^{\text{cluster1}} &= 1.304 + 0.911 h_1 - 0.021 f_1; \\
    h_{10}^{\text{cluster2}} &= 5.053 + 0.351 h_1 - 0.066 f_1; \\
    h_{10}^{\text{cluster3}} &= -0.470 + 0.562 h_1 + 0.028 f_1; \\
    h_{10}^{\text{cluster4}} &= 5.290 + 0.470 h_1 - 0.046 f_1
\end{align*}
\] (1)

Where: \( h_{10} \) = household size in 10 years; \( h_1 \) = current household size; and \( f_1 \) = current age of oldest female. These predictions can be extended beyond this 10 year time-series through the incorporation of predicted autonomous household income as:

\[
a_{10} = 3.239 + 0.374 \times (3.239 + 0.374 a_1)
\] (2)

Where: \( a_{10} \) = autonomous income in 10 years; and \( a_1 \) = current autonomous income. Then, the EPV formula to predict mean energy consumption over this time series can be defined as:

\[
e_1 = 322.665 + 32.245 h_1 - 5.635 z_c
\] (3)

Where: \( e_1 \) = total energy consumption per month; \( h_1 \) = current household size; and \( z_c \) = climatic zone. Accordingly, the total energy consumption over 50 years can be assumed to evolve as shown in Fig. 5.

![Figure 5: Time series prediction of household changes and their effect on 50 years of domestic energy consumption in electricity and gas (kWh/m) based on the EPV regression models.](image)

### 4. Final remarks

This study uses secondary analysis of publicly available datasets to forecast impacts of household changes on general patterns of domestic energy consumption in Chilean social housing. The results of the analyses suggest that space heating is the activity that consumes the largest amount of energy in Chilean social housing accounting for almost 75% of the total, followed by use in water heating, cooking, appliances, electronics and illumination. These results are consistent when consumption is analysed by fuel type, evidencing that firewood accounts for almost 68% of the total, followed by gas, electricity and then paraffin. Regression analyses suggest that household size can predict both total electricity consumption and water heating. Although no statistically significant correlations were found between household characteristics and space heating or firewood consumption, climatic zone showed strong predictive capabilities for both variables. Significantly, when firewood was excluded from the analyses, climatic zone and household size were strong predictors of total energy consumption. In terms of household size evolution, clustering by autonomous income and age of the oldest female resulted in the
best predictions for the studied period. Comparative assessment of predicted versus observed results confirmed that household size strongly predicts electricity usage and household size changes, suggesting that this variable may be fundamental to predict energy consumption patterns before occupancy.

The outcomes of this study suggest that discrete socio-economic factors can predict general patterns of operational energy consumption in Chilean social housing, and therefore may be used increase the accuracy of energy efficiency measures in technologically lagging contexts. This can be particularly valuable in developing countries were energy costs can have significantly impact the budget of low-income households. Although inconclusive, the regression models presented in this study show an increase in energy consumption at later stages of the household’s life cycle that may potentially increase the risk of fuel poverty and therefore motivate different types of intervention. Further research may focus on the incorporation of econometric estimations for energy costs and a comprehensive assessment of household’s budget. Incorporation of psychological variables such as the adoption of efficient technologies, environmental attitudes and behaviour, as well as physical properties such as construction materials and orientation of the dwellings may increase the accuracy of future models.

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Reforming housing regulation: delivering performance improvement together with affordability

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Abstract: In developed economies a significant proportion of greenhouse gas emissions result from energy demand in the building sector. Many countries have recognized the need to mandate building energy performance standards as a key element of a national energy or climate change policy. The Commonwealth of Australia included energy efficiency provisions in the national Building Code early last decade. This initiative has not been without controversy or resistance from some industry stakeholders. Typically such opposition is predicated on the assertion that more stringent energy efficiency requirements, particularly in the residential sector, would detrimentally impact on housing affordability. The State of Victoria significantly upgraded its residential energy efficiency requirements in 2004. This study of the new standard [the 5-Star Standard] investigates its effectiveness as an instrument of energy policy, testing the assumption that more stringent regulatory requirements are at odds with housing affordability, used here in its commonly understood form of initial capital cost. The analysis concludes that the 5-Star Standard has delivered significant greenhouse abatement; and encouraged industry innovation in a way that embodies regulatory best practice; while at the same time not compromising housing affordability for consumers or impacting negatively on the local housing market overall.

Keywords: Regulation; energy; housing; affordability.

1. Introduction

A substantial body of research has demonstrated the significant role that improved building performance should play in reducing global greenhouse gas emissions particularly in developed countries where most people live in urban settings; for example the work of Ürge-Vorsatz and Novikova (2008). In Australia almost a quarter of greenhouse gas emissions result from energy demand in the building sector according to the Centre for International Economics (2007). A ground-breaking report by McKinsey Company (2008) has also demonstrated that the building sector provides potentially the most cost-effective economic sector for greenhouse gas abatement.

The specific role of regulation as an effective government policy instrument was addressed in a report for the United Nations Environment Program (2007). In examining the potential for mitigating
greenhouse gas emissions from energy use in the world’s buildings. Ürge-Vorsatz and Novikova (2008) also suggest that appliance standards and building codes are particularly cost-effective. Similarly, analysis of trends in energy use and CO$_2$ emissions in the Swedish building sector by Nässén and Holmberg (2005) found that stagnation in energy efficiency levels since the nineties should be addressed by policy interventions that included regulations aimed at improving the technical performance of buildings as a priority. In tracking the development of energy efficiency provisions in Swiss building codes Groesser (2014) points out that performance levels set in building codes for both new construction and refurbishments are a “powerful lever for reducing greenhouse gas emissions”.

In the Australian context the nation’s Ministerial Council on Energy decided that reform of energy efficiency standards in the national building code should be a cornerstone of the National Framework for Energy Efficiency - articulated by the Energy Efficiency and Greenhouse Working Group (2003) - which defined the future direction of Australia’s energy efficiency policy and programs. This policy decision was taken because of the perceived economy-wide benefits of improved energy efficiency; improvement opportunities available in the building sector; and the potential contribution of building regulation as an instrument of energy policy.

This Australian case study examines the application of building regulation to energy efficiency and greenhouse gas mitigation reduction objectives. Its focus is on the role and effectiveness of building energy regulations as a policy instrument. Lutzenhiser (1994) points out in his study of barriers to energy efficiency in the United States housing industry that a range of sociological, technological and economic factors provide such barriers. Lutzenhiser goes on to observe that markets for energy efficiency often fail because the economically rational behaviour required for effective market operation is effected to a significant degree by cultural and institutional factors.

In 1991 The State of Victoria was the first Australian jurisdiction to introduce energy efficiency regulations for buildings. Then in 2002 Victoria dramatically ramped up its residential energy efficiency standards to a level defined as 5-Stars within the framework of Australia’s Nationwide House Energy Rating Scheme as part of a comprehensive Greenhouse Strategy, as set out in Department of Natural Resources and Environment (2002).

Following implementation of the national 6 Star requirements a series of analyses have been conducted to assess the effectiveness of these regulatory outcomes. This case study largely draws upon information published by the Commonwealth and Victorian Governments in the course of ongoing regulatory development in order to track the incremental cost of increased energy efficiency requirements for residential buildings. The historical trajectory of projected and actual cost increases is compared with the notional increases in capital cost postulated by industry critics of energy efficiency regulations to test assertions that housing affordability would be adversely impacted by such measures.

The analysis also sheds light on the impacts of industry learning and market transformation in facilitating or obstructing the uptake of more stringent energy performance standards.

2. Regulatory Context

2.1. The National Construction Code

Australia has had a national building code since 1996. In 2010 the Building Code of Australia [BCA] was transformed into a National Construction Code [NCC] through incorporation of the Plumbing Code of Australia. The BCA now comprises Volumes 1 and 2 of the NCC.
In Australia legal responsibility for the built environment is vested in the eight States and Territories, each of which has its own individual regulatory regime to address land planning and building control matters. Further, the NCC is only given legal force in each State and Territory by being referenced in the relevant legislation of that administration. In the case of Victoria this reference to the NCC is made in the State’s Building Regulations (2006).

The fundamental role of the NCC is to set uniform construction standards across Australia for all building classes that are based on building performance outcomes in key areas such as health, safety, durability. Since 2006 these goals have also included explicit reference to Sustainability:

“The goal of the BCA is to enable the achievement of nationally consistent, minimum necessary standards of relevant safety, health, amenity and sustainability objectives efficiently (Australian Building Codes Board, 2011).”

The rationale for the NCC is to set the minimum acceptable standards for building performance at the design stage in its defined areas of applicability. Compliance with the Code is determined by building certifiers and surveyors at a building’s design stage by establishing whether performance objectives prescribed in the Code have been met. The Code is quite flexible in deliberately providing a range of compliance pathways to encourage innovative, cost-effective design solutions. In the case of residential buildings the NCC prescribes the Performance Requirement for energy efficiency with which building solutions must comply in the following terms:

“A building must have, to the degree necessary, a level of thermal performance to facilitate the efficient use of energy for artificial heating and cooling”

2.2. Australia’s Nationwide House Energy Rating Scheme


The building design’s star rating is calculated using software accredited for this purpose under the Scheme. Compliant software package simulate the performance of buildings in service by taking into account climatic and other factors about the physical characteristics of the building envelope, its location and occupancy levels. The rating scale ranges from a minimum of 1 Star to a maximum rating of 10 Stars. A 10 Star design theoretically requires no external energy inputs for heating or cooling.

From a strategic policy perspective the NatHERS structure has a threefold function:

• Providing a regulatory tool referenced in the NCC
• Facilitating improvements in performance-based design of residential buildings
• Providing consumers with a simple basis for comparing the energy efficiency of alternatives
3. Victoria’s residential energy efficiency regulations

When the State of Victoria introduced energy efficiency requirements for residential buildings in 1991 the regulations were subject to a regulatory impact assessment which was focused around a public consultation document published by the Department of Planning & Urban Growth (1990) that set the costs and benefit of the new regulations. These prescriptive insulation regulations aimed to deliver new buildings with the equivalent of a 3 Star energy rating on the NatHERS scale.

In 2000 in an extensive study sponsored by the Australian Greenhouse Office (2000) concluded that the Victorian insulation regulations had raised the performance of new homes to a level of approximately 2 Stars on the Nationwide House Energy Rating scale. While this was a positive outcome it did not fully achieve the 3 Star policy objective originally stipulated for the 1991 regulations.

Estimates for additional cost to homeowners of implementing the 1991 insulation regulations for the typical new 160m$^3$ home being constructed at the time ranged from $1400-$2000. It was anticipated that the resulting improvement in thermal performance would reduce heat losses by 40%, saving the average homeowner around $300 on annual energy bills; and reducing greenhouse emissions from gas heating systems by 2-3 tonnes of CO$_2$ per annum.

Then in 2001 the Victorian Government decided to reform its decade-old insulation regulations as a key element of a formal Greenhouse Strategy to be progressively implemented from 2002. This Strategy focused on reducing greenhouse gas emissions in key sectors of the state’s economy such as transport, buildings, and manufacturing. A new residential energy efficiency standard was announced by the Minister for Planning (2002) which made use of house energy rating software to assess compliance; implementation was announced with a policy statement that:

Energy use in homes is responsible for around 16% of Victoria’s total greenhouse gas emissions......residential heating and cooling account for 50% of the energy consumed each year in the average Victorian home.

Regulatory stringency was significantly increased from a nominal 2 Star to an explicit 5-Star rating; which translated to a 40% reduction in permissible energy usage for heating and cooling as defined by the Building Code.

Victorian legislation requires that major regulatory reforms must be preceded by a transparent public consultation process underpinned by a Regulatory Impact Statement which incorporates economic analysis of costs and benefits. The Victorian Building Commission (2002) published a comprehensive regulatory consultation document whose cost benefit analysis was formally endorsed by the Victorian State Cabinet. This regulatory document advised that the proposed 5-Star Standard would deliver a range of significant economic, environmental and social benefits to the citizens of Victoria:

- Addition of $570M to the Gross State Product
- Creation of up to 1100 new jobs
- Annual energy savings by consumers growing to $124M - within the 20 year time horizon of the study
- Greenhouse gas abatement of 8Mt CO$_2$ over twenty years

The regulatory document also estimated that the additional cost of redesigning and re-specifying a typical new home to comply with the Standard would be in the order of $1100 - $3300 [2002 dollars] which represented an increase of 0.7% - 1.9% in the cost of the average new home at that time.
3.1. Regulatory pushback

During the subsequent period of public consultation following release of the 5-Star *Regulatory Information Bulletin* by the Victorian Building Commission (2002) the housing industry undertook a protracted political lobbying campaign opposing the proposed regulatory reform. Industry criticism was founded on the assertion that these mandatory energy efficiency requirements for new homes would cause excessive increases in the cost of construction with deleterious impacts on housing affordability. Critics also alleged that price sensitive first homebuyers would be particularly hard hit by such an unwarranted cost impost. For example, the position of peak housing industry group the Housing Industry Association [HIA] was outlined in a contemporary newspaper article by Angela O’Connor (2002):

> The Housing Industry Association’s Victorian executive director, John Gaffney, is fighting to delay the rules, arguing they are too much, too soon and impose undue burdens on builders. He says the standard should not be mandatory until 2005 or 2006, and claims it could cost up to $10,000 per house to implement, which could cut out a significant section of the population from home ownership. ‘The added cost on a basic $150,000 house would be about $8000 - enough to cut 4000 to 5000 prospective buyers out of home ownership’ he said.

In effect the HIA was asserting that a cost increase of over 5% could be attributed to the 5-Star requirements when applied to entry-level homes in the market. According to (Kate Jones (a)) the HIA CEO further claimed that the new measures would dampen the property market, predicting that up to 10 per cent of buyers would have difficulty purchasing.

3.2. Regulatory effectiveness criteria

The following criteria are proposed in this paper as appropriate for evaluating the effectiveness of the 5-Star Standard from a policy perspective:

- Did the standard represent good regulatory practice?
- To what extent have Government policy objectives been met?
- How valid were claims of excessive compliance costs and consequent impacts on the price of new homes?
- Were industry concerns about significant damage to the new home market well founded from an evidence-based perspective?

3.2.1 Good regulatory practice

In its *Victorian Guide to Regulation* the Department of Treasury and Finance (2011) notes that factors to be considered in good regulatory design should include:

- Clear articulation of the nature and extent of the problem being addressed
- Prior quantification of the costs and benefits of the proposed regulatory measures
- Performance-based approach in preference to prescriptive compliance requirements
- Effective, but not unduly burdensome enforcement regime

The outdated and prescriptive 1991 insulation regulations had been replaced with the performance based 5-Star Standard; enacted through the Building Code of Australia and administered through the
robust, well established Victorian Government (1993) building control regime; following a transparent regulatory impact assessment process. Through this process the Government’s market intervention would appear to effectively address applicable criteria for good regulatory practice.

The Victorian Competition and Efficiency Commission [VCEC] is an independent statutory body reporting to the State Treasurer whose mandate encompasses reviewing regulatory impact statements to advise on the economic impacts of new legislation; and undertaking reviews of matters referred by Government. In 2005 the VCEC was directed by the Government to undertake a comprehensive review of the state’s housing regulations. This review included a critical review of the recently enacted 5-Star Standard for energy efficiency.

In its subsequent report the Victorian Competition & Efficiency Commission (2005) included only a relatively mild critique of the 5-Star regulation, in finding that:

“Victoria’s energy efficiency regulation [embodied in the 5-Star scheme] could be improved to better deliver at least cost against its objectives, including in the future as technology changes. Some improvements that should be considered are: implementation of the 5-Star scheme be more clearly related to the Victorian Government’s energy efficiency objectives “.

3.2.2 Government policy objectives

The Victorian Government’s policy objectives for 5-Star were discussed earlier in the context of the State’s formal Greenhouse Strategy. A primary policy deliverable in this context would certainly include cost-effective greenhouse gas abatement. For which the desired outcome was articulated in an article in the Inform publication of the Victorian Building Commission (2003) stating that:

In its first year, 5-Star will cut greenhouse gas emissions by 40,000 tonnes, and save over $6 million on household energy bills. Over the next 5 years, the 5-Star standard is expected to reduce greenhouse gas emissions by 600,000 tonnes

This projection actually underestimated the regulation’s benefits as it was based on parameters that proved to be conservative in practice due to:

- A significantly higher rate of new home construction than originally assumed
- Extension of 5-Star Standard home renovations in 2008
- Subsequent mandating of solar water heater installation as part of the standard

Based on historical data for housing starts from the Australian Bureau of Statistics (2010) the author’s calculations suggests that the regulation will deliver aggregate greenhouse abatement to the levels set out in Table 1. In combination with this updated housing data, these calculations are based on estimates of greenhouse gas abatement obtained from the Victorian Building Commission (2002) regulatory document; together with the Plumbing Industry Commission (2004) Regulatory Impact Statement; using the Building Commission methodology to project aggregate abatement levels.
Table 1: Aggregate greenhouse gas abatement attributable to the 5-Star Standard

<table>
<thead>
<tr>
<th>Year</th>
<th>Cumulative abatement building fabric</th>
<th>5-Star abatement</th>
<th>Cumulative abatement solar water heating</th>
<th>Aggregate abatement</th>
<th>Nominal policy target</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>0.8 Mt CO₂</td>
<td>0.18 Mt CO₂</td>
<td>0.98 Mt CO₂</td>
<td>0.6 Mt CO₂</td>
<td></td>
</tr>
<tr>
<td>2014</td>
<td>3.0 Mt CO₂</td>
<td>0.4 Mt CO₂</td>
<td>3.4 Mt CO₂</td>
<td>NA</td>
<td></td>
</tr>
<tr>
<td>2024</td>
<td>11.4 Mt CO₂</td>
<td>0.8 Mt CO₂</td>
<td>12.3 Mt CO₂</td>
<td>7.6 Mt CO₂</td>
<td></td>
</tr>
</tbody>
</table>

It is evident from the table that Government’s key policy objective, as articulated in its 2002 Greenhouse Strategy and subsequently documented in detail by the Victorian Building Commission (2003), was achieved through implementation of the 5-Star regulation.

In 2003 national residential energy efficiency provisions were introduced in the BCA at a nominal 4 Star stringency. Then in 2006 the stringency of national BCA provisions was increased to 5-Stars following Victoria’s lead. A further step up to a 6-Star minimum performance level was included in the BCA 2010 Amendment following policy endorsement by national Building Ministers in 2009.

Once again in 2006 and 2009 major building industry bodies strenuously questioned the case for reforming BCA residential energy provisions on the basis of negative impacts on housing affordability, particularly in the sensitive first home market segment.

3.2.2 Regulatory compliance costs

All national residential energy efficiency provisions are subject to formal Regulatory Impact Assessment and Cost Benefit Analyses prior to their introduction in the Building Code of Australia. Thus analyses undertaken at a national level for progressive increase in the stringency of BCA energy efficiency requirements to the 4 then 5-Star performance levels provide an important source for quantifying compliance costs.

Table 2: Historical perspective on cost trajectory for the 5-Star Standard

<table>
<thead>
<tr>
<th>Year</th>
<th>Source document</th>
<th>Efficiency upgrade cost</th>
<th>Context for costing</th>
<th>Percentage cost increase on [base]</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>Victorian Building Commission (2002)</td>
<td>$1100 - $3300</td>
<td>Base case Vic housing stock; 5-Star target</td>
<td>0.7 – 1.9% [$160,000]</td>
</tr>
<tr>
<td>2005</td>
<td>Jetarree Limited (2005)</td>
<td>$1500</td>
<td>5-Star rating outcome using builders’ costs</td>
<td>0.4% [$230,000]</td>
</tr>
<tr>
<td>2005</td>
<td>Australian Building Codes Board (2005)</td>
<td>$653</td>
<td>Stringency increase: 2-4 Stars</td>
<td></td>
</tr>
<tr>
<td>2006</td>
<td>Australian Building Codes Board (2006)</td>
<td>$400</td>
<td>Stringency increase: 4-5-Stars</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>CSIRO (2013, p.69)</td>
<td>-$5000</td>
<td>Optimize base case design to maintain 5-Star outcome</td>
<td></td>
</tr>
</tbody>
</table>

In addition a number of publically available independent studies have now been undertaken since implementation of the 5-Star residential energy efficiency standard in Victoria in 2004. These studies also allow the incremental cost of mandated energy efficient requirements to be tracked with a degree of confidence over the last decade as stringency has been progressively increased. In this way not only
can the evidence for building costs be compared with government projections in support of proposed regulatory measures, but also with industry assertions that such costs would be so excessive as to threaten housing affordability for consumers and even the prosperity of the housing industry. Table 2 summarizes this historical cost data as collected from the range of sources now available in order to define the trajectory of compliance costs.

It is evident from Table 2 that the original estimate for the incremental cost of complying with the 5-Star Standard was reasonably accurate and possibly conservative. The CSIRO (2013) study confirms that rational design that responds to NCC performance requirements can now deliver energy performance at a 5-Star level at costs well below a less efficient business-as-usual base case. Moreover, this evidence does not support industry claims of excessive regulatory compliance costs.

A clear trend has emerged over time for compliance costs to progressively diminish in magnitude. To the point where the most recent and sophisticated studies demonstrate that well-considered design changes can actually deliver energy efficient passive solar homes at a *reduced base cost* according to a study by Sustainability House (2012) for the Department of Climate Change and Energy Efficiency. This encouraging scenario sits comfortably with the fundamental tenet of Australia’s Building Code: setting performance based standards to encourage an industry response that takes the form of innovation in both design and provision of building products and services.

### 3.2.3 The role of industry learning

A 2012 study undertaken for the national Department of Climate Change and Energy Efficiency by AECOM (2012) examined the role of “industry learning” in responding to energy efficiency standards mandated through the national Building Code. This AECOM study concluded that different sectors of the building industry responded in markedly different ways to energy efficiency improvement opportunities, whether voluntary or mandated:

- The commercial sector had a positive response, often going beyond regulatory requirements
- Volume home builders were not pro-active in embracing energy efficiency opportunities but were able to rapidly adopt cost effective design changes in response to mandatory standards
- Small residential builders were risk averse, only introducing energy performance improvements when compelled by regulation
- Importantly, small residential builders typically responded to regulation through expensive increases in building specifications rather than more cost-effective design changes

### 3.3 Impacts of regulation on the housing market

Residential building approvals in Victoria for the five-year period following implementation of the 5-Star Standard on 1 July 2004 are compared with the national market in Figure 2 based on data from the Australian Bureau of Statistics (2010).

Apart from a slight dip in 2005/2006, the proportion of residential building activity taking place in Victoria during this period hovers around the 25% level. At this time Victoria’s population remained steady at just below 25% of the national population according to the Australian bureau of Statistics (2014) so the level of residential building activity was commensurate with the State’s share of national population.
4. Conclusions

The paper has analysed the 5-Star Energy Efficiency Standard for Victorian residential buildings and shown that it was indeed an “effective regulation”. It achieved the government’s policy objective of energy efficiency and greenhouse gas abatement without significant detriment to housing affordability. Furthermore, its introduction paved the way for subsequent reform of NCC energy provisions. This review of residential energy efficiency regulation using Victoria’s 5-Star Standard as a case study has reached a number of conclusions concerning the role and effectiveness of building regulation as a government policy instrument.

- Research over the last decade suggests that government policy objectives for greenhouse gas abatement that led to regulatory intervention in 2002 were shown to have been met.
- The regulatory process itself would seem to demonstrate good regulatory practice when assessed against objective criteria.
- Formal regulatory impact assessment reports tended to underestimate both the capacity for industry adaptation to new energy requirements and the rapidity of such adaptation.
- Claims by the housing industry that mandatory energy efficiency requirements for new home construction would have a deleterious impact on housing affordability are shown to have been ill-founded on the basis of the historical cost trajectory of energy efficiency costs.
- Evidence for negative impacts on the new home market as a whole was also lacking in that Victorian housing construction rates continued to closely track those of other major states.

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The effect of building and material service life on the life cycle embodied energy of an apartment building

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Abstract: The service life of a building and its constituent materials and components plays an important role in the long-term environmental performance of a building. The replacement of materials over the life of a building results in a demand for natural resources. More frequent replacement increases this resource demand and other related environmental effects. Of particular concern is the use of energy, especially in a sector that already contributes significantly to global warming. However, the energy demand associated with material replacement over a building’s life is not well understood. The aim of this study was to investigate the relationship between the service life of a multi-unit residential building and its constituent materials and its life cycle embodied energy. An apartment building located in Melbourne, Australia was used as a case study for this analysis. The initial and recurring embodied energy of the building were calculated using a comprehensive hybrid embodied energy assessment approach, with building and material service life values based on average figures obtained from the literature. Building and material service life values were then varied to reflect the extent of service life variability likely for the building and a selection of the main building materials, and the embodied energy recalculated for each scenario. The results from this study show that the service life of a building and its materials may have a significant effect on the energy-related environmental performance of a building over its life.

Keywords: Building service life; material service life; life cycle embodied energy; recurrent embodied energy.

1. Introduction

Buildings are responsible for significant amount of energy use. They account for 30-40% of energy use and greenhouse gas emissions in Australia and many other countries around the world with a significant share of this attributable to residential buildings (UNEP, 2007). Despite the growth in renewable sources of energy use, fossil fuel-based energy use still constitutes the largest proportion of primary energy use globally with a share of 82% in 2011 (IEA, 2013). Burning of fossil fuel releases its stored carbon into the atmosphere, resulting inconsiderable effects on the natural environment and global climate. In this
context, it is of critical importance that energy demand within the built environment is addressed to avoid further degradation of the natural environment.

The building industry consumes a large amount of materials, which require a significant amount of energy for their manufacture. Previous studies have shown the significance of the energy required for the operation of buildings as well as the energy embodied in initial building construction (AGO, 1999; Treloar et al., 2001; Yohanis and Norton, 2002; Nässén et al., 2007). Fewer studies have analysed the recurrent embodied energy involved in maintenance and refurbishment activities over a building’s life (Fay et al., 2000b; Crawford et al., 2010b; Crawford and Stephan, 2013; Rauf and Crawford, 2013). However, the significance of recurrent embodied energy and how it is affected by the service life of buildings and its materials in the context of the life cycle energy performance of a building is not well known. The aim of this study was to determine what effect variations to the service life of buildings and their constituent materials have on the life cycle embodied energy demand in the context of a multi-unit residential building.

2. Background

2.1. Life cycle embodied energy analysis

This approach is based on the general principles of life cycle assessment (LCA) as outlined in ISO 14040 (ISO, 2006). In the building industry, this approach is used to quantify the energy required to initially construct a building along with the energy embodied in subsequent replacement and maintenance of components or materials across its life in order to quantify its effects on the environment throughout its life. The energy associated with the production of construction materials and the construction of a building, known as a building’s initial embodied energy, has been quantified in numerous previous studies (inter alia Treloar, 1998; Fay, 1999; Crawford, 2004). However, the quantity of energy associated with manufacturing the materials needed for maintenance and repair throughout a building’s life, known as a building’s recurrent embodied energy, is much less understood. There is a much more limited number of studies where this recurrent embodied energy has been calculated. Calculation of recurrent embodied energy is faced with a number of challenges. Recurrent embodied energy is strongly influenced by the service life of a building and its constituent materials. A lack of building and material and component service life data is among one of the major challenges. The problem is further exacerbated by the considerable variability that exists in the data available for the service life of different building types and materials. A study by Treloar et al. (2000) shows that embodied energy associated with the replacement of building materials over 30 years can represent up to 32% of the initial embodied energy of a building. Another study by Crawford on residential construction assemblies shows that the energy embodied in material replacement can represent between 7 and 110% of their initial embodied energy (Crawford et al., 2010a). In a study of office buildings, Cole and Kernan (1996) have also shown that recurrent embodied energy can be significant, representing 1.3, 3.2 and 7.3 times the initial embodied energy value for an assumed building lifespan of 35, 50 and 100 years, respectively. In another study of residential buildings, embodied energy was increased due to the maintenance and replacement of materials from 14.1 GJ/m² to 23.5 GJ/m² over 50 years and to 35.41 GJ/m² over 100 years (Fay et al., 2000a). However, studies which show the effect of building and material service life data on the recurrent and life cycle embodied energy are almost non-existent.
2.2. Building service life

Building service life is the period of time in which a building is in use. Due to the potential importance of building service life on the life cycle energy demand of buildings, service life planning must play a vital role in achieving more sustainable construction practices. There are several approaches to predict the service life of a building or its components. The first approach involves the use of structural engineering to estimate a material's structural integrity and fatigue in relation to physical loading, ongoing chemical reactions and degradation over time (Grant et al., 2014). However, this approach often excludes the effect of human activities on the service life of a material or building component (e.g. frequency of maintenance).

The service life of a building may also be affected by various sociological, economic and cultural factors including urban development plans and policies (Dias, 2003; Fu et al., 2013). The changing needs of occupants or owners over time may result in the demolition of a building, ending its service life before it would otherwise cease to be serviceable. Several other factors such as heritage considerations or tougher regulations for new construction can also force decision makers to prolong the service life of a building through significant refurbishment and repairs. In this scenario, use of empirical data is arguably considered as a reliable approach to service life prediction. However, the approach of using empirical data can present challenges in terms of the time and cost involved as well as the relevance of data over time (Grant et al., 2014).

2.3. Material service life

A material’s service life is the amount of time that it can be expected to be serviceable. While predictions of service life will often be based on empirical data, previous experience or warranty periods, a number of key factors will determine the actual service life of a material in use. These factors include material quality, design and detailing, quality of workmanship, maintenance regime and levels, material durability and exposure to deteriorating effects associated with the local climate and environment (ABCB, 2006). The service life of a material affects the number of times it will be replaced over the life of a building. The lower the service life of a material, the greater the quantity of material required for ongoing maintenance and repair and therefore the greater the embodied energy demand associated with manufacturing and installing replacement materials throughout a building’s life. As it is typically fossil fuel-based, this additional demand for energy may result in a considerable ongoing burden on the environment.

3. Research approach

In order to determine what effect a variation in the service life of a building and its constituent materials would have on the life cycle embodied energy demand of an apartment building, the total life cycle embodied energy associated with a selected case study building was quantified. This involved calculating and combining the initial and recurrent embodied energy of the building. A number of building and material service life scenarios were developed and the life cycle embodied energy demand of the selected case study building was recalculated.
3.1 Case study building

Flats and apartments are the most rapidly growing dwelling type in Australia and accounted for 11% of all dwellings in 2009-2010 (ABS, 2012). A nine-storey apartment building, known as Forte, located in Melbourne, Australia and constructed by Lend Lease in 2012 was used as the case study for this analysis (Figure 1). This building is currently the world’s tallest timber building with 197 m$^2$ of retail space on the ground floor and 23 residential apartments with a total area of 1,558 m$^2$ (Durlinger et al., 2013). Concrete is used for the footings and ground floor. From the first level up, the entire structure (including load bearing walls, floor slabs, stairwells and elevator cores) is composed of solid timber using Cross Laminated Timber (CLT). A 10 mm thick layer of Uniroll (manufactured using recycled foam rubber and cork) was applied to all CLT flooring (Durlinger et al., 2013). External walls are clad with an additional protective rain screen made of a 4 mm thick LDPE core with two aluminium sheets of 0.5 mm thickness on either side of this core. The windows are double-glazed and aluminium-framed.

![Figure 1: Floor plan and exterior view of case study building. (Source: Lend Lease, 2013)](image)

3.2 Calculating life cycle embodied energy

3.2.1. Initial embodied energy

An input-output-based hybrid analysis was used to quantify the embodied energy associated with the initial construction of the case study building. Delivered quantities of materials used in the construction of the apartment building were multiplied by the embodied energy coefficient of the respective material, obtained from Treloar and Crawford (2010). Any remaining data gaps were filled with the use of a disaggregated energy-based input-output model of the Australian economy. This accounted for non-material inputs required in the construction of the building (i.e. the energy associated with the on-
site construction process, transport of materials to site and the provision of finance, insurance etc. needed to support the construction process). A detailed description of the hybrid approach used is provided by Crawford (2011).

3.2.2. Recurrent embodied energy

The recurrent embodied energy was calculated based on the number of times each individual material would likely be replaced during the useful life of the building. Average material service life figures from the literature were assumed for this initial analysis (See Rauf and Crawford, 2013). The embodied energy associated with the materials being replaced over the life of the building was calculated as per its initial embodied energy. The delivered material quantities associated with each replacement were multiplied by the material embodied energy coefficients. Input-output data was then used to fill any remaining data gaps as for initial embodied energy. The energy embodied in each material was then multiplied by the number of replacements for that material over the life of the building, and summed to determine the total recurrent embodied. The exact number of replacements required for each material was determined by dividing the service life of the building, by the service life of the material, subtracting 1 (representing the material used in initial construction at year zero) and rounding up to the nearest whole number (to reflect the fact that materials can only be replaced in whole numbers).

3.3. Building service life scenarios

Building service life values of 50, 100 and 150 years were used for the building service life scenarios to analyse the effect of variations to building service life on the life cycle embodied energy of the case study building. These building service life scenarios can be considered to represent the potential effect of different climatic and geographic conditions on the service life of a building. Initial embodied energy was constant across each scenario as this is not affected by variations to the service life of the buildings. However, changes to the service life of materials will affect the recurrent embodied energy demand.

3.4. Material service life scenarios

The material service life scenarios were chosen to reflect the extent of service life variability likely for a selection of the main building materials used within the building. Minimum, average and maximum material service life values from the available literature were used as the basis of the three different material service life scenarios chosen for the main construction materials (i.e., timber, concrete, steel, carpet, paint etc.). A list of specific material service life values used is provided in another study by the authors (see Rauf and Crawford, 2013). The life cycle embodied energy demand associated with the building was then recalculated for each scenario. Initial embodied energy was constant across each scenario as this is not affected by variations to the service life of the materials. However, changes to the service life of materials will affect the recurrent embodied energy demand.

4. Results and discussion

This section presents the results of the analysis including the initial and recurrent embodied energy associated with each building and material service life scenario for the case study building.
4.1 Initial embodied energy

The embodied energy calculated for the initial construction of the case study building was found to be 81,441 GJ (35.7 GJ/m\(^2\) of total floor area). CLT panels were found responsible for the highest amount of initial embodied energy (35\%) followed by steel and concrete with a share of 21\% and 13\%, respectively.

4.2 Recurrent embodied energy

The recurrent embodied energy associated with the replacement of materials for the building over a period of 50 years, based on average service life figures obtained from the literature, was found to be 36,154 GJ (15.8 GJ/m\(^2\)). For the minimum and maximum material service life scenarios over the same time period, recurrent embodied energy was found to be 85,944 GJ (37.7 GJ/m\(^2\)) and 20,532 GJ (9 GJ/m\(^2\)), respectively (Figure 2). These results reflect the fact that an increase in material service life will result in a decrease in recurrent embodied energy requirements, up to 74\% in the case of the building analysed.

For the building service life of 100 and 150 years, recurrent embodied energy for the average material service life was found to be 84,413 GJ (37 GJ/m\(^2\)) and 140,264 GJ (61.5 GJ/m\(^2\)), respectively. This shows that an increase in building service life results in an increase in recurrent embodied energy. The same trend of an increase in recurrent embodied energy with an increase in the service life of building was found for the scenarios with minimum and maximum material service life. Decrease in recurrent embodied energy requirements due to increase in material service life for the building service life of 100 and 150 years was found to be 70\% and 74\%, respectively.

![Figure 2: Recurrent embodied energy of the case study building based on building and material service life scenarios.](image-url)
4.3. Life cycle embodied energy

Life cycle embodied energy demand for the building over 50 years was calculated by combining initial and recurring embodied energy for each scenario. Based on the average material service life figures, life cycle embodied energy was 117,595 GJ or 51.6 GJ/m². For the minimum and maximum material service life scenarios life cycle embodied energy was 167,385 GJ (73.4 GJ/m²) and 101,973 GJ (44.7 GJ/m²), respectively. Figure 3 shows the breakdown of the embodied energy demand by life cycle stage for each material service life scenario. Variations in material service life and thus recurrent embodied energy, results in up to a 39% reduction in life cycle embodied energy demand comparing minimum and maximum material service life results. Compared to the average material service life scenario, the total possible reduction in life cycle embodied energy demand by extending the service life of materials is up to 13%.

For a building service life of 50 years, the recurrent embodied energy of the building represents 51%, 31% and 20% of its life cycle embodied energy demand, for minimum, average and maximum material service life scenarios, respectively. This shows that when materials are poorly maintained and/or require greater frequency of replacement, the recurrent embodied energy of a building may become as significant as the embodied energy associated with its initial construction.

Figure 3: Life cycle embodied energy of the building based on building and material service life scenarios.

This proportion increases even further for a building with a service life longer than 50 years. For a building service life of 100 years, the recurrent embodied energy of the building represents 69%, 51% and 37% of its life cycle embodied energy demand for minimum, average and maximum material service
life scenarios, respectively. For a building service life of 150 years, the recurrent embodied energy of the building was found to be 78%, 63% and 49% of its life cycle embodied energy demand for minimum, average and maximum material service life scenarios, respectively. This shows that when materials are poorly maintained and frequently replaced over a longer period of time (150 years in this case), the recurrent embodied energy of case study building become 3.5 times more than the embodied energy associated with its initial construction.

Figure 4 shows annual embodied energy demand of the building for each building and material service life scenario. An increase in building service life results in a decrease in annual embodied energy demand. However, the decrease in embodied energy between a building service life of 50 and 100 years is much greater than the decrease in embodied energy between 100 and 150 years. For average material service life values, the decrease in life cycle embodied energy demand between the building service life of 50 and 100 years was 693 GJ, while the decrease in embodied energy demand between 100 and 150 years was found to be 181 GJ. This shows that after 100 years, rate of decrease in embodied energy drops as more materials have to be replaced offsetting the decrease in annual initial embodied energy.

![Figure 4: Annual embodied energy of the building based on building and material service life scenarios.](image)

5. Conclusion

This study aimed to determine what effect variations in the service life of apartment buildings and their constituent materials would have on their life cycle embodied energy demand. A case study apartment building located in Melbourne, Australia was used for this analysis. The initial and recurring embodied energy of the case study building were calculated using a comprehensive hybrid assessment approach, with material service life values based on average figures obtained from the literature. The service life values for the building and a selection of the main building materials were then varied to reflect the extent of service life variability likely and the recurring embodied energy and life cycle energy recalculated for each scenario.
This study has shown the significance of the recurrent embodied energy associated with the maintenance and replacement of materials as part of the total life cycle embodied energy of an apartment building. The study has also shown that a variation in the service life of buildings can have a significant effect on the annual and life cycle embodied energy of a building. Compared to the building service life of 50 years, the annual embodied energy demand based on an average material service life decreased by 29% and 37% for the building service lives of 100 and 150 years, respectively. This shows that despite the additional recurrent embodied energy requirement for a longer building service life, the longer a building lasts, the lower its annual life cycle embodied energy demand.

The study has also shown that a variation in the service life of materials can significantly affect the recurrent embodied energy of a building. While an increase in the service life of materials was shown to result in a reduction in recurrent embodied energy demand of up to 74% for the apartment building analysed, in terms of the total life cycle embodied energy demand of the building, the reduction was found to be in the order of up to 39%. This shows the importance of maximising the service life of materials in order to minimise the demand for energy and release of greenhouse gases into the environment. This also highlights the benefits of using more durable materials in the construction industry. However, specifying the most durable materials with the longest potential service life is not always the best choice. More durable materials may result in an increase in initial embodied energy of a building, as in some cases, more durable materials may require more energy to manufacture. Using such materials without consideration for the type or likely life of the building in which they are to be used can lead to the over-specification of a material. Therefore, the anticipated service life of buildings should be considered when specifying such materials to ensure any unnecessary energy demand or related environmental effects associated with over specification are avoided.

Appropriate selection of materials and integration of building and material service life considerations in the design process, including timely maintenance and repair, is critical for ensuring that the embodied energy demands of buildings and associated environmental consequences are kept to a minimum. Consideration of material choice in the context of a building’s thermal performance and life cycle operational energy consumption is also important. This ensures that the selection of materials to minimise life cycle embodied energy does not shift the energy consumption from one life cycle stage to another. Apart from a need to reduce the energy use across the various life cycle stages of buildings, building and material service life considerations are important in order to reduce the quantity of finite and non-renewable resources and materials used in the construction industry.

References
The next step in energy rating: the international ETTV method vs. BCA Section-J Glazing Calculator

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Abstract: The most important prevention in minimizing energy transfer in commercial buildings is the treatment of glazing in the building facade. In a commercial building, while the impacts of roof, walls and floors on the overall heating and cooling loads of the building have low effects, glazing is likely to be the most important factor. This paper investigates the BCA Section-J glazing calculator and the ETTV (Envelope Thermal Transfer Value) methods and tries to look for differences as well as similarities in calculation of building envelopes energy performance. For this investigation, a hypothetical high-rise commercial building in Melbourne, Australia is considered when evaluating the energy performance of the envelope through these two methods. Both methods consider the U-Value of glass and wall materials as well as Solar Heat Gain Coefficient (SHGC) and Shading Coefficient (SC) of the glass. Findings in this research project indicate differences and significant discrepancies between the BCA Section-J and ETTV methods in evaluating the energy performance of commercial building façades. Issues of calculation weaknesses are identified with the lack of air leakage and infiltration of a particular façade design or window to wall ratio (WWR). Suggestions have been made where improvement to the overall energy calculation through facades of a commercial building is needed.

Keywords: ETTV method, BCA Section-J, envelope energy performance, glazing.

1. Introduction

Sustainable development and environmental protection are among the major motivations of energy conservation initiatives. Energy efficiency is universally known as one of the most cost effective ways to reduce related building energy issues (Hodges, 2005). Since buildings are significant energy consumers in many countries, energy use in buildings has become a policy issue worldwide to increase energy efficiency of buildings. Particularly in commercial and high-rise buildings, energy efficiency is a concern and means to improving both the performance of HVAC systems and the mechanisms of heat transfer through the building envelope are crucial (ABCB, 2010). While, in commercial buildings, the impacts of roof, walls and exposed floors on building’s overall cooling or heating load are generally small, glazing is likely to be the most important factor. Although other factors such as efficiency of HVAC systems and
building energy management are significant and should be considered (Chua and Chou, 2010),
improving the thermal performance of building envelopes would result in reduced HVAC system sizing
and less running time, therefore, less energy consumption (ABCB, 2010).

In Australia, Commercial building energy performance has been influenced by the NABERS (National
Australian Built Environment Rating System) energy rating scheme (CBD, 1998) for over a decade. What
is lacking in this rating system are the causes that yield to a specific building energy performance result.
A report by the Centre for International Economics (CIE) indicates that building sector in Australia,
including commercial and residential buildings, is accounting for approximately 20% of Australia’s total
energy consumption in 2007 with the prediction of annual increase of 2% (CIE, 2007). Considering the
same trend, by 2014, building sector in Australia would be accounted for almost 35% of the total energy
consumption, which has significant contribution to Green House Gas emission.

On the other hand, the Australian Building Codes Board (ABCB) seeks to cover building related issues
by developing regulatory solutions through BCA ‘Section-J’, which is considered to be such a solution to
address building energy performance issues. However, this approach is considered not to be as rigorous
on the energy calculation of the envelope thermal performance as compared to the Overall Thermal
Transfer Value (OTTV) or the more recent, Envelope Thermal Transfer Value (ETTV) methods being used
in several Australasian countries.

The OTTV method was initially created in 1975 by the American Society of Heating, Refrigerating and
Air-conditioning Engineers (ASHRAE). Since then, this method was being used in the U.S. to calculate
heat transfer of air-conditioned buildings through building envelopes and also acts as an index of
building envelope thermal performance. Since then, many amendments have been proposed to improve
the accuracy of the OTTV method, however, the use of such a single thermal performance index alone
could not guarantee energy efficiency of air-conditioned buildings and it was abandoned when the new
ASHRAE Standard 90.1 took place in 1989 (ASHRAE, 1989). Despite the abandonment of OTTV method in
the U.S., ETTV, as a superior version of OTTV, is still being used in other regions of the world, particularly
in the Asian countries such as Singapore, Hong Kong and Philippine etc.

In Singapore, for instance, a recent report by BCA Singapore indicates that building sector consumes
up to 38% of the country’s wide electricity consumption. With the utilization of ETTV method for
building envelope energy performance, average Energy Utilization Index (EUI) of new commercial
buildings has been reduced over the last five years. This reduction ranges from 16% for offices, 7% for
retail buildings and 5% for hotels (BCA, 2014). This simply shows that the use of ETTV method for
calculation of building envelope energy performance is worthwhile.

2. Overall thermal transfer value (OTTV)

The initial concept of OTTV was originally proposed in the U.S. for the ASHRAE 90-75 Standard in 1975.
ASHRAE originated the use of OTTV as an index for envelope thermal performance of air-conditioned
buildings with the concept of the maximum allowable thermal transfer value in W/m² (ASHRAE, 1975).
Original calculation for OTTV consists of three major components of thermal performance; (1) wall
conduction, (2) glass conduction and (3) solar radiation through window glass. The concept is also based
on the assumption that the building envelope is completely enclosed. In a general form, the calculation
of OTTV for external walls of air-conditioned buildings is shown in equation (1), as follow:

\[ OTTV = \frac{Q_{wc} + Q_{gc} + Q_{sol}}{Area} = \frac{((Aw \times U \times ΔTs) + (Ag \times U \times ΔT) + (Ag \times I \times θ))}{Area} \]  

(1)

Where:
The next step in energy rating: the international ETTV method vs. BCA Section-J Glazing Calculator

\[ Q_{ac} \quad \text{Conduction through opaque wall} \]
\[ Q_{gc} \quad \text{Conduction through window glass} \]
\[ Q_{sol} \quad \text{Solar radiation through window glass} \]

\[ \Delta T_s = T_s - T_i = (T_o + I \times a / F_o) - T_i \]  \hspace{1cm} (2)

\begin{align*}
Aw & \quad \text{area of wall + area of glass in } \text{m}^2 \\
U & \quad \text{Transmittance value in } \text{W/m}^2 \text{ deg. C} \\
To & \quad \text{Outside air temperature in deg. C} \\
I & \quad \text{radiation intensity in W/m}^2 \\
a & \quad \text{absorbance of the surface} \\
\theta & \quad \text{solar gain factor of window glass} \\
F_o & \quad \text{Surface conductance outside in W/m}^2 \text{ deg. C} \\
T_i & \quad \text{inside air temperature in deg. C} \\
Ag & \quad \text{Area of glass in m}^2 \\
\Delta T & \quad \text{internal and external air temperature difference}
\end{align*}

According to the ASHARE Standard 90-75, the calculation of OTTV was initially based on peak heat gains, stipulating that all air-conditioned buildings must be designed to have an OTTV of not more than 50 W/m². Since 1975, when ASHRAE Standard 90-75 originated the use of OTTV, the concept and definition have also evolved along with several amendments, basing it on annual heat gains, annual cooling loads and annual air-conditioning energy use to make OTTV an appropriate indicator with the aim of obtaining an index reflecting the impact of building envelopes on energy use by air-conditioned buildings (ASHRAE, 1975). The evaluation study by Yik and Wan in 2005 shows that all the amendments to OTTV method had fundamental issues due to implicit assumptions. Yik and Wan are then concluded that the assumptions are considered to simplify the OTTV calculation method for air-conditioned buildings and the method can be evaluated based on limited or fixed values of pre-calculated TD\text{EQ} and SF, without considering the room function and dimensions (Yik and Wan, 2005). Later researches have shown that OTTV method is a useful indicator for the thermal performance of a building envelope, however, it does not accurately reflect the relative performance of different elements in an envelope system (BPNL, 1983). Specifically, it underestimates the solar radiation gain of the components through the fenestration system and hence does not represent the full extent of heat gain through the envelope (SBCA, 2004). The shortcoming of the OTTV method is that it does not account for the interactions between the envelope, internal gains and equipment efficiency, as would a true performance calculation. As a result, the use of OTTV method has been abandoned in the U.S. since the ASHRAE Standard 90.1 was launched in 1989.

3. Abandonment of OTTV

The use of OTTV in ASHRAE Standard 90 series lasted for 14 years and has been abandoned since ASHRAE Standard 90.1 was launched in 1989. The major reasons for abandonment of the OTTV method were:

- Simplistic criteria in the calculation of OTTV that did not properly account for the interactions of building façade with the energy flow within the building,
- Use of pre-calculated equivalent temperature difference (TD\text{EQ}) for the thermal storage effects of building envelope,
- Building envelope performance requirements were considered restrictive due to treating the HVAC systems and the building envelope independently.

Since the abandonment of the OTTV method by ASHRAE 90.1-1989 in the U.S., the following criteria took place as the replacement (Wilcox, 1991) (ASHRAE, 1989):
• Limits to the percentage of Window to Wall Ratio (WWR) of external walls,
• Limits to the thermal transmittance (U-value) of envelope elements separating conditioned and unconditioned areas,
• Limits to the thermal resistances of slabs and walls below grade.

The above limits consider solar position and angle to the façade, windows shading coefficient, weather conditions, heat capacitance of wall, shading device characteristics and location of insulation. Despite the abandonment of OTTV in the U.S., a superior version of OTTV continues to be used in the building energy codes of a number of other countries and regions, especially Asian countries including Hong Kong, Singapore, Thailand, and Malaysia etc. A major review of the OTTV formula was carried out in Singapore to come out with a new formula that could provide a more accurate measure of the thermal performance of building envelope. The new formula is called Envelope Thermal Transfer Value (ETTV) to differentiate it from the original OTTV formula.

4. Envelope thermal transfer value (ETTV)

ETTV is similar to OTTV in that both take into consideration the three components of heat gain; (1) wall conduction, (2) glass conduction and (3) solar radiation through window glass, for building envelopes energy performance. In addition, in ETTV method the three components of heat gain are averaged over the whole envelope area of the building to provide more accurate index of building envelope thermal performance. Singapore was the first Asian country to have regulatory control on ETTV since 1979, which has stipulated that all air-conditioned buildings must obtain an ETTV index of not more than 50 W/m² (SBCA, 2004). This means that the building envelopes are well insulated against thermal transfer, however, the amount of heat that flows through a unit area of the envelopes will impact on HVAC systems to provide cooling load of maximum 50W per unit area of the building envelopes.

In Hong Kong, since most commercial buildings consist of a tower on top of a larger podium, the 2000 Standard contained different ETTV criteria of 30 W/m² for the tower and 70 W/m² for the podium. Indonesia, Malaysia, Philippines and Thailand also have used Singapore ETTV Standard as a reference model to develop their building energy standards (ASHRAE, 1980) (METP, 1989) (DOE, 1993) (Chirarattananon, 1992). They have also made reference to ASHRAE Standard 90 series (ASHRAE, 1989).

According to regulations by Singapore Building Codes Authority (SBCA), the maximum permissible ETTV for commercial buildings has been set at 50 W/m² (SBCA, 2004). For this approach, the proposed formula for calculation of ETTV of a single external wall of a building at particular orientation is as follow:

\[
ETTV = 12 (1 – WWR).Uw + 3.4 (WWR).Uf + 211 (WWR).(CF).(SC)
\]

Where:

- \(Uw\): thermal transmittance of opaque wall (W/m² K)
- \(Uf\): thermal transmittance of fenestration (W/m² K)
- \(CF\): correction factor for solar heat gain through fenestration
- \(SC\): shading coefficients of fenestration
- \(WWR\): window-to-wall ratio (fenestration area / gross area of exterior wall)

To calculate the ETTV for the whole building, as walls at different orientations receive different amounts of solar radiation, the ETTV of individual walls needs to be calculated in order to calculate the
ETTV for the whole building. The proposed formula for calculation of ETTV for the whole building is as follow (SBCA, 2004):

$$ETTV = \frac{A_1 \times ETTV_1 + A_2 \times ETTV_2 + A_3 \times ETTV_3 + \ldots}{A_1 + A_2 + A_3 + \ldots}$$

(4)

Where:

ETTV1, ETTV2, ETTV3 ... are the ETTV of each façade, and A1, A2, A3... are the gross area of each façade.

As shown in the ETTV formula (3), thermo-physical factors of building envelope materials are considered in the calculation. These factors are:

- Thermal conductivity (K) (Steady-State condition)
- Thermal resistivity (r) (r=1/K)
- Thermal conductance (C) (C=K/b) where b is the thickness of material.
- Thermal resistance (R) (R=1/C)
- Shading coefficient (SC)
- Thermal Transmittance (U-Value) (U=1/R)

The thermal transmittance (U-Value) of the envelope material is defined as the quantity of heat that flows through a unit area of a building section under steady-state conditions in unit time per unit temperature difference on either side of the envelope material. The philosophy behind steady-state condition is based on the steady heat gain (or loss) of the façade and the temperature difference between outside and inside.

5. Section-J of BCA

The objective of Section-J of BCA is to reduce Greenhouse Gas Emission (GHG) through improving energy efficiency in buildings. In other words, producing more energy efficient building envelopes that keep the conditions inside comfortable will result in less using HVAC services, therefore reducing energy consumption and GHG emissions. There are two main assessment methods used for compliance purposes of BCA Section-J (ABCB, 2010). The first method is assessment of relevant building design elements of the proposed building against the Deemed to Satisfy (DTS) provisions of the BCA. If the proposed building did not comply with the DTS provisions, then a Verification Method (JV3) using a reference building as the second method can be performed to compare thermal simulation of the proposed building with a reference building that meets all DTS requirements of the BCA Section-J (Figure 5).
5.1. BCA glazing calculator (DTS)

The main contributors to heat loss or gain through the fabric are usually the windows or other openings containing glazing. DTS Provisions of BCA Section-J consider two major thermodynamic effects on glazing:

- Heat conduction through glass by virtue of temperature difference between inside and outside,
- Solar radiation conducted through glazing system into the building.

To this approach, ’BCA Glazing Calculator’ has been developed for the calculations required by DTS provisions in terms of energy efficiency of building envelopes.

5.2. Verification method (JV3)

Virtual thermal modelling software (Verification method) is used to estimate the annual energy consumption of a commercial building. The outcomes of this method are based on the whole building energy consumption considering building orientation, function, operating hours, HVAC systems and etc.

6. Methodology

To identify the accuracy, suitability and ease of use of the two discussed methods in this study, ETTV and BCA Glazing Calculator (DTS) for energy performance of high-rise building envelope, a hypothetical commercial building (10-storey) is considered in Melbourne, Australia. To this approach, both methods were individually applied to the proposed building and the results from each method have been analyzed and compared respectively. The building’s typology is assumed to be a square shape with the dimensions of 20m x 20m x 40m (LxWxH) and a total floor area of 4,000 m². All the building floors are considered to be air-conditioned using split system, except the ground floor. Therefore, the total façade area for the air-conditioned space is 2,880 m².
NOTE: As the main objective of this study is to evaluate the energy performance of building envelope ONLY and not the whole building, so “BCA Section-J Verification Method” is not considered in the calculation process as it is based on calculation of the whole building energy performance.

6.1. ETTV method

In order to calculate the overall ETTV for the proposed commercial building in this study, a spreadsheet has been designed including ETTV formula with relevant assumptions as shown in Table 4.

Table 4: Assumptions for the calculation of ETTV

<table>
<thead>
<tr>
<th>Glazing Systems:</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double-Glazing Reflective (E, N, W):</td>
<td>U-Value = 2.3 W/(m²·K)</td>
</tr>
<tr>
<td>Double-Glazing Low-E (South):</td>
<td>U-Value = 1.9 W/(m²·K)</td>
</tr>
<tr>
<td>WWR:</td>
<td>60%</td>
</tr>
<tr>
<td>Opaque wall:</td>
<td>U-Value = 0.8</td>
</tr>
<tr>
<td>Total floor area:</td>
<td>4,000 m²</td>
</tr>
<tr>
<td>Exterior Wall Area:</td>
<td>2,880 m²</td>
</tr>
<tr>
<td>Weather data:</td>
<td>Hourly</td>
</tr>
<tr>
<td>Maximum Allowable ETTV:</td>
<td>50 W/m²</td>
</tr>
<tr>
<td>Shading device:</td>
<td>No shading device is considered</td>
</tr>
</tbody>
</table>

6.2. BCA Section-J; glazing calculator (DTS)

Energy performance of façades of the proposed building is conducted by BCA Glazing Calculator (DTS). For this approach, following assumptions have been considered as shown in Table 5.

Table 5: Inputs for the BCA Glazing Calculator

<table>
<thead>
<tr>
<th>Glazing Systems:</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double-Glazing Reflective (E, N, W):</td>
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<td>WWR:</td>
<td>60%</td>
</tr>
<tr>
<td>Total floor area:</td>
<td>4,000 m²</td>
</tr>
<tr>
<td>Exterior Wall Area:</td>
<td>2,880 m²</td>
</tr>
<tr>
<td>Weather data:</td>
<td>Zone 6 (Melbourne)</td>
</tr>
<tr>
<td>Shading device:</td>
<td>No shading devices is considered</td>
</tr>
</tbody>
</table>

7. Results and analysis

7.1. ETTV

In calculation of ETTV for the proposed building in this study, it is considered that there are no external shading devices installed. So, the Solar Coefficient (SC) of glazing systems are calculated as follows:

\[
SC = \frac{[\text{Solar heat gain of the glass}]}{[\text{Solar heat gain through a 3mm unshaded clear glass}]} \tag{5}
\]

Therefore, SC for each glazing system are:

\[
SC_{\text{Double Glazed Reflective windows}} = \frac{0.13}{0.87} = 0.15
\]

\[
SC_{\text{Double Glazed Low-E windows}} = \frac{0.65}{0.87} = 0.75
\]
In order to calculate the Solar Correction (CF) factor for building facades, pre-calculated factors which are based on the orientation and steepness of the building envelopes, are also considered (1). Table 6).

<table>
<thead>
<tr>
<th>Pitch Angle</th>
<th>Orientation</th>
</tr>
</thead>
<tbody>
<tr>
<td>70°</td>
<td>N</td>
</tr>
<tr>
<td>75°</td>
<td>NE</td>
</tr>
<tr>
<td>80°</td>
<td>E</td>
</tr>
<tr>
<td>85°</td>
<td>SE</td>
</tr>
<tr>
<td>90°</td>
<td>S</td>
</tr>
<tr>
<td>95°</td>
<td>SW</td>
</tr>
<tr>
<td>100°</td>
<td>W</td>
</tr>
<tr>
<td>105°</td>
<td>NW</td>
</tr>
<tr>
<td>110°</td>
<td>NW</td>
</tr>
<tr>
<td>115°</td>
<td>NW</td>
</tr>
<tr>
<td>120°</td>
<td>NW</td>
</tr>
</tbody>
</table>

In addition to (SC) and (CF), U-Value of opaque walls and glass also have been identified from relevant specifications provided by relevant manufacturers. Upon calculation and collection all the requirements as per ETTV formula (3), a spreadsheet has been designed in order to calculate the ETTV of individual building envelope as well as the ETTV for the whole building (Figure 6).

![Figure 6: Calculation of the overall ETTV of the study building](image)

As shown in Figure 6, calculation of overall ETTV of the proposed building indicates that the South façade of the proposed building does not comply with the maximum allowable ETTV, however, the overall ETTV of the whole building is below the maximum allowable ETTV and complies with the ETTV compliance requirement. This simply shows that despite the fact that the South façade of the proposed building does not comply with the ETTV compliance requirement, however the whole building does comply with ETTV compliance requirement, thus the building envelope design is energy efficient.
7.2. BCA Section-J glazing calculator (DTS)

Calculation of envelope energy performance of the study building has been considered through BCA Section-J Glazing Calculator with the same inputs as into the ETTV calculation method. Additional requirement in this method, in compare to ETTV method, is SHGC of the glazing which has been provided by relevant glass manufacturer. Same specifications as ETTV have been applied and findings from this method show that the East, North and South façades of the proposed building comply with the DTS requirements, while the West façade does not comply with the DTS compliance requirements (Figure 7).

However, in BCA Glazing Calculator when at least one envelope orientation of a building does not comply with the DTS compliance requirements, then the entire rating for that building fails.

A comparison between ETTV method and BCA Section-J Glazing Calculator indicates that significant discrepancies exist which yield to specific performance results. The major discrepancy is that any same building orientations have shown different impacts on the overall building envelope energy performance. In addition, the climate data which is used in the BCA Glazing Calculator is opaque and is based on the lumped value (climate zone), while the climate data in the ETTV method is known as hourly based data. Also, the BCA calculator is only looking at the glazing part of the envelope and not the integration of wall systems including both glazing and opaque walls, while ETTV calculator does.

The argument, according to BCA Section-J requirements, is that upon failure in BCA Glazing Calculator the Verification Method (JV3) needs to be conducted in order to identify and analyse the whole building energy performance. What is lacking in this argument is that JV3 would not consider the energy performance of building envelopes in particular, but the whole building. However, JV3 can often provide great cost savings in project construction and operation. As discussed earlier, the most important prevention in minimizing energy transfer in commercial buildings is the treatment of glazing in the building façade. So, precise analysis of the building envelope characteristics (including glazing systems) on overall building energy performance is worthwhile.

Figure 7: BCA glazing calculation for the study building

In addition to the identified similarities and discrepancies between these two methods, “air leakage” or “permeability” of the building envelopes are also identified to be missing in both methods. In recent
years, efforts are made to design and construct tight building envelops, however, commercial buildings are completed much leakier than what originally planned and assumed (Emmerich and Persily, 2013). Also, most energy calculators are generally do not account for envelope infiltration and the impacts of airtightness (Ng et al., 2014). As a result, the energy impacts of air-leakage can be greater than what originally expected. Table 7 shows a summary of the evaluation between the two discussed methods.

### Table 7: Evaluation of ETTV and Glazing Calculator of BCA

<table>
<thead>
<tr>
<th>Climate Data</th>
<th>Opaque Wall</th>
<th>Glass</th>
<th>Shading</th>
<th>WWR</th>
<th>Air Leakage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lumped Value</td>
<td>Hourly Data</td>
<td>U-Value</td>
<td>Time lag</td>
<td>SC</td>
<td>SHGC</td>
</tr>
<tr>
<td>ETTV</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>BCA - GC</td>
<td>✓</td>
<td>×</td>
<td>×</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

8. Conclusion

This research project presents the beginning of examining the present and accepted BCA Section-J evaluation methods of a commercial building façade with that of other Australasian countries using the ETTV method. It queries the processes used in each of the methods and tries to look for similarities as well as differences. The calculation of energy through façades should be considered as one of the main features and differences among energy gains and losses between buildings. It is suggested here that more accurate calculators considering the Solar Heat Gain Coefficient of glass, according to angular solar irradiance and time dependent thermal heat transfer, are preferred. The ETTV method is a useful calculator for energy performance of building envelopes due to its relative ease of calculation, while providing some flexibility of trade-offs between envelope components. The introduction of the ETTV method also allows for shading devices to be considered at hourly intervals. What appears to be missing, however from all of the façade analytical methods, is a consideration of permeability or air leakage. This is an important and valid missing component since different WWR’s and wall construction types will result in different air leakage rates. Perhaps the final conclusion to all of this work is that it merits further analysis through simulation as well as real world experiential testing of different building façade types. In closing, it could be said that our present BCA Section-J Glazing Calculator requires an overview with the intention of providing more realistic measures towards actual building façade performance.

References


TRNSYS simulation and thermal performance of biomimetic façade designs

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Abstract: Biomimicry – innovation inspired by nature – is a creative methodology that translates characteristics from the biological world to the domain of human technology. Functional biomimicry offers opportunities to advance the development of flexible building facades. Following biomimetic principles, external fur and bioheat transfer (blood perfusion) and were combined into a mathematical model of a commercial office building façade for a west-facing wall of an office building situated in Melbourne, Australia. Simulation software TRNSYS was used to determine temperatures and heat transfer of this biomimetic façade in summer design conditions compared to a reference. The biomimetic façade was simulated to provide cooling of greater than 50 W/m² and reduced mean surface temperatures in the occupied zone by 2.8°C, compared with the reference.

Keywords: Biomimicry; adaption; façade; bioheat transfer.

Nomenclature (continued next page)

<table>
<thead>
<tr>
<th>$c_p$ – specific heat coefficient</th>
<th>Superscripts</th>
<th>$F_s$ – characteristic describing interaction of fur with radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h$ – heat transfer coefficient</td>
<td>$n$ – current finite difference timestep</td>
<td></td>
</tr>
<tr>
<td>$k$ – thermal conductivity</td>
<td>Subscripts</td>
<td></td>
</tr>
<tr>
<td>$L$ – length or thickness</td>
<td>$a$ – air</td>
<td></td>
</tr>
<tr>
<td>$N_{f,s}$ – non-dimensional parameter (apparent ‘optical thickness’ of fur in the solar spectrum)</td>
<td>$b$ – beam</td>
<td></td>
</tr>
<tr>
<td>$q, Q$ – heat transfer</td>
<td>$b$ – ‘blood’ (biomimetic façade cooling/heating fluid)</td>
<td></td>
</tr>
<tr>
<td>$q'$ – volumetric heat generation</td>
<td>$d$ – diffuse</td>
<td></td>
</tr>
<tr>
<td>$S$ – solar radiation</td>
<td>$eff$ – effective</td>
<td></td>
</tr>
<tr>
<td>$T$ – temperature</td>
<td>$env$ – environmental</td>
<td></td>
</tr>
<tr>
<td>$t$ – time</td>
<td>$ext$ – external</td>
<td></td>
</tr>
<tr>
<td>$W'_b$ – ‘blood’ perfusion rate</td>
<td>$f$ – fur</td>
<td></td>
</tr>
</tbody>
</table>
1. Introduction

Life has been evolving, surviving and thriving on Earth for more than 3.5 billion years and has adapted to the most extreme environments. Biomimicry – innovation through natural inspiration – offers humanity vast scope to develop more functional and sustainable technology. By studying natural adaptations, from an ever-growing body of biological knowledge, innovators can extract functional characteristics and translate these characteristics into adaptive, flexible and more efficient designs.

In the built environment, environmental concerns, and rising costs, have led to demands for energy reduction and resource conservation, alongside a desire for improved indoor environment quality. The use of functional Biomimicry offers designers, engineers and entrepreneurs a creative methodology to explore solutions to such design trade-offs. Architecture has explored biomorphic and biophilic designs since the earliest civilizations. However, only through the scientific method and a deeper understanding of biology have designers been able to apply the underlying strength of biomimicry: consideration of the functionality of biological species and harmonization within their natural habitats.

For example, the thermoregulatory systems of animals provide concepts – and details – that can be effectively applied to building design. In the natural world, mammals (including humans) have adapted to tolerate some of the harshest climates on Earth. Skin, fur and flesh have all evolved remarkable qualities. If the human brain’s hypothalamus detects excessive heat gain to the body core, sweating begins, promoting evaporation. Hairs flatten against the skin, and warm blood flows to vessels beneath the skin surface (vasodilation) maximising radiant heat transfer. In this study, two particular characteristics of mammal thermoregulation were examined in detail: fur and bioheat transfer (blood perfusion). This led to a transference of thermal qualities to a novel façade design.

The goal of this paper was to determine whether biomimetic adaptions of mammalian thermoregulation – fur and bioheat transfer – could improve the thermal performance of an office building façade and to assess the impact on occupant comfort. Just as animal skin helps to regulate body temperature, building facades can employ the same principles to efficiently maintain comfortable conditions for occupants. To ensure the functional essence of the biology was maintained, detailed physical descriptions of fur and bioheat transfer were translated to façade design.

Thermal performance of the biomimetic façade design was tested via mathematical models constructed in TRNSYS building simulation software. In the building model, the biomimetic façade was specified for a west-facing wall of an office building situated in Melbourne, Australia. A west wall was selected because large solar loads would coincide with high external ambient temperatures during summer afternoons. The design was simulated in a summer cooling scenario and compared against a reference façade.
2. Biological model

2.1. Bioheat transfer

Bioheat transfer was applied to a building façade model in Webb et al. (2013), with discussion on the relevant models of bioheat transfer. Charny (1992) presents a comprehensive review of the subject. The analysis in this paper employs the Pennes’ Equation (Pennes, 1948) fundamental perfusion model:

\[
\rho C_p \frac{\partial T}{\partial t} = k \nabla^2 T + \rho_b C_{p,b} \dot{W_b} (T_a - T) + q''_m
\]  

(1)

Pennes’ Equation was selected, because, despite its relative simplicity, it has been shown to be representative of the physical situation (Charny, 1992). Additionally, it was compatible with numerical methods applicable in building simulation software and could be combined with other biomimetic initiatives and physical effects.

In the model, a modified version of Pennes’ Equation was used to describe fluid perfusion through the façade. The homogeneity of the vascular architecture assumed in Pennes’ equation provided some freedom to create the corresponding ‘tissue’ and ‘vessels’ within the façade. It was proposed that the unitised façade system would be comprised of thermally significant minor fluid channels supplied by major ‘vessels’ (hydronic pipework). Bulk fluid flow (vertically or horizontally across the façade) would be in a direction perpendicular to the direction of major heat flow (in and out of the occupied zone). “Metabolic” heat generation was assumed to be zero, i.e. \( q_m = 0 \).

2.2. Fur heat transfer

Scholander (1950) conducted a series of experimental tests on the insulative qualities of fur. Many researchers have since conducted experimental and analytical studies on thermal properties of hair and fur. There is thus a great diversity in models of fur available to use in a simulation. All have strengths and weaknesses in terms of complexity and the inclusions and exclusions of physical characteristics and thermal processes. Following on from Webb et al. (2011) and Webb et al. (2013), the analysis of Davis and Birkebak (1974) was used as the primary model for fur heat transfer in this study. As noted in Webb et al. (2011), this treatment provided a detailed examination of fur’s physical characteristics, thus allowing a comprehensive transfer from the natural to technological domain (following the principles of functional biomimicry). Importantly, Davis and Birkebak considered short wave radiation heat transfer (i.e. solar radiation, including variation with solar angle of incidence) as well as conduction, convection and infrared radiation.

The essence of the proposed fur model involves the calculation of an effective fur thermal conductivity, \( k_{eff} \), based on the physical properties and geometric arrangement of individual hairs. Additional terms are included to account for solar radiation. Detail of the model can be found in Davis and Birkebak (1974) and Davis and Birkebak (1973) and its translation to the built environment was explored in Webb et al. (2011). The final form of the fur heat transfer equation used was:

\[
q_f = \frac{k_{eff}}{L_f} (T_{s,e} - T_{f,e}) + \left(1 - \left[\frac{\cos \theta_e}{N_{f,s} F_s}\right]\right)q_j + \left(\frac{\alpha_{f,s} (S_b + S_d)}{N_{f,s} F_s}\right)\cos \theta_e
\]  

(2)
3. Façade simulation

3.1. Biomimetic façade model

The basis for the dynamic façade model was Equation 1, describing the solid perfusion layer. For heat transfer, Equation 2, specified the external boundary condition for the façade. The internal boundary condition was specified by the façade interaction with an interior occupied zone (see below).

3.2. Reference façade model

The biomimetic façade was compared against an equivalent reference façade. This façade was composed of standard construction materials, with the physical properties of each layer combined. The basis for this façade was the one dimensional conduction heat transfer equation (Holman, 2001):

\[
\frac{1}{\alpha_w} \frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2}
\]

(3)

Where:

\[
\alpha_w = \frac{k_w}{\rho_w c_{pw}}
\]

(4)

3.3. Simulation software: TRNSYS

TRNSYS software was selected to test the performance of the façade models in the context of a dynamic building simulation in a specific geographical location. TRNSYS has an open framework that allows the construction of customised designs for buildings and building components and allows customisations to interface with standard building elements, such as air-conditioned occupied zones.

3.4. Façade integration within TRNSYS

The TRNSYS simulation engine is based on a progressive time-based calculation method with timesteps specified by the user. Therefore, the clearest means to integrate the biomimetic façade into TRNSYS was to convert the analytical model equations into numerical versions based on a given timestep, \( \Delta t \). Solutions could then be calculated at every TRNSYS timestep and integrated within the other components in the TRNSYS model. An explicit finite difference scheme was thus introduced. The stability requirements for these schemes could be met by controlling the simulation parameters in TRNSYS. While there are several options for establishing explicit finite difference schemes, a method that allowed the calculation of surface temperatures was appropriate. Given a nominal façade thickness of 0.1 m, discretising the façade into 4 spatial steps was a satisfactory balance between computational accuracy and speed.

Finite difference methods are presented in many texts, e.g. Holman (2001). Underwood and Yik (2004) discussed finite difference methods specifically for building simulations, which formed the basis for the biomimetic façade. This treatment was compatible with both the biomimetic façade model and TRNSYS integration. The current study required two finite difference models: one for the biomimetic façade and one for the corresponding reference façade. A nodal schematic for both models is shown in Figure 1 (dimensions not to scale).
The reference façade was taken as a uniform material with one set of combined properties. From Equation 3, the explicit finite difference equation to determine the temperature, $T_i$, for the $i$th internal node at timestep $n + 1$ therefore became:

$$T_i^{n+1} = F_o \left[ T_i^n - \left( 2 - \frac{1}{F_o} \right) T_i^n + T_i^{n+1} \right]$$

Where:

$$F_o = \frac{\alpha w \Delta t}{\Delta x^2}$$

Equation 1 modelled the internal heat transfer for the biomimetic façade. Similar to the reference façade, this equation was converted to its finite difference equivalent for internal nodes (assuming onedimensional heat flow) as the following:

$$T_i^{n+1} = F_o \left[ T_i^n - \left( 2 - \frac{1}{F_o} \right) T_i^n + T_i^{n+1} + \frac{\lambda \Delta t}{F_o} T_0 \right]$$

Where:

$$\lambda = \frac{\rho_p c_{p,b} W_{b,i}}{\rho_l c_{p,t}}$$
For both reference and biomimetic models, façade surface temperatures were calculated via heat transfer with a representative ‘environmental temperature’ $T_{env,ext}$ to account for convective and long-wave radiation heat exchange. Heat transfer at the internal surface, temperature $T_{s,in}$, was calculated via convection to air temperature, $T_{a,i}$, and via long wave radiation to other surfaces using a Mean Radiant Temperature $T_{MRT,i}$. The calculation method for $T_{MRT,i}$ can be found in Underwood and Yik (2004, p. 69). Hence the finite difference equations for the reference façade surface temperatures were thus:

$$T_{s,ext} = \frac{T_{1} + 0.5B_{i,ext}T_{env,ext}}{0.5B_{i,ext}+1}$$

Where:

$$T_{env,ext} = T_{a,ext} + \frac{\alpha_{i}(S_{b} + S_{d})}{h_{w,RC}} + \frac{\varepsilon_{w,ext}\Delta R_{ext}}{h_{w,RC}} ; B_{i,ext} = \frac{h_{w,RC}\Delta x}{k_{w}}$$

And:

$$T_{s,ext} = \frac{T_{4} + 0.5B_{i,ext}T_{env,ext}}{0.5B_{i,ext}+1} ; B_{i,ext} = \frac{h_{w,RC}\Delta x}{k_{w}} ; T_{env,ext} = T_{a,ext} + \frac{q_{rad,ext}}{h_{w,RC}}$$

The finite difference equation for the internal surface of the biomimetic façade was equivalent to the reference façade. However, the external surface equation was required to incorporate heat transfer through the outer fur layer. To achieve this, Equation 2 was incorporated into the heat equation and rearranged to create a finite difference equation for the surface temperature and first temperature node in the biomimetic façade:

$$T_{z,ext} = \frac{k_{f}T_{f,ext} + \frac{2k_{f}}{L_{f}}T_{1} - A_{f}q_{f,t} + B_{f}}{\frac{2k_{f}}{L_{f}} + \frac{k_{w}}{L_{f}}}$$

$$T_{1} = T_{1} + FA_{i}(T_{2} - T_{1}) + \frac{\Delta t}{c_{p,1}p_{1}\Delta x}\left[\frac{k_{eff}(T_{f,ext} - T_{z,ext}) + B_{f} - A_{f}q_{f,t}}{L_{f}}\right] + \Delta t(T_{2} - T_{1})$$

Where:

$$A_{f} = 1 - \left(\cos\theta_{z}/N_{f,1}F_{z}\right) ; B_{f} = \frac{\alpha_{f,1}(S_{b} + S_{d})\cos^{2}\theta_{z}}{N_{f,1}F_{z}}$$

The term including $\lambda$ describes the heat addition (or cooling effect) of the perfusion through the façade.

The external temperature of the fur, $T_{f,ext}$ was calculated via a convective and radiative heat exchange with the external environment at every timestep (similar to $T_{s,ext}$ for the standard façade).
The preceding finite difference approach was implemented in TRNSYS using the Equation facility (TRNSYS 16 - Volume 7 TRNEdit, 2007, p. 24). Several TRNSYS Equations were created to cater for the finite difference operations required. These included: definition of physical inputs, calculation of heat transfer coefficients, environmental temperature, mean radiant temperatures, surface temperatures and the calculation of the internal façade node temperatures.

4. Simulation inputs and parameters

4.1. Model setup

The model for testing was a typical office floor located in Melbourne. The layout of the office floor that was created in the TRNSYS Type 56 module, including HVAC zoning, is shown in Figure 2. Glazing was installed to north and south facades. The biomimetic façade (and its reference counterpart) was applied to the west façade of the ‘Biomimicry Zone’.

![Figure 2: Layout of office floor for the TRNSYS model.](image)

Table 1 describes the assumed internal gain, usage schedule, building envelope and external environment parameters. Test conditions were selected as the 31st of January in the TRNSYS weather file (Meteonorm AU-Melbourne-948660.tm2, generated using Meteonorm 5.0; see TRNSYS 16 - Volume 9 Weather Data (2007)).

4.2. Biomimetic façade variables

Relevant variables and parameters for the biomimetic façade were selected as per previous studies (Webb et al., 2011; Webb et al., 2013) and are given in Table 2.
5. Results

The TRNSYS simulation was conducted for both reference and biomimetic models over a period of 9 days from January 27 to February 5. As indicated, the specific focus of the simulation was January 31 with a maximum external temperature of 36.9°C. Table 3 shows the relevant results.

<table>
<thead>
<tr>
<th>Assumed air conditioning cooling capacity</th>
<th>External façade thermal resistance</th>
<th>2.8 W/m²K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lighting gains</td>
<td>External façade thermal diffusivity</td>
<td>2.57×10⁻⁷ m⁷/s</td>
</tr>
<tr>
<td>Equipment gains</td>
<td>Building operation times (weekdays)</td>
<td>08:00-18:00</td>
</tr>
<tr>
<td>Occupancy (light office work)</td>
<td>Internal summer design temperature</td>
<td>24°C</td>
</tr>
<tr>
<td>External roof thermal resistance</td>
<td>Peak summer external air temperature</td>
<td>36.9°C</td>
</tr>
<tr>
<td>Floor thermal resistance (internal)</td>
<td>Peak summer solar loading</td>
<td>406 W/m²</td>
</tr>
</tbody>
</table>

Table 2: Biomimetic façade properties.

<table>
<thead>
<tr>
<th>Façade specific heat</th>
<th>2300 J/kgK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Façade density</td>
<td>495.3 kg/m³</td>
</tr>
<tr>
<td>Façade thermal conductivity</td>
<td>0.18 W/mK</td>
</tr>
<tr>
<td>Fluid specific heat</td>
<td>4180 J/kgK</td>
</tr>
<tr>
<td>Fluid density</td>
<td>0.9</td>
</tr>
<tr>
<td>Fluid perfusion rate</td>
<td>5.0×10⁻⁴ m³/m³/s</td>
</tr>
</tbody>
</table>

Table 3: Simulation results.

<table>
<thead>
<tr>
<th></th>
<th>Ts,e [°C]</th>
<th>Ts,i [°C]</th>
<th>TMS [°C]</th>
<th>Qint [W/m²]</th>
<th>Qcool [W/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference facade</td>
<td>51.2</td>
<td>29.1</td>
<td>26.4</td>
<td>38.3</td>
<td>-48.4</td>
</tr>
<tr>
<td>Biomimetic facade</td>
<td>15.8</td>
<td>18.6</td>
<td>23.6</td>
<td>-52.9</td>
<td>-21.1</td>
</tr>
</tbody>
</table>

Notes:
- TMS – mean temperature of all internal zone surfaces;
- Qint – heat transfer from internal surface of façade to occupied zone;
- Qcool – heat transfer from air conditioning required to maintain internal air temperature at 24°C.

6. Discussion

6.1. Temperatures

The simulations clearly showed that the biomimetic façade temperatures were substantially lower than the corresponding reference façade. The biomimetic façade’s internal surface temperature was 10.5°C lower than the reference. At 18.6°C this would provide an effective radiant cooling effect for the occupants, since radiant exchange can account for 50% or more of an occupant’s overall heat transfer (Underfloor Heating/Cooling - Technical Information, n.d.). The lower internal façade temperature led to an overall decrease of 2.9°C in the zone’s mean surface temperature. This would improve occupant comfort as occupants prefer a mean surface temperature as close as possible to internal air temperature – a guide of <3°C is recommended (Schittich (Ed.) et al., 2006).
On the external surface, the difference in temperature between the biomimetic and reference was even greater at 35.4°C. This was due to both the insulative effect of the outer fur layer and the fluid perfusion within the façade. The external fur layer provided significant protection from extremes of temperature and solar radiation – mimicking the desired characteristics from the biological template.

6.2. Heat transfer

The cooling from the biomimetic façade was readily apparent at 52.9 W/m². While representing an idealised scenario, this was greater than conventional pipework hydronic systems, which provide 35-40 W/m² (Underfloor Heating/Cooling - Technical Information, n.d.). The biomimetic cooling starkly contrasted with the 38.3 W/m² of additional heat load added to the reference zone. The façade cooling effect largely accounted for the different air conditioning supplied to each zone – the reference zone had a cooling requirement 230% greater than the biomimetic zone.

6.3. Energy consumption trade off

The biomimetic façade incorporated both passive (fur) and active (perfusion) elements. Pumping fluid through the biomimetic façade required energy, and thus the reduction in air conditioning was not without cost. However, the greater specific heat of water compared with air – a ratio of 4.2:1 – and the greater density of water – at a ratio of approximately 1000:1 – reveals the clear advantage of using water as a cooling medium. Overall, liquid water will cool or heat at a rate 4200 times greater than an equivalent volume of air. A simple calculation illustrates this advantage in the context of the biomimetic façade. At a pressure differential of 400 Pa for airflow and 50 kPa for water flow (ASHRAE Handbook - Fundamentals, 2009, ch. 21), the required power would be 28 times greater for the air system for an equivalent heat transfer (per °C cooling). Therefore the cooling effect of the perfusion façade would be provided at a much lower energy cost than an air-based system.

6.4. Manufacturing and construction

Since the goal of functional biomimicry is to be restorative, if not regenerative, the manufacturing, installation and life cycle of the proposed fur-perfusion façade were considered. From a materialistic perspective, there are multiple options. Low-density fibrous materials were desired for the outer façade fur layer. Many companies manufacture such materials, e.g. brush tiles ("Robin Reigi - Brush," 2011), LAMA Cell ("LAMA Cell," 2011) and possibly Vectran “high-performance multifilament yarn spun from liquid crystal polymer (LCP)” ("Vectran - Liquid Crystal Polymer Fiber," 2010). Resilient natural fibres would be desirable, although life cycle costs are important. However, the advantage of a low-density outer façade covering is that it can be attached post-construction and then replaced after a specified period. This allows the fur layer face the external weather and erosion, while the underlying structural materials, e.g. metals or concrete, remain protected. This further follows the biomimetic principle of animal fur, where animals continually shed and replenish their coats.

Internal ‘tissue’ for the perfusion façade is not as straightforward. Materials processing continues to evolve and challenges existing conventions. Innovative materials trends, including ‘ultraperforming’, ‘recombinant’, ‘intelligent’ and ‘transformational’ materials as described by Brownell (2008), indicate future potential biomimetic materials. The internal structure for the perfusion component is envisioned similar to an open cell foam, where all interstitial spaces form a continuous path through which fluid can
flow. The cell structure could be modular and replaceable after a defined service life. The exterior of the façade would be a fluid-tight vessel to contain the fluid cells.

7. Conclusion

This study has shown that functional biomimicry has the potential to provide energy and comfort benefits to the built environment. While the use of hydronics is not new, the proposed design offered equivalent (if not better) performance outcomes when tested in a TRNSYS simulation. The biomimetic façade was simulated to provide cooling of greater than 50 W/m² of façade and reduced mean surface temperatures in the occupied zone by 2.8°C, compared with a reference, when the biomimetic applied to a single façade in the room. Furthermore, an outer covering of fur was found to provide a significant insulation effect and would help to protect the underlying structure.

Further work on this idea will include studies of heating and an overall annual energy simulation against a reference, air-based airconditioning system. Additional modelling of the mechanical services required will be undertaken, and further consideration will be given to the exact materials, design and construction of the proposed façade, including the internal configuration of the façade ‘tissue’ material. Still, this study was able to demonstrate potential for functional biomimetic initiatives in the built environment.

References

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Built Environment Performance Assessment
Actual performance of naturally ventilated and air-conditioned Green Star certified office buildings in New Zealand

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Abstract: In the last decade, environmental imperatives have found their way into New Zealand’s debate on the quality and performance of the built environment. The New Zealand Green Building Council launched \textit{Green Star Office Design} in 2007, soon complemented by the \textit{Office Built} tool. However, the actual performance of Green Star rated buildings seldom has been verified after occupation. Most are not dissimilar to common-practice office buildings, with high proportions of unshaded glazing, lightweight structures and air-conditioning systems. This raises legitimate questions about their overall indoor air quality and comfort, and about the efficacy of the rating tool in actually delivering the assessed quality. This paper examines the overall features of Green Star rated office buildings in Auckland, and discusses the measured performance of two case study buildings, one naturally ventilated and one air-conditioned, comparing their indoor air quality and comfort. Results of the first research phase reveal clear discrepancies between predicted and measured performance, with localized thermal comfort issues in the naturally ventilated building due to both design failures and human behaviour. They also indicate the need for further adjustments of the rating tool in order to increase its sensitivity to different ventilation systems.

Keywords: Rating tools; office building; indoor environmental quality; building performance.

1. Introduction

New Zealand has become known for its clean and green image. This reputation is confirmed by the Environmental Performance Index 2014, which assesses the environmental performance of member countries, focusing on human health and ecosystem protection: New Zealand is 16 out of 178 countries (Yale University, 2014). Despite this reputation as a green country, concern and awareness have been growing about the social and environmental issues caused by the worryingly low performance of New Zealand’s building stock. In the last two decades, the number of studies of housing energy efficiency and
thermal behaviour has multiplied, revealing the extent across the country of living conditions that are below international standards (Isaacs et al., 2004; Lloyd, 2006) and proving the direct impact of this phenomenon on population comfort and health (Howden-Chapman et al., 2012). Yet to date, not only has little research been undertaken to assess quality and performance of work spaces (Amitrano et al., 2014), but also legislation governing the construction sector has not improved the performance of commercial buildings. Despite this, the number of green properties has increased: office buildings are the type for which the construction industry most often seeks green certification (Yudelson 2008), and the first type to adopt green building rating tools. These became available in 2007, when the New Zealand Green Building Council (NZGBC) launched Green Star Office Design, which soon was complemented by the Office Built tool. Since then, 60 office buildings have been certified in the country, the majority (36) in Auckland, the largest city and New Zealand’s economic capital. The increasing interest in healthy and productive work environments has likely been a critical factor in the growth of green office buildings in the country (Heerwagen, 2000). However, the willingness of New Zealand investors to pay more for green office buildings – a trend already observed in the European and American construction market (Eichholtz et al., 2010) - could also suggest demand driven by the availability of capital to be invested in promoting the green corporate image. Indeed, behind the green façade, the actual performance of Green Star rated buildings has seldom been verified after occupation. Most are not dissimilar to common-practice office buildings, with high proportions of unshaded glazing, lightweight structures and air-conditioning (AC) systems, which raises legitimate questions about their overall indoor air quality and comfort and the efficacy of the rating tool in delivering the assessed quality (Byrd and Leardini, 2011). To fill this gap, a study was initiated in 2012 by researchers at the University of Auckland, with the aim of investigating the development of Green Star rated office buildings in Auckland and their main features, that proved conducive to successes and failures. This paper presents the initial results of this research and examines the overall features of Green Star rated office buildings in Auckland against the impact categories of the rating tool, to uncover a possible correlation between design solutions, building performance and stars awarded.

2. Green office building assessment

Green buildings can be seen as the spatial result of a conscious collective effort to minimize the significant impact of the construction sector on the natural environment. In particular, green office building design typically aims at delivering energy-conscious, healthy and productive work environments, able to reduce CO₂ emissions. The measurable performance of these buildings usually goes above and beyond minimum code requirements, thus demanding new and more challenging performance thresholds. For this reason diverse rating systems, protocols, guidelines, and standards have been developed worldwide, either to implement environmentally friendly construction strategies or to assess the environmental impact of the increasing family of green buildings. The first real attempt to assess environmental features in buildings was in 1990, when the UK Building Research Establishment introduced its Environmental Assessment Method (BREEAM). This was followed by Leadership in Energy and Environmental Design (LEED) developed in the USA in 1998, which became one of the most popular tools. In the following years many countries adapted these pioneer tools to local conditions and needs, developing their own national assessment methods (Haapio and Viitaniemi 2008); recent examples include Australia and New Zealand, which launched Green Star in 2003 and Green Star New Zealand in 2007 respectively. These tools vary to a great extent. Despite their differences though, they are all point-based systems, where a building obtains points for achieving particular performance targets in separate and differently weighted categories (Sev, 2011), including energy, indoor air quality (IAQ) and thermal
comfort, which are usually the most significant and thus highly weighted. Fundamental to most assessment tools, the definition of point and its use are the subject of much debate (Fenner and Ryce, 2008), making the comparison of performances assessed with different tools impossible. Moreover, most of these tools do not take into account lifetime parameters, assessing original building conditions only, while the performance of the building in use is not taken into consideration (Newsham et al., 2013). As the assessment tools include multiple impact factors, overall high scores do not automatically imply high thermal performance and energy efficiency; thus the performance might not reflect the declared certification objectives (Van Wyk, 2008) to ensure the healthiest possible built environment as the result of the most efficient and least disruptive use of land, water, energy and resources.

3. Green Star New Zealand

NZGBC developed Green Star New Zealand, based on the homonymic Australian tool, with some modification to fit local climate and needs. It evaluates building projects based on eight environmental impact categories and a separate innovation section. Within each category, points are awarded for initiatives that demonstrate a project has met the overall objectives of Green Star NZ and the specific criteria of the relevant rating tool credits. As shown in Figure 1, energy and indoor environmental quality (IEQ) are the two most important criteria, with the latter comprising IAQ, lighting and views, thermal comfort and noise levels. Better IEQ can provide stimulating and comfortable environments for occupants and minimise the risk of building-related health problems. On the other hand, energy has emerged as a critical economic issue and top priority for policymakers, with buildings on the front line due to their high energy demand. The system awards an overall score out of 100 by adding together the weighted category scores. The first version of the tool, Green Star NZ-Office Design v1 was soon complemented by the Green Star NZ-Office Built v1 (2008). The first is for a project to be rated at the design stage, the second after construction. The same project can seek both certifications. Later, NZGBC introduced Green Star NZ-Office Design and Built 2009, an advanced version of the previous tools. A building can achieve a maximum of six stars. To date only two buildings have met that target with both design and built certification, thus gaining World Leadership status (75+ points) in construction. 29 of the other certified office buildings are 5 Stars (NZ Excellence: 60-74 points), while the remaining 29 are 4 Stars, which corresponds to Best Practice (45-59 points).
Although the number of buildings certified annually in the country remains low, they are significant when compared to the average number of new office buildings between 2007 and 2014 – 2,555 in total (Statistics NZ, 2014), confirming the increasing awareness among developers and owners about the environmental and economic benefits of green buildings (NZGBC, 2010). Most are in Auckland, where the CBD office market occupies 1.3 million square metres, valued at approximately NZD $7.7 billion. Most of these projects were assessed during the design phase and only 10 of 32 were later certified after construction. The preliminary analysis of the NZGBC database for the Auckland region shows that more than 90% of the certified buildings are equipped with AC systems. This figure appears anomalous when considering local conditions, characterized by a subtropical climate, with warm humid summers and mild damp winters (NIWA, 2014). With this favourable climate and potential economic advantages (e.g. reduced initial investments and running costs for energy) naturally ventilated buildings seem to be the most suitable solution in Auckland — provided they are designed according to local climate and relevant international standards (ASHRAE 55-2013, 2013; ASHRAE 62.1-2013, 2013; ISO 7730, 2005; NZS 4303, 1990). However, effective natural ventilation in office buildings is difficult to implement, while centralised AC guarantees even and controlled indoor environmental conditions (Leaman and Bordass 2007). Following an internationally recognisable trend (Drake et al., 2010), AC has become the first choice of architects and designers in New Zealand — including those aiming for Green Star certification. This raises questions about the impact of the rating tool on common design features of Green Star buildings: most are not dissimilar to common-practice constructions, with high proportions of unshaded glazing that inevitably result in excessive external heat gains, easily removable only with mechanical ventilation systems.


In order to understand if naturally ventilated (NV) office buildings are suitable for Auckland and identify any resistance to their construction, in 2014 a thorough assessment campaign of two NV Green Star rated buildings in the region was started. This included a one-year measurement campaign of environmental parameters (temperature, relative humidity and CO₂) in representative office locations, post-occupancy evaluation (POE) questionnaires distributed to a sample within the monitored areas, and interviews with different stakeholders involved in the design and construction process. As control cases, two AC Green Star office buildings in Auckland were evaluated using the same methodological approach. While the assessment campaign has not yet been completed, interesting results start to emerge, pointing out dissimilarities in performance between buildings with different ventilation systems as well as various issues of acceptance and adaptation to variable indoor environmental conditions.

For this paper, only two case studies were selected and compared, one NV and one AC office building. The NV 6 Star rated complex is of five individual buildings, each with three levels of office spaces. Two offices were monitored, at levels 1 and 3 of different buildings, characterised by various orientations and solar exposure. Their main design and construction feature is the double skin façade, whose windows in the inner wall can be operated by the occupants, providing the interiors with fresh air from outside. The 5 Star AC building features a full height curtain wall incorporating high-performance glass with double skin façade. The building is equipped with smart building control systems that monitor the external environmental conditions and can deliver high volumes of fresh air to the interiors by the variable air volume AC system. The two offices monitored are at level 5 and level 7. Both buildings were designed with open plan offices that provide outside views, a valuable feature towards green
certification. Throughout the study, data loggers have been placed at representative locations within one metre of the subjects’ workstations. Occupants were invited to complete an online confidential POE questionnaire. This is based on 7-point Likert scales (1 = satisfactory and 7 = unsatisfactory) with a space for commentary, covering variables of indoor environment, thermal comfort, health, productivity, and general acceptability of the workplace.

5. Results and discussion

Results of the one-year measurement campaign in the NV building clearly show seasonal changes of indoor temperatures according to the outdoor climatic conditions. The recorded indoor temperatures during the period June 2014 to May 2015 are shown in Figure 2. In the winter months (June to August) indoor values fluctuate daily according to a recurrent path: after the nocturnal drop, morning temperatures are generally low and start increasing at around noon – due to internal and solar gains – to reach the peak in the late afternoon. However, when outdoor temperatures fall below 10°C, the building fails to provide comfortable indoor conditions, especially after the weekend. A similar dependency to outdoor climatic conditions can be seen in summer (December to February), when indoor thermal discomfort (up to 28°C) usually occurs for outdoor temperatures above 25°C.

![Temperature graph](NIWA_2015.png)

Figure 2: Temperature in the NV building for the period June 2014 to May 2015 compared to daily min and daily max outdoor temperatures (NIWA, 2015)
This temperature distribution does not comply with the thermal comfort standard defined by the New Zealand Department of Labour (1997), which states that people with sedentary occupations are thermally comfortable when the air temperature ranges between 19°C and 24°C in summer and between 18°C and 22°C in winter. Given that daily maximum outdoor temperatures in the summer period are usually below 25°C, indoor overheating is likely caused by design failures, due to high internal gains typical of office buildings. This initial assumption was later confirmed through interviews with some of the key stakeholders involved in the design process and the building management.

Comparison of these results with parallel measurements in the AC office building reveals clear differences of thermal performance. Figure 3 reports temperatures recorded in both buildings over three months, from March to May 2015, with outdoor temperatures indicating the transition from summer to winter conditions, and high relative humidity (around 80%). While indoor temperatures of the AC building are constant, with minimal fluctuations even between day and night, in the NV building they decrease progressively following seasonal variations, with sensible differences between day and night especially in the warmer period. This variability has produced uncomfortable working conditions, as revealed by the occupants’ feedback in the questionnaires.

Summer and winter temperature readings often show peaks respectively above 25°C (in the afternoon) and below 18°C (early morning till lunch time). This issue, as expected, usually occurs at the beginning of the week (Monday and Tuesday). While these values would not be acceptable according to the PMV method, verification using the CBE Thermal Comfort Tool (Tyler et al., 2013), demonstrates that only winter peak conditions do not comply with the adaptive approach as stated in current ASHRAE Standard (ASHRAE 55-2013, 2013).

Figure 3: Comparison of temperature in both NV and AC buildings for the period March to May 2015
A similar variability characterizes the CO₂ concentration in the NV building. Figure 4 compares concentrations recorded over 5 weeks in summer (February to March) and winter (June to July), confirming the expected seasonal differences, mainly for behavioural reasons. Indeed in winter, the outer façade is kept closed to reduce heat loss by trapping warm air in the cavity, limiting the flow of fresh air from outside. This explains high concentrations at times, up to 1962 ppm. Yet, on average, the limit of 1,000 ppm established in NZS 4303, 1990 is not exceeded. This standard though, was developed based on the earliest ASHRAE Standard 62-1989, 1989, and has not been reviewed since. The current ASHRAE Standard 62.1-2013 (2013) does not specify an absolute limit value: instead, it states that a concentration value of 700 ppm above outdoor air levels in spaces housing sedentary people is an indicator of satisfaction for the majority of people entering the space. Accordingly, recorded CO₂ concentration remains, on average, acceptable.

In summer, the entire outer skin opens electronically to fully ventilate the cavity (and the interiors) and occupants can open a series of sliding panels in the inner skin to regulate ventilation; the increased air change rates explain the lower CO₂ concentration recorded. Relative humidity was uniformly average throughout space and time, with mean values around 60% in the NV building and 50% in the AC building. Indoor air velocity in the NV building ranges from 0.05 m/s to 0.20 m/s, while is generally low in the AC building, yet typical for AC systems (NZS 4303, 1990; ASHRAE Standard 62.1-2013, 2013).

Environmental measures were then compared to the results of the online questionnaire, to verify trends and identify possible drivers. All occupants of both buildings are desk-based, distributed in a mix of single occupancy, low-occupancy open plan and larger high-occupancy open plan rooms. Given the limited sample, questionnaire results do not have statistical significance but rather are used to compare measured data and occupants’ perception of the work environment, to identify possible issues concerning the buildings. The majority of respondents in the NV building are male (82%), while in the AC
building male and female respondents are balanced. Both buildings’ occupants show a similar age distribution with the majority ranging between 31 and 50 years of age.

Figure 5 summarizes the satisfaction of the occupants with their indoor environment. It is apparent that the majority of the responses in the NV building are in the neutral to discomfort area of the graph, while the respondents in the AC building are in general more satisfied by their work environment. This likely reflects the large variability of indoor conditions discussed above, in particular concerning thermal comfort. Although the occupants of the NV building have full control of the openings — a factor that positively affects occupants’ perception of their thermal environment and increases their acceptability (Vischer, 2007) — most of the time, the façade remains closed for reasons of privacy and external noise from the nearby road. Indeed, noise is a cause of dissatisfaction for over 60% of the occupants. In terms of air quality, constant and uniform air changes gain the favour of the majority (70%) of the respondents in the AC building, while balanced positive and negative responses are recorded in the NV building, likely reflecting different conditions across office spaces — with workstations closer to window more likely to benefit from higher air change rates. It must be noted that late modification of the open plan offices into multiple individual spaces likely prevents the circulation of air as per design, adding to the dissatisfaction of the respondents with the air quality in the NV building.

![Figure 5: Summary of respondents’ satisfaction with the indoor environment](image-url)
With both buildings featuring large glazing surfaces, light is not a concern; however, glare is, especially in the NV building, likely due to its clear enamelled glass, while the AC building features selective glass façades to better control sun radiation. Finally, particularly interesting are the responses to questions investigating the impact of building features on occupants’ productivity, which provide a summary of previous considerations. 56% of the respondents in the NV building indicated that their productivity decreases due to the environmental conditions of the workspace, while in the AC building the majority of the respondents perceived that the environmental conditions help increase their productivity.

6. Conclusion

This paper discusses the performance of two Green Star certified buildings in Auckland, one naturally ventilated and one air-conditioned, assessed through a mix of quantitative and qualitative methods, comparing their indoor air quality and comfort. Results of the first research phase reveal discrepancies between predicted and measured performance of the NV building, with localized thermal comfort issues due to both design failures and human behaviour. The AC building instead matches expectations, providing occupants with stable working conditions. This is reflected in lower satisfaction with the indoor environment of the NV building compared to the AC building, despite individual control by the occupants of their work spaces. The study found that design is key to the success of NV buildings, especially in the mild climate of Auckland; while environmental and economic benefits provided by NV are undeniable, most of the certified office buildings in the region have been designed around the controlled environment provided by AC systems, which prove to deliver what is required by the rating tool in terms of indoor environmental quality. However, cooling and heating loads, as well as the associated energy costs, are not considered in this equation. The research demonstrates that occupants of the AC building have become finely tuned to the narrow range of indoor environmental conditions, while the design of the NV building, which partially failed to respond to the specific context, provides extremely variable indoor conditions that drive occupants out of their acceptable comfort zone. Furthermore, the central location of the two case studies increases the challenge, adding pollution and noise control to the list of requirements. While these aspects contribute to enhance the popularity of AC building in the New Zealand green building market, issues of secure energy supply require reconsideration of the assumption that air-conditioning is the best solution to the challenge of creating indoor comfort, due to the depletion of energy resources in the near future. This reinforces the need for an adaptive building design approach, which should become one of the main criteria of green assessment tools, complemented by POE surveys and commissioning practice.

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References

An early-stage design decision-support tool for selecting building assemblies to minimise a building’s life cycle energy demand

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Abstract: The significant effects of the building industry on the natural environment are well documented and improving the environmental performance of buildings is an on-going challenge. This is particularly the case for projects with restrictive budgets and timelines and because many existing environmental assessment tools are designed to be used too late in the design process. The use of tools during the early design stages may assist in achieving greater improvements in a building’s environmental performance. However, user-friendly tools with the ability to comprehensively compare environmental information between various building assemblies and materials, which can be easily adopted during the early design stages of a project, are not readily available. This paper presents the progress to date in developing a tool which supports building designers in identifying and selecting preferred building assemblies with the aim of minimising a building’s life cycle energy demand. The tool is based on comprehensive energy performance data for a broad range of building assemblies across all Australian climate zones. Allowing for adjustments to a set of pre-defined and user-defined assemblies the designer is able to see how assemblies perform in relation to each other. This provides valuable information to support decision-making relating to minimising the life cycle energy demand of buildings.

Keywords: Life cycle assessment; early-stage design; embodied energy; life cycle energy.

1. Introduction

Although the energy demand of buildings can be reduced through improvements to their construction and operation, some of the most significant energy demands are locked in during the schematic design stage. However, the ability of building designers to significantly improve the energy performance of their designs is limited by a lack of reliable and detailed energy performance information related to building materials and assemblies. Importantly, a holistic approach to low-energy building design is required to ensure that any energy efficiency strategies provide a net energy benefit over the life of the
building. The energy performance of a building design can be determined through the application of life-cycle assessment (LCA) tools during the early design stages. However, currently available LCA tools can be costly and/or time consuming to implement, and hence do not allow for quick assessment of potential assembly alternatives. Furthermore, many existing tools are predominantly concerned with reducing operational energy and related greenhouse gas emissions with little thought for the energy and emissions associated with the other stages of a building’s life. An increasing number of studies are demonstrating the significant energy consumption and emissions produced during life cycle stages other than the operational phase (Fay et al., 2000; Pullen, 2000; Treloar et al., 2000; Gustavsson and Joelsson, 2007). The initial embodied energy alone can be equivalent to the total energy required for the operation of a building over its life (Treloar et al., 2001). A limited number of tools currently exist (for example, the ATHENA EcoCalculator for Assemblies (ATHENA, 2007) and the BEES tool (NIST, 2007)) that consider a broad range of life cycle stages, from raw material extraction through to eventual demolition and disposal. None of these existing tools sufficiently covers every life cycle stage for the Australian context.

A simple-to-use, affordable and accessible tool which can be implemented during the very early design stages, coupled with comprehensive energy performance data is not currently available, particularly not for the Australian context. The development of such a tool could significantly improve the environmental performance of the building sector by facilitating more informed choices during the early design stage of a building. The aim of the work presented in this paper was to bring together the principles of LCA with comprehensive energy performance data into a tool for building designers to enable them to select materials and assemblies for building projects to reduce life cycle energy demand. However, problems can arise with the use of precompiled environmental information. For example, operational energy requirements of buildings will vary based on the individual characteristics of a building (size, location, materials etc.). This may be one reason why existing tools and databases that provide pre-compiled environmental data for building assemblies (such as ATHENA, 2007) do not consider the energy demands associated with the operational stage of a building (for heating and cooling in particular). As noted previously, this can result in misleading information that can then lead to sub-optimal design solutions.

The tool’s development involved an interdisciplinary team of architects, engineers, software developers and researchers. The intention of the tool is to facilitate more appropriate environmental considerations being made as early as possible in a project in an effort to improve the energy performance of building projects. The tool will provide building designers with more comprehensive life cycle energy information across a broad range of building assemblies. This will allow building designers to assess and select individual or combinations of building materials and assemblies for the various building elements with the aim of minimising the life cycle energy demand of a building. This paper presents the progress made in the development of this tool.

2. Background

Limited energy performance data is available to assist in informing early-stage design decision-making to reduce the life cycle energy of buildings (Crawford et al., 2010). Previous life cycle energy studies of buildings (inter alia Adalberth, 1997; Fay et al., 2000; Foster et al., 2000; Rolfsman, 2002; Gonzalez and Navarro, 2006) rarely demonstrate a particular approach or method which could readily be adopted by designers to optimise building energy performance. Typically, studies have focused on either modelling the operational energy requirements for buildings (for example, Bouchlaghem, 2000; Al-Sanea, 2002;
An early-stage design decision-support tool for selecting building assemblies to minimise a building’s life cycle energy demand

Thorsell and Bomberg, 2008) or on their associated embodied energy (for example, Lawson, 1996; Venkatarama-Reddy and Jagadish, 2003; BRE, 2008; Iyer-Raniga et al., 2008). Studies that have come closest to providing data that can be employed by designers in the selection of building materials or assemblies to optimise building energy performance include that by Yao and Steemers (2005) and Utama and Gheewala (2008) as well as that conducted by Lawson (1996) and BRE (2008). However, the energy requirements associated with the replacement, operation and maintenance of materials are excluded. An existing tool which provides energy performance data for common building assemblies, including both initial and recurring embodied energy (EE), is the ATHENA® EcoCalculator for Assemblies (ATHENA, 2007), although it excludes operational energy (OE). Studies where both EE and OE have been considered include that of Pierquet and Bowyer (1998) and Chen et al. (2001); however, the use of incomplete, potentially erroneous data is apparent, specifically in terms of the use of disparate data sources.

The importance of incorporating EE into the tool is critical to the comprehensiveness and usefulness of the information obtained. Most existing models use a process analysis approach for quantifying EE. Previous research by Crawford (2008) has shown that when assessing EE using process analysis, up to 87 per cent of the energy demands can be excluded. While the operation of buildings accounts for at least 40 per cent of national energy consumption and greenhouse gas emissions (OECD, 2003), the inclusion of the energy required for their construction (including the manufacture of materials) means that buildings are responsible for most of the nation’s energy consumption and emissions. This means that improving the energy performance of buildings across their life cycle will make a significant contribution to achieving broad environmental goals.

The early-stage design decision-support tool is envisaged as the platform by which the comprehensive assessment of the whole-of-life energy attributed to building assemblies, combining the innovative method of embodied energy assessment with thermal performance modelling, is performed. The project has established a framework for integrating the various life cycle energy demands associated with the use of specific building assemblies. It also establishes a model to support building designers in identifying and selecting preferred assemblies for building design projects based on their life cycle energy performance. By providing building designers with comprehensive environmental information at a building assembly level, and early in the design process, there is considerable potential to improve the environmental performance of buildings. Providing this information on a holistic life cycle perspective (rather than the piecemeal approach currently used) will ensure that decisions are being made based on the most comprehensive information possible, ensuring that environmental outcomes are not being compromised by missing or incomplete information.

The process of developing the early-stage design decision-support tool has been an iterative one spanning several years. Although this paper is concerned primarily with the process to date of developing the tool, the development of more comprehensive data specific to the Australian construction industry is fundamental to the overall success and functionality of the tool. The process of establishing this database and methodology is hence introduced briefly and illustrated in Figure 1 below. For more detailed information and specific results, refer to the papers cited.
Figure 1: Conceptual framework of the overall project.
2.1. Establishing a ranking protocol: proof of concept

The prior research carried out by the authors (Crawford et al., 2010) initialised the development of a method for ranking building assemblies based on their life cycle energy performance. This was the first crucial step in compiling a database of the life cycle energy requirements associated with a large range of building assemblies, for use in various climate zones across Australia. In particular, the importance of incorporating embodied energy demands with operational energy demands was demonstrated. A ranking of assemblies within each element group was seen to be most useful output from this study considering the difficulties in drawing generic conclusions from the operational energy figures obtained. Although the combined embodied and operational energy figures given were specific to the case assessed in this study, as every building will have different operational energy requirements based on orientation, internal gains, windows, operating hours etc., it was anticipated that the ranked order of assemblies would hold true regardless of the variations associated with a specific building.

2.2. Sensitivity analysis: verifying the ranking protocol

The ranking protocol was further verified through a sensitivity analysis of variations to the floor area, shape and orientation of the base model. This was done to test the reliability and applicability of the ranking approach across a broad range of circumstances (Crawford et al., 2011a). It was found that these variations did not influence the ranked order of the assemblies in terms of the life cycle energy demand associated with their use. Thus, the ranking of assemblies appeared to provide an appropriate approach for streamlining the selection of building assemblies during the building design process.

2.3. Case study 1: detached residential house

The aim of the study by Crawford et al. (2011b) was to demonstrate how the availability of comparable energy performance information at the building design stage can be used to better optimise a residential building’s life cycle energy performance. The life cycle energy demand of a case study residential building, located in the temperate climate of Melbourne, Australia, was initially quantified using a comprehensive embodied energy assessment technique and TRNSYS thermal energy simulation software. The building was then modelled with variations to its external assemblies and materials, systematically changing one assembly at a time in an attempt to optimise the life cycle energy performance of the building. The alternative assemblies chosen were those shown through the authors’ previous modelling to result in the lowest life cycle energy demand for each building element, determined using the ranked assemblies list for Melbourne (Crawford et al., 2010). The best performing assemblies for each of the main external building elements were then combined into a ‘best-case’ scenario to quantify the potential life cycle energy improvements possible compared to the original building. The study showed that significant life cycle energy savings are possible through the modelling of individual building elements for the case study building. While these findings relate to a very specific case, this study demonstrates the potential for this approach in optimising building life cycle energy performance during early-stage building design.

2.4. Case study 2: multi-unit residential building

The study by Crawford et al. (2014) demonstrated further application of the ranking model to show how the availability of comparable energy performance information during early-stage building design can be used to better optimise a building’s energy performance. As for Case Study 1, the life cycle energy
demand of the case study building was quantified using a comprehensive embodied energy assessment technique and TRNSYS thermal energy simulation software. The building was then modelled with variations to its external assemblies in an attempt to optimise its life cycle energy performance. The alternative assemblies chosen were those shown through the ranked list of assemblies to result in the lowest life cycle energy demand for each building element. The study showed that significant life cycle energy savings, up to 45%, are possible through the modelling of individual building elements for the case study building.

3. Tool development

This section of the paper describes the components of the proposed decision-support tool and outlines the development process taken and expected outputs. The project required exploratory work to develop task workflows, supporting user interfaces, and associated data structures. The interface development for the tool was dependent upon a close collaboration between the research team, software developer and input from the industry partner and potential end-users. This work was structured by identifying and prioritising the major use-cases and features to be implemented. Work was executed through an iterative process, working in cycles of one to two weeks, and focusing on a small number of features that could be completed in each cycle. At the conclusion of each cycle, the state of the tool was reviewed, through user cases and features to be implemented. From the beginning of the tool development process, it was envisaged that the tool could be developed in one of two ways. Firstly, either as an engineering tool, to be used to perform a technical task, with outputs and data being used to inform other reports - the outputs and data would not be easily interpretable by non-experts. Or, secondly, as a ‘social process’ tool – to assist in informing decisions concurrently with design activities, with tasks being fairly simple to implement by non-experts (i.e. the architect could perform the tasks themselves, without having to outsource the work to an environmental consultant). Ideally, outputs and data produced by the tool were to be in an easy-to-understand format appropriate for all stakeholders, including architects, clients, etc.. Consideration was given to: 1) the information most important to informing the selection of assemblies during the design process; 2) how the tool would fit within the broader design process; 3) compliance with minimum energy performance requirements, as outlined in the BCA; and 4) providing a comprehensive, yet simple and quick to use, approach for assessing, ranking, selecting and optimising assembly options.

3.1. Collating user stories

The first phase in the iterative process of developing the tool, encompassing the expertise of practicing architects and designers, a software developer and researchers, was to collect user stories which would help inform the required functionalities for the proposed tool. A user story can be described as ‘a short narrative describing where the tool sits in the overall design and construction process of a building and the activity of using the tool to calculate energy requirements for a project’. In order to collect user stories, the primary and proposed users of the tool needed to be identified. For the purpose and scope of this project, two primary users were identified, the client and the architect. The industry partner of this project is an independently-owned architectural firm providing expertise in the fields of architecture, planning, urban design, interior design and graphic design. The company’s approach to responsible design is to address sustainability in a holistic manner both in terms of the different facets of sustainability - social, cultural, ecological, and economic issues and with regard to a considered approach in the design process. Their design approach starts by addressing sustainability issues and
opportunities in the concept phase of any project which leads into consideration of the environmental impacts generated by the selection of building systems and services, the choice of materials, and the application of passive design strategies.

The next step in developing a tool which is appropriate and useful for architects to assist in making decisions regarding the selection of building assemblies is to consider the multi-faceted decisions which have to be made very early in a project. These decisions involve identifying and responding to competing constraints and/or opportunities. These are progressively refined or changed as new factors are identified, and decisions are confirmed. On different projects, different factors and different priorities exist. Architects draw on experience, briefings, advice, and other resources to help to make their decisions. Some key factors in the selection of building assemblies, in typical order of priority, are shown in Table 1.

| Table 1: Key factors in the selection of building assemblies, in common order of priority. |
|-----------------------------------------------|-----------------------------------------------|
| 1. Cost                                       | 11. BCA/ regulatory requirements              |
| 2. Structural adequacy                       | 12. Fire performance                          |
| 5. Appearance                                 | 15. Planning requirements                     |
| 6. Views, ventilation & other site specifics   | 16. Heritage requirements                     |
| 7. Building orientation & local climatic context | 17. Durability                              |
| 8. Existing structures on site               | 18. Sustainability                            |
| 10. Other jobs/deadlines                     |                                               |

3.2. Inputs and outputs required for tool development

In order to be able to assess the overall life cycle energy associated with an assembly, its operational energy, initial embodied energy and recurrent embodied energy demands are required. However, first the individual components and materials that make up an assembly, as well as the order that they appear in the overall assembly (as this order directly affects the way the assembly performs thermally), is identified. As the analysis is performed on a square metre basis, the exact dimensions of the building/wall element are not required at this stage. Operational performance data associated with each assembly within the tool was determined based on outputs of a detailed TRNSYS model, as described in Crawford et al. (2011a). The initial and recurrent embodied energy of each assembly was determined using a hybrid embodied energy assessment technique described by Crawford (2008) and based on average material service life values.

Tool outputs include information on the parameters and variables against which the assemblies were assessed or ranked, based on the recurrent and initial embodied energy, and thermal energy loads. Once assemblies are selected, then the tool can be used to further optimise them in order to reduce embodied and operational energy demand. This may include identifying individual materials or life cycle stages representing the most significant energy demands and substituting materials within an assembly. The intention is also for the user to be able to single out relevant improvement strategies based on specific project priorities (such as reducing initial EE demands) and to be able to weight the importance of initial embodied energy (IEE), recurrent EE (REE) and operational energy demands.
3.3. Interface design and development

Existing life cycle assessment tools are not always conducive to use in architectural practice, particularly to assist in informing decisions early in the design process. Most LCA software is intended for use with designs which are largely resolved (at least to SD stage), whereby the building designs can be tweaked to achieve particular minimum performance standards. It is more difficult and costly by this stage of the design process to make changes which will dramatically improve the environmental performance of the building.

Three key barriers to the implementation of existing LCA tools in the architectural practice environment are, 1) the level of complexity of the tools and the associated time requirements to learn how to use them; 2) the fact that most tools require a complete building envelope for analysis and hence the design is fairly resolved by this stage with assemblies generally having already been decided upon; and 3) the fact that many tools contain data and are based on building regulatory compliance requirements applicable to a single country.

The development of the early-stage design decision-support tool detailed in this paper began with consideration of the Building Code of Australia (BCA) and the standard construction assemblies used in Australia. This then led to further discussions with architects about the most commonly used assemblies in practice.

4. Conclusion and further research

This paper has outlined the development of a tool for informing life cycle energy performance improvements during the early stages of building design. This tool is innovative as it attempts to provide a basis on which to compare and select building assemblies to reduce a building’s life cycle energy demand prior to having conceived the building form or having a resolved design.

The life cycle energy demand for each assembly is based on comprehensive hybrid embodied energy data (including initial and recurrent) and operational energy demands are based on thermal loads modelled in TRNSYS software.

The ranking approach used in order to compare and inform the selection of assemblies based on their influence on the life cycle energy demand of a building was considered the best approach in the absence of an ability to conduct detailed dynamic thermal modelling for a range of assemblies for a specific project, quickly and early in the design process.

Allowing building designers to make well-informed decisions on the choice of building assemblies and materials as early as possible in the design process will help to maximise the life cycle energy performance of buildings. These decisions are often made much later in the design process, at a point where there is much less flexibility and opportunity to change. This tool provides designers with the ability to screen in or out potential assembly solutions as well as highlight areas where further improvements/alterations to existing assemblies may be possible. Time can then be saved later in the design process when more detailed analysis and refinement of building performance can focus on a narrower selection of assemblies and design solutions.

The paper has described the initial stages of the tool’s development. Further research will involve testing the tool on a range of current and built real projects within the architectural practice context and using the feedback gained from this exercise to evaluate the usefulness of, and highlight further improvements for, the tool.
An early-stage design decision-support tool for selecting building assemblies to minimise a building’s life cycle energy demand

Acknowledgements

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Analysis of urban morphological attributes and street level air pollution in high-density residential environments in Hong Kong

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Abstract: Air quality is a major concern for the quality of life in high-density urban environments. In most dense urban areas of Hong Kong air quality in street level does not depend only on the air pollutant emission rate, but also on dispersion rate. Air pollution dispersion is also a result of the physical built form; Urban Morphology. The study postulates an association between urban morphology and air quality. This paper presents a model to explain this street level air pollution phenomenon; relationship between street level air pollutant concentration and the morphology of hyper dense residential environments in Hong Kong. This study investigated 20 different high-density urban residential areas in five districts of Hong Kong through field measurements and statistical analysis. Real time street level air pollutants, microclimatic data and 21 urban morphological attributes were identified and calculated geometrically for the statistical analysis. The findings revealed that only limited numbers of micro level morphological attributes are distinguishable for street level air pollution. The finding also validating the theoretical assumptions and the method developed to model the relationship among morphological attributes, microclimatic conditions and street level air pollution phenomena which will be useful for future urban design and planning considerations.

Key words: Urban air quality; urban morphology; urban microclimate; urban environmental effects.

1. Introduction

1.1. Air quality and the high density residential environment in Hong Kong

According to the Environment Protection Department of Hong Kong (HKEPD), high usage of motor vehicle constitutes the biggest source of air pollution in Hong Kong (HKEPD 1997-2012). However, accumulated studies at the HKEPD show that street-level air pollutant concentration in downtown residential areas is almost as high as in the industrial areas (HKEPD 1997-2012). This phenomenon
indicates that sources of pollutant air may have never been the sole factor contributing to poor air quality in certain urban setting, and there must be other factors that also cause high level of air pollution in urban areas distant from major air polluting sources. Researchers have also for been suspecting that air pollution in urban settings is not only a function of the rate of emission but also that of air pollutant dispersion; and the movement of air pollutants generated by vehicle traffic could as well be influenced by the characteristics of a built-up area (De Haan et al., 2000; MAYER, 1999; Edussuriya et al., 2009). The hyper dense residential environment of Hong Kong is quite unique whose fabric cannot be compared with most other cities in terms of population and development densities, building height and building volume, and intensity in land-use mix, and so on. The unique structure of Hong Kong’s residential environment thus on the one hand has greatly increased peoples’ exposure to polluted air by concentrating considerable volume of vehicle traffic as well as population within a limited urban area; and on the other seems to have a direct or indirect impact on air pollutant concentration by everywhere creating closely-knit building walls that prevent airflow for dispersion polluted air.

1.2. Physics of street level air pollution concentration

Street level air pollutant concentration at a particular urban location (micro level) is the functions of two factors: rate of (vehicle) emission and rate of dispersion and dilution (Givoni, 1998; Hawkes et al.: 1998; Santamouris M, 2000; Edussuriya et al., 2005, 2009). While the rate of emission normally depends on the sources of air pollutant, the rate of dispersion and dilution is governed primarily by a number of other factors. In general, researches on urban atmospheric environment suggest a correlation between air pollution dispersion and the climatic conditions of a locality that include temperature, wind velocity & humidity, and similar factors (Coliani, 2001; Cuhadarouglu and Demirci 1997; Givoni, 1998; Hawkes et al., 1998; Marvroidis and Griffiths, 2001). However, more recent studies indicate that both natural (topological features, vegetation etc.) and man-made (built forms) factors also tend to have a direct or indirect impact on urban microclimate, which in turn would affect the rate of dispersion and dilution of air pollutant (Givoni, 1998; Hawkes et al.: 1998; Santamouris M, 2000; HKPD, 2005; Edussuriya et al., 2005, 2009, 2014). Therefore both urban morphological factors and micrometeorology seem to be sequentially related aspects that would impact on air pollution concentration or dispersion.

Premise of this understanding the street level air pollution phenomenon in dense Hong Kong be considered as an “air quality box” (De Nevers, 2000, pp 120). For according to this model, an air quality box can be demarcated horizontally by compact land use surface obstacles (buildings) and vertically by tall buildings (walls up to roof level). With reference to this ‘air quality box’, air pollution phenomenon below the roof level of a high-rise high-density environment can be distinguished from air pollution phenomenon above the roof level (ambient or background air pollution). This tri-dimensional medium is also suggested by Adolphe (2001, pp 185) as a “porous medium with rigid skeleton”. The concept distinguishes the climate above the roof level as ‘background conditions’ and that below the roof level as ‘local conditions’ (Adolphe, 2001; cited in Eernes, 1994). The layer in-between the ground to roof level is referred to as “urban building canopy layer” and its air pollution phenomenon is defined as “street level air pollution” (Figure 1). Since the unique urban profiles of Hong Kong have created pockets of such micro environments that tend to have their own microclimatic and air pollution conditions, modeling these micro environments as local air quality boxes
enabled this research study to link street level air pollution concentration to the morphological attributes of an urban locality, via the intermediate layer of microclimatic conditions.

Figure 1: Urban building canopy layer & street level air pollution phenomenon

1.3. The research study

Previous researches have shown that air pollutant dispersion in the urban areas depends largely on microclimatic conditions within an urban building canopy layer (Chan et al. 2002; Cionco, R.M & Ellefsen, R, 1997; Hong, 1999; Marvroids and Griffiths, 2001; Ratti et al. 2000; Hawkes et al., 1998). These studies indicate that air pollutant may get trapped and thus increase air pollutant concentration amidst urban structures (tall buildings). However, while attempting to link the movement of polluted air to the physical urban form at the macro level, these studies in general do not concern themselves in identifying urban physical built form factors at the micro level, which may prove crucial for studying of street-level air pollution in an urban environment like Hong Kong. In what follows, this research investigated the relationship between urban physical built form attributes (urban morphology) and street level air pollution in high density residential environment of Hong Kong is reported. The study starts with the search of a suitable approach to modeling the complex relationship between street level air pollution concentration, microclimate (micro-meteorology), and the morphological dimension of an urban locality, and proceeds to validate such a model through theoretical experiments and empirical analysis.

2. Method of study

2.1. Development of theoretical model

Relevant previous study identified land-use and topography as two major attributes that would affect the air quality of six different urban forms (Dispersed/Compact etc.) (Newton et al. 2000). Attempts have been also made to derive a mathematical model on urban morphology, and through laboratory and field experiments on air flow and transfer processes in the urban areas, to develop predictive tools for relating urban morphology and different building types at macro scale (Ratti et al. 2000). However, no comprehensive studies have been done to identify morphological features that specifically impact/interact on street level air pollution phenomenon, which could be due to complexity of urban fabric at the micro scale.
Early work of this research developed a crude model postulating the relationship between street level air pollution, general and specific morphological factors such as geographical location, development density and built forms, and microclimatic conditions (Edussuriya et al. 2005). Findings and insights that emerged from the work informed development of a tighter theoretical model that postulates interactions between street level air pollution concentration and the most relevant causal factors (Figure 2). Specifically the model identifies set of effective urban morphological attributes and micro-meteorology attributes/variables to be related to street level air quality under the urban building canopy layer of near field regimes (defined as a 200m x 200m urban grid; see discussions below).

Figure 2: Generic relationship model depicting street level air pollutant concentration of a place and the most relevant causal factors for Hong Kong

2.2. Design of empirical studies

2.2.1. Defining the near-field regime of study areas

Assimilation of the spatial dimension of an urban fabric is fundamental to the monitoring of street level air pollution concentration in empirical studies. Previous researches were to set the boundaries of a study area at certain scale range, typically in a 1km x 1km urban grid or a diameter of areas (Theurer, 1999, Weber et al. 2001). Most of these ranges however were based on rules of thumb and are difficult to be used for measurement of street level air pollution in the hyper dense urban fabrics like in Hong Kong. In contrast, the spatial field regime used by Santamouris (2000) for analysis of air pollutant effect suggests a more realistic range for the Hong Kong environment. Accordingly air pollutant concentration of an urban location depends upon sources of emissions in intermediate field regime (range of few hundreds of meters) and near field regime (within location of tens of meters). Air pollutant emissions from far field regime (distance beyond about 1 km) tend to have negligible or minimum impact on street level air pollutant concentration within a particular urban location due to their inability to reach that location, caused by surface obstacles such as a compact built form (Edussuriya et al., 2009).
Analysis of urban morphological attributes and street level air pollution in high-density residential environments in Hong Kong

references to these facts the near field regime of an urban location in this study is set as a 200m x 200m grid, with all concerned morphological variables obtained within that range only.

2.2.2. Representation of morphological indicators

The micro level morphological indicators for this study is based on parameters that are commonly used in the planning and design of residential developments. Although the near field regime is limited to a smaller urban fabric, there can be quite distinct variations in buildings or building blocks. As conventional urban planning and design parameters do not provide us with tools to represent these local variations for research purposes, to indicate the morphological attributes of a study area as a whole it necessary to measure the mean effects of morphological variations arising from its urban fabric. The morphological indicators used by Adolphe (2001) to analyze microclimate were based on the mean effects of a heterogeneous urban fabric. Thus, this study also used such mean effects to represent the complex morphological variations exhibited in a study area and to link them to the street level air pollutant concentration of that area. To get the most representative values for a study area, the mean values (mean effect calculated by statistical mean value) of relevant building parameters were weighted either by plan area method or frontal area method depending on the situations (Weber et al. 2001, Grimmond & Oke, 1998). Therefore morphological heterogeneity of study areas can be minimized by this “weighted mean effect value” calculation. Out of many possible morphological attributes, most relevant and effective urban morphological attributes were tested in this empirical analysis (Table 1).

Table 1: Key urban morphological variables describing street level air pollution concentration and urban microclimatic conditions

<table>
<thead>
<tr>
<th>Groups</th>
<th>Morphological Characteristics</th>
<th>Morphological Variables / Attributes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1 Land utilisation indicators</td>
<td>Plan area density (λp)</td>
<td>Mineralisation factor</td>
</tr>
<tr>
<td>A2 Land use intensity Indicators</td>
<td>Wall surface area to volume ratio</td>
<td>Complete aspect ratio</td>
</tr>
<tr>
<td></td>
<td>Mean contiguity factor (m⁻¹)</td>
<td>Frontal area density (λf)</td>
</tr>
<tr>
<td></td>
<td>Porosity (Po)</td>
<td>Sinuosity (So)</td>
</tr>
<tr>
<td></td>
<td>Occlusivity (Oc)</td>
<td>Rugosity and or FAR</td>
</tr>
<tr>
<td></td>
<td>Roughness length (Zo)</td>
<td>Zero plane displacement height (Zd)</td>
</tr>
<tr>
<td></td>
<td>Volume per building (Σ Vblg. /no. of blg)</td>
<td></td>
</tr>
<tr>
<td>A3 Building &amp; Street Geometry</td>
<td>Canyon ratio (H / Wst)</td>
<td>Aspect ratio (Lst / H)</td>
</tr>
<tr>
<td></td>
<td>Breadth ratio</td>
<td>Block ratio (street)</td>
</tr>
<tr>
<td></td>
<td>Distance between building (m)</td>
<td>Mean bldg. height (m)</td>
</tr>
<tr>
<td></td>
<td>Std. deviation of bldg. height</td>
<td>Wind angle to longer building axis –in degrees</td>
</tr>
<tr>
<td>A4 Building &amp; Street Orientation</td>
<td>Wind angle to longer building axis –in degrees</td>
<td></td>
</tr>
</tbody>
</table>
2.2.3. Monitoring street level air pollutant concentration and microclimate indicators

Both particulate (suspended particulate matters-PM$_{2.5}$) and gaseous air pollution data (Nitrogen Oxides (NOx), Ozone (O$_3$) and Carbon Monoxide (CO)) were monitored for this study, as these were considered major air pollutants for good indication of vehicular traffic related street level air pollution (Theurer, 1999, Weber et al. 2001, Edussuriya et al., 2005). Together with air pollutant concentration, site specific microclimatic conditions like temperature, relative humidity (RH) and wind speed and direction were also measured and be taken into consideration for analysis. Two portable real time monitoring devices; Dust Scan Sentinel outdoor unit used for PM$_{2.5}$ and wind distribution monitoring and ETL-2000 used to monitor NOx, CO, O$_3$, temperature and relative humidity (See Figure 3 – measuring at 2m height in both sides of street canyons). The measurements were carried out from October to March/April as atmospheric condition is reasonably stable during this cooler seasons in Hong Kong. All monitoring was restricted to repeated measurements conducted in four hours per day, in three days for each study area and sampling results were calculated for four hour average readings based on statistical methods.

Accordingly selected morphological indicators were adequate enough for a cross sectional analysis where methods and calculation procedures have been extensively represent the attributes of a spatial unit of analysis empirically. Similarly, procedures and methods for representing vehicle emissions, street level air pollution, and microclimate for a spatial unit of analysis have also been extensively used.

3. Case studies

The study investigated twenty (20) residential areas where street level air pollution data have been analyzed in relation to the twenty two (21) morphological indicators of their residential urban fabrics in Hong Kong. A main criterion in study case site selection was to maximize the representation of spatial variations of the urban morphological characteristics and sites that will report a wide range of air pollutant concentration. The above mentioned procedure has been adopted to test the relationship among relevant attributes (See Figure 4); urban morphology (independent variable), street level air...
pollution concentration (dependent variable), urban microclimate (intervening variable) and other associated factors such as locality factors, some peripheral effects, etc. (affect variables).

Accordingly, data on these variables have been analysed on the procedures mentioned below to validate the theoretical model and identifying the most effective morphological variables.

1. Screening of data using descriptive statistical approaches: to identify the nature of data; to eliminate or treat outlying or distorted data points; and to ensure that there is no possibility for district level impact (minimize location effects).
2. Identifying the most representative and meaningful variables using Principal Component Analysis (PCA – factor analysis) to reduce the number and dimensionality in variables.
3. Used the test-statistics and inferential statistics, to assess the relationship between urban morphology and street level air pollution.

Findings reported both similar and different behaviours between two physically and chemically different air pollutants: PM$_{2.5}$ and NO$_x$ and urban morphological variables. From those findings, we established...
the most explanatory/important morphological variables that explain the relationship between street level air pollution and urban morphology in urban residential environments of Hong Kong (Figure 5 & 6).

Figure 6: Results of Relationships among Key Variables; Urban Morphology, Urban Microclimate and Street Level NO\textsubscript{x} Concentration. Note: Bold letters or continuous line box indicate strong relationships

3.1. Micro-climatic conditions and street level air pollutant dispersion

Two types of air pollutants (PM\textsubscript{2.5} and NO\textsubscript{x}) interact with microclimate/urban morphology differently, results also reported CO and O\textsubscript{3} concentrations were not prominent. Dense built structures could have effectively prevented the penetration of ambient air with O\textsubscript{3} into the urban building canopy layer. Effects of local green open spaces (low mineralization factor) appear to have no or minimum impact on microclimate, likely it could be due to impervious surfaces. Therefore, in addition to the role played by building mass and road networks, these paved open spaces seem to be also contributing to the total thermal mass of an urban fabric. In other words, largely development factor effect - i.e. high albedo/emissivity of built surfaces among study areas - in effect had an impact on increase of temperature within these urban fabrics. That in turn could have caused poor street level air pollutant dispersion.

3.2. Urban morphology, microclimate, and street level air pollutant concentration

3.2.1. Urban development factors

Urban building density and porosity are two key land development indicators reported high correlation with street level air pollution. A higher urban building density and relatively low porosity level, seem to offer a plausible explanation for its higher air pollution level, despite the low vehicle density and relatively better climatic conditions in study cases. Likewise, the high air pollution level found in study areas can be also related to its higher building density and low porosity (Since the higher porosity of an urban fabric - seems to be the effect of a regular grid street network that acts as a continuous porous medium - tends to allow air pollutant to escape from a densely built area). However the high air pollutant concentration in few areas thus should be explained by some other factor than porosity/building density. The open spaces (pores spaces) in some study areas are either blocked by buildings or are shaped in court yard-like semi-enclosed or enclosed open spaces amidst tall buildings. Therefore, they tend to have lower drag-off effect on air pollutants dispersion than continuous open spaces. The frontal area density and compactness are two other development intensity indicators that,
in theory, could also cause blocking effects on airflow and hence reduce the rate of air pollutant dispersion in a densely built area. Mixed patterns in findings of this study demand further investigation.

3.2.2. Built form configuration factors

Built form configuration factors among the cases also revealed the complex relationships between urban morphology, microclimatic conditions and air pollutant concentration. The mean building height of an urban fabric would create a high building canopy this could have impacted on higher mixing height of airflow. As (the vertical plane created by) building height together with narrower street widths could create more vortices and thus decrease airflow within an urban street canyon. As a contrast, the moderate mean building height study areas could be one of the configuration factors that, despite a low vehicle density and a compact built geometry, seems to have exerted high impact on air pollutant concentration. In addition threshold in relationship between mean building height and street level air pollution is also important finding. On the other hand role played by the building height factor in affecting morphological indicators like street canyon ratio, urban roughness and roughness density etc. also important. For higher street canyon ratio and low urban roughness (expressed in high value) would create multiple vortices within a street canyon that reduce airflow (as noted above) and hence exacerbate the concentration of air pollutant like the particulates matters. This is already confirmed by theoretical experiments and previous empirical studies (Edussuriya et al., 2005). The very high urban roughness reading found in most study areas with high rise buildings and the reverse order of this indicator and vehicle density among all the cases, strongly suggest a causal relationship between morphological factors and air pollution concentration in dense urban environments dominated by high-rise buildings, mediated by climatic conditions. Another important attribute is the effects of street’s and building’s orientation in relation to urban wind. We considered “Sinuosity” (Adolphe, 2000), which indicates the “corridor effect” of an urban fabric in terms of the ability to drag off air pollutants from lower levels of streets, due to the orientation of longer axis of a street network with respect to prevailing wind conditions and the respective length of streets. Low “sinuosity factor” showed insignificant relationship in these cases. Whether its role is hidden or surpassed by other built form configuration factors in the complex pattern demands further analysis.

4. Concluding remarks

This study revealed that the urban development factors and urban built form configuration factors are relevant morphological aspects explain the air quality in hyper dense residential in Hong Kong. Out of those morphological indicators, land utilisation attributes offers little explanation, thus most land use intensity attributes suggest some describable relations to both aspects; streel level air pollution concentration and urban microclimatic conditions. Similar and even a clearer pattern is found in the relationship between urban built form configuration factors such as mean building height, street canyon and urban roughness, and microclimatic conditions and air quality among these study areas. In conclusion, findings of the study enabled the validation of our theoretical framework (model – Figure 2) that postulates the relationship between urban morphology and street level air pollutant concentration, and an effective test of the research methodology that relates urban morphological attributes to street level of air pollutant concentration, via the mediating force of urban microclimate. The analysis has enabled the narrowing down of focus on key morphological attributes and further variables whose relation to street level air pollution can be examined through more extensive empirical survey and be precisely determined in future research with more statistical rigor.
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Building as a learning tool: a student-centred POE approach to the Swanston Academic Building (SAB)

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Abstract: This paper describes the process of developing a student-centred POE project for the educational purpose of undergraduate students, using the experiential learning-by-doing approach to assess building performance. The case study building, the Swanston Academic Building (SAB) at RMIT University, is an exemplar of the Australian green educational buildings, creating a ‘vertical campus’ to support student learning. Four progressive assessment tasks were designed for the project based on time and resources availability: site visit, space analysis, energy audit and user satisfaction. The space analysis and energy audit enabled students to understand the functional, technical and environmental performance of the building, dealing with secondary data. The main focus of the project was building user satisfaction, assessing student users’ environmental comfort and satisfaction in respect of energy use and environmental impact in the case study building. A total of 193 participants responded and the respondents were satisfied with overall building performance including comfort at student portals. Although the respondents were less likely to report a significant change in health and work productivity they highly rated building facilities which support their work well. The student-centred POE project presented in this paper seems relevant to building education as it actively engages students in the learning process as a building assessor as well as a building user, reflecting on their experience of using the case study building.

Keywords: Post-occupancy evaluation (POE); green educational buildings; Swanston Academic Building (SAB); learning-by-doing approach.

1. Introduction

Post-occupancy evaluation (POE) is a systematic and rigorous process and provides insights into the consequences of past design decisions and the resulting building performance, by finding the difference between performance criteria and actual building performance of buildings-in-use. It should provide useable information about how buildings perform and how they interact with their users to help manage buildings and improve next building projects. Thus, POE does not seem to be a review of buildings it includes its process and clear performance criteria according to the scope of projects. With
this regard, in recent years, attention has been given to building performance and POE study within the architecture and building discipline, arguing that many building professionals have been trained and experienced to only create buildings, but they have not had an obligation to carry out the POE process to ensure building performance (Bordass and Leaman, 2005, Riley et al., 2010).

A student-centred POE project for undergraduate building discipline students at RMIT University was designed and conducted by using the experiential learning-by-doing approach to assess building performance. The core attributes of the experiential learning are action and reflection. Action can utilize actual experience with the phenomenon being studied to validate a theory or concept, and reflection as a planned activity, students need to relate it to their previous knowledge and test understanding of what took place (Beaudin and Quick, 1995). The 'learning-by-doing' approach based on experiential learning principles could allow students to develop a first-hand knowledge of understanding building user interaction with the building and the way it influences building performance (Gupta and Chandiwala, 2009).

This paper describes the process of developing and facilitating a student-centred POE project for the educational purpose of undergraduate students and explores its relevance to building education. The student-centred POE project in the present paper actively engages students in the learning process as a building assessor as well as a building user, reflecting on their experience of using the case study building. This allows them to identify elements which work well and those which do not work well to ensure the future building projects can learn from the outcomes of the case study building.

2. Overview of the POE project

The POE project ran over 12 weeks for undergraduate students in the school of property, construction and project management at RMIT University. This student-centred post-occupancy evaluation (POE) project focuses on assessing student users’ environmental comfort and satisfaction in respect of energy use and environmental impact in the Swanston Academic Building (SAB) at RMIT. By using the experiential learning-by-doing approach, students assess both hard and soft issues of building performance.

2.1. Case study

The case study building, the Swanston Academic Building (SAB), is an educational building at RMIT University in Melbourne, designed by Lyons Architects and completed in July 2012 (Figure 1 and 2, source: RMIT University, n.d.). With some 35,000 m² of floor space over 12 levels, SAB accommodates the college of business (850 academic and administration staff and 6000 students). Not just for the college of business, with being tied to the RMIT Timetable Services, it has 40% of RMIT teaching capacity in one building (McKee, 2013). With a range of sustainability/energy efficiency features such as innovative building façade, mixed-mode ventilation, rainwater and greywater systems and solar hot water panels, SAB is an exemplar of Australian design excellence achieving a Green Building Council of Australia (GBCA) 5-star Green Star Education Design rating. It provides an opportunity for students at RMIT to experience the latest sustainable building and further to use the building as a case study for their learning, in particular for the architecture and building students. Besides the sustainability features SAB provides a world-class educational facility with the latest technology. ‘Student Portals’ in the SAB support student learning experience, creating an environment of sharing and interaction between educators and students (RMIT University, n.d.), and ideally between student peers. It is more emphasized that having a sense of belonging and positive experience on campus for students, which has
changed the nature of space on campus, coupled with new ways of using technology in learning environment. In this context, the student portals could be an example of educational space that encourages socializing and peer learning.

2.2. Student portals

Student portals over ten levels support student learning, creating a ‘vertical campus’. The communal spaces linked to cafes and wireless technologies encourage students to have informal learning spaces where students can study and collaborate (Figure 3 and 4, source: RMIT University, 2013). One of the key sustainability features for the student portals is the spatial layout creating a ‘breathing building’ for ventilation and light. Also, a mixed-mode ventilation system used in the student portal can operate with weather conditions and student control. Using a mixture of automated systems such as opening windows, fans and water misters allows for student users to achieve their environmental comfort further through timed gas heaters and lighting fixtures. LCD screens in the portals provide information on the building performance and the way users can interact with their environment (RMIT University, n.d.).
3. POE design

This POE project involved undergraduate students who participated in a course entitled Building Services. The course provides students a comprehensive understanding of complex building systems through face-to-face scheduled lectures for 12 weeks. Besides the lectures, a student-centred post-occupancy evaluation (POE) project ran over the semester, using the experiential learning-by-doing approach to assess building performance. As both building professionals and building users students are expected to be aware of how well buildings perform and how building users interact with the building. For this project, progressive assessment tasks were designed and number of techniques for POE were considered including site visits, measurement, analysis of construction documentation, analysis of project records and costs, analysis of utility data and running costs, user satisfaction and public opinion surveys, and video or photography. Generally, not all POE techniques are used at once, they can be selected and developed internally or some techniques are available commercially. The assessment tasks were narrowed down according to time and resources availability and the following were selected: site visit, space analysis, energy audit and user satisfaction.

3.1. Site visit

A site visit was conducted in week 2 just after a project brief was given to students in class. The class size was about 70 students and student groups of four were formed for the project. All students were expected to have the experience as a building user of the case study building since their pre-requisite course was run in the building in previous semester. The student groups were instructed to visit the case study building and to provide a site visit report. The following information was presented to students prior to the site visit.

- Project summary
- Space type and use
- Project design principles
- Sustainable/green features

3.2. Space analysis

After the site visit, each student group was asked to select a floor for building performance assessment. The space analysis was based on ‘RMIT Property Central (Figure 5)’, a web portal system that is an industry-standard, GIS application and a centralised, user-friendly repository of all onshore RMIT campus building plans and facilities information (RMIT University, 2009). The following tasks are given for students to learn how to use the portal system.

- Generate room classification map
- Tabulate the area of each room category
- Calculate the ratio of each room category to total floor area

An in-depth space analysis was required to develop a space-user-technology framework and discuss how well each space supports building users to perform their tasks and activities. An example of the space-user-technology framework is presented in Figure 6.
3.3. Energy audit

An energy audit for the case study building was supported by quantitative data from ‘SAB interactive dashboard (Figure 7 and 8, source: Lucid’s Building Dashboard, n.d.)’. The hard, quantitative data includes electricity, water, natural gas, non-potable water consumptions, the student portals indoor conditions (ventilation mode and temperature) and Melbourne’s weather conditions. Using the interactive dashboard, the following tasks were given for students to analyse the utility consumption.

- Provide monthly utility consumption.
- Describe the monthly consumption pattern according to seasons and occupancy.
- Estimate annual utility consumption.
- Estimate annual carbon emissions.
3.4. User satisfaction

A standardised occupant survey was developed for student building users focusing on the student portals in the SAB. The survey questionnaire was modified from BUS methodology which enables the building performance to be compared to other buildings using benchmarks (Arup, 2015). The modified version of occupant survey includes questions specific to student experience at the student portals. The student groups were allocated over ten student portals which would reduce inconvenience to building users and it was expected that each student in a group collected 2-3 questionnaires during a three week survey period in September 2014.

The survey was conducted as a face-to-face mode using a 2 page-hard copy questionnaire. The reason selecting a hard copy, face-to face mode is to increase response rate and also it could be a learning experience for the student investigators to be in the location of the study. The student investigators were given a training session which included a summary of human research ethics before conducting the survey. On behalf of the student investigators, the human research ethics application was submitted by the course coordinator, as a chief investigator, and the ethics approval was granted on 20 August 2014 (Project number: CHEAN B 0000018826-07/14) with a low risk.

Survey participants were asked to complete a standardised survey provided by one of the student investigators. The survey took approximately 10-15 mins to complete and asked questions about building element such as heating and cooling, noise, lighting and the design of building and their perception/experience. The responses to the survey were collated and analysed by the investigators and all responses remained anonymous.

4. Results and discussion

4.1. Preliminary analysis from student survey

4.1.1. The building overall

A preliminary analysis was conducted from the student survey. A total of 193 participants responded and 87.6% (n=169) were RMIT students and the rest of them were staff and visitors. The age group of
under 30 was the largest accounting for 87.6% (n=169) of the respondents. The gender mix was 54.9% (n=106) for male and 45.1% (n=87) for female. ‘The building overall’ was evaluated by the respondents over eight items from the standardised BUS survey including ‘building design’, ‘needs’, ‘space’, ‘image’, ‘safety’, ‘cleaning’, ‘availability of meeting rooms’, and ‘suitability of storage arrangements’. Additional three items, ‘wayfinding’, ‘space at student portals’, and ‘furniture at student portals’ were developed for this student survey. All items were measured in a seven Likert-type scale (e.g. 1 unsatisfactory to 7 satisfactory). In general, the respondents were satisfied with building design meeting the building user needs. However, meeting rooms and storages were not as satisfying as others, reporting mean scores of 4.59 and 4.77 respectively. The respondents also showed some difficulty finding places using indoor signs. 

Figure 9 demonstrates the mean scores of the eleven items.

**4.1.2. Comfort, health and productivity**

This section outlines the analysis results of the student portals located over ten levels in the Swanston Academic Building. The student portals are a dedicated common space for informal study where students can study and collaborate. Using a standardised BUS survey, the student portals’ indoor environment was evaluated: ‘Thermal comfort’, ‘Noise’, ‘Lighting’ and ‘Comfort overall’. Also, building users’ work productivity, health, facilities support and their personal control over the indoor environment were assessed. All items questioned were measured in a seven Likert-type scale (e.g. 1 unsatisfactory to 7 satisfactory or e.g. 1 uncomfortable to 7 comfortable) except work productivity (measured in a nine Likert-type scale). Overall, the respondents felt thermally comfortable in both winter (4.93) and summer (5.14) and they also showed a level of satisfaction over lighting (5.63). Although they were concerned about internal noise, they seemed to be satisfied with noise overall (4.66). Regarding building users’ health and work productivity, the respondents were less likely to report a significant change, reporting a slight increase in both items: more healthy (4.65 out of 7) and about 10% more productive (6.15 out of 9). Interestingly, the building users’ overall evaluation over comfort and building facilities was highly rated than their evaluation over the individual items. They reported that they were satisfied with the overall comfort of the building environment (5.74) and that the building facilities meet their work requirements (5.66). It could be interpreted that although the
individual items did not seem to reach the building users’ expectations, the building users highly evaluated overall comfort and satisfaction due to the building design and image which they more highly evaluated than other functional items. It is evident that they provided extensive, positive comments about building design, mainly stating well-designed and innovative.

![Figure 10: Mean scores of comfort and health.](image)

4.2. Discussion

Through the progressive tasks over the semester, students gradually understood a POE process and the assessment criteria. Although this project was designed as four progressive tasks including site visit, space analysis, energy audit and user satisfaction, the main focus was on the last part, building user satisfaction, assessing student users’ environmental comfort and satisfaction in respect of energy use and environmental impact in the case study building. Based on the site visit reports submitted by the student groups, it seems that the student groups showed two patterns: one focusing more on the technical performance of the case study building including the sustainable features presented in the project brief and the other focusing more on the functional performance of the building such as each space and their relationship, for example, the service spaces, circulations and the entrance of the student portal.

Hard data for the space analysis and energy audit were collected and analysed from the RMIT online resources, which enabled students to learn how to deal with quantitative secondary data for analysis. The hard data analysis is a desktop-based analysis of the secondary data, which made the students understand the functional performance of the case study building through the space analysis, and the technical and environmental performance of the building through the energy audit. The space analysis was designed as an individual task so that the individual students in the course can have the opportunity to demonstrate their understanding and analytical skill of the functional performance of the building. Almost all of the students demonstrated how to use the space information management system (RMIT Property Central) and accurately tabulated and calculated each space based on the room classification. However, for the space-user-technology framework some students seemed to struggle to categorise or sub-categorise each space. Through the energy audit the students could understand changes in utility
consumption according to seasons and occupancy. They analysed and interpreted the collected data, trying to understand how the local weather conditions, building systems, seasons and building occupancy affect the utility consumption. Based on their analysis, while the electricity and water consumptions tend to change according to building occupancy, i.e. semester and non-semester periods, the natural gas consumption does according to seasons, i.e. higher consumption in winter due to heating.

Soft data of the building performance were collected from the student building user survey using a standardised questionnaire. The students were asked to fill in the questionnaire as a building user and to conduct the survey at their chosen student portal as a building assessor. Through this process, the students were able to understand the role of building occupants in assessing building performance. They also reflect on practical difficulties they experienced in conducting survey. All questionnaires returned were coded and a preliminary analysis of overall building performance and comfort at student portals was conducted by the chief investigator (course coordinator) and presented to the students in class. Although BUS methodology enables the building performance to be compared to other buildings using benchmarks, this project designed for the educational purpose did not attempt the comparison which can be commercially made. Rather, it focused more on understanding the factors affecting overall building performance and dealing with building assessment criteria and variables and their measurement scale. Due to time constraints, a preliminary analysis of the student survey was only completed during the semester. It could be further explored, possibly in conjunction with a research project course.

5. Conclusion

This paper describes the process of developing and facilitating a student-centred POE project, using the experiential learning-by-doing approach to assess building performance. The case study building, the Swanston Academic Building (SAB) at RMIT University, as an exemplar of the Australian green educational buildings, provides an opportunity for students at RMIT to experience the latest sustainable building and to use the building as a case study for their learning. Four progressive assessment tasks were designed for the project based on number of POE techniques: site visit, space analysis, energy audit and user satisfaction. This POE project enabled the students to understand the functional, technical and environmental performance of the case study building, more specifically through the space analysis and energy audit they learned how to deal with quantitative secondary data for evaluating building performance, and through the building user occupant survey they learn how to assess building users’ environmental comfort and satisfaction. A preliminary analysis showed that the respondents were satisfied with overall building performance including comfort at student portals. Although the respondents were less likely to report a significant change in health and work productivity they highly rated building facilities which support their work well. The student-centred POE project seems relevant to building education as it actively engages students in the learning process as a building assessor as well as a building user, reflecting on their experience of using the case study building. Further analysis of the occupant survey and the utilization of the collected data would be recommended in conjunction with other courses.

References


Building Energy Simulation, CFD and prototype testing to design an effective Under Floor Air Distribution System

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Abstract: Under Floor Air Distribution (UFAD) offers the twin benefits of energy-efficient heating and cooling while also maintaining thermal comfort and improving indoor air quality. Several design tools are available to verify and optimise UFAD designs, including Building Energy Simulations (BES), Computational Fluid Dynamics (CFD) and physical prototype testing. In this study, the methodology, applicability and accuracy of these three tools have been analysed and compared. This was undertaken as part of the design process for the 150 Collins St office project, a premium-grade office project in Melbourne. Using BES, it was found that the building would generate 33 kg CO2-e/m² p.a. with the NABERS methodology, qualifying it for a 5.5 Star NABERS (National Australian Built Environment Rating System) Rating. Analysis of CFD results indicated that the UFAD system could achieve a Predicted Mean Vote (PMV) of -0.5 to within 1.0m of the façade (under summer design conditions). Throughout the course of a year, the PMV was maintained between -0.5 and 0.5 for 98.27% of the occupied time. The design also allowed for a 150% increase over the minimum outside air for occupants. Overall, the 150 Collins St project demonstrated a successful design pathway for UFAD implementation, where integrated HVAC (Heating, Ventilation and Air Conditioning) and façade design led to significant building energy and thermal comfort outcomes.

Keywords: Under Floor Air Distribution; simulation; validation; thermal comfort.

1. Introduction

Under Floor Air Distribution (UFAD) is becoming more popular in projects due to purported improvements in energy efficiency and Indoor Environment Quality (IEQ) over ceiling-based Variable Air Volume (VAV) air conditioning. A review of the technology and its development has been published by Zhang et al. (2014). UFAD systems deliver low velocity air at floor level, which rises vertically through the occupied zone to return vents at ceiling level. Because the air enters the space at floor level, natural stratification of the air occurs and air needs to be conditioned only in the occupied zone.

However, UFAD systems pose challenges that are not encountered in traditional VAV systems. Raised floor systems supply air through an underfloor plenum. Supply air temperature needs to account
M. Webb

for temperature increases in the floor as well as the room load (Xue, 2013). Air quantities need to be tuned accurately to provide sufficient conditioning but prevent oversupply or drafts can occur. Oversupply can lead to the entire height of the space being conditioned (mixed air) and therefore more heating or cooling than required as well as excess energy (Fuller, 2004). Other barriers to technology adoption have been identified (Im et al., 2005).

Research into practical design methods for UFAD systems under varying indoor and climatic requirements is ongoing. Although several guides are available (e.g. Bauman and Daly, 2003; Megerson, 2013), researchers have also posited different design tools based on their own studies (Lee, 2011; Xue, 2011). Other aspects of UFAD systems have also been studied, such as indoor environment conditions (Tsai et al., 2014), heat transfer in the supply plenum (Xue, 2013) and thermal comfort (Alajmi et al., 2015). This research generally employs one or more of three main methods: software Building Energy Simulations, CFD and physical testing. CFD can be used with some freedom to simulate UFAD designs (Lee, 2011; Xue, 2013). Building energy simulators use a number of different approaches in their simulation of UFAD. IES Virtual Environment uses a multi-layered, stratified zone approach (APACHE HVAC User Guide, 2015, p466), IDA Indoor Climate and Energy uses an intra-zone algorithm to calculate zone stratification (User Manual - IDA Indoor Climate and Energy - Version 4.5, 2013), while EnergyPlus provides a range of different simulation options.

2. Aim

The aim of this study was to experimentally validate BES and CFD simulations of UFAD in an office design during the peak summer cooling period in Melbourne, Australia. This would confirm the suitability of the façade and UFAD building design. Additionally, this study would further develop and apply the UFAD design methodologies explored in previous research. CFD and BES results would be compared to physical experiments to determine the applicability of simulation tools for UFAD cooling design under these climate conditions. This was important because there is still some uncertainty as to the capability of UFAD system design algorithms to successfully predict the mechanical requirements for a particular building. Verification and validation was undertaken as part of the 150 Collins St project (a premium-grade office). EnergyPlus Building Energy Simulation (BES) software (with the DesignBuilder Graphical User Interface) was selected for energy modelling, while DesignBuilder CFD calculations analysed and verified thermal comfort in a perimeter office. Further validation was achieved through physical office prototype testing undertaken by VIPAC Engineers.

3. Design requirements and test inputs

The client brief require that the proposed UFAD system meet prescribed internal conditions on a peak design day for Melbourne, Australia (AIRAH Technical Handbook, 2007) as described in Table 1. The project was required to obtain a 5 Star Green Star Design and As Built Rating ("What is Green Star?," 2015) with 12 energy points. A 5 Star NABERS Energy Rating was also mandated. These requirements would be verified through BES using the NABERS (formerly ABGR) modelling protocol ("NABERS Guide to Building Energy Estimation," 2011) and the Green Star - Office As Built v2 Technical Manual 2005).

The Fanger Predicted Mean Vote (PMV) and Predicted Percent Dissatisfied (PPD) are widely used numerical measures of thermal comfort that relate the major environmental and physiological variables (ASHRAE Handbook - Fundamentals, 2009, p9.17). The multi-equation PMV model is given in ASHRAE Handbook - Fundamentals 2009, p9.17). The 150 Collins St project was required to meet PMV targets of
Building Energy Simulation, CFD and prototype testing to design an effective Under Floor Air Distribution System -0.5<PMV<0.5: (a) during extreme design day conditions in a west-facing office with a peak solar load, and (b) throughout the entire year for >98% occupied office hours (08:00-18:00).

Table 1: Internal and external design conditions.

<table>
<thead>
<tr>
<th>Design Condition</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry Bulb internal temp.</td>
<td>20°C</td>
<td>24°C</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>40%</td>
<td>60%</td>
</tr>
<tr>
<td>PMV (see next section)</td>
<td>-0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Dry bulb external temp.</td>
<td>n/a</td>
<td>34.5°C</td>
</tr>
<tr>
<td>External wet bulb temp.</td>
<td>n/a</td>
<td>23.5°C</td>
</tr>
<tr>
<td>Global solar radiation</td>
<td>n/a</td>
<td>935 W/m²</td>
</tr>
</tbody>
</table>

4. Methods and setup

4.1. Building Energy Simulation

In this study, DesignBuilder was used as the primary modelling tool. DesignBuilder offers a “full-featured user interface to EnergyPlus HVAC” (EnergyPlus Energy Simulation Software 2012). The key to DesignBuilder’s simulation capabilities is the integration of the EnergyPlus calculation engine (DesignBuilder Simulation 2010).

For the energy simulation, an accurate representation of the 150 Collins St design was created in DesignBuilder (see Figure 1 (L)). The building is 12 storeys tall, with a common envelope and HVAC zoning from Levels 5-12, hence Levels 6-11 were considered thermally equivalent. Building fabric, glazing, lighting HVAC services and zoning were added to the model as required. Underfloor supply plenums were created beneath occupied floors. For the CFD study, a representative west-facing office was created on Level 8. This is indicated in Figure 1 (R).

EnergyPlus offers the modeller several Room Air models in order to assess stratified air designs, further indicating the range of design methods for UFAD and displacement compared with a standard mixed air condition (Input Output Reference, 2012, p302). While termed UFAD, the system in question was designed for a distinct floor subzone. Therefore, modelling was done using the EnergyPlus Three Node Displacement System (TND). However, as further verification, the UFAD Exterior/Interior (UE/I) setting was also tested in an equivalent model.

HVAC schedules were set for 55 hours per week as per the design brief, from 07:30-18:30 Monday to Friday. Ventilation rates were set at 18.75 L/s/m² in accordance with the goal to achieve 3 points in the IEQ-1 credit in a Green Star Office Rating (Green Star - Office v3 Technical Manual, 2008). Internal loads were specified also specified as per the design brief: occupancy – 1 person per 10m², lighting – 10 W/m² and internal equipment – 15 W/m².

4.2. Computational Fluid Dynamics

The integral CFD module available within EnergyPlus was used to create a model of a representative west-facing facade office. DesignBuilder models the Navier-Stokes equations for continuity, momentum and energy as well as turbulence (using a turbulent viscosity term) with the primitive variable method (DesignBuilder Simulation + CFD Training Guide, 2009, p162). Navier-Stokes equations are described in many references (e.g. Anderson, 1995; ASHRAE Handbook - Fundamentals, 2009).
This study used a representative office on Level 8 as the basis for an airflow study on the UFAD system. Physical obstructions inside boundary conditions for heat sources, sinks and ventilation were added. This included an occupant, chair, desk and computer were added along with air diffusers and ceiling lighting. Heat addition by obstructions and surfaces was equivalent to the design brief requirements as implemented in the DesignBuilder BES.

Figure 1: 150 Collins St DesignBuilder Model – Building (L) and Level 8 floor plan (R).

Figure 2: 150 Collins St floor layouts – Level 5 (left) and Level 8 (right).
4.3. Physical testing

As part of verification of the facade and UFAD system and validation of software designs, a physical office prototype was constructed and tested by VIPAC Engineers to replicate the west-facing facade office. The dimensions were 4.1m (w) × 3.3m (d) × 2.7m (h). The test facade was a manufacturer sample and the loading scenario was modelled as accurately as possible and all surfaces were insulated to thermally isolate the prototype. An underfloor plenum was created, into which air at 15°C was supplied. The entire test office was constructed within a larger environmentally controlled chamber capable of maintaining temperatures from -15°C to +50°C. While solar spectrum lamps were not used, solar loading was provided through heat pads that were installed on the office floor, window and desk. These provided the equivalent solar gain calculated in the EnergyPlus BES. The internal fitout was completed by Grocon (the head contractor for the project) and associated subcontractors. Photographs of the test setup are shown in Figure 3. Measurements were taken of: air temperature and velocity (measured at 6 heights across a 63-point grid) and a representative radiant temperature (measured across the 63 points at a height of 1.5m).

4.4. Test parameters

All three test scenarios used inputs as close as practically possible. Simulation conditions from the BES informed the boundary conditions for the CFD study and both BES and CFD informed the VIPAC test office (see Table 2).

![Test setup](image-url)

**Table 2: Input parameters.**

<table>
<thead>
<tr>
<th>Input</th>
<th>BES value</th>
<th>CFD Value</th>
<th>Physical value</th>
<th>test</th>
</tr>
</thead>
<tbody>
<tr>
<td>External temperature [°C]</td>
<td>34.5</td>
<td>35.0</td>
<td>34.5</td>
<td></td>
</tr>
<tr>
<td>Internal air temperature set point [°C]</td>
<td>22.5</td>
<td>22.5</td>
<td>22.5</td>
<td></td>
</tr>
<tr>
<td>Supply air temperature (into plenum [°C]</td>
<td>15</td>
<td>n/a</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Supply air temperature into zone</td>
<td>17.4</td>
<td>17.5</td>
<td>17.5</td>
<td></td>
</tr>
<tr>
<td>External facade inside surface temperature [°C]</td>
<td>29.2</td>
<td>29.2</td>
<td>29.2</td>
<td></td>
</tr>
<tr>
<td>Air supply rate [L/s]</td>
<td>125</td>
<td>100</td>
<td>125</td>
<td></td>
</tr>
<tr>
<td>External incident solar load [W/m² facade area]</td>
<td>935</td>
<td>n/a</td>
<td>n/a</td>
<td></td>
</tr>
<tr>
<td>Resultant internal solar load to floor [W]</td>
<td>n/a</td>
<td>483</td>
<td>483</td>
<td></td>
</tr>
</tbody>
</table>
5. Results

5.1. Peak design day

Table 3 compares the key temperature and thermal comfort results for the three test scenarios. Figures 4, 5 and 6 display results of temperatures across the zones.

Table 3: Results from the 3 scenarios.

<table>
<thead>
<tr>
<th>Input</th>
<th>BES value (TND)</th>
<th>BES value (UI/E)</th>
<th>CFD Value</th>
<th>Physical test value</th>
<th>Maximum difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal temperature floor [°C]</td>
<td>19.5</td>
<td>na</td>
<td>19.7</td>
<td>20.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Internal temperature occupied zone [°C]</td>
<td>21.9</td>
<td>22.4</td>
<td>21.8</td>
<td>22.4</td>
<td>0.5</td>
</tr>
<tr>
<td>Internal temperature mixed zone [°C]</td>
<td>23.0</td>
<td>24.3</td>
<td>22.8</td>
<td>23.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Thermal gradient – floor to ceiling [°C/m]</td>
<td>1.5</td>
<td>1.4</td>
<td>1.3</td>
<td>1.4</td>
<td>0.2</td>
</tr>
<tr>
<td>Air velocity (occupied zone) [m/s]</td>
<td>0.25</td>
<td>0.25</td>
<td>0.1</td>
<td>0.07</td>
<td>0.18</td>
</tr>
<tr>
<td>PMV</td>
<td>-1.2</td>
<td>-1.17</td>
<td>-0.8</td>
<td>-0.09</td>
<td>1.11</td>
</tr>
</tbody>
</table>

Figure 4: Vertical zone temperatures from BES – Three Node Displacement (L) and UFAD Exterior (R).
5.2. Annual simulation

To meet the NABERS and Green Star requirements, a full annual simulation was conducted using the DesignBuilder/EnergyPlus model. The results from this simulation are shown in Table 4. Note that for the building’s floor area, occupied hours and energy generation mix, the calculation of 33 kg CO₂-e/m² would qualify the building for a 5.5 Star NABERS Rating, which was greater than a 40% reduction in upon the 5 Star level.
Table 4: Annual simulation results.

<table>
<thead>
<tr>
<th>Green Star Credit</th>
<th>BES / Design value</th>
<th>Available points</th>
<th>Points achieved</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEQ-1 Ventilation Rates</td>
<td>18.75 L/s/person</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>IEQ-9 Thermal Comfort</td>
<td>-0.5 &lt; PMV &lt; 0.5 more than 98.27% of occupied hours</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Ene-2 Energy Improvement</td>
<td>33 kg CO2-e/m²</td>
<td>15</td>
<td>13</td>
</tr>
</tbody>
</table>

6. Discussion

6.1. Temperatures, PMV and design considerations

Table 3 showed general agreement between simulation and physical measurement. The maximum temperature difference across the three vertical zones was less than 1°C. Slightly higher temperatures were measured in the physical tests, however all met design brief requirements. All three scenarios followed the desired trend of temperature stratification, with a maximum variation of 0.2°C/m in the thermal gradient. The similarity of the CFD and BES simulations and their agreement with the physical tests points to the accuracy of these methods and their suitability as design tools for UFAD systems.

All three tests showed a PMV below zero, meaning the occupants would feel cool rather than warm. It was noted that the design brief required a PMV between -0.5 and 0.5, however occupants feeling too cool under summer conditions indicated that the air conditioning capacity of the HVAC systems was more than adequate to cope with the required cooling loads. PMV calculations across the simulations did show variation. Differences were probably more attributable to the different inputs (particularly relative humidity), rather than variation in simulated and measured conditions. In addition, air velocity was different. The BES applied a user-input value of 0.25 m/s, while in the CFD simulation and physical test the velocities 0.1 m/s and 0.07 m/s, respectively.

In this study, a lower supply air temperature enabled sufficient cooling while maintaining air stratification. This prevented excess air flow, a loss of stratification and higher fan energy consumption.

6.2. Comparison with other studies

The simulations of Yu (2010) showing the vertical temperature profile in a zone using the UCSD two-zone model in EnergyPlus showed very similar results to the simulations conducted for this study. While the building in Yu’s study was situated in San Francisco, the typical vertical profile in the UFAD system gave a floor supply temperature of 18.7°C, an occupied zone temperature of 23.9°C and a mixed (upper zone) temperature of 25.9°C. These results show a consistent approach to the application of UFAD, whether in an interior or perimeter office space, however the plenum supply temperatures were different due to facade loading variations.

Despite using different supply air temperatures, the effective air temperatures, air velocities and PMV at occupant level were very similar to those recorded by (Alajmi et al., 2015). In Alajmi et al. (2015), similar temperature differences were noted between measured air temperatures and the CFD model, which also used DesignBuilder for CFD modelling.

Unlike traditional mixed air methods of cooling, the supply temperature to the underfloor plenum is not delivered directly into the occupied space. It was found that, with a substantial solar load on the floor, the temperature pickup between the supply duct outlet and the floor diffuser could be as large as
Building Energy Simulation, CFD and prototype testing to design an effective Under Floor Air Distribution System

3°C, meaning temperatures of 14°C from air handling cooling cools would be required. This aligned with Xue (2013) who found that a UFAD system could require a higher cooling load on a peak day, but would use less chiller energy annually because the UFAD system was able to maximise free cooling.

While the review of Zhang et al. (2014) reported potential savings in chiller energy due to the higher supply air temperatures, this study and subsequent design have noted that supply temperatures from the cooling coil can be lowered to around 13.5-15°C, which is in fact similar to those used in mixed air systems (11-12°C). Zhang et al. (2014) also note the period of free cooling available with UFAD systems compared with conventional mixed air systems. Importantly, and consistent with the present study, Zhang et al. (2014) describe the importance of considering the thermal decay in the supply plenum which can account for 40% of the cooling load for the system.

6.3. Limitations

While the study showed good agreement between the software and experimental temperatures, there were several simplifications in the process. In particular, both the CFD and physical tests were limited in their application of the solar load, which was input purely in the infrared spectrum rather than as a radiation component across the entire solar spectrum.

Furthermore, this study and the entire mechanical design for the project highlighted the critical role of the floor supply plenum, as studied by Xue (2013).

Future work focusing on accurately replicating solar loads and the subsequent interaction with the occupied zone and supply zone plenum would benefit future UFAD designs. Additional validation studies during non-peak periods of the year would also add confidence that BES in particular presents an accurate estimation of annual energy consumption.

6.4. Building current status

The development at 150 Collins St has reached beyond Practical Completion and is currently in its Defects Liability Period. Actual NABERS tracking continues against the modelled benchmarks. As of July 2015, the building was performing at a rating of 4.7 stars.

7. Conclusion

On the basis of the simulations and testing completed for the 150 Collins St project, UFAD can assist in meeting thermal comfort and energy goals.

Using BES, it was found that the building would generate 33 kg CO₂-e/m² p.a. with the NABERS methodology, qualifying it for a 5.5 Star NABERS Rating. Analysis of CFD results indicated that the UFAD system could achieve a Predicted Mean Vote (PMV) of -0.5 to within 1.0m of the façade (under summer design conditions). Throughout the course of a year, the PMV was maintained between -0.5 and 0.5 for 98.27% of the required time. Physical tests corroborated BES and CFD results and further confirmed several physical effects of air movement and temperature differentials between stratified zones. Physical testing on design day conditions measured a result of -0.09 PMV. This further confirmed the suitability of the façade and UFAD design and provided additional confidence for the client.

The consistency in the results for BES, CFD and the physical tests proved the digital UFAD design calculations valid for an office in summer cooling in Melbourne. This contributed to the body of
knowledge in UFAD design methods and strengthened the validity of CFD and BES (specifically EnergyPlus) as design tools for UFAD systems.

Overall, the 150 Collins St project demonstrated a successful design pathway for UFAD implementation, where integrated HVAC and façade design led to significant building energy and thermal comfort outcomes. The use of three different design tools – BES, CFD and physical prototyping – provided an opportunity to validate the design (and design methodology) and revealed the benefits in terms of energy consumption and thermal comfort. This in turn provided client confidence in success of the eventual outcome.

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Evaluating building design for thermal comfort with single rating parameter- hot-dry region of India

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Abstract: In the wake of Green Building Revolution in India, more buildings are now attempting to build and certify green. The rating systems which are applicable for certification, evaluate these buildings based upon established criteria ranging from building envelope, water efficiency, energy efficiency, landuse, material optimization, indoor air quality to transport, operations, maintenance etc. However no credit is awarded to spatial design in achieving efficiency. In response to this issue, a new evaluation tool was evolved namely Difference in Uncomfortable Hours Outside Vs Inside. This tool evaluated the building in response to the climate in which it was placed. In simple terms, thermal conditions outside the building were compared with thermal conditions created inside due to design. However, to use DUHOI as an established tool for evaluating efficiency of architectural design in bringing in thermal comfort, bandwidths for each climatic zone have to be set. This can be done by evaluating best examples and also the seemingly bad examples based upon our understanding of passive architecture. This research work is limited to establishing a bandwidth of DUHOI for Hot-Dry climate of India. A range of buildings from hot-dry climatic zone are identified and simulated using whole building simulation tool. DUHOI is then calculated for each building. In this manner, a benchmark can be set and all buildings aspiring for green building certification would work for architectural design efficiency as a prerequisite. This would lead to an overall improvement in building performance.

Keywords: Thermal comfort performance assessment.

1. Introduction

Architects and engineers across the world are attempting to create buildings which consume zero energy or at least minimum energy. This is evident from the steep statistical rise in the floor area registered with various leading Green Building Rating systems in India and world over (www.igbc.in). The buildings are rated on the basis on a number of parameters ranging from Site and transport, Energy, Indoor Environment, Materials and waste, Water and Operations and maintenance (Liu, 2010). Different rating systems across the world have classified parameters under these broad themes however the
weightage of themes vary from one system to other (Fowler K M et al, 2006). Of all the themes, maximum weightage is given to energy by all rating systems uniformly (Agrawal et al., 2014).

While quantifying the energy efficiency of a building, weightage is assigned for Building envelope, HVAC, Service Water Heating, Power, Lighting and other systems. Building envelope focuses on Building Orientation, WWR, Fenestration design, type of glass being selected and opaque assemblies (Fowler et al., 2006; Ballinger, 1988). Whether the approach is prescriptive or whole building performance method, quantitative assessment of design for achieving energy efficiency doesn’t feature anywhere (Happio, 2008). Therefore in most of the certified green buildings, it is seen that buildings have employed best systems which reduce the operational energy requirement (better lighting fixtures, HVAC systems, pumps etc.) and also the building envelope (improved glass, wall assembly, insulation, roof material etc.). However majority of the buildings have not really considered architectural spatial design as the first step. Architectural spatial design implies inter relationship of spaces with each other and outdoors through envelope and fenestration. In essence, envelope and fenestration material (also WWR) is often included in rating systems. But, the capability of architectural spatial planning in bringing in substantial reduction to energy consumption has largely been ignored (Cole, 2012).

One of the most important reasons is that rating systems which are applicable in India are all borrowed in principle from western countries which are predominantly cold. For improving energy efficiency of buildings in cold climate, building envelope needs to be insulated and tight with minimal infiltration, more sun facing glass with low U-value and efficient HVAC and lighting systems are required. The issue becomes significant and different for a country like India where there is a variety of climates (ECBC, 2007). The response is required in terms of better designed buildings which can provide thermally comfortable environment even without addition of any mechanical means. This approach is a preventive approach and also affects the stakeholder behavior (Plessis et al., 2011). However, the motivational factor in terms of rating system (policy push) is required. Thus the need is to develop a tool which evaluates the effectiveness of any architectural spatial design (inclusive of envelope) in any climatic context (normalization) in bringing in energy efficiency (Haas, 1997).

2. Existing attempts towards normalization tools

At present, the way building efficiency is evaluated with the help of whole building simulation tools is prejudiced and biased. It considers a hypothetical base case based upon the prescriptive values as per standard document or code; say ASHRAE 90.1 in case of LEED or energy consumption baseline in case of GRIHA (ASHRAE 90.1; ECBC, 2007). Architectural design remains same for base case and proposed case. Energy Conservation Measures (ECM’s) are then added to proposed case (which mainly comprise of alternatives of building construction/ building envelope and mechanical systems) and performance of building is evaluated. In this entire process, potential of a better spatial design’s contribution towards energy efficiency is not being evaluated. The aim should be to evaluate performance of building design including building envelope and fenestration (location and schedule of operation) in achieving thermal comfort which would lead to energy efficiency.

For achieving this aim, a simple tool may seem to be the use of Thermal Comfort Indices. However, the issue of normalization for different climatic zones is ignored through this. For example, a building in Jaipur (hot-dry climate) may be good yet be having more uncomfortable hours as compared to a building in Bangalore (moderate climate) simply because outside climate has more number of comfortable hours in Bangalore as compared to Jaisalmer. Several attempts have been made across the world by researchers towards normalization and evaluation of building efficiency. The prime objective
however was to normalize weather to calculate the impact of weather variations on building performance. The Princeton Scorekeeping Method (PRISM)’ (Fels et al., 1986), was developed to calculate energy consumption for individual house’s cooling and heating without integrating the two (Reynolds et al., 1988). Building Energy Analysis Consultant (BEACON) system was developed by Haberl et al (1988), which is capable of continuously monitoring and diagnosing the operation and maintenance problems identifying the causes of abnormal energy consumption. Eto (1988) developed a simulation model which accounts for temperature forecasting based on weather conditions of a decade. Radu Zmeureanu (1992) presented a new method for weather-normalization which considers weather as a factor contributing to energy consumption. However, none of the weather normalization techniques discuss the impact of architectural design on thermal comfort normalized to the weather to which building is exposed.

3. DUHOI – Difference in Uncomfortable Hours Outside vs Inside

DUHOI- The tool is a simple calculation tool based upon TSI (Tropical Summer Index). As the name suggests, the tool is intended to calculate the difference of TSI from outside to inside. If the difference between TSI outside and TSI inside is more (where TSI inside falls in the range of Thermal Comfort), the ability of building design to convert uncomfortable hours outside into comfortable hours inside is better. Or in other words, Higher value of DUHOI would imply a better performing building.

3.1. Tropical Summer Index

TSI is defined as the temperature of calm air, at 50 percent relative humidity which imparts the same thermal sensation as the given environment. The 50 percent level of relative humidity is chosen for this index as it is a reasonable intermediate value for the prevailing humidity conditions (Sharma, 1986); SP 41 (2001); SP 7 (2005). Mathematically, TSI (°C) is expressed as:

\[ TSI = 0.308 \text{Tw} + 0.745 \text{Tg} - 2.06 \sqrt{(V+0.841)} \]  

(1)

Where

\[ \text{Tw} = \text{Wet Bulb temperature in ° C}, \text{Tg} = \text{Globe Temperature in ° C}, \text{V} = \text{Air Velocity in m/s}. \]

For indoors, Globe temperature can be replaced with Dry-Bulb temperature. It is because Globe temperature takes into account Dry-Bulb temperature as well as effect of direct radiation also. Thus in the absence of radiation, globe temperature is almost the same as DBT. The environment was found comfortable between 25 to 30 TSI. It was tolerable up to 34 and down to 19. Lesser than 19, it was considered as too cold and beyond 34 it was considered as too hot. The TSI decreases further with increase in air velocity.

3.2. Calculating DUHOI

DUHOI can be very conveniently calculated using building simulation data from existing building simulation software in a step wise manner as follows (Table 1).

- Building is modelled as per the proposed geometry and construction systems but without any energy consuming/energy producing active system in place such as lighting, HVAC, equipment
etc. Fenestration is modelled as proposed with opening schedules. Occupancy schedules, natural ventilation schedules, activity schedules and infiltration rate is input as proposed.

- Annual simulation on hourly basis is carried out to obtain data for each habitable zone— Air temperature, relative humidity and air speed. However since most software are unable to calculate air speed inside the building, it has to be calculated manually using SP41.
- Once the data has been obtained for the three parameters, TSI is calculated for all habitable spaces hourly as per the expression of TSI. Along with it, TSI for outside conditions is also calculated without taking into considering the radiation. It is done to ignore the effect of building providing only shade from sun.
- Difference in TSI outside (TSIo) and inside is then calculated to know whether building has contributed towards thermal comfort or not based upon assumptions and guidelines in section 3.3 of this paper.
- Difference of TSI for all habitable spaces for all the hours is calculated and averaged for number of habitable spaces and total number of hours. The value thus obtained is called DUHOI. Each building will have only one value for DUHOI.

<table>
<thead>
<tr>
<th>Time</th>
<th>Baithak (Living)</th>
<th>Rasodha (Kitchen)</th>
<th>Chaughara (Master Bedroom)</th>
<th>Pauli (Transition)</th>
<th>Sal 1 (Bedroom)</th>
<th>Sal T (Bedroom)</th>
<th>TSI o (TSI Outside)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:00</td>
<td>31.8</td>
<td>32.1</td>
<td>32.1</td>
<td>32.5</td>
<td>31.1</td>
<td>32.6</td>
<td>34.3</td>
</tr>
<tr>
<td>1:00</td>
<td>31.6</td>
<td>31.9</td>
<td>31.8</td>
<td>32.2</td>
<td>30.9</td>
<td>32.3</td>
<td>33.6</td>
</tr>
<tr>
<td>2:00</td>
<td>31.3</td>
<td>31.6</td>
<td>31.5</td>
<td>32.0</td>
<td>30.6</td>
<td>32.1</td>
<td>32.8</td>
</tr>
<tr>
<td>3:00</td>
<td>30.9</td>
<td>31.3</td>
<td>31.2</td>
<td>31.7</td>
<td>30.4</td>
<td>31.8</td>
<td>31.0</td>
</tr>
<tr>
<td>4:00</td>
<td>30.7</td>
<td>31.1</td>
<td>30.9</td>
<td>31.5</td>
<td>30.3</td>
<td>31.7</td>
<td>30.2</td>
</tr>
<tr>
<td>5:00</td>
<td>30.4</td>
<td>30.9</td>
<td>30.7</td>
<td>31.3</td>
<td>30.1</td>
<td>31.5</td>
<td>29.4</td>
</tr>
<tr>
<td>6:00</td>
<td>30.5</td>
<td>31.0</td>
<td>30.8</td>
<td>31.4</td>
<td>30.3</td>
<td>31.6</td>
<td>30.4</td>
</tr>
<tr>
<td>7:00</td>
<td>30.9</td>
<td>31.3</td>
<td>31.2</td>
<td>31.7</td>
<td>30.6</td>
<td>32.0</td>
<td>31.2</td>
</tr>
</tbody>
</table>

3.3 Assumptions and conditions

- Only habitable spaces are accounted for in this calculation. Service and ancillary areas such as circulation, toilets, machine rooms, kitchens etc are not included while calculating TSI and DUHOI.
- When TSI inside is brought towards comfort it is counted as positive; if it is taken away from comfort it is taken as negative; based upon the comfort limits of TSI i.e. 25-30. Table 2
- If there is an open area in the building which is being used as suggested through the schedule of activity; and when TSIo is in comfort range and TSIi is outside comfort range during use of such an open area, negative difference will be ignored.
- In case of large building complexes, such as campuses, mutual shading and local wind pattern of building complex will be accounted for in simulation.
- If outside TSI is in comfortable range and inside also is in comfortable range, the difference is not counted.
Table 2: Table showing Difference of TSI Outdoors Vs Indoors for Uncomfortable Hours Outside. Table continues for 8760 hours.

<table>
<thead>
<tr>
<th>Time</th>
<th>Baithak (Living)</th>
<th>Rasodha (Kitchen)</th>
<th>Chaughara (Master Bedroom)</th>
<th>Pauli (Transition)</th>
<th>Sal 1 (Bedroom)</th>
<th>Sal T (Bedroom)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:00</td>
<td>2.5</td>
<td>2.2</td>
<td>2.2</td>
<td>1.8</td>
<td>3.2</td>
<td>1.7</td>
</tr>
<tr>
<td>1:00</td>
<td>2.0</td>
<td>1.7</td>
<td>1.8</td>
<td>1.4</td>
<td>2.7</td>
<td>1.3</td>
</tr>
<tr>
<td>2:00</td>
<td>1.5</td>
<td>1.2</td>
<td>1.3</td>
<td>0.8</td>
<td>2.2</td>
<td>0.7</td>
</tr>
<tr>
<td>3:00</td>
<td>0.1</td>
<td>-0.3</td>
<td>-0.2</td>
<td>-0.7</td>
<td>0.6</td>
<td>-0.8</td>
</tr>
<tr>
<td>4:00</td>
<td>-0.5</td>
<td>-0.9</td>
<td>-0.7</td>
<td>-1.3</td>
<td>-0.1</td>
<td>-1.5</td>
</tr>
<tr>
<td>5:00</td>
<td>-1.0</td>
<td>-1.5</td>
<td>-1.3</td>
<td>-1.9</td>
<td>-0.7</td>
<td>-2.1</td>
</tr>
<tr>
<td>6:00</td>
<td>0.7</td>
<td>0.2</td>
<td>0.4</td>
<td>-0.2</td>
<td>0.9</td>
<td>-0.4</td>
</tr>
<tr>
<td>7:00</td>
<td>0.3</td>
<td>-0.1</td>
<td>0.0</td>
<td>-0.5</td>
<td>0.6</td>
<td>-0.8</td>
</tr>
</tbody>
</table>

\[
DUHOI = \frac{(\sum \Delta T)}{N \times h} \tag{2}
\]

Where
- \( \sum \Delta T \) = Summation of difference in TSI values of all habitable spaces to TSI Outside
- \( N \) = Number of Habitable Spaces Analyzed
- \( H \) = Number of Hours

3.4 Interpreting DUHOI

Negative value of DUHOI implies that building is unable to convert outside uncomfortable conditions to comfortable conditions inside. This implies building has an ineffective architectural design which is unable to bring in thermal comfort. In such a case architectural design needs to be revised in order to make building more comfortable. A positive value of DUHOI implies that the building has been able to convert uncomfortable hours outside into comfortable hours inside. Hence architectural design is efficient and appropriate.

Higher positive value of DUHOI implies building is more efficient and the difference from outside to inside in bringing in comfort is high. Thus the building would be able to perform well even in extreme climatic conditions. A smaller positive value implies building will be able to provide comfort but not in extreme conditions. In such a case the climatic data needs to be analysed to see how much difference is appropriate. However for DUHOI to be used as a standard tool to evaluate building performance, a range needs to be calculated to know what value of DUHOI is good, best or just sufficient.

4. Calculating DUHOI range for hot-dry region of India

4.1. Hot Dry region of India

A hot and dry climate is characterized by a mean monthly maximum temperature above 30 °C. The region in this climate is usually flat with sandy or rocky ground conditions. Solar radiation is intense and sky is mostly clear. Humidity is very low owing to scanty rainfall. In this climate, it is imperative to control solar radiation and movement of hot winds. <http://high-performancebuildings.org>
4.2. Traditional vernacular architectural features

Physiological objectives of buildings in Hot-dry regions are (Koenigsberger et al., 1973)- To cut off direct solar radiation; To increase thermal mass; To divert hot winds; To ventilate during night to flush out the heat gained during the day. In order to achieve these objectives, some architectural features have found a continued use in buildings; such as Jali screens (for cooling the hot air from outside to inside by Venturi effect), thick walls (to increase thermal mass in order to maintain time lag), shading over walls and fenestration (to cut off direct sun), courtyard (to induce air movement during day and to facilitate night flush out), semi open verandahs and colonnades (to cut off direct sun from reaching enclosed spaces) etc (Cooper et al., 1998).

4.3. Case studies

For the limited scope of this paper, five cases have been selected. These are- Sangath- Architect B V Doshi’s studio in Ahmedabad; Youth Hostel, Jodhpur; Haveli (residence) of Babulaji Gudha, Mukundgarh, Rajasthan; Haveli of Ishwaridas Modi, Jhunjhunu, Rajasthan; and one contemporary individual residence in Jaipur.

Table 3: Case Study Details

<table>
<thead>
<tr>
<th>Name</th>
<th>Ground Floor Layout</th>
<th>GF area</th>
<th>Floor</th>
<th>Construction Details</th>
<th>Additional feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sangath- Architect’s Studio, Ahmedabad</td>
<td></td>
<td>300 m²</td>
<td>01 (02 in some areas)</td>
<td>Cavity brick wall-315-100-230, China mosaic on roof (10cm thick) with semi circular vault</td>
<td>Cavity wall with windows on inner wall at the top and outside at regular height</td>
</tr>
<tr>
<td>Youth Hostel, Jodhpur</td>
<td></td>
<td>100 m²</td>
<td>02</td>
<td>315mm thk brick wall, concrete slab roof with cavity 40cm thick</td>
<td>Shaded and recessed windows; staircase as wind tower; Cavity wall in room for exhaust</td>
</tr>
<tr>
<td>Name</td>
<td>Ground Floor Layout</td>
<td>GF area</td>
<td>Floor</td>
<td>Construction Details</td>
<td>Additional feature</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>---------------------</td>
<td>---------</td>
<td>-------</td>
<td>----------------------</td>
<td>-----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Babulalji Gudha Haveli, Mukundgarh, Sikar, Rajasthan</td>
<td><img src="image1.png" alt="Babulalji Haveli Floor Plan" /></td>
<td>539 m²  (including courtyard)</td>
<td>01 + 130 m² on first floor</td>
<td>50 cm thick wall with lime plaster, Lime mortar roof 25 cm thick, wooden shutter for windows</td>
<td>Courtyard with semi open verandahs; small windows with thick wooden shutters; Projected jharokhas cutting direct sun; Reflective lime plaster inside; High plinth; Soft court inside; Hard paved court outside; Longer N-S axis</td>
</tr>
<tr>
<td>Ishwaridas Modi Haveli, Jhunjhunu, Rajasthan</td>
<td><img src="image2.png" alt="Ishwarida Modi Haveli Floor Plan" /></td>
<td>1100 m² (including courtyard)</td>
<td>01 + lower ground floor/d half basement</td>
<td>230 mm brick wall, 150 mm concrete roof, single glazed windows</td>
<td>No particular consideration for orientation; Design attempts to achieve mandatory ventilation in all spaces</td>
</tr>
<tr>
<td>Contemp orary plan</td>
<td><img src="image3.png" alt="Contemporary Plan" /></td>
<td>60 m²</td>
<td>02</td>
<td>230 mm brick wall, 150 mm concrete roof, single glazed windows</td>
<td>No particular consideration for orientation; Design attempts to achieve mandatory ventilation in all spaces</td>
</tr>
</tbody>
</table>

The first four cases have been appreciated as excellent examples of energy efficiency and passive designing. The fifth one is a contemporary design which is common in India scenario these days. The design as well as construction of the residence is a typical representation of current practice.

### 4.4. Schedule for openings

In hot-dry regions of India, in naturally ventilated buildings, people close their windows in winter nights and summer noon to cut off the extreme heat exchange. Accordingly, for all the case studies, same
window opening schedule has been used considering that if the building is correctly operated, what would be the building performance.

4.5. Lighting, HVAC and Activity

Lighting and HVAC loads have been simulated to be zero with building being assumed to be day lit and naturally ventilated. It has been done to ensure that only building design (including envelope and fenestration) is evaluated. No artificial systems have been incorporated. However the activity has been simulated as proposed. This has been done in order to evaluate the performance of building design and construction irrespective of mechanical and electrical systems.

5. Results and discussion

All the cases are simulated using Design Builder v4 and Energy Plus engine for entire year. Air temperature and humidity for all the habitable spaces is obtained from simulation data. For each space air velocity has been calculated manually on the basis on rules and formula given in SP41. TSI is then calculated for entire year on hourly basis for outside as well as all habitable spaces. The difference between TSIi and TSIo is calculated for and the total is then averaged for number of hours and number of spaces as per the formula for DUHOI. A final number is achieved for each case study.

From Table 4, it can be clearly seen that Case 5 is able to maintain comfortable inside in the winter night even when the outside environment is uncomfortable (cold). However during the day, inside and outside both remain comfortable hence the difference will not be accounted.
Table 4: Table Showing Values of DBT, WBT and TSI for one of the Habitable Spaces of case 5

<table>
<thead>
<tr>
<th>Date</th>
<th>Inside DBT (°C)</th>
<th>Outside DBT (°C)</th>
<th>Relative Humidity</th>
<th>WBT (°C)</th>
<th>TSIi (°C)</th>
<th>Difference of TSI dT (°C)</th>
<th>WBTo (°C)</th>
<th>TSIo (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/30/2002 16:00</td>
<td>30.99</td>
<td>33.47</td>
<td>25.24</td>
<td>16.1</td>
<td>27.1</td>
<td>0.0</td>
<td>16.4</td>
<td>29.1</td>
</tr>
<tr>
<td>3/30/2002 17:00</td>
<td>31.12</td>
<td>33.1</td>
<td>23.38</td>
<td>15.7</td>
<td>27.1</td>
<td>0.0</td>
<td>15.6</td>
<td>28.5</td>
</tr>
<tr>
<td>3/30/2002 18:00</td>
<td>31.26</td>
<td>31.73</td>
<td>22.22</td>
<td>15.5</td>
<td>27.1</td>
<td>0.0</td>
<td>14.6</td>
<td>27.2</td>
</tr>
<tr>
<td>3/30/2002 19:00</td>
<td>31.28</td>
<td>29.8</td>
<td>21.37</td>
<td>15.3</td>
<td>27.1</td>
<td>0.0</td>
<td>13.5</td>
<td>25.4</td>
</tr>
<tr>
<td>3/30/2002 20:00</td>
<td>31.27</td>
<td>27.2</td>
<td>21</td>
<td>15.2</td>
<td>27.0</td>
<td>4.0</td>
<td>12.1</td>
<td>23.1</td>
</tr>
<tr>
<td>3/30/2002 21:00</td>
<td>31.2</td>
<td>24.92</td>
<td>20.92</td>
<td>15.1</td>
<td>27.0</td>
<td>5.9</td>
<td>11.0</td>
<td>21.0</td>
</tr>
<tr>
<td>3/30/2002 22:00</td>
<td>31.03</td>
<td>22.98</td>
<td>20.88</td>
<td>15.0</td>
<td>26.8</td>
<td>7.5</td>
<td>10.0</td>
<td>19.3</td>
</tr>
<tr>
<td>3/30/2002 23:00</td>
<td>29.96</td>
<td>22.13</td>
<td>22.04</td>
<td>14.8</td>
<td>25.9</td>
<td>7.4</td>
<td>9.8</td>
<td>18.6</td>
</tr>
</tbody>
</table>

Similar exercise was done for all the zones of all the case studies. DUHOI was finally calculated for all of them. DUHOI winter and DUHOI summer were calculated using only summer hours and winter hours so that building performance in summer and winter could be evaluated and design optimization could be done accordingly.

Table 5 Table Showing DUHOI Values

<table>
<thead>
<tr>
<th>Case Study</th>
<th>DUHOI</th>
<th>DUHOI Winter</th>
<th>DUHOI Summer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sangath</td>
<td>1.33</td>
<td>0.82</td>
<td>1.63</td>
</tr>
<tr>
<td>Youth Hostel</td>
<td>2.32</td>
<td>1.95</td>
<td>3.47</td>
</tr>
<tr>
<td>Haveli Mukundgarh</td>
<td>1.41</td>
<td>1.32</td>
<td>1.99</td>
</tr>
<tr>
<td>Haveli Jhunjhunu</td>
<td>1.86</td>
<td>1.88</td>
<td>1.76</td>
</tr>
<tr>
<td>Contemporary residence</td>
<td>-0.17</td>
<td>2.32</td>
<td>-1.43</td>
</tr>
</tbody>
</table>

6. Conclusion

- As compared to other case studies, contemporary residence performed poorly in summers because the entire structure receives direct solar radiation, cross ventilation is poor, envelope is light and there is no shading over fenestration and envelope. However, it performed better than other residences in winter as lighter fabric heated the insides during day when sunlight was available.
- Youth hostel performed best in summers and overall because of the ventilation strategy achieved, shading devices which shaded the walls as well as fenestration, service areas are arranged on east and west; and building was fully cooled during night.
- Traditional Havelis performed good in summers and overall because of their heavy thermal mass and courtyard arrangement, shading of habitable spaces using semi open verandas.
- An exhaustive exercise is required to arrive at the bandwidth, yet from the limited work done here, it can be concluded that minimum DUHOI summers should be 1.75 and overall DUHOI should be 1.25.
References


M. F. Fels, C. L. Reynolds, and D. O. Stram (1986) PRISMONPC. Documentation for Heating-only or Cooling-only Estimation Program: Version 4.0, Center for Energy and Environmental Studies, Princeton University, Princeton, NJ.


Evaluating the pedagogical effectiveness of learning spaces

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Abstract: This paper describes the development and ongoing use of the School Spaces Evaluation Instrument (SSEI): an evaluation tool developed to gather information about how effectively school architecture supports teaching and learning. In 2009, the Australian Federal Government pledged $16.2 billion towards the Building the Education Revolution (BER). Over the following three years learning spaces were built or refurbished in 9,526 schools nationwide. In Victoria, Catholic Education Melbourne (CEM) encouraged schools to work with architects to design bespoke solutions. This process led to the design and construction of hundreds of new learning spaces, each with different spatial arrangements. Approximately five years on, questions remain about which architectural solutions worked best. To help answer these questions, and inform decisions about how capital budgets should be spent in the future, the Learning Environments Applied Research Network (LEaRN) and CEM collaborated to develop the SSEI tool, including Module 3 – Alignment of Pedagogy and Learning Environments. This tool will be used over the coming three years to evaluate school facilities in the Catholic education sector for the purpose of generating new knowledge about how best to design and use school facilities for contemporary teaching and learning.

Keywords: School architecture; learning spaces; evaluation; pedagogy.

1. Introduction

Do our existing and newly built school facilities meet the needs of today’s teachers and learners – not to mention their future needs? While many architects and educators hold strong views about how schools should be designed for contemporary education, there remains little substantive evidence on the impact of different architectures (spatial arrangements, interior design, furniture selection) on the behaviours and performance characteristics of students and teachers.

In the state of Victoria, Australia, it is no longer an assumption that schools will be composed of a suite of discrete classrooms and specialist spaces for subjects like art and science. Over the past decade a range of ‘innovative spaces’ have been developed by the Catholic, state and private education sectors. As the trend towards creating resource and technology rich facilities (Monahan, 2005; JISC, 2006; Dudek, 2008) is expensive, it is vital to ascertain ‘what works’ and ‘what doesn’t work’ in terms of how
well different school architectures support the contemporary educational practices of teachers and learners.

This paper describes the development of an evaluation tool aimed at gathering evidence about the pedagogical performance of school buildings. The School Spaces Evaluation Instrument (SSEI) was developed to inform school leaders, teachers, asset managers and architects about ‘what works’ when designing new schools or refurbishing existing facilities. The long-term aim of the SSEI project is to create a database that can collate data about the qualities of different school building typologies (Dovey & Fisher, 2014) and to subsequently generate progressive planning and design principles/guidelines.

2. Literature review

Post-occupancy evaluation (POE) was defined by Zimring and Reizenstein (1980, p. 429) as “the examination of the effectiveness for human users of occupied designed environments” and by Preiser (2002) as “a process of systematically evaluating the performance of buildings after they have been built and occupied for some time” (p. 42). The information gained through building evaluations may be valuable to a range of stakeholders, including those engaged in new building projects and those who wish to gain enhanced value from the spaces they already have.

Many studies have evaluated educational facilities using POE techniques (Preiser, 2002; Preiser and Nasar, 2008; Ornstein et al., 2009). Most of these studies have tended to focus on the technical performance of buildings and have not considered their suitability for various forms of pedagogical practice. Most examine the fitness for purpose of facilities in a technical way, using energy and other services analytics and observational studies.

With the recent development of new building typologies in many developed countries that are intended to support contemporary approaches to teaching and learning, the evaluation of such learning environments has become an important issue (OECD, 2009a; 2009b). In keeping with change in the design of learning spaces, the focus of post-occupancy evaluation in education has begun to shift. The creation of ‘innovative’ learning environments has encouraged researchers to search for novel evaluation methodologies and methods that can be used to assess the effectiveness of educational facilities in supporting the learning process (Radcliffe et al., 2008). Such a shift appears to represent renewed interest in evaluation at the intersection of the physical and the social and a return to the origins of POE in environmental psychology (Zimring & Reizenstein, 1980). It also supports Preiser and Nasar’s (2008) opinion that a new perspective on building evaluation is emerging that values the opinions of users, and Ornstein et al.’s (2009) conclusion that,

“user-informed assessments increase the likelihood that a given school building fulfils its intended educational purposes to the greatest degree possible” (p. 364).

In 2008, Temple concluded that,

“further research is needed to illuminate the connections between space and institutional effectiveness” (p. 229).

Subsequently, in a paper titled The evaluation of physical learning environments: a critical review of the literature, Cleveland and Fisher (2014) identified the following key issues and aspirations in the field of learning environment evaluation:
• A number of tools have been developed to evaluate school learning spaces. Most focus on features of the physical environment itself, rather than on the influence of architecture on teaching and learning practices, activities and behaviours.
• Poor indoor environment quality (IEQ) can lessen the effectiveness of good pedagogy.
• New evaluation methodologies are required if we are to understand what types of learning spaces can support the educational programs and practices of the 21st century.
• Evaluations that assess the alignment of space and learning are in their infancy and require further development.
• Evaluation approaches and tools are required that can be modified to accommodate specific physical and social contexts, and the various interests of those commissioning evaluation.

3. Development of the SSEI framework

SSEI was developed to address the shortcomings of existing school learning environment POE tools. It is composed of three modules that can be used to evaluate general-purpose teaching and learning spaces in primary and secondary schools.

[diagram of SSEI framework]

The three SSEI modules are:
• SSEI Module 1 – Design Process Evaluation (Future Module)
• SSEI Module 2 – Technical Performance Evaluation/Indoor Environment Quality (IEQ)
• SSEI Module 3 – Alignment of Pedagogy and Learning Environments

Each module has a different focus. Module 1 focuses on the process of design and the performance of the design team; Module 2 focuses on indoor environmental conditions and sustainability; and Module 3 focuses on the alignment of teaching and learning activities and the design of the learning environment. These modules may be used independently or all three may be applied to generate an evaluation that integrates a range of different perspectives on the quality and performance of educational facilities.

3.1. Overview of SSEI Module 3

SSEI Module 3 was developed based on the following premise:
If learning environments are to be assessed for the ways they can support desired teaching and learning practices, activities and behaviours, they must be assessed subjectively within the context of the educational model(s) they are intended to support. Furthermore,

“such assessments should be based on the educational visions that informed the design and on the opinions of the school leaders, teachers and students who experience the complex physical and social interactions that occur in these learning environments following occupation” (Cleveland, 2011, p. 245).

The purpose of SSEI Module 3 is to:

• Evaluate the alignment between desired teaching and learning activities and the design of learning environments (general purpose) in primary and secondary schools.
• Generate data that can inform decisions about the design and use of learning environments.

SSEI Module 3 collects information about a school’s educational objectives and uses that information to evaluate the alignment between teaching and learning activities and the design and use of space. The information collected refers specifically to the educational objectives associated with the learning space(s) being evaluated. This approach distinguishes SSEI Module 3 from other school post-occupancy evaluation tools, as it (1) recognises that the educational values and beliefs of a school community (and its parent agency) should inform learning environment evaluation, and (2) enables information about a school’s context, culture, educational philosophy and vision for learning to be integrated into the evaluation process. Figure 2 (below) outlines the general relationships between pedagogy and learning environments, as conceived for the purposes of the tool.

Figure 2: Aligning pedagogy and learning environments.

4. Development and pilot testing of SSEI Module 3

This study investigated the development and pilot testing of SSEI Module 3. The study involved (1) further development of the module in readiness for conducting evaluations in schools and (2) pilot testing to determine the future viability of the tool. The development and pilot testing of the module was driven by the following research questions:

• How can the pedagogical effectiveness of school learning environments be evaluated?
• How effective is SSEI Module 3 in evaluating the pedagogical effectiveness of school learning environments?

4.1. Methodology and methods

Following initial development of SSEI Module 3, it was pilot tested in five schools between July 2012 and February 2013. Convenience sampling (Bryman, 2004) was used to select specific samples (schools and individual participants) for investigation. Participants from within each school were identified in consultation with school Principals based on the following criteria: (1) their willingness to participate in the study; (2) their familiarity with the space(s) being evaluated. School leaders, teachers and students were invited to participate in the study. This invitation was supported by written plain language statements and consent forms.

Participant numbers varied between schools depending on how many people regularly used the learning environment(s) being evaluated. Overall, five Principals, four Assistant Principals, 40 teachers and 222 students participated in the study. In addition, the CEM Regional Managers from each of the four metropolitan regions took part in the focus group events associated with the school(s) in their region.

To evaluate the evaluation program/pilot study, data were collected in the form of complete SSEI Module 3 Final Reports, as well as field notes taken by the researchers during focus groups and later discussions with school Principals and CEM staff. These field notes were analysed using a process of thematic narrative analysis (Riessman, 2008).

Data collection associated with the pilot evaluations was acquired using three methods: online surveys (school leaders, teachers and students), an expert facilitated observational walkthrough (school design expert and teachers) and a focus group (school leaders, teachers and Regional Managers). This iterative process supported a ‘drill down’ approach that enabled the key evaluation issues arising at each school to be thoroughly investigated. These data were distilled into final reports for each evaluation.

4.1.1. What participants were asked to do

The evaluation process at each school was led by an Infrastructure Project Officer from CEM, and supported by school leaders and teachers at each site – as required by the design of the module. The specifics concerning what each group of participants were asked to do in relation to (1) the actual evaluation process, and (2) the set-up and review of the evaluation process, is outlined below:

• Principals and/or Assistant Principals were interviewed and asked to provide background information regarding their schools’ facilities and educational vision (60 minutes). They were also asked to complete a survey (50-60 minutes), report on the results of the teacher and student surveys (3-5 hours) and participate in a focus group (60 minutes).
• Teachers completed a survey (20-25 minutes). A sub-sample of teachers at each school also participated in the observational walkthrough (2 hours) and a focus group (60 minutes).
• Students (Year 4 and above) completed a survey (15-20 minutes).
• An Infrastructure Project Officer from CEM led the observational walkthrough (2 hours) and focus group (60 minutes) at each school and wrote interim and final reports for each participating school (10 hours approx.).
• CEM Regional Managers attended a focus group (60 minutes).
4.1.2. Analytical framework

To investigate the research questions, an analytical framework was devised to enable the evaluation program/pilot study to be evaluated.

Table 1: Analytical framework used to evaluate the evaluation program/pilot study. (adapted from: Larson & Berliner, 1983)

<table>
<thead>
<tr>
<th>Inputs (resources and methodologies employed for the evaluation program/pilot study)</th>
<th>Process (conduct of the evaluation compared with that planned in the evaluation design)</th>
<th>Outcomes (decisions influenced by the evaluation program/pilot study)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SSEI Module 3 objectives:</strong> Provide an informative evaluation using a straightforward and cost effective process.</td>
<td><strong>SSEI Module 3 objectives:</strong> Involve a range of stakeholders in the evaluation and share the ‘lessons learned’.</td>
<td><strong>SSEI Module 3 objectives:</strong> Support continuous improvement in the design and use learning environments in primary and secondary schools.</td>
</tr>
<tr>
<td></td>
<td>Support improved communication between the various stakeholders involved in school design.</td>
<td>Support the development of online databases that can be used for benchmarking and to create online resource banks that illustrate best practice in learning environment design and use.</td>
</tr>
<tr>
<td></td>
<td>Provide feedback for school communities about the design and use of their learning environments. Improve the functional fit between school communities and their facilities.</td>
<td>Establish advisory guidelines/principles that can inform the master planning, design and use of teaching and learning environments in primary and secondary schools.</td>
</tr>
<tr>
<td></td>
<td>Provide feedback for education agencies about the design and use of the learning environments in their schools.</td>
<td></td>
</tr>
<tr>
<td><strong>Evaluation factors:</strong></td>
<td><strong>Evaluation factors:</strong></td>
<td><strong>Evaluation factors:</strong></td>
</tr>
<tr>
<td>Duration of the evaluation program/pilot study.</td>
<td>Types, intensity and frequency of interactions between evaluators and program participants.</td>
<td>Decision by program participants or funding agency to modify any of the evaluation program/pilot study procedures.</td>
</tr>
<tr>
<td>Timing of the evaluation program/pilot study.</td>
<td>Extent to which acquired information was fed back to program participants.</td>
<td>Decision by program participants or funding agency to act on outcomes of the evaluation program/pilot study.</td>
</tr>
<tr>
<td>Skills of evaluation personnel (e.g. training, experience, “world view”).</td>
<td>Adaptiveness of evaluation design. Methodology: the formal and informal processing of information leading to evaluative findings.</td>
<td>Decision by one or more members of the research community to study further questions/issues raised in the evaluation program.</td>
</tr>
<tr>
<td>Skills of program personnel (Principals, teachers and students) e.g. experience, commitment, capacity.</td>
<td>Communication of findings to various stakeholders.</td>
<td>Decision by one or more other funders to initiate, modify, or terminate similar programs.</td>
</tr>
<tr>
<td>Budget and other resources available for the evaluation program.</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Evaluating the pedagogical effectiveness of learning spaces

The framework shown in Table 1 (below) was based on the broad objectives of SSEI Module 3 and integrated with an evaluation framework adapted from Larson and Berliner (1983). Using a process of qualitative analysis, this framework was used to evaluate the relative success of the evaluation program/pilot study.

5. Findings and discussion

In keeping with the analytical framework shown in Table 1, the key findings of the study are presented below under the following headings; inputs, process and outcomes.

5.1. Inputs

The total time taken to complete each pilot evaluation was 4-5 months – an elongated period due to the limited availability of the Regional Managers. Had these people not been required, the duration of the data collection processes could have been achieved over six weeks and the entire evaluation process could have been completed in 8-9 weeks.

School leaders suggested that data collection should take place in the later part of Term 1, or early in Term 2, and that final reports should be completed during Term 3 to enable them to act upon the evaluation outcomes ahead of the following year.

An Infrastructure Project Officer from CEM led the evaluations at each of the five participating schools, following a briefing on the evaluation process. As all five pilot evaluations were completed successfully, this briefing and the information contained in the SSEI Module 3 User Guide appears to have provided adequate information about how to conduct the evaluation process.

Students (Year 4 and above) were reported to have had no difficulties answering the survey questions in four of the five pilot schools. At one school it reported that the ‘younger students’ required assistance to ‘unpack’ some of the questions. Across all five pilot schools, teachers and Principals were readily able to answer the survey questions. Teachers and Principals were readily engaged in the observational walkthroughs and focus groups. One Head of Learning and Teaching commented that, “the walkthrough was the most enlightening hour of last year”.

The analysis and reporting on the survey questions was conducted by school leaders from within participating schools. These people were able to follow the analysis process, as set out in the User Guide, and complete this process in 3-5 hours. One aspect of evaluation process that was not completed by any of the pilot schools was the forwarding of master plans, schematic design drawings and photographs of the spaces/facilities being evaluated. These documents/images were not forthcoming.

The major costs involved in conducting the evaluations were associated with human resources. The time required for the various groups to participate in the evaluations were in keeping with initial expectations (please refer to section 4.1.1).

5.2. Process

The SSEI Module 3 pilot study showed that the evaluation process could be conducted as planned. However, it revealed that improved methods for delivering the instrument and managing the data collected could lead to a more efficient, and potentially more effective, evaluation process.

The evaluators were well received at each pilot school. Principals and teachers reported that they found the observational walkthrough to be a positive and enlightening experience. Program participants
were forthcoming with comments and discussion points during the focus groups. Email and telephone correspondence was adequate for the purposes of supporting the evaluation process.

The participation of Principals and teachers in the observational walkthrough provided them with an opportunity to contribute to and engage with the information acquired, while the focus groups promoted the formal feedback of early findings and further discussion with participants. It was suggested that a fourth phase should be added to the evaluation process, asking participating schools to identify what actions they have or intend to take in response to the evaluation reports produced.

A number of CEM staff and Principals suggested possible modifications to the evaluation design to make it more adaptable. These suggestions included, (1) making it possible to record impromptu points/issues in the observational walkthrough questionnaire, (2) including the voices of teacher aids in the evaluation and (3) including the voices of Prep-Year 3 students in the evaluation.

The processing of data collected via surveys was collated by school leaders, while the data collected via observational walkthroughs and focus groups was done by CEM staff. Both processes met with expectations. However, it was suggested that the creation of a bespoke online interface should be explored to support more efficient collection and processing of data.

It was suggested that summaries of school evaluations, including schematic design drawings and images, should be made available to a wider audience via an online resource bank. Such a resource could broadcast valuable information to school communities and architects about the issues pertaining to the alignment of pedagogies and learning environments. The value of a resource bank would be further enhanced by periodic meta-synthesis of the data held in it, along with the publication of such findings.

5.3. Outcomes

The pilot study showed that the outcomes of the evaluations were valued by the participant schools. The feed-forward outcomes of the evaluations were acted upon in a number of different ways. Information derived from the evaluations informed the renovation of existing spaces at one school and the design of new spaces at another. Furthermore, the evaluation findings from the second school were taken into consideration in connection with the design of spaces at two further schools. A number of pilot schools also embedded discussion of learning environments into their professional learning programs. Table 2 (below) provides a brief summary of the issues that were identified as ‘in need of attention’ at each pilot study school.
Table 2: Summary of issues highlighted in evaluations for each pilot study school. Issues marked ‘X’ identified as issues in need of attention.

<table>
<thead>
<tr>
<th>Issue</th>
<th>School A (Primary)</th>
<th>School B (Secondary)</th>
<th>School C (Primary)</th>
<th>School D (Primary)</th>
<th>School E (Primary)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spatial/physical issues</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Differentiation of activity settings limited</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Furniture and joinery in large common area not supportive of differentiated activity settings</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Indoor environment quality in need of better management by staff</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Acoustics in large common area poor</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Connections between indoor and outdoor learning spaces limited</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Parent gathering spaces (outdoors) limited</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Locker areas problematic</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Multimedia display technology limited</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Airflow/cross ventilation insufficient</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Display space limited</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storage space limited</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Artificial lighting control insufficient</td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pedagogical/social issues</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large common area underutilised</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Teacher professional learning required</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shared vision for learning and teaching in common areas lacking</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Student and teacher ownership and mastery of common areas lacking</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Teacher meeting room(s) potentially better utilised as breakout spaces for students</td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Breakout room (small) underutilised</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pedagogical and spatial transitions between primary and secondary school in need of closer consideration</td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Inflexible timetable restricting the variety of activities undertaken in common area</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

6. Conclusion

This study indicated that further research/development of SSEI Module 3 was warranted. The evaluation program/pilot study showed that such attention should focus on the development of an online system that provides the capacity to (1) disseminate briefing materials on how to conduct evaluations to evaluators and participating schools, (2) host the survey tools, (3) streamline data management and analysis, (4) store the outcomes of the evaluations in a database that would enable the meta-synthesis of selected evaluations to produce ‘big picture’ lessons learned and (5) develop an online system that showcases case studies of effective learning environments and disseminates the findings of meta-synthesis studies.
With the backing of CEM, this work is currently underway and a program of evaluation has been agreed for the next three years (2015-2017). The **Towards Effective Learning Environments in Catholic Schools: An Evidence Based Approach** project will develop an evidence base to inform both the design and pedagogical use of learning spaces (school facilities) in the Catholic schools in the Melbourne Diocese—and hopefully beyond as the project is expanded to other parts of Australia.

**Acknowledgements**

We extend our gratitude to Catholic Education Melbourne (CEM) and the Learning Environments Applied Research Network (LEaRN) for supporting this project. In particular, we would like to thank Patrick Love, Dr Wesley Imms, Associate Professor Clare Newton, Dr Janet Clinton and Dr Gerard Calnin for their input into this project over the past four years.

**References**


Human factors in naturally ventilated sedentary working environments

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Abstract: The challenges proceeded by intense global energy consumerism such as global temperature increase are predicted to be mitigated by good low-energy design. However mixed mode and other low energy systems such as natural ventilation and advanced natural ventilation constitute a considerable interaction between context, climate, building and the occupant. The tolerance of sensory stimuli are influenced by variety of internal processors attributed to feedback between building occupants and their environment. This research explores the influence of natural ventilation on evaluation of indoor environmental quality (IEQ) in office buildings, in the tropical monsoon context of Sri Lanka. A questionnaire survey is used to measure the subjective evaluation of IEQ. Empirical measurements of indoor environment conditions are collected during the survey period. The subjective and objective performance of naturally ventilated buildings are compared against two air conditioned building types (central air conditioning and mini split system air conditioning).

Keywords: Natural ventilation; human factors.

1. Introduction

Colombo is located at 6.93440N and 79.84280E. The Köppen Climate Classification System identifies Colombo as a tropical monsoon climate. The major climatic considerations for building in this region are; heavy precipitation, high solar radiation, high temperature and humidity. This climate induced by monsoon winds is broadly defined by four seasons, categorized according to the amount of precipitation; Northeast Monsoon (December-February), first inter monsoon (March and April), Southwest monsoon (May-September) and Second inter monsoon (October- November). Colombo receives the highest rainfall during two stages, from May to July during the southwest monsoon and October to November during the second inter-monsoon. The region reports a high annual rainfall of 2200mm and, the highest number of rainy days reported is 200 per year. The warmest period of the year proceeds the monsoon from March to mid-June. The temperature and humidity is high throughout the year with little temporal variability.
The heat balance model of thermal comfort, recommends year round cooling and de-humidification to achieve comfort in the tropics (Fanger, 1982). Heating ventilation, air conditioning (HVAC) and lighting accounts for over 50% of the end use energy in buildings (Pérez-Lombard et al., 2008). Further ideal indoor environment conditions available in artificially conditioned buildings with little or no variability influence the behaviour and perceptions of building occupants (De Dear and Brager, 1998). People in naturally ventilated buildings were identified to be more tolerant of indoor thermal conditions as compared to requirements predicted by thermal comfort standards (Nicol and Humphreys, 2002). A study conducted by Kim and de Dear identified a difference in expectations and evaluation of specific IEQ factors in distinctive ventilation systems (Kim and de Dear, 2012). They attributed these differences to varied experiences in differently ventilated buildings. The study further suggest that; Adaptive opportunity is a generic attribute of buildings that influences thermal comfort and other indoor environmental quality factors.

The physical work environment effect performance and satisfaction of building occupants (Sundstrom, 1987). The physical environment triggers arousal, stress, distraction, overload and fatigue which influence performance and satisfaction, adaptation may modify these impacts (Bluyssen, 2013). Adaptation is identified as a response by the occupant(s) of an environment directed towards an increase in comfort or ease of functioning. Adaptation may include; metabolic changes, automatic physiological responses, changes in perception, habits and actions designed to alter the inhospitable environment or its effects. Numerous empirical studies demonstrate the positive influence of operable windows (Humphreys, 1992), personal comfort systems (Ackerly et al., 2012), higher perceived control (Bordass and Leaman, 1997) for increased productivity and satisfaction of the indoor environment condition.

2. Method

This research employs a questionnaire survey to identify the influence of natural ventilation on subjective evaluation of indoor environmental quality (IEQ). The questionnaire is used to rate the perceived performance of four primary IEQ aspects; Thermal comfort, Air quality, Illumination and Acoustics in four naturally ventilated office buildings located in Colombo. The perceived performance of naturally ventilated buildings are compared against two air conditioned building types typical to Colombo (central air conditioning and mini split system air conditioning). Table 1 summarizes the descriptions for surveyed buildings. Table 2 summarizes questionnaire items used to evaluate IEQ factors.

Empirical measurements of temperature and humidity were collected using HOBO data logger (U12-012), for three consecutive days during the warmest period of the year (February to April). Valid responses from 523 respondents were analysed using IBM SPSS Statistics software (version: 23.0). All selected naturally ventilated buildings utilized operable windows and ceiling fans and/or portable fans to regulate the indoor thermal environment. All building were occupied for eight hours on average, and the building occupants were engaged in sedentary activity of 1.0 to 1.3 met and the clothing insulation ranged from 0.47 to 0.51 Clo.
Table 1: Descriptions for surveyed buildings.

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Ventilation system type</th>
<th>Number of buildings in group</th>
<th>Number of subjective responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>NV-1</td>
<td>Naturally ventilated with operable windows and fans</td>
<td>1</td>
<td>63</td>
</tr>
<tr>
<td>NV-2</td>
<td>Naturally ventilated with operable windows and fans</td>
<td>1</td>
<td>65</td>
</tr>
<tr>
<td>NV-3</td>
<td>Naturally ventilated with operable windows and fans</td>
<td>1</td>
<td>57</td>
</tr>
<tr>
<td>NV-4</td>
<td>Naturally ventilated with operable windows and fans</td>
<td>1</td>
<td>48</td>
</tr>
<tr>
<td>AC-1</td>
<td>Centrally air conditioned</td>
<td>3</td>
<td>178</td>
</tr>
<tr>
<td>AC-2</td>
<td>Ductless mini split air conditioning</td>
<td>3</td>
<td>145</td>
</tr>
</tbody>
</table>

Table 2: Questionnaire structure.

<table>
<thead>
<tr>
<th>Index</th>
<th>Question</th>
<th>Abbreviation</th>
<th>Scale point</th>
</tr>
</thead>
<tbody>
<tr>
<td>wellbeing</td>
<td>Rating for Overall comfort in the indoor work area of the building, considering all indoor environment factors</td>
<td>OC</td>
<td>Unsatisfactory</td>
</tr>
<tr>
<td></td>
<td>Does the building effect occupants health (perceived health impact)</td>
<td>PHI</td>
<td>Less Healthy</td>
</tr>
<tr>
<td>IEQ</td>
<td>Comfort of temperature in the work area of the building</td>
<td>TC</td>
<td>Uncomfortable</td>
</tr>
<tr>
<td></td>
<td>Sensation of temperature in the work area of the building</td>
<td>TSV</td>
<td>Too hot</td>
</tr>
<tr>
<td></td>
<td>Draft in the work area of the building</td>
<td>DRAFT</td>
<td>Still</td>
</tr>
<tr>
<td></td>
<td>Air Freshness in the work area of the building</td>
<td>AF</td>
<td>Fresh</td>
</tr>
<tr>
<td></td>
<td>Satisfaction with overall lighting</td>
<td>OL</td>
<td>Unsatisfactory</td>
</tr>
<tr>
<td></td>
<td>Amount of natural light</td>
<td>NL</td>
<td>Too little</td>
</tr>
<tr>
<td></td>
<td>Glare from sun and sky</td>
<td>GLARE_S</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Glare From lights</td>
<td>GLARE_L</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Satisfaction with Noise in the work place</td>
<td>NOISE</td>
<td>Very dissatisfied</td>
</tr>
</tbody>
</table>

3. Results

Table 3 compares the mean scores and standard deviations for wellbeing and satisfaction with IEQ aspects across the NV, AC-1, and AC-2 groups. For the six factors measured using a unipolar scale (OC, PHI, TC, AF, OL and NOISE) building NV-1 reports the most satisfactory score for four factors (PHI, AF, OL, NOISE) whereas building NV-3 reported the lowest satisfaction rating for five factors (OC, PHI, TC, OL and NOISE). AC-2 group also reports high satisfaction rating for factors PHI, OL, NOISE.

When compared with the mean score for TSV for AC-1 and AC-2 groups, all NV buildings reports a warmer thermal sensation (M: 3.58, 3.51, 3.55, 3.17). Occupants in NV buildings report the most satisfaction for air freshness when compared with AC-1 and AC-2 groups (M= 3.28, 4.05, and 3.47). The
highest satisfaction for NL and GLARE_S is reported for buildings NV-1 and NV-2 (NV-1 M= 4.38, 3.84, NV-2 M= 4.26, 3.86). The lowest satisfaction for NOISE is reported in building NV-3.

Table 3: Mean scores and standard deviations for perception of indoor environment quality.

<table>
<thead>
<tr>
<th>Question</th>
<th>Mean</th>
<th>St. Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NV-1</td>
<td>NV-2</td>
</tr>
<tr>
<td>OC</td>
<td>4.87</td>
<td>4.25</td>
</tr>
<tr>
<td>PHI</td>
<td>4.95</td>
<td>4.49</td>
</tr>
<tr>
<td>TC</td>
<td>4.14</td>
<td>4.41</td>
</tr>
<tr>
<td>TSV</td>
<td>3.58</td>
<td>3.51</td>
</tr>
<tr>
<td>DRAFT</td>
<td>3.36</td>
<td>3.30</td>
</tr>
<tr>
<td>AF</td>
<td>3.28</td>
<td>4.05</td>
</tr>
<tr>
<td>OL</td>
<td>5.47</td>
<td>5.06</td>
</tr>
<tr>
<td>NL</td>
<td>4.38</td>
<td>4.26</td>
</tr>
<tr>
<td>GLARE_S</td>
<td>3.84</td>
<td>3.86</td>
</tr>
<tr>
<td>GLARE_L</td>
<td>3.67</td>
<td>3.32</td>
</tr>
<tr>
<td>NOISE</td>
<td>5.43</td>
<td>4.21</td>
</tr>
</tbody>
</table>

Table 4 is a correlation matrix between OC, PHI and nine IEQ aspects in NV buildings. The two variables OC and PHI were strongly correlated for all NV buildings (r = .768, .477, .749, .766). Occupants who were satisfied with the overall IEQ of the building also perceived the building to have a positive impact on their health. In all NV buildings, the indoor environment quality aspects which had an overall strong to moderate positive correlation with OC and PHI were; TC, OL and NOISE. AF had a strong to moderate negative correlation to OC and PHI.

Table 4: Correlation Matrix for perception of indoor environment quality.

<table>
<thead>
<tr>
<th></th>
<th>PHI</th>
<th>TC</th>
<th>TSV</th>
<th>DRAFT</th>
<th>AF</th>
<th>OL</th>
<th>NL</th>
<th>GLARE_S</th>
<th>GLARE_L</th>
<th>NOISE</th>
</tr>
</thead>
<tbody>
<tr>
<td>NV-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OC</td>
<td>.768**</td>
<td>.493**</td>
<td>.551**</td>
<td>-</td>
<td>.069</td>
<td></td>
<td>.414**</td>
<td>.080</td>
<td>.030</td>
<td>.383**</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>.479**</td>
<td>.479**</td>
<td>-.013</td>
<td>-.327*</td>
<td>.379**</td>
<td>.019</td>
<td>-.011</td>
<td>.065</td>
<td>.303*</td>
</tr>
<tr>
<td>NV-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OC</td>
<td>.477**</td>
<td>.228</td>
<td>-.054</td>
<td>.116</td>
<td>.077</td>
<td>.370**</td>
<td>.490**</td>
<td>.133</td>
<td>-.059</td>
<td>.360**</td>
</tr>
<tr>
<td>PHI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>.265</td>
<td>-.039</td>
<td>.232</td>
<td>-.169</td>
<td>.163</td>
<td>.022</td>
<td>-.226</td>
<td>-.194</td>
<td>.202</td>
</tr>
<tr>
<td>NV-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OC</td>
<td>.749**</td>
<td>.454**</td>
<td>.303*</td>
<td>.317*</td>
<td></td>
<td>.417**</td>
<td>-.065</td>
<td>.052</td>
<td>.036</td>
<td>.560**</td>
</tr>
<tr>
<td>PHI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>-</td>
<td>.472**</td>
<td>.257</td>
<td>.271</td>
<td></td>
<td></td>
<td>.350**</td>
<td>-.079</td>
<td>-.203</td>
<td>-.021</td>
</tr>
<tr>
<td>NV-4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td>OC</td>
<td>.766**</td>
<td>.447**</td>
<td>-.050</td>
<td>-.129</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>.500**</td>
<td>.058</td>
<td>-.088</td>
<td></td>
<td></td>
<td>-.053</td>
<td>.032</td>
<td>.010</td>
<td></td>
</tr>
</tbody>
</table>

4. Discussion

The indoor environment temperature and humidity in the naturally ventilated buildings were plotted onto the psychometric chart generated using Climate Consultant 5.5 developed by U.S. Department of Energy (Figure 1). The Chart also features the annual outdoor weather data from station located at 6.820N and 79.880S, summer comfort zone recommended by ASHRAE 55 (Standard, 2013) and adaptive comfort zone recommended by ASHRAE 55 (Standard, 2004). Almost all humidity and temperature conditions for the surveyed naturally ventilated buildings are located outside the ASHRAE summer
comfort zone (Standard, 2013) but are within the ASHRAE adaptive comfort zone (Standard, 2004). Elevated Air speeds greater than 0.2m/s can be used to increase the upper temperature limit of the comfort zone in certain circumstances.

TSV in all surveyed NV buildings are lower (warmer thermal sensation) than the two air conditioned building groups. Building NV-1, which reports the highest TSV (closer to neutral) among the NV buildings also reports the second highest mean score for OC (M= 4.87, SD= 1.45) and highest mean score for PHI (M= 4.95, SD=1.48). However a strong and positive correlation is observed between OC and TC r(63) = .493, p=.0005 and TSV r(63) = .551 p=.0005. Nicol and Humphreys (Nicol and Humphreys, 2002) identified that increased opportunity to adapt to indoor environment conditions by means of behavioural adaptation or environmental options may result in increased discomfort alleviations. As presented in Table 5 occupants in building NV-1 exercised the highest control of operable windows (84.4%) in the naturally ventilated building group. NV-1 also utilized environmental controls such as; curtains (76.6%) and ceiling fans (70.3%). Further favourable design strategies which may be associated with increased air movement in NV-1 include; narrow floor plans (Average depth= 4.8m), fixed timber lattice which allowed day/ night ventilation and shading by roof eves or cantilevered floors (Figure 2). The climatic relevance of day/night ventilation for residential buildings in hot humid Singapore was demonstrated by Liping and Hein (Liping and Hien, 2007). They identified day/ night ventilation to be the most successful ventilation strategy to minimize thermal discomfort which also reported the lowest dissatisfied hours by building occupants.

Previous research reveals indoor lighting to have considerable impact on occupant’s mood, health and behaviour (Veitch and Gifford, 1996). The continuous spectral distribution of daylight has been shown to have a positive influence on perception of health outcomes related to buildings (Bluyssen, 2013). Among the surveyed buildings, OL was moderately correlated with OC. Further NL doesn’t have a significant correlation to OC in all naturally ventilated buildings. In building NV-1 and NV-2 occupants report close to neutral ratings for NL as well as higher satisfaction rating for GLARE_S. In building NV-3 occupants reported too much NL as well as unsatisfactory GLARE_S (M= 4.76, 5.46). Building NV-1 and NV-2 had well shaded fenestrations while building NV-3 did not have any external shading (Figure 2). Discomfort by disability glare is one critical factor which needs to be considered when designing for natural lighting in buildings. Daylight glare has been identified to be more acceptable for those working on horizontal reading than those working on computer tasks (Velds, 2000). While room orientation has been identified to have an insignificant impact on glare sensation (Hopkinson, 1971), discomfort glare has been reported to decrease proportional to distance from the façade (Velds, 2000).

<table>
<thead>
<tr>
<th>No.</th>
<th>Layout</th>
<th>Utilized control %</th>
<th>Ventilation type</th>
<th>Width of plan (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Curtains/ blinds</td>
<td>Portable fan</td>
<td>Operable window</td>
</tr>
<tr>
<td>NV-1</td>
<td>Open plan</td>
<td>76.6</td>
<td>34.4</td>
<td>84.4</td>
</tr>
<tr>
<td>NV-2</td>
<td>Open plan</td>
<td>63.2</td>
<td>52.9</td>
<td>73.5</td>
</tr>
<tr>
<td>NV-3</td>
<td>Open plan</td>
<td>14.8</td>
<td>53.2</td>
<td>61.3</td>
</tr>
<tr>
<td>NV-4</td>
<td>Open plan</td>
<td>45.3</td>
<td>29.6</td>
<td>15.1</td>
</tr>
</tbody>
</table>
Figure 1: Psychometric chart with comfort zones, indoor and outdoor conditions.

Figure 2: Fenestration; L-R; NV-1, NV-2, and NV-3.
Noise control is one of the main considerations for naturally ventilated buildings. Noise is unwanted sound perceived by the listener as being unpleasant, bothersome, distracting and psychologically harmful (Bluyssen, 2013). Noise originating in the workplace results from the outside road traffic, office equipment, installations, HVAC systems and human speech. Noise from human speech has been recognized to be problematic especially in open plan offices (Navai and Veitch, 2003). All surveyed buildings utilized open plan layout, while the surveyed buildings had varied densities and working conditions. Building NV-3 reports the lowest satisfaction rating for NOISE (M= 2.93 SD= 2.07). The low satisfaction rating for noise was attributed to heavy traffic noise generated from the adjacent road. The results indicate the critical need to mitigate admittance of outdoor noise through well informed design decisions, especially in naturally ventilated buildings. The success of noise control in NV buildings is demonstrated by the high satisfaction rating received for building NV-1. In building NV-1 the window openings were located perpendicular to the main road. In building NV-3 NOISE was strongly negatively correlated with OC $r(57) = .560 \ p=.0005$ and PHI $r(57)= .540 \ p=.0005$ whereas when occupants in other NV building reported satisfaction for NOISE, NOISE did not have a significant impact on the evaluation of OC and PHI.

5. Concluding remarks

The interaction between context, building and the occupants influences the subjective elevation of indoor environmental conditions. Although cooling and de-humidification is recommended for buildings in the tropics, the high satisfaction scores reported in building NV-1 when compared with AC-1 and AC-2 groups, indicates the potential to utilize passive and low energy ventilation systems in this region. Opportunity to adapt to indoor environment conditions is a key criteria for discomfort alleviation and acceptance of variable of internal conditions in passive and low energy buildings.

References


Measuring sky view factor of urban canyons using hacked Gopro hemispheric video processing

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Abstract: Increased urbanisation and densification is producing urban fabric with increasingly deep ‘urban canyons’, trapping longwave radiation and contributing to the Urban Heat Island (UHI) phenomenon. With global temperatures along with heat related mortality predicted to increase, there is a critical need to understand urban canyons and heat retention in cities. Methods for analysing urban canyon through Sky View Factor (SVF), an established contributing parameter in the prediction of UHI, have until now been limited to relatively manual, time intensive calculations using individual points of assessment from still photographs. This paper describes a method for rapidly capturing the extent of urban canyon enclosure by way of mobile video SVF processing. A lightweight GoPro™ video camera was hacked to capture on-the-go 180° hemispherical (fisheye) video. This video was analysed using our custom pixel-based image processing tool calculating SVF. This SVF analysis was synchronised with logged GPS, air temperature, humidity and light levels data captured by linked Bluetooth sensor and smartphone to record city wide urban canyon and atmospheric longitudinal cross-sections. The approach is inexpensive and has potential for continuous, detailed, city wide data collection by mounting on public transport. This investigation provides a new, rapid analysis tool for urban researchers enabling further study of the relationship between urban heat retention and urban form.

Keywords: Sky view factor; urban heat island; urban canyon; sensor data.
1. Introduction

1.1. Aim

The aim of this investigation is to develop and test a tool for rapid Sky View Factor (SVF) evaluation, from in-situ fisheye video of continuous, city-wide longitudinal cross-sections of urban contexts, providing an urban form and microclimate analysis tool to aid researchers studying the relationship between urban canyons and the Urban Heat Island phenomena.

1.2. Urbanisation, densification and heat retention

Many Australian cities are experiencing rapid urban densification (DOI, 2012). Though there is a greater understanding of the relationship between densification, transport, and sustainability (Newman and Kenworthy, 1999; Beatley et al., 2009), there is also great pressure to accommodate higher population densities in established, well serviced, inner urban areas (Dodson and Sipe, 2008) often in the form of high-rise developments. These forms of development can have the unintended consequence of creating a denser urban fabric with deep ‘urban canyons’ [see Figure ]. These resulting dense urban areas can have a profound impact on local atmospheric conditions contributing to the phenomena known as the urban heat island (UHI) which can increase temperatures within urban centres considerably when compared to surrounding rural areas (Oke, 1981, 1988; Mills, 2004; Basara et al., 2010). Temperature differences between central urban areas and nearby rural areas can be more than 3°C on a clear and calm night (Wong and Hogen, 2011) (see Figure ).

![Figure 1: Temperature and urban form relationship diagram of a longitudinal cross-section through Greater Melbourne overlaid with temperature readings (taken on a clear summer night) from outer western suburbs, through the CBD to the outer south-eastern suburbs – based on diagram from City of Melbourne’s Urban Forestry Strategy (Melbourne, 2012) and longwave radiation dispersion diagram by Grimmond (2007).](image-url)
This heat retention in urban centres has been documented since the late 1960s (Bornstein, 1968). As the UHI can intensify extreme climatic events (Patz et al., 2005) and is considered a major contributing factor to heat-related mortality in urban regions, acting to worsen the adverse health effects from exposure to extreme thermal conditions (Luber and McGeehin, 2008; Tan et al., 2010), UHI is now becoming a key consideration in the design for the growth of cities.

1.4. Urban canyon modelling using Sky View Factor (SVF)

The modelling of UHI is complex (Shao et al., 2011) with a great number of variables such as wind, material colour, street orientation, tree coverage, permeability of ground surfaces, and building heights in relation to street width or “urban canyon” (Oke, 1988).

The urban canyon is where, in dense urban environments, buildings on each side of a street enclose a space obscuring the sky and therefore restricting the amount of long-wave radiation that can escape, a phenomenon particularly acute at night (Wong and Hogen, 2011) [Figure 1]. The urban canyon is considered by many to be the most important contributing factor to the UHI effect (Ibrahim et al., 2011); it is a critical variable considered by microclimate researchers in the study of urban heat island (Brandsma and Wolters, 2012; Ewenz et al., 2012) and the measurement of this variable is the focus of this paper.

The measure of the degree to which the sky is obscured at a given point is commonly calculated as either Height to Width ratio (H/W) or as Sky View Factor (SVF) (Johnson and Watson, 1984). SVF has been found to be a more effective measure as it can take into account the complexity of real streets in which buildings are irregularly aligned and which vary in height and length (Johnson and Watson, 1984).

SVF ($\Psi_{sky}$) is a dimensionless measurement of openness between $\Psi_{sky} = 0$ for totally obscured and $\Psi_{sky} = 1$ for open spaces where the sky is completely unobstructed allowing all outgoing radiation to radiate freely to the sky (see Figure 2) (Brown et al., 2001). SVF as a method for modelling has been shown to have a strong correlation with UHI (Kakon and Nobuo, 2009; Unger, 2009; Ewenz et al., 2012) and is therefore critical to understanding the impact of densification and urban form.

Figure 2: Conceptual diagram of sky view factor projected onto a hemisphere for a single point.
2. Calculating SVF

SVF has traditionally been very difficult to measure (Grimmond et al., 2001). There are however several methods for modelling and assessing SVF. Unger (2009) lists five common modelling methods as:

- scale model (Oke, 1981);
- analytical method (2D angle measurements, height/width) (Johnson and Watson, 1984; Johnson, 1985; Bottyan and Unger, 2003);
- evaluation using GPS signals (Chapman and Thornes, 2004);
- computational evaluation using digital elevation databases describing surface geometric elements (Brown et al., 2001; Souza et al., 2003; Lindberg, 2005). There are also developments on this method of generating SVF with the use of Lidar aerial mapping with raster based three-dimensionalisation of two-dimensional data using Digital Elevation Models in GIS (Kokalj et al., 2011);
- and manual and computer evaluation of fisheye photos (Bradley et al., 2001; Holmer et al., 2001; Blankenstein and Kuttler, 2004).

In addition to these methods, tools used in forestry to measure leaf area index such as the LAI 2000 have been suggested (Grimmond et al., 2001). There are also relatively recent microclimatic modellers such as SOLWEIG and Envi-Met which can be used to analyse a low detail street canyon model to a resolution of 0.5 m (Levermore and Cheung, 2012).

Each of these methods has been shown to have a reasonable level of accuracy, but vary greatly in speed of application. Scale models involve a great deal of manual labour. The “analytical measurement” angle measurement or “height/width” method of assessment is problematic, as it is a purely two dimensional approach that does not take into account the complexities of a real street where a section may change dramatically along its length.

Digital modelling methods such as those described by Brown, Grimmond and Ratti (2001) can be applied and computed more rapidly to a resolution of a 2x2 metre grid, though restricted to using Digital Elevation Models which are essentially two dimensional with a height attribute (2.5D), meaning that they cannot assess more complex three dimensional urban forms such as where a street has weather protecting canopies at lower levels or has elements of buildings that may cantilever or protrude from a building at an upper level.

Where fully three dimensional GIS models have been assessed using hundreds of rays projected from a series of points (Chen et al., 2012; Kidd and Chapman, 2012; Kastendeuch, 2013) it has been computationally intensive – requiring powerful hardware taking up to 10 hours to assess a precinct (Gal et al., 2009; Unger, 2009). Light-based SVF approaches can be extremely rapid or even real-time (White and Langenheim, 2014) but still require a full 3D digital model of the city.

Fish-eye still photography can be used without extensive digital elevation model data or 3D mesh data. Though the fish-eye photography method is very accurate, it has been extremely time consuming to acquire and process even with greatly improved software (Brown et al., 2001). This method has been limited to assessing specific points of interest in an existing urban context and extrapolating between the points for urban scaled analysis (Ewenz et al., 2012).
4. Method

The method used to develop and test our video based SVF analysis of in situ hemispheric video involved five parts. First, capture of 180° video by hacking a GoPro to add a custom Panoramic Fish Eye Lens 180° lens thus overcoming the limitation of the standard 160° lens. Second, development of and application using the Processing™ programming language to analyse SVF in hemispheric images on a per-pixel basis. Third, the accuracy of the technique was verified against known geometry mathematically. Fourth, the analytical capability of the tool was extended with sky area ‘blob’ detection and relative angle of sky area measure. Fifth, the tool’s applicability to real world data collection was tested with hemispheric video of urban streetscapes taken in Melbourne with the hacked GoPro, along with GPS and temperature sensor data.

5. Results

5.1. Hacking the Gopro

To capture the 180° video footage, a mobile and robust video camera was found – the popular GoPro Hero 3™ which is relatively affordable (compared with DSLR fisheye cameras), weather proof and light enough to be strapped to a bike or helmet or car rooftop. The camera’s stock proprietary 160° lens was removed using a heat gun (to melt glue) and pliers then replaced with a custom RageCams™ 180° circular fisheye lens.

5.2. Analysis of SVF in Processing

Rather than analysing static photographs taken at single points of interest with currently available software such as HemiView™ or CAN-EYE™, we used the Java-based Processing™ programming language to create a bespoke application to sequentially analyse frames of hemispherical video taken in existing urban context. The application was developed to use three main steps to analyse each source frame: the image is thresholded, the circular fisheye image within the frame is identified, and pixel-level area analysis is performed.

The image of the source frame is thresholded on a per-pixel basis by brightness. The pixel’s brightness value is then tested against a thresholding limit; if it is above the limit the pixel is set to white (sky) and if it is below the limit it is set to black (obstructions to viewing the sky such as buildings, vegetation, and ground) [Figure 3]. Through experimentation a threshold limit of approximately 55% of the maximum possible brightness value was found to discriminate well between sky and obstructions for images captured under an overcast, daytime sky however the limit may be set for other conditions. It should be noted that the thresholding can falsely classify sky as obstruction (such as for dark clouds) and obstruction as sky (such as for glare on windows and very light coloured materials) and as noted by Grimmond et al. (2001), uniform, overcast conditions provide the most accurate results.

The circular skydome image within the rectangular source frames is identified and extracted by centre and radius values given in a configuration file (see Figure 3).
The area of each pixel is calculated by projecting it onto a unit hemisphere (see Figure 4). The lens used for capturing the source images is assumed to be equidistant – the radial angle of a pixel projected onto the unit hemisphere is proportional to its radial distance in the image – however the algorithm can be modified for other lenses. The pseudocode below is used to find the area of each pixel:

- a: calculate the radial angle of the pixel projected onto the unit hemisphere;
- b: calculate the circumference of a circle on the unit hemisphere at that angle;
- c: calculate from this circumference the axial pixel width as projected on the unit hemisphere;
- d: calculate the radial pixel width as projected on the unit hemisphere;
- e: and calculate the area of the pixel from the axial and radial widths.

The method was tested for accuracy against the known area of a unit hemisphere of $2\pi$ or 6.2831853. The sum area of projected pixels for a fisheye image of radius 500 pixels with a field of view of 180° when calculated using this method is 6.2819486 which is an error of -0.02%. For a radius of 50 pixels the error is -0.12%. In general, the greater the radius in pixels of the fisheye image to be analysed the greater the accuracy of the area found under this method. For any reasonably sized fisheye image the error is considered to be well below that likely to be introduced by thresholding artefacts. Further, the error is consistent for images of the same size and so does not vary between frames of source video.

Given the above method of finding the relative area of a pixel within a fisheye image the SVF of a thresholded fisheye image is found by the sum of the area of all white pixels divided by the total area [Figure 4].
5.3. Sky area ‘blob’ detection

A custom algorithm was used to detect contiguous areas of sky in the thresholded image and allows separate calculation of SVF for these areas [Figure 6]. While the exploration of this was limited in this investigation it has potential for further application such as filling in areas of objects, for example those with window glare, that are falsely identified as sky during the thresholding process, identification of foliage, and tracking the permeability to longwave radiation of fragmented surfaces.

Figure 6: Raw image, thresholded image, thresholded image with detected blobs coloured based on sky view area in which the SVFs due to open sky and shading device can be calculated independently.

5.4. Measurement of relative angle of sky area

The ability to measure the radial angle and relative area of each pixel was used to create a metric of the ‘enclosure’ of the sky due to objects in an image. By summing the SVF of pixels with a radial angle ≥ 45° from the zenith, and comparing this to the total SVF, a measure of overhead obstruction is obtained [Figure 7].

Figure 7: LHS and centre thresholded fisheye images with high levels of overhead obstruction, RHS thresholded fisheye image with equally distributed areas of obstruction, bottom graph of total SVF (blue) and SVF ≥ 45° from the zenith (white) with points corresponding to fisheye images marked.
5.5. Testing with Melbourne video

The applicability of the Processing application was tested with fisheye video taken of existing urban context in Melbourne. The hemispherical video was captured with the hacked GoPro with custom 180° field of view equidistant lens concurrently with the GPS route data from a smartphone and temperature sensor data from a Bluetooth Sensordrone™ Tricorder. These data sets were obtained simultaneously mounted on a bicycle riding from lower density suburbs through the city centre, in a mobile data collection approach similar to that used by Brandsma and Wolters (2012).

The resulting animation allows rapid evaluation of changing SVF along the route of the video [Figure 7]. The SVF record is displayed in a graph that allows the overall profile to be seen and locations of interest to be identified. The graph also displays temperature as well as SVF ≥ 45° from the zenith that allows locations with particular levels of overhead obstruction to be easily determined. The thresholded fisheye frame has five display overlays to assist analysis: the raw frame thumbnail shows the original context, a map pulled from openstreetmap.de gives the current location, the overall SVF, angle from the zenith in 10° bands, and separate SVF labels for any large contiguous areas.

The application successfully synced these various sources of data so that as the camera moved through the urban fabric, SVF was calculated alongside microclimatic measurements.

Figure 8: Progressive screen grabs of analysis output. In each image is, clockwise from top left, the raw frame, the thresholded frame with degrees from the zenith and SVF for large areas marked, the SVF for the frame, a location map, and a graph showing the SVF, SVF ≥45° from the zenith, and temperature.

6. Discussion

The hacked GoPro™ video Processing based SVF analysis method described in this paper has proven to give very accurate results and its application is considerably more rapid for multi-point analysis than other existing methods of SVF analysis where detailed 3D models do not exist. As the analysis can be done on video footage, not just still photographs, larger areas of cities can be assessed.

Our initial applicability testing of the tool showed that it is possible to synchronise the SVF analysis data captured with GPS location, temperature, humidity, wind and other sensors allowing lateral cross-sectional urban form and microclimate studies to be done by riding through suburbs into the CBD and out again, building upon the cross-sectional data collection approach by Brandsma and Wolters (2012) allowing the studies to be done in cities without 3D urban data. In addition, the synchronised
data and analysis can be displayed simultaneously in visually compelling animated video showing SVF analysis with ‘subscreens’ displaying actual fish eye video footage alongside mapped GPS location and graphed microclimatic readings [Figure 8]. This data synchronisation has great potential for aiding further analysis of the relationship between SVF and UHI in different climate areas and cities potentially allowing microclimate researchers, urban planners and designers to rapidly analyse existing urban context for SVF and thereby assist better understanding of existing city forms and enable identification of potential UHI problem areas.

The measure of SVF of pixels with a radial angle greater than or equal to a given angle from the zenith currently uses 45° to measure the level of overhead obstruction. Further research could be undertaken to find the most meaningful cut-off angle for particular urban condition or area and be extended as a metric.

In addition to the urban cross-sectional analysis, the rapid video processing method allows the possibility of distributed collection of SVF information to build SVF maps of an area or whole city. Cameras, along with GPS sensors, could be attached to public transport or fleet vehicles such as buses and taxis. With the appropriate hardware the gathered data could be wirelessly uploaded to base for processing. This SVF map data could also be integrated with GIS applications or with online mapping platforms such as Google Maps through the Google Maps API v3.

The method is financially accessible to researchers given the relatively low cost of the GoPro (under $500), custom lens ($200), Sensordrone™ ($200) and logging with any recent Android phone.

The method could also potentially be implemented as a smartphone application for real-time, on-site analysis that either accounts for a smartphone’s native camera and lens characteristics or links to a GoPro via its wireless capacity.

7. Conclusion

Using a hacked GoPro™ with scripted analysis of fisheye video allows continuous, city-wide longitudinal cross-section analysis of existing urban contexts synced with microclimate data to be obtained rapidly.

The approach is inexpensive and has potential for continuous, detailed, city wide data collection by mounting on public transport or fleet vehicles. This investigation provides a new, rapid urban canyon analysis tool for urban design and microclimate researchers enabling critical further study of the relationship between urban heat retention and existing urban forms.

References


Optimisation of energy consumption and daylighting using building performance surrogate model

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Abstract: Today, the architects are expected to identify solutions that provide best trade-offs among an excessively large number of possible design alternatives. Within this context, computational intelligence techniques prove to be valuable decision support tools. In parallel to this agenda, the current study aimed to present a novel approach towards identifying non-dominated design solutions that minimize annual building energy consumption and improve indoor daylight conditions. We applied the method to an L plan shaped office design. In this hypothetical building design, parameters of footprint area, number of levels, fenestration, shading, U-Values of building elements and HVAC system selection were set as variables; whereas total floor area and floor height were kept as constants in order to facilitate further practical relevance. A total of 105 simulations were performed for various values of the parameters. The resulting dataset was used to obtain two approximation models, for each of the objective functions. A Multi-Objective Evolutionary Algorithm was subsequently used to obtain the set of non-dominated solutions for the problem. Our results indicated the applicability of the proposed approach for decision-making practices at the conceptual design phase of relevant cases.

Keywords: Energy; daylighting; artificial neural network; optimisation.

1. Introduction

Energy consumption and daylighting are two very essential yet conflicting performance objectives of building design. Providing design solutions that reduce energy consumption while maintaining adequate level of daylighting requires an architect to evaluate large number of design alternatives at the conceptual design phase. Due to complexity involved in the building design, the task is neither practical nor realistic when the design approach is traditional. However, advances in computational tools for design applications, coupled with techniques from the field of artificial intelligence, have led to new possibilities in the way the computers can inform and actively interact with the design process (Caldas and Norford, 2002). Recent works (i.e. (Chatzikonstantinou et al., 2015; Dursun et al., 2015; Ekici et al.,
Optimization of energy consumption and daylighting using building performance surrogate model

have demonstrated global optimization techniques such as differential evolution (DE) or genetic algorithms (GA) may present significant advantages to architects towards searching for near optimum design solutions.

Since every building design is unique, simulation is the adequate method to evaluate the performance of a building which is subject to a set of characteristic conditions such as location, weather, construction materials, occupancy loads and etc. To determine optimum solutions based on simulation results, an architect first develops a detailed model of the building. Following, various parameters of proposed design are altered manually, such as fenestration ratio. Next, simulation is run for the created case, and finally the process is repeated until multiple performance criteria are satisfied. Although advances in simulation tools has been introduced in recent years, computational cost of the simulation process is excessive. Thus, running simulations for each alternative in the possible search space requires massive amount of time. To reduce the size of search space and therefore the time necessary to execute simulations, the architects rely on their subjective assessments that may lead to depart from near optimum set of design alternatives.

To address the issue of computation cost through optimization of design parameters, building surrogate models were offered (Machairas et al., 2014). Wong et al. (2010) trained an Artificial Neural Network (ANN) model using results by EnergyPlus simulations to predict energy consumption of a square shaped plan office development located in Hong Kong while taking daylighting factor into account. Magnier and Haghighat (2010) developed an ANN model using TRNSYS simulation results in order to characterize building behaviour. The ANN model, in turn, combined with multi-objective Genetic Algorithm (NSGA-II) for optimisation of pre-determined design parameters. Eisenhower et al. (2012) studied building energy optimization using a metal-model which is developed by employing Support Vector Machines method. The previous works made significant contributions towards introduction of surrogate models for energy optimization. However, the problem of interest mostly studied by researchers from engineering domain. Engineers, who traditionally participate in the project team at the detailed design stage, consider design parameters that significantly differ than the architect’s. Therefore, further investigation is essential when the target is optimization of the building performance at the conceptual design stage.

Addressing the gap, the aim of the current study is to offer a surrogate model which intends to predict the building average daylight autonomy and minimize annual energy consumption. Subsequently, we make use of the resulting model together with stochastic search in order to improve performance with respect to said quantities. Application of the proposed model at the conceptual design phase is considered.

2. Methodology

As the first step of the study, we aim to develop a generic office building simulation model. The model is located in İzmir, Turkey and has an L-shape footprint area. Next, changing the values of pre-determined design parameters, a data set was constructed by running simulations in the interest of the subsequent development of objective functions. Following, using these approximation functions, optimum values of selected design parameters was reached. Thus, a significant reduction in necessary time to reach optimum design parameters was achieved. The adopted method is presented in Figure 1.
2.1. Generation of database

The aim of this section is to demonstrate the process associated with generation of annual energy consumption ($Y_1$) and building average daylight autonomy ($Y_2$) database for the subsequent development of objective functions. Daylight Autonomy is a climate-based daylighting metric, which has been developed by Reinhart and Walkenhorst (2001), with the aim of providing a concise figure of the sufficiency of daylighting for the interior. DA denotes the percentage of hours within a year that a point in the interior receives sufficient daylight. Sufficient, here, is determined according to the needs of the space. For instance, in office buildings, it is common to take 500 lux as a threshold. The simulation platform used in this study was OpenStudio. Developed by National Renewable Energy Laboratory, OpenStudio is a cross-platform (Windows, Mac, and Linux) collection of software tools to support whole building energy modelling using EnergyPlus and advanced daylight analysis using Radiance. More, it is integrated to SketchUp with the help of a designated plugin. Working in a computer aided design interface, to which the architects are accustomed, introduces a significant advantage of utilizing OpenStudio against other alternatives.
A generic office building with the L-shaped plan, which is located in Izmir, Turkey, was considered as the reference case. In spite of common approach in relevant studies, number of storeys was nominated as a variable. That is, the generic office design has number of storeys varying from 1 to 5. Since total floor area is determined as certain percentage of the plot area by the municipalities in the location under investigation; it was set constant at 1000 m$^2$. Holding total floor area constant, generic office designs presented varying footprint areas for a given number of storeys. For instance, the building design having 2 and 4 storeys occupied 500 m$^2$ and 250 m$^2$ of floor area per storey, respectively. For each storey, the perimeter dimensions of L-shape plan, which has 4 parameters, were determined randomly using Microsoft Excel Solver. Unlike others, the current study considered and offered simplified, if not detailed, layout solutions for the proposed designs. In total, 5 different layout solutions for each number of storeys were created as base models (Figure 2). This led to creating variety of space types, such as offices, circulation, meeting rooms, and restrooms that were practically subject to different occupancy conditions and must be represented by different thermal zones for the purpose of energy simulation. More, assigning separate thermal zones to each space, made it possible to generate designated illuminance maps, daylighting controls, and glare sensors for detailed daylight simulations.

Design parameters, that were subject to vary, were restricted in consistent with the time-point of our investigation, in this case conceptual design phase. At this stage, design responsibilities of an architect involves in creating schematic elevations in consistent with several layout solutions based on building program. Accordingly, optimisation of building envelope parameters, such as fenestration ratio, is the major interest when the target is to maximise building performance at the conceptual design stage. Therefore, decision variables that are relevant to building envelope was the primary concern of this investigation, and listed as:

- Fenestration ratio (X1): Ratio of window area to external walls area
- Overhang projection factor (X2): Ratio of length of overhang to the height of the windows
- U-value of external walls (X3): Heat transfer coefficient of external walls construction in W/(m²·K)
- U-value of roof (X4): Heat transfer coefficient of roof construction in W/(m²·K)
- U-value of windows (X5): Heat transfer coefficient of window construction in W/(m²·K)
- Number of storeys (X6): Number of storey count for a given design
- Footprint area (X7): Average floor area in square meters
- HVAC type (X8): A choice of pre-defined HVAC type in OpenStudio.

Facility type was selected as Office which introduces 16 space types and 1 construction set. Climate zone of the study location was determined as 3C based on standard climate zone definitions offered by American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE). Further, EnergyPlus database introduced detailed weather data used in this study for the location of interest. According to the selected climate zone and facility type, default constructions were assigned. Based on the space types that are present in the generic designs, occupancy, electrical equipment, and interior lighting loads and rule set schedules were defined. Shading elements, when present, were introduced to the sub surfaces of windows in East, South, and West cardinal directions. The clear intent to include HVAC type (X8) as one of the decision variables was to provide the architect an intuitive idea regarding the type of HVAC that outperforms the alternatives (see Table 2). This, in turn, may offer the architect vital information regarding sizing requirements of HVAC system which in practice is useful to eliminate...
design clashes. Parameters of the HVAC systems, on the other hand, was beyond the scope of our investigation and therefore their default setting were utilised. Initial values and range of decision variables for the base models were further presented in Table 1.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>Base-case value</th>
<th>Unit</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>Fenestration ratio</td>
<td>0.20</td>
<td>-</td>
<td>0.20 – 0.70</td>
</tr>
<tr>
<td>X2</td>
<td>Overhang projection factor</td>
<td>0.00</td>
<td>-</td>
<td>0.00 – 0.70</td>
</tr>
<tr>
<td>X3</td>
<td>U-value of external walls</td>
<td>0.65</td>
<td>W/(m²·K)</td>
<td>0.10 – 0.80</td>
</tr>
<tr>
<td>X4</td>
<td>U-value of roof</td>
<td>0.23</td>
<td>W/(m²·K)</td>
<td>0.10 – 0.80</td>
</tr>
<tr>
<td>X5</td>
<td>U-value of windows</td>
<td>6.4</td>
<td>W/(m²·K)</td>
<td>0.8 – 6.4</td>
</tr>
<tr>
<td>X6</td>
<td>Number of storeys</td>
<td>1</td>
<td>-</td>
<td>1 – 5</td>
</tr>
<tr>
<td>X7</td>
<td>Footprint area</td>
<td>1,000</td>
<td>m²</td>
<td>200 – 1,000</td>
</tr>
<tr>
<td>X8</td>
<td>HVAC type</td>
<td>7</td>
<td>-</td>
<td>1 – 7</td>
</tr>
</tbody>
</table>

OpenStudio platform provides simultaneous consideration of performance measures using Radiance and EnergyPlus. According to the simulation workflow of OpenStudio, first daylighting analysis was carried. Following, the outputs of Radiance analysis were fed as the inputs of EnergyPlus; hence energy consumption is influenced by the daylighting conditions of the building. To further observe the effect of daylight analysis on the energy consumption, a comparison was made between two simulations having identical properties. The energy simulation in the absence of daylighting analysis presented a uniform distribution of interior lighting consumption throughout the year, which violates the common sense. Opposing, the energy simulation in the presence of daylighting analysis was able to capture the role of daylighting on interior lighting loads as the interior lighting consumption of the model dramatically decreased during the summer season. Considering heating and cooling consumptions, similar trends were observed. Thus, daylighting analysis contributed towards gathering realistic, and reliable numerical results from energy simulations as well as being one of the major objectives of the current study. It should be noted that the effects of thermal stratification within each room have not been taken into account.

<table>
<thead>
<tr>
<th>HVAC Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type 1</td>
<td>Packaged rooftop unit</td>
</tr>
<tr>
<td>Type 2</td>
<td>Packaged rooftop heat pump</td>
</tr>
<tr>
<td>Type 3</td>
<td>Packaged DX rooftop VAV with reheat</td>
</tr>
<tr>
<td>Type 4</td>
<td>Packaged rooftop VAV with parallel fan power boxes and reheat</td>
</tr>
<tr>
<td>Type 5</td>
<td>Packaged rooftop VAV with reheat</td>
</tr>
<tr>
<td>Type 6</td>
<td>VAV with parallel fan powered boxes and reheat</td>
</tr>
<tr>
<td>Type 7</td>
<td>No HVAC – Ideal air loads</td>
</tr>
</tbody>
</table>

Simulations were run annually, on hourly basis. Changing the value of the decision variables in the given range, 21 simulations were run for each storey level with individual layout solutions. This aggregates to the total number of 105 simulations, which corresponds to the size of the sample to be employed for subsequent development of objective functions. Simulations were run using a personal computer having Intel® Core™ i7-4510U CPU@ 2.60GHz processor, 8 GB of installed memory, and 750 GB HDD hard drive. The computational cost to run one simulation was measured approximately between 20 and 25 minutes, based on model properties such as number of thermal zones and illuminance maps.
Table 3 presented descriptive statistics of the response variables, in this case annual energy consumption in kWh ($Y_1$) and building average daylight autonomy ($Y_2$), for the generic office building after 105 simulations. Results of Anderson-Darling test suggested that the normality for both variables were slightly violated. Repeating the design of experiment for a large count, one can be 95% confident that the true mean of annual energy consumption and building average daylight autonomy would lie between 89,030 kWh to 96,111 kWh, and 0.39 to 0.42, respectively. Given the significant level of difference between simulation scenarios, the large variance within the responses were of no surprise. More, this reinforced the motive to employ machine learning techniques over traditional statistical methods towards development of objective functions, which was further reported in Section 3.

<table>
<thead>
<tr>
<th>Var.</th>
<th>N</th>
<th>A-squared</th>
<th>p</th>
<th>Mean</th>
<th>St. Dev</th>
<th>Min.</th>
<th>Max.</th>
<th>95% Confidence Lower</th>
<th>95% Confidence Upper</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y_1$</td>
<td>105</td>
<td>1.11</td>
<td>0.006</td>
<td>92,570</td>
<td>18,295</td>
<td>59,202</td>
<td>144,493</td>
<td>89,030</td>
<td>96,111</td>
</tr>
<tr>
<td>$Y_2$</td>
<td>105</td>
<td>0.82</td>
<td>0.033</td>
<td>0.405</td>
<td>0.089</td>
<td>0.196</td>
<td>0.555</td>
<td>0.387</td>
<td>0.422</td>
</tr>
</tbody>
</table>

2.2. Development of objective functions

We defined two objective functions for the problem at hand, namely minimization of energy usage and maximization of the Daylight Autonomy metric. These quantities were initially established through simulation using validated tools, and subsequently approximated, through the use of an approximation model, which was used during optimization. We have used Feedforward Artificial Neural Networks (FANN) for function approximation of the objective functions, and train them using an improved version of the Backpropagation algorithm (Rumelhart et al., 1988), termed Resilient Backpropagation (RProp) (Riedmiller and Braun, 1993).

FANNs are a well-established machine learning technique, which has been applied to a variety of learning and approximation tasks. The computation in FANNs forms an abstraction of the function of the biological neurons in the human brain; a series of layers of densely connected neuron-like processing units propagate the input signal until it reaches the output. Each neuron in every layer except the input receives a weighted sum of the output of the previous layer, and performs a transformation on it. The transformation used is in many cases non-linear, which enables the network to provide good approximations to non-linear functions. Different compositions of neuron weights result in different patterns of neuron activation for a given input signal, as such the weights in the network are said to encode the knowledge of the network. The signal is ultimately presented to the output layer, where it may be obtained by reading the values of the nodes on that layer. It is typical for most networks to include one or two hidden layers.

FANNs offer much of their popularity and success to the rigorous mathematical underpinnings associated with the training algorithms used to derive the compositions of the weights. In particular, the Backpropagation algorithm offers an efficient and fast way of calculating the gradients for a specific set of network weights, and therefore enables optimization of the network to be carried out using simple gradient descent algorithms. For this study, we made use of an improved version of the Backpropagation algorithm, termed Resilient Backpropagation (RProp), (Riedmiller and Braun, 1993). In RProp, the partial derivatives of the weights are used to dictate the direction of search, however the step size is disconnected from the gradient, and follows a rule of incremental augmentation, until a
valley is reached, where the step size is reduced and inversed. RPRop offers a significant improvement in speed and helps come over some difficulties encountered in regular Backpropagation learning.

We have chosen to employ two separate models for each of the objective functions, energy consumption and daylight autonomy. FANNs have a number of parameters that need to be established to ensure optimal model generalization. These are the number of hidden layers, the number of nodes in each layer, the training iterations and the regularization factor (\(\lambda\)). Determining these parameters was not a trivial task, and as such heuristics were used in many cases. In our case, we performed a simple grid search over the parameter space, and tested the performance in 10-fold cross validation with five repetitions per fold. For each set of parameters, we tested network generalization using a 10-fold Cross Validation. That is, we split the training samples randomly in two sets, of 100 and 5 samples, respectively, trained on the first and used the resulting model to predict the second, recording the mean prediction performance. This process was repeated for the remaining nine out of ten sets. We made use of the Coefficient of Determination, \(R^2\), to evaluate the performance of the model:

\[
R^2 = 1 - \frac{\sum_{i=1}^{N} (y_i - f_i)^2}{\sum_{i=1}^{N} (y_i - \bar{y})^2}
\]

In equation (1), \(y\) is the actual value, \(f\) denotes the model prediction and \(\bar{y}\) corresponds to the sample mean of the actual values. In the best models identified, we have obtained an \(R^2\) value of 0.958 for the Daylight Autonomy approximation, and 0.922 for the Energy Consumption approximation. Both represent 10-fold cross-validation results, and are as such indicative of the model’s generalization capability. These values were deemed satisfactory for our purpose. The established network characteristics for the optimal energy consumption model are: single hidden layer with five nodes, training iterations 8000, regularization factor (\(\lambda\)) 0.0001. The established network characteristics for the optimal daylight autonomy model are: single hidden layer with five nodes, 5000 training iterations, and regularisation factor 0.0001. As a final step, we trained the models with the established optimum parameters on the training dataset of the 105 examples, and transferred the model parameters to the optimization environment for inclusion in the objective function definition.

2.3. Optimisation

In the current study, we made use of Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) in order to search for best trade-off solutions. NSGA-II is a Multi-Objective Evolutionary Algorithm (MOEA), developed by Deb et al. (2002) at Kanpur Genetic Algorithms Laboratory. It is acknowledged as one of the most preferred MOEA for not only to enhance the results of benchmark problem in the field of computer science, but also to deal with complex real-world problems. The key features, which take a step forward to this algorithm, are non-dominated sorting procedure, crowding distance calculation, diversity preservation, elitism, and genetic operators. We formulated the optimisation problem to minimize \((Y_1)\) and maximize \((Y_2)\), which were driven by the estimation models subject to decision variables.

Figure 3 illustrated sequence steps of NSGA-II. As first step, in compliance with each member’s non-domination, the parent population was sorted. During this step, a value, which was assigned to each individual, presents its rank in the population. Afterwards, all the population members were sorted by combining the number of solutions dominating, and positions to solutions that were dominated with any member in the population. Regarding to discrete sets of the population members in the Pareto ranking, this procedure went on. In the second step, for each population member, crowding distance
was computed by considering average distance of two individuals. In order to execute this step, we sorted population in accordance with the value of each objective function. Third step is creating the mating pool by selecting individuals from the parent population. This step went on until the mating pool is filled. Fourthly, mating pool individuals were exposed to genetic operators in order to arrange the next generation. Finally, the elitism, which kept the current and previous population members, was performed. Individuals, belonging to the first rank, were included as much as possible.

![NSGA-II optimisation loop](image)

**Figure 3: NSGA-II optimisation loop**

3. **Computational Results**

We determined the population size as 500 to observe many non-dominated alternatives in the Pareto-front as well as to show the significance of settled approach in terms of computational cost. Throughout the optimization process, we noted that Pareto-front has not performed any alteration after 30 generations. After the verification of convergence with different runs, we decided to take 50th generation into account. In accordance with computational cost assessment, we measured that the computer spent 2.4 minutes for the all function evaluations that equals to multiplication of population size and generation count. That is, the method settled for this study was capable to evaluate 25,000 alternatives in terms of energy and daylight performance in such a short time. Using conventional simulation approach, time necessary to complete the same operation would be approximately 340 days. Therefore, a dramatic reduction in computation cost was achieved. More, conducting systematic comparison among all alternatives would take an extra effort when conventional simulation is considered. In contrast, using MOEA provided to observe all the alternatives in a systematic way. The architect is able to observe the trade-off relationship between two objective functions in the final set of solution, which is shown in Figure 4. We note that y-axis denotes value of 1-building average daylight autonomy.
4. Discussion

The results indicated annual energy consumption and daylight autonomy values of optimum solutions varied between 61,229 kWh and 94,304 kWh, 0.30 and 0.53, respectively. Based on computational results office designs having 3, 4 and 5 storeys provided optimum solutions towards minimising energy and maximising daylight. Bearing in mind that all designs have identical total floor areas of 1000 m², the footprint area decreases as the number of storeys increases. Therefore, the ratio of daylight penetration into the building substantially increases, when the design offers 3 storeys height or above, which had a major role to satisfy objective of daylight maximisation. Energy consumption, on the other hand, presented a more complex behaviour with the changing number of storeys. We observed, enhanced provision of daylight caused a significant decrease in the energy consumption associated with interior lights and heating; whereas cooling consumption showed an increase. Since the target was to minimise energy consumption, we deduced that decrease in interior lights and heating consumption surpassed the energy loss caused by additional cooling demand in these cases.

Considering the fenestration ratios, we observed the optimum design solutions having 4 and 5 storey height offered the maximum value of 0.7 within the range of our investigation. Due design of experiment, overhang size increased as the fenestration ratio increases. Therefore, these solutions having maximum fenestration enjoyed protection from direct excessive sunlight, which led to a substantial gain in cooling consumption. The solution set of 3 storey buildings, on the other hand, presented rather a stimulating pattern. For this particular storey height, fenestration ratio of non-dominated solutions varied between 0.2 and 0.7, corresponding to all possible values within the search space. In this set of solutions, U-value of external walls and windows were also minimised, taking values of 0.1 and 0.8, respectively. Increasing the fenestration ratio had a negative impact on energy consumption and positive impact on daylight autonomy as we observed both values of optimisation targets increased. This suggests the loss in cooling consumption surpasses the gain in interior light and heating consumption for this particular set of solutions. What is more, the outcomes of optimisation process strongly underlines the vital role of computational optimisation towards observing the trade-off between optimisation targets when values of multiple decision variables were varied in a simultaneous fashion.
On observing the distribution of HVAC systems, we noted that there are two types of systems selected: Type 2 – Packaged Rooftop Heat Pump, and Type 6 – VAV with Parallel Fan Powered Boxes and Reheat, as defined in Energy Plus. It seems that this choice of systems leads to more favourable energy performance overall for the types of offices that we consider. What is more interesting even, is that the Type 2 systems dominate solutions in the three and four storey range, with limited five-storey solutions demonstrating use of this HVAC type. At the same time, five-storey solutions demonstrate mainly use of Type 6 HVAC. This may only lead to the conclusion that Type 6 HVAC proves to be more efficient in certain building types. While a detailed consideration of reasons behind this phenomenon is beyond the scope of this paper, we may indicate as reasoning for it the different requirements in heating and cooling that are introduced by the different building forms and, to a lesser extent, by the different fenestration ratios. For instance, one may consider that the narrow five-storey layout, with large glazed surfaces, and long shading overhangs faces a bigger problem of energy losses during the winter, and less so a problem of overheating in the summer; this creates different conditions for HVAC system efficiency, and thus may explain the choice of different systems.

Last but not least, we estimated the trade-off function between annual energy consumption and building average daylight autonomy using non-linear regression method. The intent was to increase practical relevance of the main findings by offering the architect the ability to determine optimum daylight autonomy level of a proposed office design for a given value of energy consumption. Type of relationship between independent variable of energy consumption and building average daylight autonomy follows a concave shape that best fits to a model with three parameters. Our analysis yielded following empirical model:

\[
\text{daylight autonomy} = 0.5335 - 0.2540 \times \exp(-11.2587 \times \text{energy consumption})
\]  

Where energy consumption values were standardised to the values between 0 and 1 with the intent of a better fit. In the proposed equation, the model parameters converged after 11 iterations. The final sum of squared errors and mean squared errors were 0.004 and 0.000008, respectively, offering a flawless fit towards explaining the trade-off relationship.

5. Conclusions

In the current work we offered an optimisation methodology based on combination of multiple techniques, namely, simulation, artificial neural networks, and multi-objective evolutionary algorithm. Using generic office designs, 105 simulations were run to gather the database for the subsequent development of objective functions. After 10-fold cross validation, ANN models were able to explain 96% and 92% of variance in annual energy consumption and building average daylight autonomy, respectively. Therefore, high level of prediction accuracy in the objective functions was achieved. Through optimisation process 25,000 design alternatives were evaluated by using NSGA-II algorithm in 2.4 minutes. This corresponds to a dramatic reduction compared to 340 days when one elect to use conventional simulation tools. We discussed the influence of number of storeys, footprint area, U-values, HVAC type, fenestration ratio, and overhang projection factor on objective targets of the current work in a simultaneous fashion. Our findings suggests office designs having 3 to 5 storeys height, with varying fenestration and overhang ratios, utilised Packaged Rooftop Heat Pump and VAV with Parallel Fan Powered Boxes and Reheat provided the near optimum solutions. Since the cost of construction, as an objective function, was not included in the current work, we observed the algorithm converges to solutions having minimum U-values, as expected. We note this as a limitation which shall be addressed.
in the future study. Lastly, the trade-off function between optimisation targets were determined to offer further practical relevance. Using provided equation (2), we offer an architect the ability to determine the optimum level of daylight autonomy of an office design for the given annual energy consumption.

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Overcoming the “black box” approach of urban metabolism

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Abstract: Urban areas cover 2% of the Earth’s land surface, while hosting more than half of the global population and are estimated to account for around three quarters of CO2 emissions from global energy use. In order to mitigate existing and future direct and indirect environmental pressures resulting from urban resource use, it is necessary to investigate and better understand resource and pollution flows associated with urban systems. Urban Metabolism (UM) is an urban environmental assessment framework that measures resource and pollution flows that enter and exit urban systems. However, UM presents an important shortcoming, namely its “black box” approach. Indeed, standalone, UM figures are not enough to explain why they are specific and exclusive to a city and whether this city is heading towards a more sustainable state. In this study, four transversal aspects that attempt to overcome this “black box” approach are presented. These additional layers of understanding include temporal evolution, spatialisation and disaggregation, identification of resource use and pollution drivers and finally the indirect resource use and pollution emissions that occur outside of the urban boundaries.

Keywords: Urban metabolism; temporal evolution; spatialisation; embodied impacts.

1. Introduction

While urban areas cover only 2% of the Earth’s land surface (Balk et al., 2005), they now host more than 50% of the global population and are estimated to account for 71-76% of CO2 emissions from global final energy use and between 67-76% of global energy use (Seto et al., 2014). In fact, cities can be seen as the complex expression of a global-local articulation in an ever globalising world and economy. Cities are the nexus of global and local challenges ranging on the one hand from climate change, degradation of ecosystem services, global financial crises and global conflicts due to resource scarcity; to unemployment, city cleanliness, and housing affordability on the other hand. In environmental terms, cities or urban systems are hotspots of resource consumption, that mobilise material and energy flows from around the world in order to match its inhabitants’ needs. Considering that the urban population is likely to continue to increase, especially in developing countries, it can be expected that cities will continue to be created and expanded to host this additional population. The creation and expansion of
cities in the near future will require a considerable amount of new urban infrastructure, resulting in significant demand for natural resources and further exacerbating existing environmental pressures.

In order to mitigate existing and future direct and indirect environmental pressures resulting from the functioning of cities, it is necessary to investigate and better understand how resource flows are associated with the urban system. Urban Metabolism (UM) is an urban environmental assessment framework that measures resource and pollution flows that enter and exit the urban system. While the urban metabolism field is now well established and is continuously evolving either with new accounting developments or with new case studies, it still has a number of shortcomings (Golubiewski, 2012). The most significant limitation of the UM framework, is its “black box” approach. In other words, UM only provides a synthetic environmental profile of a city with no reference to the local specificities and the drivers that govern these resource and pollution flows.

This study proposes a comprehensive framework for expanding the urban metabolism approach. The framework adds four additional layers of analysis to the traditional UM approach, namely, the temporal evolution, spatialisation, the assessment of indirect environmental effects, and the identification of metabolic drivers. Thus, this framework will provide a context-specific and spatio-temporal analysis that will attempt to shed some light on the complex behaviour and environmental effect of an urban system. This complex analysis is not only necessary to propose coherent and comprehensive environmental policies but is also useful in order to model and forecast the future metabolic state of the studied urban system.

This paper is structured as follows. The next section will briefly present the current UM framework as well as some strengths and weaknesses. The four aspects proposed to overcome the “black box” approach of UM will then be presented followed by the elaboration of a more complex urban environmental assessment framework. This study will conclude by discussing some limitations and future pathways for investigation.

2. Urban Metabolism: a brief definition

While the first use of UM from Marx date back to late 19th Century to describe the material relationship between humans and nature, this metaphor has been employed by a great number of disciplines ranging from social theory, to cultural and ecological anthropology and social geography, to finally urban environmental assessment (Ayres and Ayres, 2002). However, the first study that used the UM metaphor in order to assess the environmental impact of a city was the one of Wolman (1965). Since then, more than 75 UM studies have been carried out, of which 20 were relatively comprehensive (Kennedy and Hoornweg, 2012).

In contrast with other environmental accounting tools such as Life Cycle Assessment, Economy Wide-Material Flow Analysis (EW-MFA) and Input-Output Analysis (IOA), UM still lacks a common definition or methodology (Ioppolo et al., 2014). Instead, UM has been used as an accounting framework rather than a methodology per se and could be described as a “large data collection exercise” (Kennedy, 2012). These data or metabolic flows are divided into three main categories: inputs (e.g. energy, materials, water, etc.), outputs (e.g. solid, pollutants, materials, etc.) and stocks.

This being stated, UM has become a central tool to understand and address urban resource and waste flows. Indeed, the comprehensive approach of UM treats each resource, emission and waste flow individually and with its appropriate unit providing governments and administrations with more relevant data to implement relevant urban environmental policies. In addition, UM’s loose framework allows it to adapt to specific characteristics of each case study such as administrative boundaries. This flexibility of
the UM framework and the pool of case studies that make comparisons between urban systems possible (although accounting methodologies and available data differ from case to case) make UM perhaps the most relevant accounting framework at the urban scale.

However, UM still presents a number of shortcomings that hinders its acceptance amongst researchers. A number of drawbacks of UM are very similar to EW-MFA such as the “black box” approach (Golubiewski, 2012). The elaboration of an UM does not capture the complexity and interrelationship between internal mechanisms from neither social nor economic activities while it can be argued that it is impossible to separate urban metabolism from its urban characteristics due to their constant interrelationships (Pincetl et al., 2012). Finally, as UM only measures all flows entering and exiting the urban boundaries it does not take into account the environmental effects over its global hinterland embodied in trade (Baynes and Wiedmann, 2012). This can highly overestimate the “sustainability” of a city and lead to misleading environmental policies (Baynes et al., 2011).

3. Some transversal aspects to overcome the “black box” approach

Aside from the accounting framework used during the environmental assessment of cities, some transversal aspects are needed to comprehensively include the complexity of their functioning. Indeed, cities are not static, homogeneous and isolated systems. They perpetually and dynamically evolve from external and/or internal forces. The interrelationship of urban system components (such as society, economy, the built environment, politics, etc.) can influence its overall environmental effect. On the other hand, the use of natural resources and the emissions generated by a city could have a considerable influence on some of the urban components. Finally, in the present globalized economy, cities are reliant on a global hinterland in order to meet their resource use and waste disposal. This section will briefly present four perspectives to better understand the environmental state and effect of cities and how to overcome the “black box” approach of UM.

3.1. Temporal evolution

The first element necessary to better understand current and near future resource consumption and their environmental effects, is a time series evolution of resource use. In fact, by constructing the resource use trajectory, it is possible to understand several aspects of urban consumption. Firstly, a temporal evolution enables the positioning of an environmental assessment on a timeline. Instead of analysing a snapshot of a city’s consumption, it is possible to situate a punctual assessment on a trajectory that will reveal if this urban system is heading towards a more sustainable state. Another valuable aspect that a time-series assessment offers, is the identification of structural changes and eventually the drivers of these changes (Krausmann et al., 2009). The structural change in consumption pinpoints not only technological innovations but also an evolution of urban infrastructure and consumption behaviours. A further element that temporal evolution of urban environmental assessments enables, is to confirm whether implemented policies had the desired effect or not. Finally, constructing the temporal evolution of the environmental state of a city and identifying its main trends can ultimately help to forecast future consumption and environmental effects. However, in practice, time-series assessments are seldom available for UM studies due to their data intensive nature.
3.2. Spatialisation

Another fundamental aspect that needs to be incorporated in UM studies, in order to avoid seeing cities as static and homogeneous entities, is spatialisation. By mapping metabolic flows it is possible to discern how consumption is distributed across an urban system. The emergence of different consumption patterns pinpoints different land uses; territorial organisations; infrastructures; economic activities; but also different consumption patterns (Howard et al., 2012). Thus, mapping urban consumption can lead to a preliminary identification of drivers and measure the efficiency of territorial organisations. An additional issue that can be addressed with the spatialisation of results, is that not all territorial units face the same consumption and environmental issues and therefore do not assign the same importance and priority for these challenges. To overcome this issue, spatial analysis should therefore be supplemented by a multi-scale analysis (Munksgaard et al., 2005). Multi-scale analysis, can in fact illustrate more comprehensively the full environmental effects of cities and give a better understanding of which are the most important drivers at which scales. Nonetheless, similarly to temporal evolution, the major issue of mapping urban consumption is the availability of data at different and especially small territorial scales.

3.3. Measuring indirect environmental effects of cities

The third aspect that it essential to include, in order to take into account that cities are not isolated systems, is the assessment of indirect environmental effects of cities. Accounting for the resource use and environmental effects embodied in trade is not only important to provide a full environmental profile, but also to map the complex environmental effects of urban consumption across the global economy and its supply chains (Kanemoto and Murray, 2013). In reality, calculating the indirect environmental effects of cities can be proven to be extremely difficult. To perform this calculation it is necessary to use household expenditure data at a city level and combine it with an Input-Output Table (IOT) at a city level to measure the local direct and indirect effects of local consumption. The local IOT should then be linked with a Global Multiregional IOT in order to measure the direct and indirect effects of local consumption at a global scale. To our knowledge, except for the work developed by the Australian IELab (Lenzen et al., 2014), IOT at such level are not available at an urban scale. This implies that so far, it is only possible to obtain such results based on regional or national averages of production and consumption figures (Baynes et al., 2011).

3.4. Identification of drivers

The last aspect that is necessary to add to the current UM framework, in order to make it more relevant for urban systems and for more informed decision-making when it comes to environmental pressure, is the identification of drivers. In reality, the identification of drivers is a major step towards a better understanding of urban resource use and the intertwined relationships that exist between components of a city mobilizing matter and energy; but also between the city itself and its wider environment. The relationship between resource use and local factors helps to contextualize environmental assessments and determine why such figures are exclusively valid for one city (Pincetl et al., 2012). This is especially relevant for the urban scale which is an amalgam of economic, social, cultural, political and many other forces that constantly evolve, thus making each urban system unique and incomparable to any other.

In addition, identification of drivers is a necessary step towards context-specific solutions and policies for mitigating our environmental impact. In fact, different case studies identify different local
Overcoming the “black box” approach of urban metabolism factors as predictors of resource use and pollution emission ranging from territorial organization, climate, income, age, number of persons per household, lifestyle, etc. (Heinonen et al., 2013; Wiedenhofer et al., 2013). However, it is important to keep in mind that the results of this identification of drivers are very different at a macroscale (city scale) compared to a microscale (smaller spatial scales such as municipalities). For instance, Kennedy et al. (2015) find that while urbanized area per capita is strongly correlated with energy use at a macroscale, this correlation is less significant at a microscale.

Finally, a regression analysis between resource use, pollution emission and local factors, greatly depend on the indicators used. In fact, correlation of direct or indirect resource use with local factors can give completely different results (Wiedenhofer et al., 2013). Hence, when identifying drivers, it is necessary to consider a variety of indicators and metrics to best reflect the environmental state of a city (Ramaswami and Chavez, 2013).

4. Establishment of a comprehensive urban metabolism framework

After briefly presenting the UM framework along with its main strengths and weaknesses, the previous section identified four layers that should complement UM in order to achieve a more comprehensive and insightful understanding of the environmental state of cities. This section will in turn attempt to integrate the current UM approach with these four layers in order to establish a more comprehensive UM framework. This comprehensive UM framework illustrated in Figure 1, indicates a number of steps that can help to better comprehend the complex behaviour of cities in terms of resource use and environmental effect.

![Figure 1: An overview of a comprehensive urban metabolism framework. Note: UM: Urban Metabolism, IOA: Input-Output Analysis, TEMP: Temporal evolution, SPAT: Spatial analysis, DRIV: Identification of drivers. Dark grey boxes represent the UM approach, while light grey represent the IOA approach. Numbers in dotted circles represent the combination of UM and IOA approaches while numbers in solid line circles indicate that approaches where considered separately.]

4.1. Including temporal and spatial dimensions for a better understanding of UM drivers

The first and most important step (I) as the base of a complex urban environmental assessment is to carry out a comprehensive UM with as many flows as possible and when possible disaggregated by
sectoral use. Based on this UM study it is possible to trace the temporal evolution (II) of each flow enabling the identification of any significant trend. Comparing the temporal evolution of different metabolic flows enables an understanding of whether the needs of an urban system change over time, if there has been any structural change (e.g. due to a technological innovation), if there has been an economic shift towards primary, secondary or tertiary activities or finally the effect of mitigation or efficiency policies on metabolic flows. Similarly, spatialisation (III) of a comprehensive UM would also help to investigate whether the urban system is a homogeneous entity or if each spatial scale has different patterns for each of the resource use and pollution emissions flows considered.

While establishing temporal evolution and a spatial evolution of the current UM framework adds two new dimensions of understanding, these additions do not enable the identification of underlying drivers of the metabolic flows. Indeed, steps (I), (II) and (III) are more descriptive than analytical. However, it is important to note that without the temporal and spatial elements, it would be impossible to search for local drivers. In order to find any relationship between a metabolic flow and a socio-economic or territorial organisation factor there needs to be at least two values for each metabolic indicator. Depending on the statistical test, the number of values needed to establish a relationship between metabolic indicators and local factors can vary and reach up to several hundreds.

Temporal evolution of local factors data is usually available through census and surveys data or from reports elaborated from the appropriate administration. However, surveys and census are very time consuming and therefore their periodicity can vary from yearly up to intervals of 10 years. In addition, in some cases, the questions asked or indicators measured within surveys and census may change over time. Finally, a more delicate issue is that the spatial classification within which data is collected or the urban boundaries may vary over time, creating thus a discontinuity within a longitudinal analysis. In practice, long-term annual time-series are only available if the urban boundaries correspond with administrative boundaries and both have been unchanged for this period of time.

In any case, identifying the effect of local drivers on the temporal evolution of an UM (IV) can provide insightful information about the relationship between the urban development of a city and the associated metabolic flows needed at each stage of this development. The results could also be helpful to estimate the resource use and pollution emission of other cities that will undergo similar stages of urban, demographic, economic and social development.

Establishing a statistical relationship from a spatial perspective on the other hand, implies that data values should be available for a large sample of spatial entities. In this study, two options for spatialising an UM are explored. The first option of a spatialised UM could be achieved by disaggregating UM into smaller spatial entities. For the statistical relationship to be meaningful, the division of the urban system into smaller spatial entities should be carried out in a way that all units should have a comparable number of inhabitants but also homogeneous social and territorial characteristics, i.e. a similar land-use, building typologies, socio-economic and socio-demographic profiles. Similarly to the temporal case, disaggregated and meaningful local data can be easy to obtain through national, regional or urban census and surveys. However, metabolic data at smaller urban scales are very difficult to obtain due to the sensitivity of these data. In order to obtain accurate data for energy and water (this is not possible for other materials), it is necessary to access data from energy and water suppliers or grid operators. In a number of cities, the energy and water market is owned by one or a number of public and/or private companies. Therefore, mapping the metabolism of an entire city could reveal to be the difficult task of putting together a patchwork of confidential data. However, the results from a correlation at a spatial scale would be of great importance as it could identify patterns of consumption or pollution of different
local socio-economic and socio-demographic profiles as well as building typologies, land use, population or built-up density.

Another way to take into account the spatial element of UM is by doing a multi-scale analysis where different administrative scales are considered ranging for instance from household or neighbourhood, to urban and metropolitan scale or even national scale. This would complement the traditional metabolic approach with a micro- and macro-scale analysis. However, obtaining data at different spatial scales from the same data source, for the same year or with the same periodicity can prove to be quite difficult. In addition, in many cities, the metropolitan scale is a geographical delimitation convention more than an administrative entity that collects data. Ideally, to obtain an accurate multi-scale analysis regardless of whether the spatial boundaries considered coincide with administrative data, it would be necessary to have precise data at the smallest spatial scale possible and then aggregate this data for all the larger spatial scales. The issues of obtaining data at smaller spatial scales were presented, however, in practice, to achieve a multi-scale approach it is often necessary to combine top-down and bottom-up data. Nevertheless, identifying multi-scale metabolic drivers helps to manifest the complex interrelationship between all the nested spatial entities that compose an urban system as well as the importance of the global hinterland for the provision of natural resources and the disposal of waste. This helps to stress that cities are not isolated systems and that while spatial entities can be nested they face different sustainability challenges and priorities at each spatial scale.

To sum-up, identifying metabolic drivers from a spatial perspective (V) highlights that there is no one-size-fits-all policy for every territorial scale. Indeed, each spatial entity has a different metabolic profile that can be influenced by a different set of local factors. In addition, a statistical relationship for a given territorial scale is not necessarily true for another one. Thus, applying a similar policy for the entire city or metropolitan area may lead to conflicting, counter-productive or even non-desired results.

4.2. Combining temporal and spatial dimensions

The previous section considered the benefits of adding temporal and spatial perspectives for the identification of metabolic drivers and therefore for a more comprehensive understanding of the UM of cities. The present section will discuss the relevance of combining these two layers to obtain a more context-specific analysis (steps (VI) and (VII)). Similarly to the two options available for the spatialisation of UM, there are two options for combining a temporal and spatial approach. In addition, the data limitations presented for each of the options are also relevant here.

The first approach to combine spatial and temporal perspectives is to perform a temporal evolution of a disaggregated UM into smaller spatial entities. This approach would essentially need the same data as the first spatialisation option but for several points in time. Indeed, if metabolic data at smaller spatial scales are previously accessed through energy and water suppliers or grid operators, obtaining them for a series of years (or even months) should be an easy task. However, as these data are only available through digital databases of suppliers or grid operators, the available data over time could be limited. In addition, as energy and water companies may supply and operate different areas over time, the temporal evolution of spatially disaggregated metabolic flows can prove to be challenging. On top of that, it is important to consider that geographical classification of surveys and census data also evolve over time which makes it very difficult to carry out a longitudinal study over the same small spatial units. All in all, the identification of drivers using this option of combining temporal and spatial dimensions can enable for instance a deeper understanding of the environmental effects of certain building typologies across their lifecycles. The identification can also help to determine, if the same statistical relationships
between metabolic flows and local factors remains valid for each year of analysis or if they have altered over time. Thus, assessing if local factors have a similar effect on UM over time ensures that the correlation for a given year is not an exception or due to a particular conjuncture.

The second approach is to perform a temporal evolution of different spatial scales UM’s. This approach is confronted with similar limitations from step I to V and with the first approach. The interest of identifying the drivers of an UM temporal evolution at different spatial scales, is to trace changes at micro- and macro-scales and their effect on metabolic flows. These changes can be socio-economic changes such as financial crisis and unemployment; the shift of economic activities from secondary to tertiary; urban sprawl; the introduction of transportation infrastructure projects; etc.

4.3. Combining UM and IOA-based approaches for a better understanding of metabolic drivers

The previous sections (steps I to VII) covered how to add spatio-temporal context to current UM studies and what type of information their corresponding drivers could provide. While such analysis can become very data intensive it should be kept in mind, that so far all metabolic data were direct use of natural resources and emission of pollution. Measuring indirect metabolic flows (VIII) enables the assessment of the overall environmental effect of cities over their global hinterland. This is important especially for a number of cities based on tertiary activities economy that do not import metabolic flows for manufacturing but only import flows necessary to operate the built environment and end products to satisfy the consumption needs of its inhabitants. Similarly, as there are no or few industrial activities present in these urban systems, they do not export (semi-)manufactured goods or particular pollution flows. As primary and secondary activities tend to leave the urban or national boundaries of developed countries, resource use and pollution emission is not typically accounted for within their territory. Combining local and global multi-regional IOTs for measuring indirect metabolic flows will also enable tracing of the origin and destination of input and output flows. This enables a measurement of the span of each flow’s hinterland, showing the dependence and vulnerability of a city. However, as IOA results can have considerable uncertainties, comparing them with UM results (XV) would also help to validate them. In addition, their combination would also enrich UM results by providing information that is not bounded to the urban territorial boundary.

In addition, measuring the temporal evolution of indirect metabolic flows (IX), can illustrate how the evolution of trade can affect the overall environmental profile and hinterland of a city. Identifying the drivers of this temporal evolution (XI) could inform which demographic, socio-economic and urban development indicators have the highest influence on the trade global supply chains. It would also be possible to identify which economic activities and which consumption products add the most pressure to the environment as well as which products are coming from local activities and which from international trade. Comparing the temporal evolution of UM- and IOA-based metabolic flows (XVI) as well as their respective drivers (XVIII) helps to take into account the local and global parameters that influence metabolic flows entering and exiting a city. This also enables the creation of a hinge between global and local conjunctures, helping to understand this complex connection.

Spatialising the indirect metabolic flows (X), would essentially provide information about the environmental effect of household consumption and production patterns at smaller spatial scales. The drivers of this spatialisation could help to inform which socio-demographic and territorial organisation indicators influence household expenditure and thus its environmental effect (XII). Comparing the spatialised UM- and IOA-based metabolic flows (XVII) as well as their respective drivers (XIX) enables a
comparison of the flows used by the built environment and production activities (UM) vs. the flows used by the consumption and production activities (IOA). This can be of great interest as material consumption at small scales is practically impossible to assess for the UM approach. In addition, comparing UM and IOA results at smaller spatial scales would help to further validate the IOA results by expanding the sample of comparisons.

Finally, the four last steps that this comprehensive urban metabolism framework takes into account are the assessment of the temporal evolution of spatially explicit indirect metabolic flows (XIII), the identification of their drivers (XIV), as well as the comparison of the two previous steps with UM results (XX and XXI). The first of these steps can help to explain changes in household consumption patterns and their environmental effects along their global supply chains. Exploring the evolution of these particular drivers may help to understand how urban development and lifestyles are connected with global environmental and socio-economic challenges.

5. Discussion and Conclusion

The extended UM framework presented here, provides a number of steps to overcome the “black box” approach that current urban environmental assessment studies suffer from. This comprehensive framework can provide a vast matrix of information encompassing the complexity that revolves around the UM of cities. However, there are limitations inherent to data and accounting approaches and therefore to all of the steps presented here. In addition, in the use of this wealth of context-specific data and indicators, it is recommended that extreme caution be used as they provide a multitude of slightly different angles to view the metabolism of a city that only when assembled can be used to describe the complex, dynamic, heterogeneous, interconnected and ever-changing character of a city. It should also be noted that more elaborate identification of drivers is possible through more complex statistical analyses such as multivariate analysis and principal component analysis.

To conclude, this comprehensive UM framework creates a solid basis for better understanding cities and their metabolism. Comparing the temporal evolution of spatialised UM and IOA metabolic flows, helps to construct a complex understanding of cities as the articulation of local and global environmental, social and economic challenges. Upon this solid basis it is ultimately possible to create a theoretical model that describes urban systems and urban dynamics within a set of non-linear equations. In turn, this complex UM model could serve to forecast different scenarios of environmental effects based on different policies, socio-economic and territorial organisation inputs. It also serves as an important tool for the sustainable design and management of new and existing cities.

Acknowledgements

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References


Quantitative exploration of winter living room temperatures and their determinants in 108 homes in Melbourne, Victoria

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Abstract: Indoor temperatures are key mediators of housing related health outcomes. In Australia, policy makers have implied improved thermal comfort and better health through more stringent residential energy efficiency, yet empirical evidence is scarce. This study used temperature measurements in the living rooms of 108 detached houses in Melbourne, Victoria, to calculate indoor temperatures indices, assess them against health based guidelines and to explore the association of indoor temperatures with household characteristics and the homes’ energy efficiency AccuRate star ratings. The mean home energy rating was $4.7 \pm 0.82$ AccuRate stars. The mean winter room temperature was a satisfactory $18^\circ$C, yet occasional over- and underheating may have adversely impacted health. Continuous occupation and heater use as well as higher energy costs were significant predictors of warmer living rooms. Star ratings were a poor predictor of indoor temperatures. Possible reasons are discussed. The findings were limited by the small, non-representative sample and the reliance on self-reported fuel expenditure. The findings highlighted that a residential energy efficiency rating tool may need to be complemented by built quality controls and consider the efficiency of the heating system in order to be predictive of satisfactory indoor temperatures. More research into the heating practices of householders is needed.

Keywords: Housing; indoor temperature; energy efficiency, Australia.

1. Introduction

Epidemiological evidence suggests that indoor temperatures are important mediators of health in winter (Howden-Chapman et al., 2012). Determinants of indoor temperatures include outdoor temperatures, the thermal performance of the building fabric, the efficiency of the space conditioning systems (Oreszczyn et al., 2006) and householder practices. Main factors for heating practices are the affordability of fuel and householder preferences (Critchley et al., 2007). Economically disadvantaged householders living in energy inefficient homes may be at risk of ill health if they compromise on
adequate heating (Boardman, 1991; DCCEE, 2013). According to engineering–based models, improved
energy efficiency of dwellings should result in more comfortable indoor temperatures and reduced
heating costs (Oreszczyn et al., 2006).

In Australia, policy makers have implied improved thermal comfort and health benefits from more
stringent residential energy efficiency regulations (Victorian Government Department of Sustainability
and Environment, 2006; ABCB, 2010), yet there is scarce empirical information on the link between
home energy efficiency ratings and indoor temperatures (Williamson et al., 2009). Ratings are expressed
as stars that reflect the dwelling’s heating and cooling demand per square metre of conditioned floor
area with reference to the climatic zone of the new home’s location. The more stars the home is
awarded, the more energy efficient it is deemed to be. Compliance may be demonstrated by adhering to
deeded-to-satisfy rules or by using one of the Nationwide House Energy Rating Scheme (NatHERS)
certified modelling tool such as AccuRate in Victoria. At present the regulations only address the
thermal quality of the building envelope without consideration of the efficiency or control of the space
conditioning systems, fuel costs or fuel choices. In Victoria, energy performance certificates are not
mandatory for residential buildings.

The Australian Commonwealth Scientific and Industrial Research Organisation (CSIRO) conducted an
empirical study into the benefits of residential energy efficiency in Australia. The aim of the Residential
Building Energy Efficiency (RBEE) study was to explore the effects of the introduction of the mandatory
5-Star energy efficiency rating for new homes in 2006 (Ambrose et al., 2013). This study engaged over
100 homes that were built after 2003 in Melbourne, the capital of the state of Victoria. Participation was
voluntary. As part of the study, living room temperatures were monitored for twelve months. This RBEE
data set provided the basis for the present analysis.

While thermal comfort and perceptions of warmth are subjective assessments, guidelines aiming at
protecting occupant health commonly refer to acute exposures and threshold values. The World Health
Organisation recommends a general comfort range for dwellings of 18°C to 24°C (WHO, 1987). Other
sources also recommend temperatures between 18°C and 25°C for health purposes (Santamouris and
Kolokotsa, 2014; Kolokotsa and Santamouris, 2015). The NatHERS energy rating software applies living
room temperature settings for Melbourne between 20°C and 26.5°C (NatHERS, 2013a; b).

This quantitative analysis of the RBEE data pursued two aims. Firstly, the study was to provide a
better understanding of the indoor temperature levels of dwellings in Melbourne in winter. Secondly,
the study was to explore the relationship of indoor temperatures, household characteristics and the
homes’ energy efficiency ratings. The research objectives were to calculate various living room
temperature indices in these homes in winter, to assess them against health-based guidelines and to
statistically test hypothesised determinants.

2. Description of the data

The RBEE data set contained the dwellings’ energy efficiency ratings, their conditioned floor area, the
monitored indoor temperatures, outdoor temperatures obtained from the Australian Bureau of
Meteorology and surveyed household characteristics for 108 detached homes located in the mild
temperate climate zone of Melbourne, where residential energy consumption for space conditioning is
dominated by heating demand (ABS, 2013b). The data used in this analysis was restricted to the three
winter months June to August 2012.
2.1. Dwelling and household characteristics

The dwellings’ mean energy efficiency AccuRate rating was 4.7 ± 0.82 stars, their mean conditioned floor area was 117.4 ± 54.98m². Four out of ten homes were occupied throughout the day. Less than a third of householders felt uncomfortable winter. In general, householders used gas and forced air to heat their homes, with less than a fifth of homes being heated continuously. About two thirds of the respondents reported to pay less than $1500 for electricity and/or less than $1000 for gas. As the RBEE raw data set did not contain information on household income, recourse was taken to the Australian Bureau of Statistics’ Index of Economic Resources (IER) (ABS, 2013a). Postal code-based indices of socio-economic ranking within the state of Victoria suggested that these volunteer households had an above average income. Table provides an overview of the dwelling and household characteristics.

<table>
<thead>
<tr>
<th>Household characteristic</th>
<th>n</th>
<th>%</th>
<th>Household characteristic</th>
<th>n</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Household size (No of persons)</td>
<td></td>
<td></td>
<td>Weekly household attendance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>3.9</td>
<td>Nobody at home in the mornings</td>
<td>10</td>
<td>9.3</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>23.5</td>
<td>Nobody at home in the afternoon</td>
<td>3</td>
<td>2.8</td>
</tr>
<tr>
<td>3</td>
<td>17</td>
<td>16.7</td>
<td>Nobody at home all day</td>
<td>22</td>
<td>20.4</td>
</tr>
<tr>
<td>4</td>
<td>37</td>
<td>36.3</td>
<td>Nobody at home during school hours</td>
<td>26</td>
<td>24.1</td>
</tr>
<tr>
<td>5 plus</td>
<td>20</td>
<td>19.6</td>
<td>Someone is home all day</td>
<td>47</td>
<td>43.5</td>
</tr>
<tr>
<td>Electricity Costs</td>
<td></td>
<td></td>
<td>Gas Costs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;$500</td>
<td>14</td>
<td>13.7</td>
<td>&lt;$300</td>
<td>5</td>
<td>4.9</td>
</tr>
<tr>
<td>$500 - $1500</td>
<td>52</td>
<td>51.0</td>
<td>$300 - $1000</td>
<td>62</td>
<td>60.8</td>
</tr>
<tr>
<td>$1500 - $2500</td>
<td>23</td>
<td>22.5</td>
<td>$1000 - $1600</td>
<td>29</td>
<td>28.4</td>
</tr>
<tr>
<td>$2500 - $3500</td>
<td>10</td>
<td>9.8</td>
<td>&gt;$1600</td>
<td>6</td>
<td>5.9</td>
</tr>
<tr>
<td>&gt;$3500</td>
<td>3</td>
<td>2.9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heater use - frequency</td>
<td></td>
<td></td>
<td>Winter comfort vote</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuously</td>
<td>20</td>
<td>18.5</td>
<td>Cold</td>
<td>10</td>
<td>9.3</td>
</tr>
<tr>
<td>Few hours a day</td>
<td>60</td>
<td>55.6</td>
<td>Cool</td>
<td>22</td>
<td>20.4</td>
</tr>
<tr>
<td>Most days</td>
<td>26</td>
<td>24.1</td>
<td>Comfortable</td>
<td>68</td>
<td>63.0</td>
</tr>
<tr>
<td>Once a week</td>
<td>2</td>
<td>1.9</td>
<td>Warm</td>
<td>8</td>
<td>7.4</td>
</tr>
<tr>
<td>Index of Economic Resources (IER) - deciles within Victoria</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st decile</td>
<td>5</td>
<td>4.6</td>
<td>6th decile</td>
<td>33</td>
<td>30.6</td>
</tr>
<tr>
<td>2nd decile</td>
<td>4</td>
<td>3.7</td>
<td>7th decile</td>
<td>27</td>
<td>25</td>
</tr>
<tr>
<td>3rd decile</td>
<td>1</td>
<td>0.9</td>
<td>8th decile</td>
<td>8</td>
<td>7.4</td>
</tr>
<tr>
<td>4th decile</td>
<td>7</td>
<td>6.5</td>
<td>9th decile</td>
<td>9</td>
<td>8.3</td>
</tr>
<tr>
<td>5th decile</td>
<td>5</td>
<td>4.6</td>
<td>10th decile</td>
<td>9</td>
<td>8.3</td>
</tr>
</tbody>
</table>
2.2. Outdoor and living room temperatures

Outdoor temperatures at the homes’ nearest weather stations were measured at thirty minute intervals by the Australian Bureau of Meteorology. The winter 2012 was characterised as a typical winter. The average meteorological mean temperatures of all three winter months June (9.6°C), July (9.7°C), and August (10.0°C) was 9.8°C, close to the historic average of 9.83°C (Bureau of Meteorology, 2014).

Indoor temperatures were recorded by Thermochron iButton Devices DS1921G with an accuracy of ±1.0°C and a resolution of 0.5°C (Maxim Integrated, 2014). Two data loggers taking alternate half-hourly readings were placed at about head height and away from heating or cooling sources (Ambrose et al., 2013). While readings of sensors on internal walls differ from mid-room air temperatures to which occupants are exposed (Page et al., 2011), following the methods of other studies, e.g. (Kane et al., 2015), they are taken here as proxies for indoor temperatures.

3. Results

3.1. Levels of winter living room temperatures

Descriptive statistics of the dwellings’ logged temperatures provided indoor temperature indices that could be compared with indoor temperature guidelines. Analysis of the data of all homes (N=108) in the statistical software IBM SPSSv22 revealed a mean temperature of 18.0 ± 1.8°C. The minimum temperature recorded was 6.0°C, the maximum temperature 36.0°C. On average the temperatures recorded in the individual homes ranged by 13.9 ± 3.2°C. Mean daily indoor temperatures were dependent on ambient conditions with a slight rise when mean daily outdoor temperatures dropped below 6°C (Figure ). This may have been due to a change in householder practices on very cold days or due to the small number of cases from which these temperatures were calculated which may have affected the robustness of the outcomes.

Under- and overheating was a common occurrence (Table 2). Exposure to low temperatures may have adverse health effects. During the evening hours, when householders could reasonably be expected to have been home, nine percent of living rooms did not reach a mean temperature of 18°C. In eight out of ten homes temperatures below or equal to 16°C were recorded for an average of 33 minutes, potentially putting vulnerable householders at increased risk of respiratory diseases (Collins, 1986). Overheating may cause heat strain and be interpreted as an unnecessary fuel expenditure. Over half of the homes presented temperatures above the WHO guideline threshold of 24°C during the evening. Almost a fifth of homes reached temperatures above the upper summer comfort limit of the NatHERS rating tool of 26.5°C for an average of 11 minutes. As the data loggers had explicitly been placed away from heating or cooling devices or solar radiation (Ambrose et al., 2013), measurement error was deemed unlikely.
Quantitative exploration of winter living room temperatures and their determinants in 108 homes in Melbourne, Victoria

Figure 1: Daily mean indoor temperatures at daily mean outdoor temperatures. Error bars show the standard deviations of the mean of the daily mean living room temperatures of the houses with available data at the reference outdoor temperature.

Table 2: Summary of unsatisfactorily low or high temperatures recorded in all homes (N=108) during the evening (6:00pm to 9:59pm) over the winter period.

<table>
<thead>
<tr>
<th>Homes that recorded mean temperatures below 16°C</th>
<th>Homes that recorded mean temperatures above 18°C</th>
<th>Homes that recorded mean temperatures above 24°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number (%)</td>
<td>Number (%)</td>
<td>Number (%)</td>
</tr>
<tr>
<td>3 (3%)</td>
<td>10 (9%)</td>
<td>2 (2%)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Homes that recorded minimum temperatures below or equal to 9°C</th>
<th>Homes that recorded maximum temperatures above 26.5°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number (%)</td>
<td>Number (%)</td>
</tr>
<tr>
<td>4 (4%)</td>
<td>20 (19%)</td>
</tr>
<tr>
<td>21 (19%)</td>
<td>59 (55%)</td>
</tr>
<tr>
<td>89 (82%)</td>
<td>105 (97%)</td>
</tr>
<tr>
<td>16°C</td>
<td>24°C</td>
</tr>
<tr>
<td>10°C</td>
<td>26.5°C</td>
</tr>
<tr>
<td>3 (3%)</td>
<td>2 (2%)</td>
</tr>
<tr>
<td>10 (9%)</td>
<td>2 (2%)</td>
</tr>
</tbody>
</table>

3.2. Determinants of winter living room temperatures

3.2.1. Household characteristics and impact on average winter indoor temperatures

Independent sample t-tests were performed to explore significant differences between the mean living room temperature and binarised household characteristic. The results (Table 3) suggested that the energy expenditure, home occupation and length of heating period significantly predicted the average indoor winter temperature in these homes. Households that reported to spend more than $1500 on electricity or more than $1000 on gas presented average temperature in their living rooms above 18°C.
In addition, where someone was at home all day or where the heater was used continuously, the average winter living room temperatures were statistically significantly higher than in other households.

Table 3: Results of independent samples -t-test results of average living room temperature during the winter months and household characteristics.

<table>
<thead>
<tr>
<th>Group statistics</th>
<th>t-Test for equality of means</th>
<th>Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>%a</td>
</tr>
<tr>
<td>Weekly householder attendance Binary 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nobody at home during some hours</td>
<td>61</td>
<td>56%</td>
</tr>
<tr>
<td>Someone is home all day</td>
<td>47</td>
<td>44%</td>
</tr>
<tr>
<td>Household size less/ 4 or more</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Household size &lt;3.9</td>
<td>45</td>
<td>44%</td>
</tr>
<tr>
<td>Household size =&gt;4</td>
<td>57</td>
<td>56%</td>
</tr>
<tr>
<td>Electricity Costs Binary 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; $1500</td>
<td>72</td>
<td>67%</td>
</tr>
<tr>
<td>&gt; $1500</td>
<td>36</td>
<td>33%</td>
</tr>
<tr>
<td>Gas Costs Binary 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt; $1000                   b</td>
<td>72</td>
<td>67%</td>
</tr>
<tr>
<td>&gt; $1000</td>
<td>35</td>
<td>33%</td>
</tr>
<tr>
<td>Heater use Binary 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuously</td>
<td>20</td>
<td>19%</td>
</tr>
<tr>
<td>Intermittently b</td>
<td>88</td>
<td>81%</td>
</tr>
<tr>
<td>Winter comfort vote Binary 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cold or Cool</td>
<td>32</td>
<td>30%</td>
</tr>
<tr>
<td>Comfortable or warm</td>
<td>76</td>
<td>70%</td>
</tr>
<tr>
<td>IER lower/ upper 5 deciles within VIC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>in lower 5 deciles</td>
<td>22</td>
<td>20%</td>
</tr>
<tr>
<td>in upper 5 deciles</td>
<td>86</td>
<td>80%</td>
</tr>
</tbody>
</table>

* Statistically significant at p<0.05

* Highly statistically significant at p<0.01

*a 'Valid percents' based on the number of responses

*b While score for the group of homes exhibited evidence of non-normality, the central limit theorem ensured that t-test could be applied as the sample size of this group was bigger than 30.
3.3. AccuRate star ratings and impact on levels of indoor temperatures

The association of the homes’ star ratings with selected indoor temperatures indices was explored by fitting linear regression models in SPSSv22. The results revealed that the star ratings were poor predictors of indoor temperatures (Table 4). While the change in average temperatures occurred in the expected directions, with higher star rated homes being warmer, the *p*-values did not reach the significance threshold of 0.05. A statistically significant negative association was only found for the standard deviation of the average winter living room temperature although the star ratings could only explain less than 4% of the association. Heating in more efficient homes may have been better controlled with thermostats rather than with manual controls that do not refer to temperature thresholds. Linear regression models for the relationship between the exposure to unsatisfactory indoor temperatures and star ratings did not show statistical significance at the 95% level of significance.

4. Discussion

Despite implied benefits of improved residential thermal performance on thermal comfort and health, to date there has been little empirical knowledge on indoor temperatures of Australian homes and their determinants. This observational study has provided insight into the warmth of 108 detached homes built between 2003 and 2012 in Melbourne, Victoria, during a typical winter and has identified several determinants.

The mean temperatures in the living rooms of these probably more advantaged households seemed to have satisfied the WHO guideline of 18°C. Compared to homes in similar climates, the sample Melbournian homes were about as warm during winter as dwellings in the UK (17.8°C) (Kane et al., 2015) and slightly warmer than homes on the North Island of New Zealand (16.5°C) (Isaacs et al., 2010) and those of deprived households in Greece (15.9°C) (Santamouris et al., 2014). However, periods of under- and overheating, which may have compromised health, were common and may have been due to shortcomings in heating control, as found in Ireland (Rugkåsa et al., 2004) and New Zealand (Isaacs et al., 2006) or preference, as observed in England (Critchley et al., 2007).

The results concurred with international evidence that home attendance and continuity of heater use are predictive of higher indoor temperatures (Kelly et al., 2013). The lack of a significant association between indoor temperatures and area-based household socio-economic status has also been observed in a retrofit intervention study of low-income homes in the UK (Oreszczyn et al., 2006).

Statistical tests showed star ratings were a poor predictor of indoor temperatures. This result was surprising considering that improved ratings of dwellings of low-income households in the UK (Oreszczyn et al., 2006) and increased insulation in a representative sample in New Zealand (Isaacs et al., 2010) have led to warmer homes. A possible explanation is that these Melbournian householders, who appear to have been better off financially, were able to afford heating even their less efficient homes to comfortable temperatures. Higher star rated homes used, however, less energy than lower star rated homes to achieve these comparable levels of warmth (Ambrose et al., 2013). The lack of a clear relationship between star ratings and indoor temperatures may also have been due to the sample having been too small or because poor workmanship in the insulation and air tightness in the higher rated RBEE homes compromised their thermal performance (Ambrose et al., 2013). While it would be advantageous to test the influence of the dwellings’ heat loss on indoor temperature, as this is a better indicator or the buildings’ thermal performance than the normalised values on which AccuRate star ratings are based, this was not possible due to lack of data.
This study was limited by the sample size, the non-representative housing and population sample, and the reliance of self-reported fuel expenditure. In addition, the study only used simple statistical methods. As the probabilities were not re-calculated using a multiple comparison procedure, the results should be interpreted as hypotheses that should be tested in future, more focussed, research.

This study leaves a gap in knowledge on poorer performing homes that are dominating the Victorian housing stock (Victorian Government Department of Sustainability and Environment, 2006) and low income households who may compromise on adequate heating (DCCEE, 2013). Deliberations on the general relationship between energy efficiency ratings and indoor temperatures in the state of Victoria require data from a larger, representative sample of homes. In addition, more research is needed to identify how householder heating practices mediate between the thermal quality, efficiency and control of heating systems and indoor warmth.

Table 4: Results of linear regression model predicting the effect of the star rating on selected indoor temperature indices.

<table>
<thead>
<tr>
<th>Variable</th>
<th>ANOVA</th>
<th>Unstandardised coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>R²</td>
</tr>
<tr>
<td>Average indoor temperatures during the whole winter period (1 June - 31 August)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>.047</td>
<td>0.002</td>
</tr>
<tr>
<td>Average</td>
<td>.080</td>
<td>0.006</td>
</tr>
<tr>
<td>Max</td>
<td>.090</td>
<td>0.009</td>
</tr>
<tr>
<td>Range (Max-Min)</td>
<td>.107</td>
<td>0.011</td>
</tr>
<tr>
<td>LR average 8:00am-7:59pm</td>
<td>.077</td>
<td>0.006</td>
</tr>
<tr>
<td>LR average 8:00pm-7:59am</td>
<td>.075</td>
<td>0.006</td>
</tr>
<tr>
<td>LR average 6:00pm-9:59pm</td>
<td>.058</td>
<td>0.003</td>
</tr>
<tr>
<td>LR average @ 3:00am</td>
<td>.123</td>
<td>0.015</td>
</tr>
<tr>
<td>LR average @ 6:00am</td>
<td>.091</td>
<td>0.008</td>
</tr>
<tr>
<td>LR average @ 8:00pm</td>
<td>.075</td>
<td>0.006</td>
</tr>
</tbody>
</table>

| Standard deviations of indoor temperature variable | | | | | | | |
| Average SD | .211 | 0.045 | 107 | 4.945 | .030 | * | -0.18 | 3.3 |
| LR Living room | | | | | | | |
| SD Standard Deviation | | | | | | | |
| * Statistically significant at p<0.05 | | | | | | | |

5. Conclusion

This study could not provide statistically significant evidence that higher star rated homes predicted more satisfactory indoor temperatures. While it would not be appropriate to base policy recommendations on this small, unrepresentative study, this work suggests possible strategies for social change and the design of residential energy efficiency rating tools. The finding that self-reported fuel expenditure was a better predictor of mean indoor temperatures than energy efficiency star ratings is
relevant in the debate around fuel hardship and mandatory disclosure. These results suggest that winter fuel cost assistance may be more effective in achieving satisfactory warmth than improving homes through thermal retrofits. In addition, these findings suggest that residential energy efficiency rating schemes such as NatHERS, which are compliance tools carried out at the design stage, could usefully be complemented by mandatory disclosure of in use energy consumption data which would provide occupants with a guide to as-built and in use performance. With regards to residential energy efficiency assessments, the failure to find significant associations between star ratings and indoor temperatures seems to support the ‘whole of building’ approach proposed in the Draft National Building Energy Standard – Setting, Assessment and Rating Framework (DCCEE, 2012). The current NatHERS rating scheme is focused on the designed performance of the dwellings’ thermal envelope, yet concerns about non-compliance have been raised (Pitt & Sherry and Swinburne University of Technology, 2014). The results of this study suggest that a residential energy efficiency rating tool may need to include consideration of the efficiency of the heating system and ensure the thermal quality of the building fabric thermal in order to predict improved winter warmth in higher rated homes.

Acknowledgements

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Re-measuring density: alternative methods for assessing and progressing Australia’s suburbs

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Abstract: This paper undertakes a critical review of existing paradigms in built environment performance measurement methodologies within Australia’s strategic planning processes. It argues that current density modelling, which is used to assess the effective integration of population distribution, infrastructure investment and land use strategies, is more misleading than it is revealing. This is due to a fundamental misalignment between the reality of land use capacity and its relationship to infrastructure investment, and assumptions about reality informed by existing density measurement techniques, which establish an inaccurate and problematic base for strategic planning. The paper proposes alternative modelling approaches, based on dwelling capacity per linear meter of public road network, which more accurately measure population density relative to infrastructure investment than dwelling density per hectare. The proposed models also enable density maps to become a forecasting tool, tailored to measure alternative typologies of concentrated development, and a facilitator of density strategies by enabling density modelling to direct economically realistic and culturally appropriate suburban residential development. By accurately assessing the built environment, government can realign policy to the realities of current suburban conditions to direct the evolution of Australian cities in a more appropriate, realistic and strategic manner.

Keywords: Density; mapping; Hobart, strategic planning methodology.

1. Introduction

As Australian cities face increasing population growth, the federal government, through the Council of Australian Governments (COAG) Reform Council, directed its capital cities to undertake strategic planning exercises. The task aimed to ensure that the future growth of Australia’s largest settlements is realised in a liveable, productive and sustainable manner and focused on the distribution of population, and use of land, relative to infrastructure. The main measure used to determine the success of infrastructure leveraging strategies is the measurement of dwelling density per hectare. This is based on the notion that higher density housing, concentrated around key transport corridors and activity
centres, will render networks and clusters of new economic activity as viable and provide citizens with a reduced cost of living.

Although this study’s genesis is in capital city strategic planning, the intended application of findings is not large urban centres but rather the suburban context predominant in both outer-metropolitan and regional cities. Whilst Australia’s inner city settlements will face significant growth pressures, their property markets support development models that align with government’s strategic ambitions. However in lower density contexts, which have traditionally been directed by the same strategies as high-density settlements, despite considerable economic, cultural and social differences, there is a need to create appropriate strategies relative to these realities. Although cities like Hobart, Darwin and Geelong are only expected to experience modest population growth over the next fifty years, their low-density composition is more akin to the majority of Australian settlement’s composition than inner Sydney or Melbourne (West, 2013). Thus if Australia is to become a more liveable, sustainable and productive country, a tailored strategic focus should also be applied to traditionally ‘underperforming’ contexts like the suburbs.

Hobart exemplifies the composition of most regional and outer metropolitan settlements and the inherent failure of strategic planning to effectively direct development. The introduction of an urban growth boundary for Greater Hobart first occurred in 1964 (Tasmania, 1964). Yet despite the uncontrolled growth beyond its boundaries over the proceeding half-century, a similar border was proposed in 2011 as part of the COAG Reform Council capital city-planning directive (Tasmania, 2011). With the majority of land within the growth area currently rated at 5 dwellings per hectare (dw/ha) or less, the new targets set within the Greater Hobart Capital City Plan for a minimum of 15 dw/ha, and a best practice of 25 dw/ha, are an ambitious target.

This unquestioning adoption and repetition of processes, definitions and ambitions are the focus of recent critique by Neil Brenner (2015) and the Urban Theory Lab at Harvard. This paper will adopt Brenner’s premise of critically assessing dominant paradigms and seeks to realign the ambitions of the government’s strategic planning processes with the legislative mechanisms and realities of the context of Australia’s lower density cities. In doing so, the paper aims to develop new methods that not only accurately assess the current state of Australian cities but also progress collective strategic development ambitions.

2. Current assessment methodology

Brenner’s (2015) proposition is that a lack of agreement on a cohesive strategic direction for contemporary city planning has lead to a fall back on ideologies and definitions that were developed in the eighteenth century, and that these may prove problematic in their application to the contemporary context. In particular, he identifies the categorisation of land, as either urban (associated with human settlement) or rural (landscape that is predominantly free of settlement), as problematic. For example, land used for mining is typically categorised as rural as it does not contain the built composition associated with an urban environment. Yet its very nature as a landscape that is mined as a resource for human settlement intrinsically makes its function fundamentally urban and thus should be classified accordingly. When Brenner amended maps of human settlement to reflect this broader definition of urbanity, it revealed that almost all land is inherently urban and thus new sub-definitions are needed to understand the complexities within this expanded landscape. He proposed to shift the categorisation from ‘settlement vs. non-settlement’ to ‘agglomeration vs. operational landscapes’. In doing so the broader social, economical and environmental consequences, inherent in the relationship between
different landscapes, are made apparent and the opportunities and implications of future strategies can be more accurately and appropriately considered.

When examining the density definitions that currently direct Australian strategic planning processes, similarly we see a clear lineage of their use in government policy development despite significant shifts in the context (Pafka, 2013). In particular, this paper will focus on the ‘dwellings per hectare’ (dw/ha) density metric, that Griffiths (2009) claims is the most prevalent measure for urban density in the Australian strategic planning context.

2.1. Accuracy

In the COAG Capital City policies, the dwellings per hectare metric has commonly been used for two key maps; the first recording current dwelling density per hectare and the second indicating the required density levels around potential public transport stops or local activity centers for network viability. Despite the geographic scope, the relationship between the two maps is detached; the latter disregards the former and solely communicates the density strategy related to an infrastructure proposal. Consequently, the strategic density targets are applied tabula rasa.

Even if the existing conditions were considered, the dwellings per hectare metric only records the quantitative aspects of the distribution of houses and doesn't convey social, cultural or economic factors that may be effecting development (Pafka, 2013). In order to gain an accurate picture of the influences on existing population distribution, Pafka proposed a multi-strand approach to assessment that combined the dwellings per hectare metric with other established measures such as the Floor Area Ratio and Plot Factor. Whilst this approach does provide more information, the misalignment of conventional definitions with the reality of the assessed context, as Brenner has cautioned, may not provide accurate information and thus may undermine the basis of research collected to inform strategic direction. Therefore the successful use of a multi-variable methodology relies on definitions that are both relevant to issues that they are assessing and the context to which they are applied.

2.2. Ambiguity

Assessing the suitability of definitions and metrics requires an understanding of both their original and contemporary contexts. The first use of the dwellings per hectare metric in Australia was in 1944 (Pafka, 2013) and coincided with the postwar ideal of the Great Australian Dream- a detached dwelling on a quarter acre plot; a notion which is now in conflict with the government’s strategic ambitions to maximise the efficient use of land. Additionally, the notion of a dwelling has evolved beyond a physically defined unit, in the form of a detached house, to a plethora of typologies including row houses, apartment blocks, villas, etc. Whilst houses and even apartments can be easier to define as dwellings, the delineation of emerging typologies such as granny flats and independent sublets within traditional detached dwellings is less clear. Further, the idea of dwelling developed in relation to the concept of the nuclear family; a unit which was the social norm for the average household size and composition for the era. However, over the past seventy years, the nuclear family has receded in prevalence with the average Australian household composition falling from 4.5 people in 1911 to 2.5 in 2011 (Capuano, 2012). This has significant ramifications for strategic design, which continues to assume that each dwelling contains four to five individuals, when in reality it is likely to be two to three. Further, the average Australian household size has increased significantly over the past three decades, from 150m² in 1991 to 219m² in 2006 (ABS, 2010). Consequently the relationship between the definitions of
dwellings, household and capacity are less than clearly defined, creating a misalignment between built fabric capacity and population density. Despite contextual shifts, like Brenner’s criticism of the unquestioned adoption of the urban and non-urban classification system, Australia’s built environment performance is still measured with, and consequently undermined by, the dwelling density per hectare metric.

2.3. Alignment

The functional and spatial evolution of residential properties has lead to a further complication: how to distribute the boundaries of each hectare in a logical manner? Dwellings per hectare measurements in Australia are based on the boundaries of the Australian Bureau of Statistics (ABS) census blocks (see Figure 1) which include whole cadastral parcels and thus enables a clear allocation of a plot’s statistics to the defined study area. However the ABS blocks also contain public land, such as roads and parks, making this relationship between the ABS statistics and actual distribution more ambiguous.

![Figure 1: Battery Point (left) and Opossum Bay (right) indicating dwellings per hectare. (source: author, using Australian Bureau of Statistics data)](image)

Additionally, the ABS blocks vary significantly in size, shape and composition. Opossum Bay, one of the Hobart suburbs that developed beyond the 1964 Hobart growth boundary, appears to have a similar level of dwelling density, at the street level, to the inner city suburb of Battery Point; each contain solid street edges of one and two storey dwellings, very minimal setbacks between, and many buildings appear to contain multiple apartments. Despite this, the dwelling density per hectare rating for Opossum Bay is at least three times lower, on average, than that of Battery Point. One of the explanations for this is due to the difference in the composition of ABS census blocks between the two suburbs. In examining the blocks for Opossum Bay in the densest area of the settlement (Figure 1), which is primarily concentrated along one linear strip of road, the majority of the large area defined per ABS block includes large plots of undeveloped farming land. This dilutes the concentration of dwelling density and makes the area appear well below acceptable levels of dwelling density. However, the actual concentration of development around the road network, like the distribution of development in Battery Point, optimises the use of the infrastructure network by connecting the maximum number of habitable space to the network within a small area of land. Thus, this example demonstrates that the ABS census blocks do not always accurately represent the relationship between land use, population distribution and infrastructure. However, if density was more objectively measured with a Cartesian
grid, the connection between ABS statistics and distribution would be even further complicated. Consequently, in the context of a parcel-based allocation of land use data, measuring density per hectare is an approximation only.

This lack of accuracy in the parameters of hectare distribution, as Pafka (2013) notes, creates ambiguity that is often politicised and makes it difficult for strategic density ambitions to be realised. Firstly, the method of distributing boundaries can significantly affect the density figure of a precinct and consequently can be manipulated to serve political needs. For example, as Figure 1 demonstrates, joining and then averaging the density of multiple hectares can significantly increase or decrease the collective density rating for an area and thus the rating for an individual plot. This may allow inappropriately scaled developments, whether they are too big or small, to be ‘disguised’ by the neighbouring composition, and thus be approved or rejected by government despite the objections of developers or the community. Secondly, the setting of new minimum density targets across hectares makes it difficult to enact. Government can shape the private development of the built environment via planning schemes. Whilst planning schemes include some collective strategic planning directives, such as the distribution of use zones, these align to cadastral parcels and consequently clearly define both the allowable use for an individual block and the collective strategy for a precinct. Even if there were an objective way to assess density across an area, how can an individual plot also be assessed objectively? Do all plots within the defined area need to achieve the same minimum dwelling rating, or is the composition of each individual plot taken into account? In reflecting on this misalignment between the strategic planning process and the development mechanisms of government, it is clear to see why growth boundaries have been compromised and, more broadly, why government has had very little influence over the shaping of cities.

3. Alternative assessment methodology

What is needed to accurately assess, and successfully progress, the contemporary built environment is a new metric that measures the existing relationship between land use, infrastructure and population distribution and aligns with government development control mechanisms. Three alternative approaches are outlined below.

3.1 Dwellings per 100 meters

The first alternative approach to measuring addresses the problems associated with accuracy and realisation through alignment. By shifting the density metric to a plot-scaled unit, that is also the same scale and form of the infrastructure network, the relationship between, infrastructure, land use and population can be clearly assessed. Like contemporary housing, most infrastructure is not distributed evenly across hectares within an urban settlement area but rather concentrated to linear networks and conduits that align with the road network. Thus a more accurate alternative could be to measure density not in gross land area but in a linear fashion relative to the distribution of the infrastructure network itself.

Density, in the context of planning, is traditionally considered an area based measurement unit and consequently a definition that assesses linear density seems fundamentally flawed. However in examining the broader definition of density used within science and engineering, measuring linear density is common for recording either one dimensional objects or one dimension of three dimensional objects. For example, in measuring the density of fabrics, whose composition is a network
of individual threads, a more accurate description of the composition comes from assessing the density of the individual threads and their relationship to one another. Similarly, as the aim of measuring dwelling density is based on assessing the relationship between population distribution and infrastructure networks, it is more accurate to consider the density of population relative to the infrastructure conduits, and then to assess the relative distribution of the conduits within the network, than to simply count people over a given area.

An example of measuring linear density is a tool that the Australian Urban Research Infrastructure Network (AURIN) use to assess existing and potential patronage of rail services (AURIN, 2015). Rather than measuring the catchment area of a network via a 400m radius of residences around each station, instead the 400m distance is measured linearly along roads and the houses adjacent to this path are counted as the catchment area. This realigns the potential catchment directly to the research behind the radius concept: that 400 meters is a realistic distance that most commuters would be willing to walk to a station (Daniels, 2011). Thus measuring the actual walking path and accommodating the realities of the spatial condition, rather than an assumption based on radial proximity, a more accurate picture of viability can be attained.

Similarly, the linear approach could be used to assess the viability of other infrastructure networks, such as the number of properties that are serviced by a road or telephone line. In this instance, instead of measuring the number of dwellings per hectare, which is an area of 100m x 100m, the linear equivalent is to measure the number of dwellings per 100 meters. For example, Figure 2 illustrates the possible dwelling density figures generated for the same survey area indicated in Figure 1. However in Figure 2, dwelling density is assessed relative to infrastructure distribution - the road network - and is generated by counting the number of dwellings per length of road corridor (with roads subdivided into segments between intersections and plots allocated once according to their point of access). When re-measured in this way the dwelling density figures for Battery Point and Opossum Bay figures are much closer, reflecting reality of the built fabric composition as observed from the street. This simple shift in measurement could have significant ramifications for the assessment of the existing context as it more accurately shows the relationship between dwelling and network distribution.

Figure 2: Battery Point (left) and Opossum Bay (right) indicating dwellings per 100 meters. (source: author)
3.2 Households per 100 meters

Despite the increased accuracy in the relationship between dwelling and infrastructure distribution, as outlined in section 2.2, counting dwellings alone does not guarantee a clear assessment of the size of the population that is connected to the network. Several international empirical studies, in locations similar to the suburban context in Australia, observed the actual occupation of detached dwellings and discovered an interesting trend. Studies in suburban Honolulu (Lau, 2014), Vancouver (Lister, 2013), and many other North American west coast cities with Accessory Dwelling Unit (ADU) policies, found that there is a growing trend towards the dual occupation of detached dwellings in typical suburban contexts, both facilitated by and in spite of legislation. ADU policies allow two to three households per plot through the reconfiguration of buildings within each parcel, essentially realigning the capacity of each plot from the current average of 2.5 occupants to its intended 4.5 nuclear family configuration. ADU typologies include the addition of small freestanding dwellings, such as granny flats; extensions and additions, such as the construction of an apartment above a garage on or top of an existing dwelling; and the internal horizontal and vertical subdivision of existing dwellings (Brown, 2013).

If Australian legislation shifted to allow two to three households per plot, which is the common allowance for residential plots in cities with ADU policies, meeting minimum density targets in suburban contexts could be easily achieved. The small scaled, plot based densification of individual parcels is more suited to the scale of the construction industry in suburban settlements like Hobart, is more economically viable for the market and, facilitates development that is in keeping with the existing character. Local studies have shown that ADU development would be suitable for the Australian context and could significantly assist in the realisation of government’s ambitions to increase residential density within existing serviced areas, to address housing supply issues and improve the cost of living for the community (Faulkner, 2009).

Based on the way that Australian census data is collected, and the continuously shifting nature of residential occupation, accurately assessing existing households occupancy per plot is difficult. However, if assessment is instead focused on potential household capacity, it could have significant benefits for strategic planning. Assuming that each existing suburban plot is considered to be accommodating one independent household (in accordance with current planning laws), but plots over a certain size are capable of housing two or three, mapping the difference between existing and potential occupation could provide a more productive insight: the capacity of a suburb.

Figure 3: Battery Point (left) and Opossum Bay (right) indicating household capacity. (source: author)
Further, measuring the capacity of an individual parcel establishes an objective development density target per plot and an assessment of the ability of a precinct to appropriately accommodate more households. For example, Figure 3 illustrates that although the combination of conjoined cottages and apartment blocks in Battery Point have lead to higher dwelling per hectare ratings, the detached dwellings in Opossum Bay have greater capacity to leverage infrastructure if an ADU based approach to densification were applied. This is because many of the plots within Battery Point already meet or exceed the allowable ADU density of two households per plot, and thus have no further capacity for growth. Shifting the focus of mapping from existing density and illustrations of proposed density to a visualisation indicating the capacity of a suburban precinct to accommodate appropriate and realistic levels of density, bridges the gap between reality and strategic potential. Simultaneously, by mapping the household capacity per 100 meters, the viability of supporting infrastructure networks can also be assessed.

3.3 Entries per 100 meters

Allowing individual plots to accommodate additional households may encourage such development to occur, but can the planning scheme be used to facilitate this shift? What the initial alternative studies in Figure 3 begin to suggest is that the way to optimise the relationship between infrastructure and population is to ensure that there are more households per linear meter of road. Thus a street composed of narrow plots, each of which with the potential to accommodate two households, is a more optimal relationship than a single household on a wider plot. One existing typology that supports this relationship is the row house or terrace house model. These traditionally operate on very narrow plots typically with a side entry which can allow multiple levels to be accessed and occupied independently. Whilst this model is exceptional from a strategic point of view it’s lack of uptake in the suburban context indicates that it isn’t highly desired by or viable for the property market, particularly in suburban contexts, and it’s introduction would mark a significant shift in the character and composition of regional and outer metropolitan suburban settlements.

How then can typical volume housing models be encouraged to facilitate the accommodation of multiple households without impacting on the character of the streetscape? Hawaii, a state which has had an Ohana (Hawaiian for ‘family’) ADU dwelling policy in place since 1982, allows single plots to accommodate multiple households as long as they are related. However, as Lau (2014) discovered, many households are illegally and independently accommodating unrelated households to financially benefit from the high rental rates created by a significant housing shortage. Lau’s studies found that illegal occupations were facilitated through the devious configuration of architectural elements and floor plans to facilitate dual independent occupation within a single building without being detected by inspectors. Whilst this is problematic in terms of compliance with health and safety legislation, it offers a suggestion as to how Australia’s large volume housing market may be directed to encourage multiple household configurations.
In comparing the attributes that Lau identified in the illegal multi-household configurations on the island of Oahu with the typical Australian volume housing market offerings there are many similarities. Illegal ADUs contain two food preparation areas (one referred to as a kitchen, the other as a bar), two bathrooms (a main and an ensuite) and multiple bedrooms and living areas. The inclusion of multiple living spaces and bathrooms are also common in many contemporary Australian volume-housing models and thus the attributes of typical market housing are very much aligned with the typologies of multi-household configurations. However Lau identified a further common attribute: the inclusion of at least two entrances from the dwelling to the street, and two independent circulation paths within each dwelling, that enabled each ‘set’ of minimum household amenities to operate independently.

The floor plan on the left in figure 4, which is typical of contemporary Australian volume housing plans, demonstrates circulation based around a singular access point which makes it impossible for multiple households to occupy the space independently. The plan on the right, however, contains similar spaces but is designed to be occupied by either one or two households independently. If each new build and renovation to an existing property was required to ensure that each dwelling had a minimum of two independent entrances, and configured the internal spaces accordingly as demonstrated in the second plan in Figure 4, dwelling targets could be met within existing residential typologies. As the planning scheme can define the minimum requirements for an individual building, the government could use the planning process to guide the community to further leverage infrastructure investment. Simultaneously, it could facilitate the realignment of housing stock to household sizes whilst also directing the volume housing market to produce more adaptable and resilient suburban housing.

4. Conclusion

The three alternative linear measurement methodologies address the issues related to the use of the dwellings per hectare metric in contemporary strategic planning processes. The shift towards a linear metric can be used to more accurately assess the organic development activity that the community is undertaking and how this might be leveraged. Further, adjusting the focus of strategic planning mapping from abstractions of existing and potential conditions to one map that concretely indicates the capacity of an established suburb, facilitates a more efficient use of existing land and infrastructure resources. Finally, by aligning the metrics of the strategic planning process to the attributes of the planning scheme, strategic ambitions can align with the mechanisms that enable their realisation.
Whilst this alternative methodology has the potential to shift the metric from operating simply as a measurement device to a facilitator of a strategic policy, further research is needed to assess its broader applicability. In particular, the current lack of available data on existing household and dwelling compositions, which are often masked due to the restrictive nature of the current regulatory condition, may limit the applicability of this approach beyond concentrated study areas until new ways to assess existing capacity are developed. Further, more complex metropolitan configurations may require alternative assessment attributes that take into account existing hierarchies such as the compositional nature of different road types, the varying models of housing typologies and a broader range of infrastructure such as a rail based public transit.

This example of re-measuring density relative to contemporary issues, in this case housing affordability and infrastructure investment, is just one example of the importance of questioning the validity of metrics relative to the actual issues that they are being deployed to address. As such, this methodology itself, if applied to other misalignments between strategic planning and built environment legislation, could have a significant impact on the way that government is able to guide the development of cities.

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The Australian construction industry’s approach to embodied carbon assessment: a scoping study

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Abstract: The building sector is responsible for a significant proportion of a nation’s greenhouse gas emissions. In an attempt to mitigate these emissions, industry and government have been mainly focussed on reducing operational emissions associated with buildings, leaving the embodied emissions largely ignored. As operational emissions continue to decrease, embodied emissions will start to play a larger role in the life cycle emissions of the built environment. Several tools and datasets have been created internationally and locally within Australia that seek to quantify these embodied carbon emissions. However due to lack of information, it is unclear first of all how the Australian construction industry is currently approaching embodied carbon analysis and secondly what tools and databases are being used for this analysis. A survey was executed as part of the Integrated Carbon Metrics (ICM) Project that aimed to not only addresses this lack of information but to also inform the ICM project tool outputs. These tool outputs will seek to address these often ignored embodied emissions and aim to quantify the carbon fabric of Australia’s built environment.

Keywords: Embodied carbon; construction industry; Australia.

1. Introduction

1.1. Background

Greenhouse gas (GHG) emissions from the building sector have more than doubled since 1970 to reach 9.18 GtCO₂ eq in 2010 representing 19% of all global 2010 GHG emissions (IPCC, 2014). In Australia, 20% of all GHG come from the operation of commercial and residential buildings alone (Climate Works, 2013). These GHG emissions have been demonstrated to negatively contribute to the effects of climate change (IPCC, 2014) with growing emphasis placed on the need to implement mitigation strategies. These mitigation strategies have been largely focused on reducing these direct (operational) emissions, however the indirect (embodied) emissions from materials and manufacturing, transport, maintenance and disposal has been estimated to make up another 11% of national emissions (Schinabeck and Wiedmann 2014). With growing international pressure to decrease national GHG, coupled with the fact
that Australia is one of the highest GHG emitters in the world on a per capita basis (Garnaut, 2011), there is a need to address both the direct and indirect GHG emissions from buildings if Australia is to achieve their commitment of reducing GHG to 26-28% below 2005 levels by 2030.

A new project, launched in 2014, under the Cooperative Research Centre for Low Carbon Living (CRCLCL), sets out to correct this exclusion and help quantify the carbon fabric of Australia’s built environment by including these largely ignored indirect emissions. The project, called the Integrated Carbon Metrics (ICM) aims create a multi-scale life cycle approach to assessing, mapping and tracking carbon outcomes of the built environment. The creation of a comprehensive embodied carbon (EC) database is a fundamental aspect of this research. This database will then be used within the ICM Tool, which will map Australian carbon flows and identify carbon hot spots. The Precinct Information Modelling (PIM) carbon extension tool will complement the ICM tool by providing a 3D visualisation aspect for the calculation of EC at a precinct level. In order to ensure tools get created that are not only internationally relevant but also relevant to the Australian construction industry, it was deemed necessary to launch a scoping study, as part of the project, to gain an understating of how the Australian construction industry currently approach EC analysis.

Even though previous research exists that looks at industry’s perceptive of EC, they have been largely UK and American focused, such as Ariyarante and Moncaster (2014) and De Wolf and Ochsendorf (2014). There is currently a limited amount of research about EC within the Australian context and a severe lack of understanding as to how the Australian construction industry currently approach EC analyses (if at all) and what tools and datasets gets used for this analyses. The aim of this research was to conduct a scoping study that could provide this necessary insight. From the amount of companies currently providing this service; to the tools used for this service and to further identify any potential areas for tool improvement along with any perceived strengths and weaknesses of current tools. The survey result, which would be built upon in the next phase of the project, will be used to inform the ICM project and tool outputs. This research and survey focusses solely on carbon emissions related to the built environment. The survey is aimed to gain insight from industry and does not intend to provide insight from other project stakeholders, such as clients. Industry was selected as they are most often the project member utilising EC assessment tools within the project phase, not the homeowner, client or building occupant.

The following section will provide a brief overview of EC and include detail about current assessment methods and relevant standards. This will be followed by a mention of the similar surveys used as informants for this research’s’ survey along with survey method, design and sampling. This paper will then conclude in a discussion of the survey results and highlight any limitations associated with its findings.

1.2. Embodied carbon

A building will emit carbon during a number of separate phases over its lifetime. These ‘phases’, as defined within BS EN 15978:2011, are broadly split up into the following four phases: product stage; construction process stage; use stage and end of life stage. Industry and government have been mainly focused on reducing the carbon emissions from the use phase, leaving the other phases largely ignored. However even before a building is occupied, between 30% to 70% of its lifetime carbon emissions have already been accounted for (ASBP, 2014). With the continuing decrease in OC, EC represents an increasingly significant component of the GHG emissions attributable to the built environment.
The increasing awareness has resulted in the following developments related to embodied carbon:

### 1.2.1. Methods of embodied carbon assessment

Life Cycle Assessment (LCA) is widely acknowledged as providing an appropriate framework for assessing carbon emissions throughout the whole building life cycle (Menzies et al., 2007; Zuo et al., 2012). LCA is a method for evaluating the environmental impacts of products holistically, including direct and supply chain impacts (Lenzen et al., 2004). There are four fundamental steps for conducting an LCA namely: goal; inventory analysis; impact assessment and interpretation (Crawford et al., 2010). However each step requires a certain level of subjectivity. From defining the system boundary (to what extent each life cycle phase is included in the calculation) to interpretation of results (Treloar, 1998). This subjectivity can result in differing and often incomparable EC results for the same building element. Another aspect affecting the EC results is the inventory which is influenced by a wide range of factors, from age of data; geographic location and degree of completeness (Crawford et al., 2010).

This LCA process is often seen as complex and time and resource heavy. There has been an increase in the amount of available tools and software to aid calculation. From commercially available tools, such as, SimaPro (Netherlands); GaBi (Germany); Boustead (UK) and eTool (Australia) to in-house developed data and tools, such as Arup’s Project Embodied Carbon & Energy (PECD) dataset that consists of Arup projects with data extracted from Revit models. Each tool employs inventories that include the EC coefficients of building products and materials. The origin of these datasets ranges from ICE (UK); Ecoinvent (Switzerland) or AusLCI (Australia), to name but a few. Most of these datasets provide data from cradle to gate (resource extraction to factory gate). Several researchers have analysed and compared these available tools and concluded their advantages and disadvantages (Ariyarante and Moncaster, 2014 and De Wolf and Ochsendorf, 2014). The outcome of these comparisons often reflect some of the same characteristics that plague LCA as mentioned earlier, from inconsistent calculation methodologies and system boundaries resulting in a range of reported EC figures dependent on what tool is used. In addition to this, several upstream phases are left out of the calculation due to only relying on cradle to gate data (instead of cradle to cradle, i.e. resource extraction to re-use), resulting in a degree of incompleteness which has been shown to be 50% or more (Crawford, 2008).

### 1.2.2. Standards and legislation

Even though there is no mandatory legislation requesting the assessment of EC, there is growing evidence that the international community is embracing the challenge of decreasing the embodied emissions associated with buildings. From the emergence of voluntary actions, where local city councils, such as Borough of Guildford in the UK, requests, as part of their planning requirements, the use of low embodied energy materials (Guildford Borough Council, 2011). To more mandatory actions, such as the Netherlands requiring the reporting of building material GHG emissions as part of their Dutch Building Decree. Some of Australia’s local governments have followed suit and have set their own targets, such as City of Melbourne’s Zero net emissions by 2020 with a strategy in place to create a carbon neutral city (City of Melbourne, 2014).

To help counteract the inconsistent methodologies and incomparable datasets, as mentioned earlier, that plagues EC analyses, there has been a move to standardise the calculation procedure. From the UK’s PAS2050 (2008) Specification for the assessment of the life cycle GHG emissions of goods and services (Developed by the British Standards Institute, BSI) to the internationally recognized ISO
1.2.3. Embodied carbon and industry

There is a limited amount of information available as to how the construction industry currently approach EC analyses. Surveys have been conducted, mostly in the UK or USA, and have largely been focused on challenges and barriers towards EC analyses uptake (UKGBC, 2014) or opinions on EC (ASBP, 2014). One study did explore four specific LCA tools through interviews with six industry experts, however the tools identity were not provided and specific tool recommendations were not included. Table 1 provides a brief breakdown of the relevant surveys consulted for this research. Even though these surveys do provide some insight into industry’s current attitude towards EC and highlights some of the issues affecting EC analyses, no specific insight can be drawn as to what recommendations can be brought forward for new EC tools, which Arriyante (2014) has identified as an industry need. And due to lack of Australian based surveys, no clear insight is available as to how the Australian construction industry currently approach EC analyses and what tools and datasets are used within their organisations.

Table 1: Consulted surveys about embodied carbon assessment and industry.

<table>
<thead>
<tr>
<th>Author , year and location</th>
<th>Survey Method</th>
<th>Survey topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>UKGBC (2014) UK</td>
<td>Paper based survey with open-ended questions. Data was organised under four key themes identified from the feedback: Key messages; challenges; Next steps and Leadership.</td>
<td>UK industry’s attitude towards EC. Key messages, challenges and next steps.</td>
</tr>
<tr>
<td>De Wolf et al (2014) UK and USA</td>
<td>Semi-structured interview with structural engineering and design firms</td>
<td>Critical review of what needs to be included in an EC database and how it needs to be presented.</td>
</tr>
<tr>
<td>Ariyarante and Moncaster (2014) UK</td>
<td>An initial scoping stage survey included collecting opinions from industry professionals on the methods used for EC assessment. This stage was then followed by ‘expert’ interviews, which were used to explore some of the identified EC tools and software.</td>
<td>Opinions on EC assessment. Exploration of four EC analysis tools.</td>
</tr>
<tr>
<td>ASBP (2014) UK</td>
<td>Interviews and consultations with industry professionals. Key themes and messages were identified and categorised.</td>
<td>Industry attitude and business case for EC; industry capacity and allowable solutions.</td>
</tr>
</tbody>
</table>

2. Survey

2.1. Survey design

The survey was designed based on method discussed by Vaus (2002) and Creswell (2007). The questions were based on some of the critical aspects raised in the surveys consulted in Table 1 and a review of
current literature on the subject. The question types were a mixture between closed or forced-choice questions and open-ended questions. Space for respondents comments were also provided in the form of an optional comments box. The survey was built using the online survey software called Survey Monkey (Survey Monkey, 2011). This software generated a link to the survey which was then included in the email to the selected sample along with a brief introduction and explanation of the project and the survey instructions. Survey Monkey was also used for response collection. The survey was tested on a small sample to test the questions and usability of the online system. The test indicated that the time taken to complete the survey was acceptable and any additional feedback, such as rephrasing, was incorporated into the final survey. Survey was distributed via email and advertised on the CRCLCL website. The email included an invitation to participate in the survey (on a voluntary basis) with a brief description of the ICM project and the relevant URL link.

2.2. Survey population and sample

The population of the survey was construction industry professionals located within Australia. The sample identified were specifically professionals who work with building or building material related aspects. These professionals ranged from architects; engineers; LCA consultants; quantity surveyors and material manufacturers. The sample selection was identified via a web-based search. The selection criterion was based on the fact that the professionals had to be based in Australia. The intention of this study was to provide a base case that could be developed further and in more detail for the next phase of the project. This base case could be based on a small sample size that would provide a preliminary insight into the Australian construction practice with regards to embodied carbon. A total of a 100 questionnaires were distributed via email with 45 responses were collected over a two month period. The greatest percentage of responses came from LCA practitioners (27%); followed by sustainability consultants (20%), engineers (18%) and then contractors (11%). Most of the organisations represented, consisted of less than 10 people with 56% of the respondents mostly involved with residential projects and a further 24% stating they specialise in both residential and non-residential projects.

2.3. Survey analyses

The responses were collected via Survey Monkey, which automatically categorized the questions and counted the number of responses for each question. The percentage of each response in each category was calculated and translated into graphs, as illustrated in this report. Exploratory factor analysis was carried out on the open-ended questions, such as ‘recommendations to new EC tools’ (and questions such as the listing of strengths and weaknesses of current EC tools) to extract common codes and divide the items into the most common categories.

2.4. Survey results and discussion

2.4.1. Embodied carbon assessment provided as a service

The current focus on OC assessment is quite evident from the survey results with over 85% of the respondents providing this as an in-house service with only a small percentage outsourced, as illustrated in Figure 1 below. The next most prevalent service selected from the provided survey options was ‘Energy/ Green ratings’ (such as Green Star) with approximately 20% outsourced. Just over 60% of the organisations provided EC assessment services, but with a greater percentage outsourced. One respondent stated that “when requested on projects we complete these services; however the industry
focus is on operational energy”. Another respondent provided further insight by stating that these services are provided on a project specific basis with preliminary in-house assessments being undertaken regularly but outsourced for Green Star Projects. For those organisations that don’t provide EC assessment as a service, the main reason given was lack of project budget (59%) followed by client disinterest (41%) lack of set standards (35%) and no clear cost/profit incentive (29%). However, when asked whether these organisations would consider providing EC assessment as part of their services in the future, 65% said they would.

![Services provided by percentage of respondents.](image)

What is evident from these results is that first of all there is significant interest from an industry perspective to provide EC assessment as a service. This can be seen from both the large percentage of industry professionals already providing this as a service and from the fact that for those organisations that don’t, there is intention to include it as a service in the future. Secondly, that the in-house capability for EC assessment has not evolved as much as OC assessment, as is evident from the greater percentage outsourcing this service when compared to OC assessment.

2.4.2. Embodied carbon assessment: existing tools and databases

This section of the survey specifically focused on the organisations that provide EC assessment as part of their services. When asked what tool is used for this service, the most popular choice was the software tool SimaPro, as illustrated in Figure 2. SimaPro is a commercially available software tool, available for purchase, originating from the Netherlands. eTool, an Australian designed tool originating from Perth, was only 4% behind SimaPro in terms of popularity. The ‘Other’ option tools, as illustrated in Figure 2 as the third most popular, included 2 respondents stating they use the ‘Footprint Company’, 1 respondent using Passivhaus PHPP, 1 respondent using LCADesign and another respondent stating AccuRate Sustainability. For the database used for EC assessment, both the Australian ‘AusLCI’ and databases
within ‘SimaPro’ were stated as the most popular, closely followed by ‘In-house’; ‘eTool’ and ‘Ecoinvent’ preferences.

![Graph showing tools used for embodied carbon assessment]

*Other:
Footprint Company
Passivehaus PHPP
LCA Design
AccuRate

Figure 2: Tools used for embodied carbon assessment, by percentage of respondents.

When asked to list the strengths and weakness of current EC assessment tools used by the organisation the following five themes became most evident (as detailed in Table 2 below) - data; method; usability; regulation and outcomes.

<table>
<thead>
<tr>
<th>Theme</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>Ability to access multiple databases; Comparable metric</td>
<td>Lack of Australian data; lack of product specific data; Data source questionable</td>
</tr>
<tr>
<td>Method</td>
<td>Comprehensive and in-depth analysis; integrated with thermal performance</td>
<td>Inconsistent methodology; Not a holistic assessment</td>
</tr>
<tr>
<td>Usability</td>
<td>Affordable; Simple and online platform</td>
<td>Time consuming; requires expert knowledge and additional training; no Building Information Modelling (BIM) integration</td>
</tr>
<tr>
<td>Regulation</td>
<td>Compliant with existing ISO standards</td>
<td>Boundary and accuracy questionable</td>
</tr>
<tr>
<td>Outcomes</td>
<td>Multiple impact reporting; Ability to model recommendations; Nested templates; Ability to compare scenarios</td>
<td>Lack of benchmarks; Inability to compare building products ; No 3D integration; Life Cycle Cost Model</td>
</tr>
</tbody>
</table>

Tool users prefer having the option to access multiple databases through a simple, online tool that performs comprehensive analyses. Tools that are compliant with ISO standards are preferred along with the option to include multiple impact reporting through nested templates that are able to compare scenarios. However, there is an overall concern about the lack of Australian data and the inconsistent methodology employed for this assessment. In addition to the data weaknesses, some of the tools are considered to be time consuming and requiring expert knowledge to use, presenting considerable
barriers for their uptake. Desired outcomes include the availability of benchmarks; 3D visualisation and integration of life cycle costing into the analyses.

What is evident for these results is that even though internationally developed tools dominate the EC assessment tool preference options, there is overwhelming interest in Australian developed tools, such as eTool, with the fact that it is second most popular from an industry perspective. However based on the amount of weakness, there is still much room for improvement in current tools.

2.4.3. Embodied carbon assessment: new tool recommendations

When asked to indicate the top features desired in EC assessment tools, ‘material cost’ was deemed the most popular with 80% of respondents selecting this option, followed by ‘data on recycled materials’ (62%) and then ‘source of materials’ (57%). When asked to rank important features and functionality, ‘Reliability of findings’ and ‘Ease of use’ came out on top along with a need for a ‘List of mitigation measures’ and ‘Comparison against a benchmark’.

The recommendations provided by the respondents for future EC assessment tools can be classified under the same themes as earlier, namely data; method; usability; regulation and outcomes (Table 3). Users want a tool that relies on sound data that is easy to update. A consistent and transparent methodology is needed that looks at EC holistically while adhering to Australian standards and practices. These findings suggest that either a new tool, or improvements to existing tools, are needed as none of the existing tools adequately address all of these user needs.

<table>
<thead>
<tr>
<th>Theme</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data</td>
<td>Sound data; Access to a broad range of databases; Easy to update; Data quality measures are in place.</td>
</tr>
<tr>
<td>Method</td>
<td>Transparent and consistent; Comprehensive; Whole footprint; Integration with existing tools.</td>
</tr>
<tr>
<td>Usability</td>
<td>Stream-line user interface that is simple to use with Building Information Modelling (BIM) compatibility.</td>
</tr>
<tr>
<td>Regulation</td>
<td>Adherence to Australian policies, standards and procedures.</td>
</tr>
<tr>
<td>Outcomes</td>
<td>Option for ‘quick’ analyses; Comparison against a benchmark and compatibility with Green Star.</td>
</tr>
</tbody>
</table>

3. Conclusion

This survey provided a brief insight into the construction industry’s current approach to EC assessment, identifying which tools and services are the most prominent along with providing further insight into what features these users would want from new and improved EC assessment tools. What is most evident from the survey is that there is overwhelming interest from the Australian construction industry in either providing EC assessment or intending to provide EC assessment as a service in the future. Another conclusion to be drawn is that there is interest in locally developed tools but there are still several potential areas for improvements that need to be worked upon. As part of the ICM project, the
ICM Tool and PIM Tool can help address these weaknesses and incorporate the suggested improvements so as to better support industry needs. There are still a few hurdles to overcome in order to evolve EC assessment uptake, such as lack of project budget, client disinterest, no clear cost incentive and lack of set standards. This ‘lack of set standards’ is further evidenced by the overall concern towards data, especially the lack of Australian data. Another ICM output would be a comprehensive database which will help address this data hurdle and help contribute to more reliable, holistic EC data.

This survey demonstrated that there is interest from the Australian construction industry to further develop Australian based EC research projects, such as the ICM project, and further identified the several potential areas where the ICM project outputs can help contribute to the current EC assessment method.

3.1. Limitations

There are several limitations to this study to be aware of when interpreting the results. The small sample size of 46 has implications on the limited amount of varied responses. However the study was aimed at providing a general overview of industry’s current approach to EC so that future areas of research can be highlighted and investigated at a later stage. The non-response error was addressed through advertising the survey through multiple mediums (from email link, to twitter and on the CRC LCL website). Follow up emails were sent to the selected sample. Due to time constraints other techniques to minimize the non-response error was not employed, such as weighting or proxy respondents. Another limitation is that fact that the responses are dominated from professionals involved with LCA, thus potentially alluding to a higher percentage of industry organisations involved with EC assessment than in reality. However the results are still valid as the survey is primarily aimed at professionals involved with EC assessment (LCA practitioners, sustainability consultants and engineers), thus providing an adequate sample selection for this study. Another aspect affecting the results is reliability. The questions and results are subject to unreliability either due to bias of the researcher of the participant and depend on the motivation of the participant for completing the survey (whether it was to demonstrate and showcase their own tool or show genuine interest). In order to ensure reliability was achieved as much as feasibly possible, several techniques were used. Such as careful wording of questions so as not to pre-empt a desired answer; minimal use of ‘do not know’ responses and the use of multiple-item indicators (such as the Likert scale). Regarding the non-response rate, according to Vaus (2002) a 20% non-response rate can be expected. This survey incurred a 55% non-response rate. This could have been affected, as suggested by Vaus, by either survey length, content or method of administration. This survey results are also dependent on the researchers email list and the participants access to email.

3.2. Further research

A detailed study of existing EC assessment tools needs to be conducted in order to learn from current weaknesses and identify any recommendations for improvements to these tools. Further research into the prevalence of in-house EC assessment tools and datasets in order to determine the reasoning why commercially available software and data is not sufficient in these organisations is also needed. The development of an appropriate benchmark for EC of various building types, materials and components as well as the development of a consistent methodology is also required.
Acknowledgements

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Abstract: Prefabricated relocatable learning environments form an important component of school infrastructure in Australia but their light-weight construction means they often require air-conditioning for a comfortable indoor environment quality (IEQ). The ‘envi Sustainable Education Spaces’ were recently constructed by the Department of Education and Training (DET) in Victoria to showcase a more sustainable alternative to the traditional ‘relocatables’. Evaluation had been undertaken by others to assess the design ambitions to reduce operational energy by 90% and lifecycle emissions of CO₂ production by 50%. What was not known was how the spaces accommodated learning and learners. This was the focus of research undertaken by the authors in 2014. In this paper, we present the methodology and findings and argue a case for holistic post-occupancy evaluation in order to paint a more complete picture regarding the costs and benefits of innovative spaces even when innovation is primarily focused on environmental benefits. The research applies a mixed methods approach, utilising quantitative and qualitative data. Commentary by students and staff on the indoor environment quality, including acoustics and temperature, provides useful cross-linking data with earlier studies. This research is part of broader research on prefabricated learning environments undertaken by the authors and others.

Keywords: Post-occupancy evaluation (POE); learning space evaluation; learning space design; mixed methods research.

1. Introduction

In 2014, the Victorian Department of Education and Early Childhood Development—now Department of Education and Training (DET)—commissioned the Learning Environments Applied Research Network (LEaRN) at the University of Melbourne to undertake post-occupancy evaluation research of their recently completed ‘envi Sustainable Education Spaces’. The envi prefabricated education spaces had been designed and detailed with the aim of reducing operational energy by 90% and lifecycle CO₂ emissions by 50% from the standard prefabricated classrooms in circulation (DET, 2013). While an evaluation of the energy and CO₂ performance had been completed, what was not known was how the
spaces performed for learning and learners. This research addressed that question using a mixed methods approach in a three-phase data collection process. We began with an online survey of key stakeholders and occupants of the facility including students, teachers and the principal. We then undertook an observational walk through the spaces with the principal and occupant teachers. The final stage consisted of a focus group at which the earlier findings and observations were reflected upon and opportunities for improvements were discussed. The data generated through this process can inform future designs but also, importantly, assists current users to better align space and pedagogy.

LEaRN’s School Spaces Evaluation Instrument (SSEI), Module 3 — Alignment of Pedagogy and Learning Environments was utilised for this research commission. This instrument helps evaluate links between learning activities and the physical setting. It consists of three modules: Module 1 is focused on the design process; Module 2 on the quality of the indoor environment; and Module 3 considers the alignment of space and pedagogy. This instrument was developed by Cleveland as Research Fellow for LEaRN in collaboration with design and education academics at the University of Melbourne and industry partners including Catholic Education Melbourne, architecture firms and schools.

2. A critical review of the literature

The need for a more comprehensive Post-Occupancy Evaluation (POE) tool was established by a critical review of the literature related to learning space evaluation (Cleveland & Fisher, 2014). This literature review noted a recent spike in interest in learning environment evaluation at the intersection of the physical and the social using strategies which incorporated the opinions of the occupants and ‘called for two-way communication, community building, cooperation, trust and honesty’ (Preiser & Nasar, 2008, p. 88). However, strategies for the evaluation of pedagogical effectiveness are still in their infancy and there is a need for further work to ascertain appropriate methodologies (Lee, Tan, Learning, & Council, 2011; Pearshouse et al., 2009; Radcliffe, 2008). The literature review reveals that a number of research instruments have been developed in various countries to evaluate learning spaces, however most share the shortcoming of focusing on the physical environment rather than how the learning spaces facilitate desired educational practices and behaviours. A difficulty with POE strategies is that they tend to be conceived from disciplinary rather than interdisciplinary perspectives.

There is a paucity of comprehensive building evaluation methodologies for all education sectors within the literature. In particular, there is little work available on formative evaluation methodologies that could not only support the evaluation of educational facilities but also help occupants better align pedagogy and space using a form of action research. Much research has focused on attempting to ascertain the causal links between space and learning outcomes, particularly within the United States (Higgins, Hall, Wall, Woolner, & McCaughey, 2005). The conclusion of Higgins et al’s review states that:

The evidence is unequivocal with regard to the importance of user engagement in defining and solving design problems in schools, and a necessary consequence of this is the realisation that design solutions will be individualised, organic and local. Indeed, the most successful are likely to be those which are seen as interim solutions and which have within them elements of flexibility and adaptability for new cohorts of learners and teachers, new curriculum demands and new challenges (p. 37).

This observation highlights the need for design solutions to be perceived as organic and able to adapt to new cohorts. Likewise, a more recent literature review notes that there is,
... little empirical research that considers how students and teachers as well as communities negotiate and create new relationships, organisational structures and processes in the use of new learning spaces (Blackmore, Bateman, Loughlin, O'Mara, & Aranda, 2011, p. 11).

The evaluation of buildings more generally was initially conducted in the 1960s by academics interested in the interaction between people and environment (Cooper, 2001). We consider this process as being post-occupancy evaluation (POE) defined as ‘the examination of the effectiveness for human users of occupied designed environments’ (Zimring & Reizenstein, 1980, p. 429). In the 1980s many post-occupancy evaluations were undertaken on public projects in the UK, USA, Canada, Australia and New Zealand (Preiser & Nasar, 2008). They were implemented differently in different countries and this led to a proliferation of POE methodologies (Hadjri & Crozier, 2009).

These were grouped into three categories by Crozier (2009): indicative, investigative and diagnostic. Indicative POE consists of quick walkthrough evaluations supplemented by structured interviews with key personnel as well as group meetings with building users. Investigative POE includes more in-depth analyses usually across a numbers of buildings of similar type. Diagnostic POE involves evaluating across a number of comparable facilities from a broad range of technological and anthropological perspectives (Cleveland & Fisher, 2014; Preiser & Nasar, 2008).

These POE processes do not focus on the transitional aspects of occupation highlighted above as being a specific concern for learning spaces. For example, the POE process was narrowly defined within the recent review of the Federal Government’s 2009 Building the Education Revolution (BER) to assess whether the policy funding had achieved value for money. The BER Taskforce focused its evaluation on quality, value for money, and on-time delivery. A critique of that methodology by one of the authors argued against the narrow definitions provided by the Taskforce on quality and value for money (Newton & Gan, 2012). The Taskforce focused on construction quality at the expense of design quality and was unable to assess the performance of the BER designs in terms of enabling learning. Likewise, value for money and on-time delivery were narrowly defined. For example, life-cycle costing was not included. In this research, we focus particularly on the evaluation of space in terms of occupation with an understanding that spaces and pedagogy should ideally be aligned.

3. The pros and cons of prefabricated learning environments

Before further elaborating on the research it is useful to understand the content of the learning space that was designed as a relocatable prefabricated building. Relocatable prefabricated learning environments are an important component of Australia’s school infrastructure. They usefully accommodate changing school enrolment numbers as the demographics of suburbs fluctuate. They also support remote community needs and accommodate students in times of disasters such as fires, floods and cyclones. In principle, they could be a sustainable and agile solution for changing needs but in reality they are not given the same design attention as permanent infrastructure. By the end of high school, students have spent around 15,000 hours at school (Rutter, Maughan, Mortimore, Ouston, & Smith, 1979). With relocatable classrooms accommodating up to thirty per cent of students in some states across Australia, the prefabricated learning spaces should be optimally designed and fit for purpose. For too long prefabricated buildings have not been given the same design attention as permanent buildings. Around Australia they are variously referred to as ‘relocatables’, ‘demountables’ and ‘transportables’ as well as ‘Mod 5’ or ‘Mod 10’ depending on their size and the number of modules used in construction. In the US and UK they are also called ‘modular classrooms’ and ‘terrapins’ which is the proprietary name of
The design of prefabricated learning environments was the subject of an earlier research undertaking funded by the Australian Research Council Linkage Project called *Future Proofing Schools* and led by one of the authors. In an interview undertaken as part of that research, one teacher aptly said that ‘today’s relocatables fit a truck, not a learning experience’ (Future Proofing Schools research interview, April 2011).

As part of the Future Proofing Schools’ research project, stakeholders were asked what they would like for their learning spaces. The image below summarises their suggestions (Future Proofing Schools, 2011, p. 20). Perhaps unsurprisingly, the students’ responses were primarily linked to comfort while the educators focused on facilities and the principals on logistics and costs. We were interested to see if the same division of focus was found within the occupants of the ‘envi’ space.

![Image](image.png)

*Figure 1: What we’d really like.* (source: Future Proofing Schools, 2011)
The ‘envi’ prefabricated prototype building contributes a new approach to prefabricated learning spaces. The ‘envi’ design includes strategies such as extra insulation to the external envelope, double-glazing, efficient lighting and automatic systems to monitor and operate the lighting, heating, cooling and ventilation of the indoor environment. The design improvements are largely focused on sustainability issues rather than considering how future learning might occur. The floor plan largely duplicates the common Victorian ‘Mod 5’ plans which typically consist of two classrooms linked partly by an operable wall and partly by a small retreat room.

Figure 2: Internal and external views of ‘envi’. (source: Authors, 2014)
4. The research methodology

The research methodology recognises that the educational values of the school community and the administrative body should inform the learning evaluation. The evaluation is therefore intrinsically linked to the school’s context, its culture, educational philosophy and vision for learning.

A mixed-methods approach was used for data collection to ensure that the shortcomings of each individual method were overcome by the strengths of others and to triangulate across methods to support validity. Data was collected via surveys, structured observations and walkthroughs and a focus group presentation and discussion. In addition, photographs of the spaces in use were taken. A ‘walkthrough’ is an architectural observation method where an expert uses a checklist to evaluate the performance of specific spaces within a site. Walkthroughs are normally undertaken by architects during the defects liability period in order to discover faults or further work required to meet the contract delivery. In this study, we broaden the concept of the walkthrough to encompass how effectively the spaces are being used for learning. The researchers, as the ‘experts’ on space and pedagogy, conducted the walkthrough in partnership with three ‘informed participants’; the principal, a teacher and a representative of the infrastructure section of the education department. By sharing observations from the various perspectives of occupant, principal, bureaucrat and academic, our aim was to develop a more nuanced understanding of the strengths, shortcomings and missed opportunities in how the learning spaces were designed and occupied for learning and learners.

![Figure 3: Balancing pedagogy and space. (source: Cleveland, 2011)](image-url)

Researching the occupation of learning spaces is concurrently an opportunity and a dilemma because the research crosses the discipline boundaries between architecture and education. It is necessary to adopt and adapt research methodologies from both fields in order to make links between the policy and practice of education and the issues driving built environment design and practice research. Another important source of information was the surveys completed by the principal and
assistant principal (50-60 minutes) and the follow-up focus group (60 minutes). The teachers identified by the principal as being the most knowledgeable about the spaces were invited to complete a shorter survey (20-25 minutes) as well as participating in the focus group (60 minutes). The quantitative data collected through the surveys was analysed using descriptive statistics, while the qualitative data was analysed using thematic narrative analysis (Riessman, 2008). The observational walkthrough and focus group data were also analysed using thematic narrative analysis.

Before commencing the in situ research, ethics approvals were applied for and granted by the host university and the administering education department. As part of the ethics approval, faces of teachers and students were required to be blurred to avoid identification in any published images.

The ‘envi’ building accommodated two traditional class groupings, each with a teacher and around 25 students. With permission from DET and the school principal, the researchers invited the teachers and students occupying the ‘envi’ spaces to participate in the study. The invitation to participate was supported by a written plain language statement and consent form. Primary students with signed permissions from their guardians or parents participated in a short online survey (15-20 minutes) and their answers and opinions form part of this analysis. Fourteen grade four students responded to the survey along with three teachers.

5. The findings

5.1. The vision for learning and teaching

The most successful schools tend to have a shared vision for teaching and learning which is well understood and able to be articulated by both staff and students. The interview with the principal for the ‘envi’ spaces summarised the school’s visions as being focused on:

- **Essential skills development**: literacy and numeracy, critical thinking and problem solving, and skills development for lifelong learning and community participation.
- **Teacher choice**: Teacher freedom to choose different tools, resources, settings and teaching approaches.
- **Shared teacher responsibility**: Collective ownership by teams of teachers for student learning across each year level based on a Professional Learning Community (PLC) model.
- **Measurable learning outcomes**: Goal-oriented learning supported by clear success criteria and data-driven teaching that is responsive to assessment feedback.
- **Timely interventions to support student-learning needs**: The school uses a carefully constructed timetable to allow year-level groups to work together for thirty minutes most days. This enables targeted cross-class teaching focused on individual student needs. Students are allocated into groups according to their learning needs for intensive teaching.

5.2. General findings

There was a high level of satisfaction with the ‘envi’ spaces when accommodating the traditional classroom practice of one teacher per class of students. The ‘envi’ building consists of two interlinked classrooms so there is some potential for teaching larger cohorts across the dual classrooms. The size of the space limits the occupants to around 56 students and the design restricts the movement of students and teachers to other indoor and outdoor learning settings. If the spaces were enlarged beyond the dual classroom there would be further flexibility for the teachers to work more collaboratively in ways that
would be better aligned with the education vision developed for this school. The evaluation highlighted the difficulties faced when modular facilities do not support collaborative practices that teachers and students may have developed in the permanent more flexible learning spaces.

Staff reported positively about the overall allocation of floor space when compared with the smaller classrooms in the permanent facility. In particular they appreciated the light-weight chairs and tables which were readily able to be reconfigured to suit different modes of learning. They also appreciated the pinup space and ramp access. Because of timber floors, lightweight relocatables are normally located above ground level requiring steps. Staff appreciated the withdrawal space shared by the two classrooms.

In terms of comfort, students and staff considered the indoor environment quality to be good for acoustics, natural and artificial lighting, temperature (when mechanical systems were operating normally) and air quality. Students commented on the noise of the automatically operating louvre systems.

The spaces could have been made more effective if they afforded greater flexibility to support a broader range of pedagogies and were more interconnected with other learning spaces to allow for greater collaboration. Access to more varied learning settings and furniture types, as well as a wet area construction zone, would help expand the modes of learning possible. The teacher workspaces located within each of the classrooms took up a substantial part of the footprint and these might have been more efficiently collocated to free up floor space and encourage teacher collaboration.

General access to outside areas for learning was limited even though a large deck adjoined the ‘envi’ space. A difficulty was the lack of visual access between the inside and the outside areas. Access to toilets was not easy, particularly in inclement weather. Best practice learning spaces tend to distribute toilets for easy access from teaching spaces rather than house them in blocks away from learners.

5.3. Suggested actions in response to the evaluation

There is an opportunity to further review the design and furnishing of modular buildings in ways that allow schools to have input into how the spaces are configured and furnished to more strongly link the spaces with the educational vision developed by the school. In this case, the school was keen for whole year levels to work collaboratively at times during the week to ensure students had access to explicit teaching to meet their needs. A ‘kit of parts’ approach may be suitable to enable facilities of various sizes and configurations to be created.

The ‘envi’ space is well suited to traditional classroom practice (single teacher model) but does not provide the flexibility required to support more collaborative practices and wet area activities. The potential for more collaboration in teaching and teacher preparation is limited to the dual classroom at this stage although there is potential for this building to be more closely linked across the decking to another dual classroom, particularly if the outdoor decking is rain protected.

6. Discussion

LEaRN’s SSEI tool is still evolving. It helps to highlight spatial possibilities and hindrances and also helps students and teachers to think constructively about space and reflect on their learning and teaching. In particular it begins to develop a spatial literacy in teachers to consider the physical environment as a third teacher.
Sometimes the quantitative responses raise issues that deserve further investigation. These formed part of the discussion within the focus group and during the observational walkthrough. Currently these do not include children and so even though we get useful qualitative data from their comments within the survey, we do not have the same rich overlay of qualitative data from students. For example, in the survey all teachers ‘strongly agreed’ they liked the views to the outside but over a third of the students did not like the views. We could surmise that the windowsill height works better for teachers who are predominantly standing but without further discussion we cannot be certain.

In earlier related research on prefabricated learning spaces we asked students, staff and principals open-ended questions about the types of learning spaces they would like. Students focused on comfort, educators on facilities and principals on logistics and costs. In this research we also asked students and teachers to highlight what they did and did not like about the ‘envi’ space. In this case, both groups focused primarily on comfort, with both groups also appreciating the furniture.

Even though the study was not focused on the environmental credentials of the space, there is a strong overlap between how the space works from an environmental perspective and how it works from a pedagogical perspective. Without prompting, over a third of students highlighted the noisy operation of the automatic ventilation louvres as a negative, saying ‘windows sometimes open and close and distract us with the noise’, ‘the windows are annoying, they are very noisy’, ‘the windows sometimes get distracting with the noises when they open and close’, ‘the windows are noisy when they move’ and ‘the windows keep making a noise’. An explanation for this consistency may be that children are still developing the ability to block out extraneous noise. This kind of knowledge is useful for future designers of school spaces.

7. Conclusion

In this paper, we describe one application of a post-occupancy school evaluation instrument that uses a mixed methods approach to develop a more nuanced understanding of how space and pedagogy align. The application was commissioned by the Department of Education and Training in Victoria to better understand the learning and teaching implications of the ‘envi’ building where design innovation was focused on sustainability rather than teaching per se. Prefabricated learning spaces form a significant proportion of Australia’s school infrastructure and this research contributes to their ongoing improvement. The tool complements other post-occupancy strategies and highlights how design and space can support or hinder learning and teaching.

Acknowledgements

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The use of Integral Theory to evaluate architectural sustainability – a case study

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Abstract: DeKay’s concept of Integral Sustainable Design (ISD) is based on Integral Theory, a framework proposed by the American philosopher, Ken Wilber. It offers four simultaneous perspectives (represented by quadrants) which each take a different view of the problem. The ‘experiences’ quadrant focuses on individual human experiences. The ‘behaviours’ quadrant looks at environmental performance. The ‘cultures’ perspective focuses on the collective interpretation of meaning, symbolism and worldviews and the ‘systems’ quadrant investigates the response and interaction with context. Integral Theory can act as a reminder for architects of the different perspectives that a sustainable building should address. In order to evaluate ISD, the Waterfront Campus Building of Deakin University has been used as a case study. The building, its performance, impact and perception, has been evaluated using both quantitative and qualitative data. Two surveys have been conducted to gather qualitative data to: (i) determine the experience of building users (staff and students) and (ii) the perception of non-users (Geelong residents and tourists). Data from building services and a site analysis has enabled quantitative assessments to be made. These inputs have been analysed, guided by ISD, to evaluate the usefulness of ISD as a sustainability assessment tool.

Keywords: Sustainability; assessment; Integral Theory.

1. Introduction

The built environment in all its forms is probably the single biggest contributor to the increased human impact on the planet. The impacts are wide ranging, numerous and well researched. For example, there is the: operational energy to heat and cool the structures; embodied energy in the construction materials used; loss of biodiversity at all stages of manufacture and use; water consumption and effect on run-off; and the waste generated from cradle to grave. These are the conventional metrics by which, at the very least, we should be evaluating our new buildings. The built environment has other impacts, however. The built environment shapes the way we behave, think and experience the world around us. If we are serious about building in harmony with the planet, rather than against it, we must consider a
wider context, one that includes surrounding ecosystems, their interaction, dynamics and interdependence. If our actions are seen and framed in a more holistic way, we may then truly embrace ‘sustainable development’.

This latter term was first brought to global prominence by Gro Harlem Brundtland nearly 30 years ago (WECD 1987) and, despite the criticisms, it has remained on the world agenda ever since. It explicitly (or implicitly) underpins much of what those who care about the planet do in their private and professional lives. Today, as we face the life-threatening impact of changing the planet’s climate, the concept of any future ‘development’ and what it looks like is probably the single biggest challenge confronting humankind. It has been suggested that sustainable development has four key principles (Palmer et al. 1997) - futurity, environment, participation and equity – and these principles are a useful reminder of the interaction between the environment and society. Sustainable development as a concept has unfortunately been found wanting and not delivered a clear way forward. It has been interpreted in many different ways, usually to suit the purposes of the proponent. Others have argued that ‘weak’ and ‘strong’ sustainability must be differentiated and that only the latter which places the planet (environment) at the centre of all decisions should be adopted.

An alternative theory that brings a new perspective to the thinking about our built environment and one that might guide our future actions is Integral Sustainable Design (ISD). The framework of ISD aims to provide an approach to sustainability, that is not just more holistic in terms of criteria considered but which seeks to establish a new paradigm where buildings are evaluated from a perspective of ‘being within nature’, rather than outside of it, no matter how sensitively. The aim of this paper is test the appropriateness of ISD to evaluate the sustainability of a particular building. To the authors’ knowledge this has not been attempted previously although some generalizations of the applicability of ISD to the built environment have been suggested (Du Plessis and Brandon, 2014). To acquaint the reader with the fundamentals of ISD, this paper begins with the theoretical considerations and model proposed by DeKay and Bennett (2011). The building used as a case study in this research is then briefly described followed by an overview of the methodology adopted in this analysis. A detailed description of the research method used to address each of the four components is then given together with the particular results generated. Discussion of these results, both separately and as a whole then follows. Some conclusions of the strengths and weakness of the ISD method are then drawn.

2. Background Theory

According to DeKay and Bennett (2011 xxiii), the concept of ISD aims to improve the relevance, meaning and positive effect on people and nature.

“Integral Theory is a meta-theory, a network structure of other valid theories from multiple domains of knowledge. Its primary offering is that the world is disclosed differently depending on the perspective taken and that many perspectives are necessary to get a whole and complete understanding of the world, or even fully grasp any particular occurrence. As such it uses two primary frameworks: 1. The four perspectives (quadrants), which arise from fundamental distinctions of value, and 2. Levels of complexity, which arise from the unfolding sequence of development in human individuals, cultures and physical systems, which manifest as developmental sequences such as those for values, cognition, biological evolution, economic systems and worldviews.”
ISD seeks to overcome the ‘art vs science’, ‘design vs technology’ and ‘analysis vs creativity’ thinking that has dominated the design disciplines for the past decades. Although it acknowledges the intention and worthiness of environmental rating schemes such as LEED, it questions the objective-only approach and gives no credit for experiences of beauty and the relationship people have with nature. ISD is based on Integral Theory, a framework proposed by the American philosopher Ken Wilber. ISD suggests that four simultaneous perspectives on a problem can be represented by quadrants each of which takes a different view of the problem (Figure 1). The ‘experiences’ quadrant (upper left) focuses on the individual human experiences, while the ‘behaviours’ quadrant (upper right) looks at the environmental performance. The ‘cultures’ perspective (lower left) focuses on collective interpretation of meaning, symbolism and worldviews, and finally the ‘systems’ quadrant (lower right) investigates the response and interaction with context. Although developed as a philosophical framework, for architects Integral Theory can act as a reminder of the different perspectives that a sustainable building should address in the following way:

- the building should perform well (upper right quadrant) i.e. consume a minimum of resources and have minimal environmental impact. This can be evaluated by quantitative and measurable criteria, which are commonly represented in building rating schemes.
- the building should be well-integrated into its context (lower right quadrant) and consider the immediate site and climate, the biological and cultural region, responding to a comprehensive theory of place, engaging local, regional, global and universal forces such as climate change and urbanisation.
- the building should offer a rich experience to different individuals (upper left quadrant). It should stimulate all the human senses (not just the visual sense), trigger positive feelings and emotions, provide health, well-being, comfort and delight, and enforce the consciousness of natural cycles, transformations (i.e. seasons, weather, time of day), ecologies and evolutions to strengthen the connection of individuals to nature.
- the building should convey symbolic meaning about cultural values (lower left quadrant). It should fit into the cultural context; the design should express what is important to society on a local regional and global level; it should be ethically responsible; and is itself a product of practices and perceptions embedded in the building culture and pattern languages used by that building culture.

Figure 1: Quadrants and levels of Integral Theory (source: DeKay and Bennett, 2011).
The two left hand side quadrants are therefore qualitative (subjective) and the two right hand side quadrants are quantitative (objective). While DeKay uses the term ‘behaviours’ for the upper right quadrant and ‘systems’ for the lower right quadrant, for the sake of clarity in the discussion with architects and occupants, the term ‘performance’ is added to the upper right and the term ‘context’ is added to the lower right quadrant. Table 1 summarizes the focus of each quadrant and the main method of investigation. While the quantitative quadrants are more straightforward to measure numerically, the evaluation of qualitative quadrants might require the additional expertise of social scientists and psychologists.

<table>
<thead>
<tr>
<th>Quadrant</th>
<th>Qualitative or quantitative</th>
<th>Main question</th>
<th>Method of investigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper left - Experiences</td>
<td>Qualitative</td>
<td>How does an individual person experience the building?</td>
<td>Human senses, feelings, emotions, consciousness, experience</td>
</tr>
<tr>
<td>Lower left – Cultures</td>
<td>Qualitative</td>
<td>How is the building perceived by society?</td>
<td>Mutual understanding, worldviews, symbolism</td>
</tr>
<tr>
<td>Upper right - Performance/Behaviours</td>
<td>Quantitative</td>
<td>How does the building perform?</td>
<td>Measurement, calculations</td>
</tr>
<tr>
<td>Lower right - Context/Systems</td>
<td>Quantitative</td>
<td>How well is the building integrated into its context?</td>
<td>Mapping, systems understanding</td>
</tr>
</tbody>
</table>

3. The Waterfront Campus Building

The building chosen for analysis using the ISD concept is the Waterfront Campus Building (WCB) of Deakin University in Geelong (Figure 2). The building was originally constructed as a woolstore for Dalgety and Co. in 1891. However, it has undergone various transformations in use (including the assembly of the ‘Dalgety Ford’) and appearance prior to its current transformation into a university building in 1996.

Figure 2: Deakin University's Waterfront Campus Building.
4. Research methods overview

The research methods used to analyse the sustainability of the building were guided by the four quadrants shown in Figure 1. The performance of the building (upper right quadrant) was analysed using traditional performance metrics namely energy and water consumption, as well as lighting and thermal comfort. Estimates of embodied energy were also made. An architectural site analysis was conducted to determine how well the building fitted within its context (lower right quadrant). An on-line survey was used to determine the experiences of users of the building (upper left quadrant) and a street survey in two locations in Geelong was used to assess how well the building was perceived by outside society. The results of each individual analysis are presented below.

5. ISD-guided analysis

5.1. How do users experience the building? (Upper left quadrant)

This part of the study investigates the perception of the building user. The participation rate for the on-line survey was very high. Of the 220 people who participated in the survey, 54% were students and 46% were staff (Q1). The next two questions asked participants to identify their ‘favourite space’ within the campus, either inside or outside (Q2), and the importance of the various human senses (sight, hearing, smell, taste and touch) in experiencing that favourite space (Q3). Participants were also asked what they preferred to do in their favourite space (Q4) and whether it enabled them to be aware of conditions outside the building (Q5).

As the question about ‘favourite space’ was open-ended, a number of spaces were identified such as the library, café, staff lounge room on Level 6 and courtyard. The library was the most preferred space for most of the students and staff lounge room on Level 6 was the most preferred room for most of the staff. In terms of the importance of various human senses, sight was the most important followed by hearing. Both smell and touch were similar in terms of importance and taste was found to be the least important (Table 2). The majority of the people felt that their favourite place enabled them to identify the time of the day i.e. they experienced daylight (Table 3). In summary, most of the favourite spaces have one thing in common i.e. a lot of windows and a view of Corio Bay. This finding is not unexpected as the users find sight as the most important sense.

<table>
<thead>
<tr>
<th>Table 2: Relationship of human senses to favourite space.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Sight</td>
</tr>
<tr>
<td>Hearing</td>
</tr>
<tr>
<td>Smell</td>
</tr>
<tr>
<td>Touch</td>
</tr>
<tr>
<td>Taste</td>
</tr>
</tbody>
</table>
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Table 3: Favourite space and ability to experience natural conditions.

<table>
<thead>
<tr>
<th>Natural conditions</th>
<th>Number of responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of the day</td>
<td>204</td>
</tr>
<tr>
<td>Rainfall</td>
<td>179</td>
</tr>
<tr>
<td>Patterns And Intensity Of Sun</td>
<td>164</td>
</tr>
<tr>
<td>Wind</td>
<td>152</td>
</tr>
<tr>
<td>Seasonal change of flora and fauna</td>
<td>120</td>
</tr>
<tr>
<td>Temperatures</td>
<td>117</td>
</tr>
</tbody>
</table>

5.2. How do outsiders experience the building? (Lower left quadrant)

The purpose of this part of the investigation was to determine the attitude of ‘outsiders’ to the building. By ‘outsiders’, we mean local residents or visitors to Geelong. The views of these people would hopefully be an indication of whether the building fitted into its cultural context and whether it expressed to them what is important at a local and regional level. In other words, how well the building conveyed cultural meaning (DeKay, and Bennett 2011). To determine these local perceptions, street surveys were conducted over two days in two different locations of Geelong. Both locations were within 500 metres of the building and in busy pedestrian thoroughfares. Passers-by were asked if they would take part in a survey for Deakin University and told that the survey only contained 11 questions and therefore it would not take long to complete. Surprisingly, only 21 responses were collected over the two days, with people seemingly reluctant to take part. The surveyor thought that people may have believed that she was selling something and this explained their reluctance to participate. The level of response is in sharp contrast to the on-line survey of users of the building, namely staff and students, where the response was more than ten times the street survey number.

The first question (Q1) simply asked if the person being surveyed recognized the building. Over 90% of people responded in the affirmative. Over 76% of those interviewed had actually been inside the building (Q2), which indicates that despite its location on the edge of the CBD and down on the waterfront, the local community had ventured inside and experienced the building more deeply for some reason. The building’s café is open to the public and is sometimes used for ‘events’. In addition, concerts are also held in the large performance space within the building. The general reaction to Q3 was that the building improves its waterfront location with nearly 62% responding positively. However, the survey discovered that it was not the main interest when visiting the waterfront location. Perhaps unsurprisingly, over 70% focused on their natural surroundings i.e. Corio Bay and the surrounding views rather than the buildings. The building’s importance to Geelong was recognized by a positive response (76%) to the next question (Q5) but those surveyed were much more equivocal about whether the building fitted their image of a university building (Q6). People were fairly equally split (52-48%) on this question and perhaps these mixed feelings are reflected in the response to subsequent questions. A positive (57%), although not overwhelming, response to whether the building reflected an important view of Geelong to visitors (Q7) was offset by a strong view that the building was not particularly attractive (Q9) with only 38% saying ‘Yes’ and the same percentage even thought a new building should have been constructed rather than re-using an existing building (Q8). However, two out of three
respondents did feel the building had something to offer society. Table 4 summarises the results of the survey.

Table 4: Summary of street survey questions and responses (percentages).

<table>
<thead>
<tr>
<th>No</th>
<th>Question</th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q1</td>
<td>Do you recognize the building?</td>
<td>90</td>
<td>10</td>
</tr>
<tr>
<td>Q2</td>
<td>Have you been inside the building?</td>
<td>76</td>
<td>24</td>
</tr>
<tr>
<td>Q3</td>
<td>Do you think the building improves its waterfront location?</td>
<td>62</td>
<td>38</td>
</tr>
<tr>
<td>Q4</td>
<td>When you are down at the waterfront, what do you mainly look at – the buildings or nature?</td>
<td>29</td>
<td>71</td>
</tr>
<tr>
<td>Q5</td>
<td>Do you think the building is important to Geelong?</td>
<td>76</td>
<td>24</td>
</tr>
<tr>
<td>Q6</td>
<td>Does the building fit with your idea of a university building?</td>
<td>52</td>
<td>48</td>
</tr>
<tr>
<td>Q7</td>
<td>Does the building reflect a view of Geelong that you would like visitors to understand rather than re-using an existing building?</td>
<td>57</td>
<td>43</td>
</tr>
<tr>
<td>Q8</td>
<td>Do you think a brand new university building should have been constructed on this site rather than re-using an existing building?</td>
<td>38</td>
<td>62</td>
</tr>
<tr>
<td>Q9</td>
<td>Do you think the building is attractive?</td>
<td>38</td>
<td>62</td>
</tr>
<tr>
<td>Q10</td>
<td>Do you think the building offers anything to society?</td>
<td>67</td>
<td>33</td>
</tr>
<tr>
<td>Q11</td>
<td>Do you have further comments you would like to make about the building? If so, what are they?</td>
<td>24</td>
<td>76</td>
</tr>
</tbody>
</table>

Further comments were made by five (24%) of those surveyed (Q11). Four out of the five comments were ‘negative’ and related to the appearance of the building in one way or other. Perhaps this is not surprising since the respondents were not ‘users’, rather they were ‘observers’ of the building. Of interest and significance to this research are the following statements that:

- “More work should have been done on the façade. It is a box”;
- “More signs to clearly state that it is a university”;
- “It should look more like the old days when it was the woolstore”;
- “Having the university in the city is fantastic for Geelong”;
- “Could have a façade face lift”.

5.3. How well does the building perform? (Upper right quadrant)

This quadrant represents the area with which most building designers and others interested in sustainable buildings will be familiar. How well does the building perform in a technical sense? Several metrics have been used to evaluate the building: energy and water use, embodied energy, thermal comfort and lighting, and each of these is discussed below.

5.3.1. Energy

The WCB has a gross building floor area of 56,000 m² and there are 3,938 full time equivalent students who attend this campus. In addition to the students, 600 staff use the building. The campus building consumes 13,097 MWh of energy per year and produces 10,855 tonnes of greenhouse gas emissions. There are several benchmarks against which this criterion can be evaluated. One of the benchmark available is the Tertiary Education Facilities Management Association (TEFMA). According to TEFMA (2012, cited in GHD, 2014), the best practice energy benchmark for existing buildings is 740 MJ/m² per year. The energy usage intensity of the WCB is 841 MJ/m² which exceeds the TEFMA best practice by 13%. The energy consumption per student is 25% more than the TEFMA benchmark. Another metric is the Australian NABERS commercial office building rating (NABERS 2003). By supplying the measured
energy consumption and associated carbon emissions, estimates of star rating can be made in various usage and occupancy scenarios. Ranges of 50-70 hours per week for 1000-1800 occupants were assumed. In the five scenarios considered, the WCB had the performance equivalent of a 3.5-4.0 star-rated building. Considering that the WCB is a refurbished building and that a 6.0 star rating is the optimum, this is considered to be a reasonable performance.

5.3.2. Water

The total annual potable water consumption is 6,992 kL and the waste water produced is 3,798 kL. Dividing this by the total equivalent full-time student load (EFTSL), the total water use including consumption and waste is equivalent to 2.74 kL/EFTSL. This is only 20% of the TEFMA benchmark of 13.6 kL/EFTSL.

5.3.3. Embodied energy

Estimation of the energy embodied in a building is a complex calculation process requiring large amounts of data, which is beyond the scope of this research. Nevertheless an approximation of the emissions avoided by re-using an existing building can be made, as opposed to the emissions generated by constructing a new building. Crawford (2011) has calculated the carbon dioxide emissions for a new three-storey commercial office building. The floor area of building was 11,600 m², compared to the WCB which is 56,000 m². Crawford estimated that emissions from the embodied energy in the construction of the smaller building were 22.9 kt CO₂-e. Maintenance and refurbishment of the building over a 50-year timeframe are assumed to be the equivalent of 1% per annum of the building’s initial embodied energy i.e. 11.4 kt CO₂-e. Using this ratio as an indication of the energy embodied in the initial refurbishment of the WCB means that the embodied energy of the refurbished building is approximately 55 kt CO₂-e, compared to 110 kt CO₂-e that would be incurred if a new building had been constructed.

5.3.4. Thermal Comfort

Measurements were conducted in four selected locations to analyze internal thermal comfort conditions. As the building is fully air-conditioned, the PMV/PPD model has been used. Figure 3 shows the Predicted Percentage Dissatisfied in each of the four selected areas. Note that the measurement time varies in each area. Since measurements were taken in winter, a clothing value (CLO) of 0.8 and the activity level of 1.2 MET (metabolic rate) was assumed.
Interestingly, our results indicate that there can be a high variability in comfort for specific areas (cafeteria and 4th floor offices). For most of the areas the PPD is quite reasonable; however, in areas of greater activity and transition such as the cafeteria, comfort can vary significantly throughout a day. Again, considering that this is a refurbished building, the energy and comfort performance appear to be reasonable.

5.3.5. Lighting

Lighting measurements were taken in one of the atrium spaces adjacent to the design studio on the 4th floor on a cloudy day in May using a handheld lux meter. Figure 4 shows the floor plan and view of the 48 m² space. Natural light enters through glazing of the saw toothed roof. Artificial lighting is provided by four T5 fluorescent lamps, 39 W each, giving the total lighting power density is 3.3 W/m². The artificial lighting system is integrated with daylighting through motion sensors. According to the Australian Standard (AS 1680.1), the minimum recommended lighting levels in such spaces is 160 lux. BCA section J mandates 6 W/m² as the lighting power density of such space. The lux levels varied from 300 to 800 lux during the day which was significantly above the minimum levels. However, at night, the lux levels were 50-200 lux leaving the corners under-lit.

Figure 4: Floor plan, view and section of the atrium space chosen for lighting evaluation.
5.4. How well does the building fit in its context? (Lower right quadrant)

The purpose of this part of the investigation is to evaluate to what degree the context of the WCB has been used to its full potential with regards to sustainability. This section is discussed as a site analysis commonly performed in early stages of architectural projects. While for architectural projects a site analysis is typically performed to generate design ideas, in the context of this paper the intention is to define potentials for sustainability and then to evaluate to what degree the WCB uses those potentials.

5.4.1. Climate

The climate in Geelong is temperate (Peel et al. 2007). The mean maximum temperature is highest in January and February (25 °C) and lowest (about 14 °C) in July and August with a gradual decrease/increase in the transition seasons (BOM 2015). The mean minimum temperature shows a similar distribution with highest values (around 14 °C) in December to February and lowest values in July (about 5 °C). In case of natural ventilation, the comfort zone for the operative indoor temperature in Geelong ranges from a minimum of 17.4 °C to a maximum of 27.3 °C (ASHRAE 2010), as determined with the software climate consultant (DAUD 2015) based on climatic data generated with Meteonorm (2015). The outside temperatures are: within the indoor comfort temperature range for about 15% of the year; below the comfort zone for more than 80% of the year; and above the comfort zone for less than 5% of the year. Although an assessment of outdoor temperatures alone is of limited value for indoor comfort assessment, it at least gives an indication that the climate requires heating rather than cooling and that the climate offers a potential for natural ventilation. With regards to the WCB, it can be concluded that the current operation as a fully air conditioned building is a missed opportunity. The climate analysis indicates potential for operation of the building in mixed mode, with natural ventilation potentially possible for a number of months of the year. This offers a reduction potential for energy consumption due to air conditioning.

The mean solar exposure in Geelong varies significantly between summer and winter, with highest values (about 25 MJ/m²) in December and January and lowest values (about 7 MJ/m²) in June and July with gradual decrease/increases in between. The saw-tooth roof of the original wool stores is still in place and this provides perfectly north-oriented sloping roof areas with minimal roof obstructions for the integration of photovoltaic installations. Only buildings to the south of the campus are taller, therefore there is little solar obstruction by surrounding buildings. A preliminary analysis (GHD 2014) investigating PV feasibility for the WCB estimated that if the majority of the available roof space was used, approximately 480 kWp of solar energy could be generated to complement the site energy demand. This could potentially provide 30% of the peak demand during summer and offset 9% of the campus electricity consumption. It is also useful to note that the solar generation during daytime aligns well with the peak electricity demand. The mean rainfall is lowest in January (30 mm) and highest between May and November (45-50 mm) with a gradual increase from January to May and a more significant decrease from November to December (BOM 2015). Given the large roof area of the WCB, this offers the potential for water harvesting. Collected grey water could be used for toilet flushing and significantly reduce the potable water consumption. This, however, requires significant storage space within the campus.

5.4.2. Energy supply
According to the Deakin Energy Audit (GHD 2014), the energy consumption of the WCB is covered to 44% by natural gas and to 56% by electricity purchased from the grid. The predominant primary energy source for electricity generation in Victoria is brown coal, resulting in a greenhouse gas emission factor of 1.32 kg CO₂-e/kWh (DIICCSRTE 2013) which is the least efficient in Australia. This further strengthens the above-mentioned potential for the use of renewable energy as a cleaner alternative.

5.4.3. Transport to and from the site

The WCB caters for more than 3900 full time students and a large number of staff. Travel surveys undertaken by Deakin University indicate that more than 60% of staff and 30% of students drive to Deakin as a sole occupant driver, which is responsible for 39,000 tonnes of greenhouse gas emissions each year (DU 2015). Alternative modes of transport available at the WCB are the local bus network with important interchanges in Moorabool Street (10 minutes walk from the WCB and the Geelong railway station (5 minutes walk). The campus does not currently have a dedicated station in the public bus network. Deakin University encourages carpooling and operates an intercampus bus between the WCB and other campuses as well as several car parks. For students and staff commuting from Melbourne, the regional train network provides an alternative, with the station in Geelong located in walking distance from the campus. While local students are eligible for a price reduction on the public transport network, international students as well as staff are not offered a financial incentive to consider more environmental modes of transport. It can be concluded that the resulting greenhouse gas emissions due to travel to and from the WCB have potential for further reduction.

5.4.4. Land use

The WCB is located in a zone dedicated to public use such as retail, commercial, restaurant as well as institutional and public facilities. The surrounding area around the campus is largely sealed by buildings and roads and there is limited space for vegetation. The waterfront along the north of the campus buildings is dedicated to recreational use and one of the major attractions in Geelong. The nearest green spaces from the campus are at the waterfront as well as Johnston Park to the South. The large amount of sealed surface has potential to increase the heat island effect (Steele 2013) which in may influence the effectiveness of natural ventilation. In the south-east corner of the WCB, there is a small grassed area would provide potential for planting of native species, which could enhance the experience of the campus users as well as contribute to mitigate the heat island effect and strengthen native flora and fauna. The WCB itself has a heritage as well as design and development overlay, which needs to be considered in developments and refurbishments of the campus.

6. Discussion

Being only a pilot project, the scope of this study was limited in scale, and thus the authors feel that the requirement for breadth in terms of the integration of qualitative and quantitative assessment to some degree compromised the depth of evaluation in each individual quadrant. For most quadrants additional parameters could have been investigated or the selected ones could have been investigated in more depth, which was beyond the scope of the study. One important insight gained was that the current framework of Integral Theory does not give guidance as to what the ideal level of depth vs breadth of investigated parameters should be and whether this ratio should be similar for all investigated buildings or change depending on the project.
Another observation was that the interrelatedness of investigated parameters sometimes made it difficult to ‘file’ them in just one specific quadrant. For example, the potential to install a photovoltaic system is driven by the climate, a contextual parameter \( \text{(lower right quadrant)} \), but the system itself contributes to the reduction of the building’s primary energy consumption which is a performance metric \( \text{(upper right quadrant)} \). Also, most respondents in the field study of building users selected a favourite space that had a visual connection to the outside \( \text{(upper left quadrant)} \), but particularly to the views at the waterfront \( \text{(lower right quadrant)} \). Additionally, sometimes the recommendations in different quadrants were found to be in conflict with one another. For example, the field study among the Geelong public revealed that the façade of the WCB does not communicate the interior of a university very well and did not seem visually appealing to many respondents \( \text{(lower left quadrant)} \). However, the performance analysis \( \text{(upper right quadrant)} \) revealed that a significant amount of embodied energy had been saved by reusing the building with its original façade as opposed to a new construction. This raises the question of a weighting or prioritising of the different quadrants and perspectives.

The answer to the question of how to prioritise between the different investigated parameters can potentially also be derived from the findings. For example, a number of respondents in the survey among building occupants selected the cafeteria as their favourite space. The thermal comfort analysis for this space, however, indicated a rather large percentage (up to almost 45%) were dissatisfied throughout the day, which would be categorised as a thermally unacceptable space, according to AHSRAE Standard 55. This indicates, that individual occupants consciously or subconsciously prioritise different parameters in their use of the building and further research to reveal these decision-making processes could be interesting.

Overall, the following main conclusions can be drawn from each quadrant: \( \text{(upper left)} \): all selected favourite spaces allow occupants contact with the outside environment, and in particular sight of the waterfront views which are a major attraction at the site. It has to be noted in this context that this view is only available to a minority of spaces and a large number of spaces are internal with no external views. \( \text{(lower left)} \): the WCB is known to the public in Geelong, however more appreciated for its societal value as a university as opposed to its aesthetic value. \( \text{(Upper right)} \): In terms of energy performance the WCB performs worse than comparable standards, however in terms of water consumption, lighting and embodied energy it performs better, while thermal comfort varies depending on the space. \( \text{(lower right)} \): The context analysis revealed a number of underused potentials, e.g. for mixed mode ventilation instead of year around air conditioning, integration of photovoltaics and water harvesting as well as improved public transport. In summary it can be concluded that the WCB scores well in some parameters of each quadrant but not in others, which could be interpreted as an average but not excellent overall rating. The mix of strengths and improvement potentials seems about even in the lower left and upper right quadrant. The lower right quadrant shows more improvement potentials than strengths. The strengths of the upper left quadrant are largely related to the context of the building and there does not seem much variety with regards to the qualities that occupants appreciate a space for.

### 7. Conclusions

This study indicates that ISD can be a useful framework to evaluate a building’s sustainability in a more holistic sense than current building rating schemes, as it allows for the integration of qualitative and quantitative parameters. A building which performs very well in the sense of the upper right quadrant, without offering the occupants an experiential quality will be an incomplete attempt as much as a highly
experiential building which completely ignores the context or results in a very poor performance of quantitative performance criteria. Further research and application of this framework would be helpful to gain additional experience. While Integral Theory in its current stage cannot replace building energy rating schemes, it can act as a reminder for building designers, who are commonly more concerned with the qualitative parameters and engineers or energy auditors who are commonly more concerned with the quantitative side of a more holistic view on sustainability. This framework can also prove useful in the environmental teaching of architecture students. Further research is required to establish the minimum breadth and depth of parameters to investigate for each quadrant in order to produce meaningful holistic results. In this context the balance between accuracy and diversity of investigated parameters, as well as time and money spent on the investigation will be important, and should be addressed in the future development of ISD as an evaluation framework.

References


Steele, P (2013) Urban Heat Island Report, City of Greater Geelong and Wyndham City Council, AECOM Australia Pty Ltd.

User satisfaction with academic buildings – findings from post occupancy evaluations

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Abstract: This paper summarises the results of post-occupancy evaluations of eighteen academic buildings spread over a range of countries and climatic zones. These were carried out using a Building Use Studies questionnaire under licence. Responses were elicited from around 1,000 staff and postgraduates and approximately twice that number of undergraduate students. The mean values, on a seven-point scale, for twelve factors are tabulated and the buildings ranked by a Summary Index. The context, design characteristics and users’ perceptions of eight of these buildings are then described in more detail, four of which had high indices and four low. It is concluded that while the owners and designers of all of these buildings had high aspirations, and that all of them applied appropriate design methods, more strenuous efforts were needed in order to successfully apply full natural ventilation in climates towards the hot-humid end of the range. Noise issues were also evident in naturally ventilated buildings where air transfer routes also acted as sound transmission paths, frequently compounded by associated hard surfaces. The non-availability of building user guides for the occupants was also noted.

Keywords: Academic buildings; user satisfaction; post occupancy evaluation.

1. Introduction

The overarching aim of the author and his various collaborators for many years has been to provide an independent evaluation (i.e., independent of the influence or potential bias of the design teams, the building operators or the management of the occupying organisation) of commercial and institutional buildings from the users’ point of view. It is an indictment of the building industry that relatively few projects are evaluated in this way. After all, the users are the experts on how the building is working in terms of its influence on, inter alia, their comfort, health and productivity (Baird et al, 1996).

The author’s immediate goal is to identify well-performing buildings and to highlight their common features (Baird, 2014a). A further aim is to develop reliable user performance benchmarks (Dykes and Baird, 2013), and the ultimate challenge is to incorporate these into KPIs and rating tools for building projects (Baird, 2009).
Triggered by the relatively poor performance of a recently evaluated building on his own university campus (Gandhi and Baird, 2015), the aim of this paper was to look specifically at the performance of a world-wide set academic buildings. The intention was to assess them in terms of their users’ perceptions of the buildings’ performance. The paper will list the buildings evaluated, outline the methodology used, note the context and the design features of the ‘best’ and ‘worst’ performers in terms of an overall index, and summarise their key characteristics.

2. The buildings and their users

The eighteen buildings selected are listed on Table 1.

<table>
<thead>
<tr>
<th>Building and Academic Institution</th>
<th>City</th>
<th>Climate</th>
<th>Floor area m²</th>
<th>Year built</th>
<th>Year survey</th>
<th>Staff &amp; postgrads surveyed</th>
<th>Undergrads surveyed</th>
</tr>
</thead>
<tbody>
<tr>
<td>CANADA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CompSci&amp;Eng, York University</td>
<td>Toronto</td>
<td>C-T</td>
<td>17,500</td>
<td>2001</td>
<td>2005</td>
<td>70</td>
<td>94</td>
</tr>
<tr>
<td>Liu Institute, UBC</td>
<td>Vancouver</td>
<td>C-T</td>
<td>1,750</td>
<td>2000</td>
<td>2005</td>
<td>21</td>
<td>na</td>
</tr>
<tr>
<td>ENGLAND</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZICER Building, U of East Anglia</td>
<td>Norwich</td>
<td>M-T</td>
<td>2,900</td>
<td>2003</td>
<td>2005</td>
<td>67</td>
<td>na</td>
</tr>
<tr>
<td>NEW ZEALAND</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alan MacDiarmid, Victoria U</td>
<td>Wellington</td>
<td>M-T</td>
<td>6,200</td>
<td>2010</td>
<td>2011</td>
<td>75</td>
<td>na</td>
</tr>
<tr>
<td>Cotton Building, Victoria U</td>
<td>Wellington</td>
<td>M-T</td>
<td>6,700</td>
<td>1979</td>
<td>2011</td>
<td>70</td>
<td>na</td>
</tr>
<tr>
<td>Vivian St (2002), Victoria U</td>
<td>Wellington</td>
<td>M-T</td>
<td>6,000</td>
<td>1994</td>
<td>2002</td>
<td>68</td>
<td>324</td>
</tr>
<tr>
<td>Vivian St (2011), Victoria U</td>
<td>Wellington</td>
<td>M-T</td>
<td>6,000</td>
<td>1994</td>
<td>2011</td>
<td>55</td>
<td>na</td>
</tr>
<tr>
<td>Wigan St, Victoria U</td>
<td>Wellington</td>
<td>M-T</td>
<td>2,200</td>
<td>2005</td>
<td>2011</td>
<td>29</td>
<td>na</td>
</tr>
<tr>
<td>Erskine Building, Canterbury U</td>
<td>Christchurch</td>
<td>M-T</td>
<td>11,600</td>
<td>1998</td>
<td>2001</td>
<td>57</td>
<td>205</td>
</tr>
<tr>
<td>UCOL (Blocks 6, 7 &amp; 8)</td>
<td>Palmerston N</td>
<td>M-T</td>
<td>6,900</td>
<td>1998</td>
<td>2002</td>
<td>86</td>
<td>226</td>
</tr>
<tr>
<td>Inform’n Services, U of Otago</td>
<td>Dunedin</td>
<td>M-T</td>
<td>15,000</td>
<td>2001</td>
<td>2004</td>
<td>36</td>
<td>200</td>
</tr>
<tr>
<td>AUT Akoranga</td>
<td>Auckland</td>
<td>W-T</td>
<td>1,000</td>
<td>2001</td>
<td>2003</td>
<td>25</td>
<td>na</td>
</tr>
<tr>
<td>AUSTRALIA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red Centre, UNSW</td>
<td>Sydney</td>
<td>W-T</td>
<td>17,500</td>
<td>1996</td>
<td>2002</td>
<td>122</td>
<td>327</td>
</tr>
<tr>
<td>Institute of Languages, UNSW</td>
<td>Sydney</td>
<td>W-T</td>
<td>3,000</td>
<td>1999</td>
<td>2004</td>
<td>26</td>
<td>380</td>
</tr>
<tr>
<td>General Purposes, Newcastle U</td>
<td>Newcastle</td>
<td>W-T</td>
<td>2,100</td>
<td>1995</td>
<td>2005</td>
<td>23</td>
<td>na</td>
</tr>
<tr>
<td>Student Services, Newcastle U</td>
<td>Newcastle</td>
<td>W-T</td>
<td>2,700</td>
<td>2001</td>
<td>2005</td>
<td>50</td>
<td>na</td>
</tr>
</tbody>
</table>
User satisfaction with academic buildings – findings from post occupancy evaluations

SINGAPORE
Institute Technical Bishan H-H 20,300 1994 2001 37 154

Notes: C-T, M-T, W-T & H-H indicate cold-temperate, medium-temperate, warm-temperate and hot-humid climates respectively; na indicates undergraduate students were not housed in the building.

All were tertiary-level academic teaching buildings ranging from 1000 to over 20,000 m² in floor area and located in climates from cold-temperate to hot-humid, with ten in New Zealand, four in Australia, two in Canada and one each in England and Singapore. With the exception of the older buildings (Kirk and Cotton) most were recipients of national awards or ratings for sustainable or low energy design, or in some way pioneered sustainable architecture. Fuller details of a number of these are given elsewhere (Baird, 2010).

Most had been built or refurbished in the course of the last fifteen years, and all had been occupied for at least two years before the survey work was carried out, giving most occupants time to experience their surroundings over at least a full annual cycle.

3. Survey Methodology and Analytical Procedures

Generally speaking, these investigations involved undertaking several visits to each of the buildings to personally distribute and collect a questionnaire survey seeking the users’ perceptions of a range of factors. The questionnaire used was the Building Use Studies (2011) standard two-page office version for staff and postgraduates, with a shorter version for undergraduates. This was selected as it enabled the researcher to survey buildings during relatively short trips to different localities with minimal disturbance to the building users and their organisations followed by rapid analysis and feedback. During these visits a detailed tour was undertaken of each building and its facilities, photographing key features, and collecting relevant documentation. Key architectural and environmental engineering members of the design teams were also interviewed to gain an understanding of the design intent.

The sixty or so questions of the standard two-page questionnaire used cover a range of issues. Fifteen of these elicit background information on matters such as the age and sex of the respondent, how long they normally spend in the building, and whether or not they see personal control of their environmental conditions as important.

However, the vast majority asked the respondent to score the following aspects of the building on a seven-point scale:

- operational – image to visitors, space in building, space at desk, furniture, cleaning, meeting-rooms availability, storage arrangements, and facilities;
- temperature (overall and whether it is too hot or cold, stable or varies) and air (overall and whether it is still or draughty, dry or humid, fresh or stuffy, odourless or smelly) in both winter and summer;
- lighting (overall, whether there is too much or too little Natural Light and Artificial Light, and whether there is Glare from sun and sky or from the artificial lights);
- noise (overall, and whether there is too much or too little from colleagues, other people, inside sources, and outside sources; and the frequency of unwanted interruptions);
- personal control - of heating, cooling, ventilation, lighting, and noise; and
- satisfaction - design, needs, comfort overall, productivity, and health.
Overall, there were some 985 respondents to the full questionnaire from staff and postgraduates and some 1,910 to a shorter questionnaire for undergraduate students – see Table 1. Analysis of the responses yielded a mean value on a 7-point scale for each variable (other than productivity). In addition to calculating these mean values, the analysis also enabled the computation of a number of indices in an attempt to provide indicators of particular aspects of the performance of the building or of its ‘overall’ performance. These include a Comfort Index which was dependent on a set of seven ‘environmental’ factors; a Satisfaction Index, which was dependent on the scores for design, needs, productivity, and health; and a Summary Index which is the average of these two indices. These are intended to ‘provide snapshots of how a building works for its occupants’ (Leaman and Bordass, 2001, 130). The Summary Index for each building, together with the scores for the various factors from which it is calculated (see Baird (2014b) for the method of calculation), are listed in Table 2. Note that the Summary Index scale is from -3 to +3, the productivity scale is in per cent, and in all other cases the scale is from 1 to 7 with a score of 7 being the best.

<table>
<thead>
<tr>
<th>Building</th>
<th>Sum Index</th>
<th>Image</th>
<th>Comf</th>
<th>Light</th>
<th>Noise</th>
<th>Temp W/S</th>
<th>Air W/S</th>
<th>Des</th>
<th>Need</th>
<th>Health</th>
<th>Prod %</th>
</tr>
</thead>
<tbody>
<tr>
<td>ERSKINE</td>
<td>2.39</td>
<td>6.26</td>
<td>5.86</td>
<td>5.71</td>
<td>5.39</td>
<td>5.25/5.14</td>
<td>5.07/5.23</td>
<td>5.61</td>
<td>5.80</td>
<td>4.52</td>
<td>+9.80</td>
</tr>
<tr>
<td>AUT</td>
<td>1.18</td>
<td>6.00</td>
<td>5.20</td>
<td>4.88</td>
<td>4.92</td>
<td>4.39/4.95</td>
<td>3.96/4.27</td>
<td>5.46</td>
<td>5.26</td>
<td>4.18</td>
<td>+3.64</td>
</tr>
<tr>
<td>AMAC</td>
<td>1.05</td>
<td>6.18</td>
<td>5.50</td>
<td>5.62</td>
<td>4.42</td>
<td>5.31/4.68</td>
<td>5.26/4.84</td>
<td>5.51</td>
<td>5.32</td>
<td>4.06</td>
<td>+2.79</td>
</tr>
<tr>
<td>CS&amp;E</td>
<td>0.81</td>
<td>5.83</td>
<td>4.91</td>
<td>5.49</td>
<td>4.28</td>
<td>4.47/4.41</td>
<td>4.38/4.33</td>
<td>5.11</td>
<td>5.34</td>
<td>3.86</td>
<td>+2.54</td>
</tr>
<tr>
<td>WIGAN</td>
<td>0.43</td>
<td>4.72</td>
<td>4.52</td>
<td>4.46</td>
<td>4.68</td>
<td>4.72/4.95</td>
<td>4.50/4.67</td>
<td>4.79</td>
<td>5.10</td>
<td>3.76</td>
<td>-4.13</td>
</tr>
<tr>
<td>SSC</td>
<td>0.34</td>
<td>4.72</td>
<td>4.52</td>
<td>5.24</td>
<td>4.04</td>
<td>3.93/4.77</td>
<td>4.62/4.76</td>
<td>4.33</td>
<td>4.92</td>
<td>3.44</td>
<td>-2.04</td>
</tr>
<tr>
<td>SoA 02</td>
<td>0.30</td>
<td>5.96</td>
<td>4.49</td>
<td>4.18</td>
<td>4.11</td>
<td>4.52/3.95</td>
<td>4.20/3.93</td>
<td>5.25</td>
<td>5.07</td>
<td>3.54</td>
<td>-4.39</td>
</tr>
<tr>
<td>OTAGO</td>
<td>0.16</td>
<td>6.17</td>
<td>4.59</td>
<td>4.60</td>
<td>4.65</td>
<td>4.66/3.88</td>
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<td>4.91</td>
<td>4.34</td>
<td>3.06</td>
<td>-4.84</td>
</tr>
<tr>
<td>COTTON</td>
<td>0.14</td>
<td>3.27</td>
<td>4.63</td>
<td>5.50</td>
<td>4.19</td>
<td>3.95/4.72</td>
<td>3.90/4.52</td>
<td>4.16</td>
<td>4.57</td>
<td>3.78</td>
<td>-3.48</td>
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<tr>
<td>IoL</td>
<td>0.12</td>
<td>5.27</td>
<td>4.65</td>
<td>5.86</td>
<td>3.93</td>
<td>4.23/3.63</td>
<td>4.05/3.50</td>
<td>4.42</td>
<td>4.64</td>
<td>4.04</td>
<td>+0.48</td>
</tr>
<tr>
<td>ZICER</td>
<td>0.07</td>
<td>4.66</td>
<td>4.41</td>
<td>3.80</td>
<td>4.27</td>
<td>5.39/4.90</td>
<td>4.77/4.63</td>
<td>3.55</td>
<td>4.45</td>
<td>3.31</td>
<td>-7.81</td>
</tr>
<tr>
<td>SoA 11</td>
<td>-0.08</td>
<td>4.74</td>
<td>4.13</td>
<td>4.54</td>
<td>4.23</td>
<td>4.43/4.52</td>
<td>4.19/4.21</td>
<td>4.21</td>
<td>4.67</td>
<td>3.29</td>
<td>-2.44</td>
</tr>
<tr>
<td>UCOL</td>
<td>-0.34</td>
<td>4.25</td>
<td>3.76</td>
<td>4.87</td>
<td>3.64</td>
<td>4.14/3.78</td>
<td>4.07/3.84</td>
<td>3.83</td>
<td>4.01</td>
<td>3.33</td>
<td>-6.54</td>
</tr>
<tr>
<td>RED</td>
<td>-0.37</td>
<td>5.10</td>
<td>3.75</td>
<td>5.32</td>
<td>3.29</td>
<td>3.54/3.22</td>
<td>3.72/3.35</td>
<td>3.63</td>
<td>4.11</td>
<td>3.72</td>
<td>-5.00</td>
</tr>
<tr>
<td>GP</td>
<td>-0.39</td>
<td>4.59</td>
<td>3.48</td>
<td>5.70</td>
<td>3.78</td>
<td>3.57/2.18</td>
<td>4.23/2.86</td>
<td>4.00</td>
<td>4.78</td>
<td>3.55</td>
<td>-11.60</td>
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<td>KIRK</td>
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<td>2.34</td>
<td>3.64</td>
<td>4.25</td>
<td>3.92</td>
<td>3.94/4.26</td>
<td>3.98/4.25</td>
<td>3.54</td>
<td>4.07</td>
<td>3.40</td>
<td>-5.55</td>
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<tr>
<td>LIU</td>
<td>-0.71</td>
<td>5.43</td>
<td>3.55</td>
<td>3.79</td>
<td>2.47</td>
<td>3.20/4.44</td>
<td>3.32/3.87</td>
<td>4.00</td>
<td>4.24</td>
<td>3.70</td>
<td>-13.00</td>
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<tr>
<td>ITE</td>
<td>*</td>
<td>3.60</td>
<td>3.29</td>
<td>4.52</td>
<td>3.29</td>
<td>2.70/3.60</td>
<td>2.85/3.55</td>
<td>2.86</td>
<td>3.03</td>
<td>3.00</td>
<td>-10.61</td>
</tr>
</tbody>
</table>

Notes: * In the case of Building ITE a Summary Index was not estimated and the Temperature and Air figures are for naturally ventilated spaces and air-conditioned spaces respectively.

In what follows the characteristics of the buildings with the highest and lowest Summary Indices will be outlined in an attempt to discern those particular features that may have led to these user perception scores and indices. In most cases both staff and postgraduate students were surveyed using the full questionnaire, but where there were large numbers of undergraduate student users the shorter questionnaire was utilised.
4. Characteristics of buildings with highest and lowest Summary Indices

The features of four of the high-scoring and four of the low-scoring buildings of this set will now be outlined. The reasons for high and low perception scores amongst those buildings will be explored, in an attempt to reveal the factors that influenced them, and the design features that could be involved.

4.1. The Erskine Building (ERSKINE)

Located at latitude 440S in the medium-temperate climate of Christchurch (winter/summer design temperatures of -10C/+26 OC) this 11,551m2 building is part of the University of Canterbury. The building is split approximately equally between a seven-storey academic block, containing staff and postgraduate student offices, and a four-storey undergraduate teaching block, linked by a glass roofed atrium space (Spence, 1998; Johnston, 2002). The offices and the majority of the adjacent seminar rooms in the academic block are naturally ventilated and heated by a conventional radiator system. With their northerly orientation and fixed overhangs, exposed thermally-massive interior walls and ceilings, fixed and adjustable exterior and adjustable interior solar shading devices, and large number of window/natural ventilation opening options, the ninety or so office modules are equipped with a full range of passive thermal environmental control systems. The undergraduate teaching block and basement computing laboratories have separate air handling units.

With by far the best Summary Index of this set of buildings, all but one of its overall scores was in the 5 to 6 range. The building’s score for comfort overall (5.86 for staff, 5.44 for students) was also the highest, reflecting the good overall scores for all of the environmental factors. This building has been able to satisfy the varying needs of a diverse staff and student population.

4.2. AUT Akoranga (AUT)

At just under 1000m2, this building accommodates academic offices, a small registry and the main reception area for a satellite campus of the Auckland University of Technology, situated at latitude 37ON and with winter and summer design temperatures of around +3 and +24OC. The single-storey building is naturally ventilated, roughly U-shaped in plan, and houses five separate areas linked by a circulation corridor (Energy Wise News, 2002). The corridor is taken up higher than the surrounding single-storey accommodation, enabling it to perform both ventilating and daylighting functions. Natural ventilation and daylighting is enabled through a range of perimeter window openings coupled with automatic windows at high and low level along the corridors with glare control by means of external louvres and motorized retractable awnings.

With a Summary Index of +1.18 its overall performance is very good from the point of view of the users. Most of the overall scores were between 4 and 5, comfortably better than the mid-point of the 1-7 range, though temperatures in winter were assessed as too cold and variable. Lighting overall scored well at 4.88, but component scores indicated there was too much glare from sun and sky. Likewise, noise overall at 4.92 scored well, but noises from colleagues, other people, and inside the building were all rated slightly worse. Perceptions of comfort overall, design, and needs all scored above 5, and the score for health was higher than the mid-point of the scale implying the staff felt healthier in the building.
4.3. Alan MacDiarmid Building (AMAC)

The building is comprised of 6,140m$^2$ of laboratories, offices and teaching spaces on four levels, together with two levels of basement car parking (2,810m$^2$). It is located at Victoria University of Wellington in New Zealand (43°S and a mild-temperate 2 to 22°C design temperature range). Despite the extensive laboratory spaces with their 30 fume cupboards requiring specialist ventilation systems and controls, the design team applied environmentally sustainable design principles wherever possible (Beca, 2014).

Ranking 3rd ‘best’ of the set with a Summary Index of +1.05 none of the individual scores on the 1 to 7 scales dropped below 4. Comfort overall, light, temperature and air in winter, design and needs were all rated greater than 5 on average, while image scored 6.18. Noise from colleagues, potentially a result of the relatively open nature of the workspaces, some with contiguous kitchens and others acting as circulation routes, may have contributed that aspect’s relatively low score of 4.42.

4.4. Computer Science & Engineering (CS&E)

The 10,700m$^2$ Computer Science and Engineering Building houses lecture theatres, computing and research laboratories and staff offices at York University, in the cold-temperate climate of Toronto (latitude 44°N) with design temperatures in the -17.2 to -28.7°C range. The four-level, 67m by 30m plan building has two atria which fulfil, inter alia, a daylighting and natural ventilation role (McMinn, 2002). While the building’s air handling units are connected to the campus’ heating and cooling system a mixed-mode approach has been taken to its thermal environmental control.

The last of the (four) buildings in which the staff perceived their productivity to have increased, it also had excellent scores for design, needs and health – for both staff and students. Environmental factors overall were also very satisfactory, though there as a perception of too much artificial and too little natural light.

4.5. The Red Centre (RED)

This 17,500m$^2$ building is located on the University of New South Wales’ campus in Sydney (latitude 34°S). With a university policy in which air-conditioning was restricted to specialist areas and winter and summer outside design temperatures of 6.8 and 29.5°C respectively, passive environmental control was a challenge for the design team. To meet that challenge the facades are fitted with automated shades and manually operated louvres, air shafts and thermal flues fitted with long volume turbines enable natural ventilation, and thermal mass is exposed internally (Cantrill, 1997).

Image and lighting overall at 5.10 and 5.32 respectively scored well and while almost all of the other factors were between 3 and 4 in the survey of staff, most were on the low side. These scores resulted in a Summary Index of -0.37. A concurrent but more limited survey of the students found that in general they rated the overall environmental and satisfaction factors higher than the staff.

4.6. General Purposes Building (GP)

Located at 33°S in the warm-temperate climate of New South Wales on the campus of the University of Newcastle, this 2,100m$^2$ three-storey building houses offices and classrooms (Dixon, 2005). Designed from the outset to enable passive environmental control, the rectangular plan has offices on the north
façade, classrooms on the south and a central atrium acting as a circulation and airflow spine. The upper floors step out to shade those below and the atrium has high-level, automated, clerestory glazed baffles.

While most scores averaged in the 4±0.5 range, temperature and air in summer were very low at 2.18 and 2.86 respectively.

4.7. Liu Institute (LIU)

Located on the Point Grey Campus of the University of British Columbia in the cold-temperate climate of Vancouver (49°N), this 1750m² three-storey building caters for the 37 staff of the Institute. The main 45m by 12m research wing is designed to enable natural ventilation of the mainly single-person offices via perimeter windows and transom openings to vertical ducts at each end of a central corridor. Space heating is by terminal units located under the windows (Macaulay and McLennan, 2006).

While the Summary Index of -0.71 for this building was at the lower end of the set considered here, most of the scores on the 7-point scale were within the ‘break-even’ range (4±0.5) and image scored a creditable 5.43 However noise overall only rated 2.47 and acoustic issues attracted entirely negative comments. It is understood that a degree of trade-off between acoustic privacy and the free flow of air by natural ventilation had been agreed at the design stage.

4.8. Institute of Technical Education, Bishan (ITE)

Located close to the equator at around 1°N in the hot-humid climate of Singapore (design temperatures ranging from 23 to 32°C), this 23,500m² building caters for 1,600 students and 85 staff. Its twin parallel teaching blocks are curved in plan and placed on site to exploit the prevailing winds for natural cross-ventilation (Powell, 1994). The blocks are extensively shaded and while the main hall and most of the teaching spaces are naturally ventilated some are air-conditioned by individual split systems.

The overall design was a ‘pioneering’ attempt to use natural ventilation in one of the more challenging climates in which to do so, rather than simply resort to expensive-to-operate air-conditioning. The staff rated this building the lowest for comfort overall (average score 3.29) and for temperature and air quality under natural ventilation (with scores of 2.70 and 2.85 respectively).

Thermal ‘shock’ when moving from naturally ventilated to air-conditioned spaces seemed to be an issue; while conditions in the naturally ventilated teaching spaces were not helped by the perverse placement, immediately outside their open windows, of the spit system condensers rejecting heat from the air-conditioned spaces! Noise was also an issue for the naturally ventilated spaces, related mainly to the movement of other students outside the classrooms and that generated by the condensers.

5. Discussion and conclusions

So what were the common characteristics of these buildings and why did the users perceptions differ so markedly between the ‘best’ and the ‘worst’.

In terms of the design process, all of these projects involved clients who were strongly committed to sustainability principles and energy efficient outcomes. Their design teams were similarly committed and all were familiar with that locality and had a track record in this kind of project. All of the design teams used integrated design processes and had adequate time to employ them.
In terms of the building outcome, all of these designs attempted to maximize the use of natural ventilation and daylight where appropriate. High levels of insulation and double glazing; air tight or permeable envelopes relevant to the climate or season; appropriate wind and solar orientation and shading; judicious use of thermal mass where appropriate – these features were all in evidence.

A range of HVAC systems had been employed ranging from full natural ventilation, through mixed-mode systems with automated natural ventilation openings when appropriate, to full air-conditioning for specialist areas.

A commitment to commissioning and continued building management was also evident and to be expected in buildings that in all cases were part of major campuses or institutions.

With all these positive indications why were there such large differences in users’ perceptions between the ‘best’ and ‘worst’ buildings?

It was evident from these results and from the associated site visits, interviews with designers and building managers, and conversations with building users, that hot-humid and warm-temperate climatic conditions posed major challenges for the application of full natural ventilation techniques. Users’ perceptions of the pioneering designs at the Red Centre and the General Purpose Building in Australia and the Institute of Technical Education in Singapore were at the lower end of most of the scales for comfort overall and for temperature and air.

Noise issues were also evident in a number of buildings. This was not confined to particular climatic zones but was frequently associated with the provisions that had been made to facilitate air transfer within or across the building – these acted as un-attenuated sound transmission paths between, for example, offices or teaching spaces and adjacent circulation corridors. This should not be compromised as was the case at the Liu Institute where the situation was further exacerbated by corridors with hard surfaces. Good acoustics should be a high priority in the design of academic buildings.

At the other end of the scale the full natural ventilation designs of the Erskine Building and AUT Akoranga had the best scores for noise overall, thanks in part to good acoustic design of the air transfer routes.

In only one instance (the Erskine Building) was a user guide available for the occupants of these buildings – the time is really long overdue for designers to let the users know how to get the best performance out of their buildings.

Finally, it is essential to avoid mixing potentially incompatible functions, especially from a noise transmission point of view; layouts that lead to multiple thermal shock situations between air-conditioned and naturally ventilated spaces; and never ever place condensers outside opening windows.

Acknowledgements

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References

Using life cycle assessment to reduce the energy use and global warming impacts of a detached house in Melbourne, Australia

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Abstract: The aim of this study was to use a life cycle assessment (LCA) to identify the potential global warming impacts associated with the construction and on-going use of a 158 m² single-storey house located in Melbourne, Australia. This information was then used to inform improvements to the performance of the house with the aim of minimising energy demand and associated global warming impacts across its life. A streamlined LCA approach was used to quantify inputs of energy across the entire life of the house. Embodied energy associated with the initial construction of the house as well as the replacement of materials and components throughout its assumed 50-year life were quantified using embodied energy coefficients for specific construction materials. Energy demand associated with the operation of the house over its life was determined with the use of IES-VE software. Total energy demand in primary terms was converted to global warming potential (GWP) (in t CO₂-e) with the use of greenhouse gas emissions factors to provide an indication of the associated global warming impacts. The results of the analysis were then used to identify strategies for improving the environmental performance of the house, which was then reassessed to estimate the level of improvement.

Keywords: Life cycle energy analysis; residential building; Melbourne; global warming impacts.

1. Introduction

Building designers and owners are increasingly looking to improve the environmental performance of buildings due to an increasing understanding of the considerable effect buildings have on the natural environment and the health and comfort of those who use them. The focus of this improvement is predominately on reducing the resources (energy and water) used during their operation. Rarely do building designers or owners consider the broader implications of a building project on the environment or even more so, across the full life cycle of a building. This more holistic life cycle approach has only recently become of interest and importance to many building designers, especially due to the availability of credits for the use of life cycle assessment in USGBC’s LEED or the GBCA’s Green Star tools, for example. This study demonstrates how a life cycle assessment can be used to better inform
the design process for improving the environmental performance of buildings by analysing and reducing the energy and global warming impact of a 158 m$^2$ single-storey house located in Melbourne, Australia.

2. Research approach

This section describes the case study house used in the study as well as the approach used to analyse the life cycle energy demand and greenhouse gas emissions of the house.

2.1. Case study house

The house analysed is a single-storey, two bedroom unit located in Melbourne, Australia (Figure 1). The house is constructed of insulated timber-framed brick veneer walls, steel roofing, plasterboard internal wall linings and a reinforced concrete slab. This house was chosen as it was considered representative of many of the houses being built on the increasingly small residential sites in Australian cities.

![Figure 1: Floor plan and front (south) elevation of the case study house.](image)

2.2. System boundary

The study includes energy demand associated with raw material extraction, manufacturing of construction materials and the construction process (hereafter referred to as the houses’ initial embodied energy) as well as the operation of the house (for heating, cooling, lighting and appliances) and for on-going maintenance (including production and replacement of materials throughout the useful life of the house, referred to as the houses’ recurrent embodied energy) (Figure 2). Greenhouse gas emissions associated with each of these life cycle stages was also included in order to determine global warming potential (GWP).
The demolition, disposal and/or reuse and recycling stages were excluded from the study as the energy demand associated with these processes is generally considered to be relatively small. The embodied energy associated with the production of materials used in appliances, fit-out, services (hydraulic, mechanical, electrical) were also excluded as these were considered too difficult to quantify.

2.3. Impact category and category indicator

Impact categories considered in this study were energy use (in primary terms) and global warming (an increase in the temperature of the earth’s atmosphere due to an increased concentration of greenhouse gases such as carbon dioxide, methane and nitrous oxide (WWF, 2014)). The category indicators are gigajoules of primary energy and global warming potential (t CO₂-e), respectively.

2.4. Life cycle inventory analysis

The life cycle inventory analysis (LCI) involves the collection of embodied and operational energy data.

2.4.1. Initial and recurrent embodied energy

The initial embodied energy covers energy required for raw material extraction, manufacturing of materials and construction of the house. Recurrent embodied energy is that energy associated with replacement materials throughout the life of the house, which in the case of this study was considered to be 50 years. Material quantities were estimated based on architectural drawings of the house. These quantities were then multiplied by a wastage multiplier based on data from CSIRO (1994), Fay (1999) and Wainwright and Wood (1981), providing the total quantity of materials delivered to site. Material embodied energy coefficients from Crawford (2011) were used to calculate embodied energy by multiplying them by the respective delivered material quantities. Material replacement rates, based on data published by Ding (2004), in conjunction with the total quantity of replaced materials and respective material embodied energy coefficients were used to estimate recurrent embodied energy demand over the life of the house. This study uses a hybrid embodied energy assessment approach, providing the most comprehensive assessment of embodied energy possible (Treloar, 1998).
2.4.2. Operational energy

Operational energy was estimated based on a SketchUp model of the house and using IES-VE. IES-VE is a dynamic building energy simulation tool that considers location, lighting, daylight and solar analyses to provide the predicted energy consumption of a building (IES, 2015). The energy analysis within IES-VE is based on several key assumptions, including 4-person occupancy, 50% daytime occupancy, temperature range of 21-24 degrees, heating COP of 0.83 and heating and cooling operating between 8am and 6pm daily for the entire house. The analysis was based on the use of a split system air conditioner for cooling and natural gas for heating. IES-VE provides a figure for the total annual energy use of the house for heating, cooling, lighting and equipment, which was then linearly extrapolated to 50 years.

Dynamic energy simulation tools such as IES-VE tend to overestimate predicted energy use compared to actual energy used within a building (AGO, 1999). In order to better reflect actual energy use of the occupants of the house, AGO (1999) recommends the use of constraint factors to account for zoning and occupancy patterns. The constraint factors used in this study for heating and cooling were 0.45 and 0.4, respectively (AGO, 1999).

2.5. Life cycle impact assessment

The life cycle impact assessment (LCIA) involves converting the energy use data obtained as part of the LCI into an impact on the environment. In order to convert embodied energy figures to greenhouse gas emissions for the global warming impact category and determine the GWP associated with the embodied energy of the house, a characterization factor of 60 kg CO$_2$-e per GJ of initial and recurrent embodied energy was used. Emissions intensity figures for brown-fired coal electricity (for cooling, lighting and equipment) and natural gas (for heating) together with the GWP of the three main greenhouse gases (carbon dioxide (CO$_2$), nitrous oxide (N$_2$O) and methane (CH$_4$)) were used to determine the GWP associated with the operational energy demand of the house.

2.6. Assumptions

A number of assumptions needed to be made during this study and the data used is unlikely to be completely reliable. Due to data variability and uncertainties, an error range of ±40% was used for initial and recurrent embodied energy figures and a potential variation in operational energy figures of ±30% was assumed, based on data from Crawford (2011).

2.7. House redesign

The life cycle energy analysis of the original house was used to identify the building elements and systems with the most significant initial and recurrent embodied energy and operational energy demands. A range of potential strategies for reducing the energy demands and GHG emissions associated with the house were then able to be identified. These included HVAC system and material replacements - the materials with high embodied energy were replaced with materials of lower embodied energy, i.e. steel, ceramic tiles, substructure. The house was then redesigned through an iterative process where the analysis was redone based on collections of these design strategies in order to identify the design outcome with the lowest energy demand and GHG emissions for the range of design strategies considered.
3. Life cycle energy demand of original house

This section presents the results of the life cycle energy and greenhouse gas emissions analysis of the original house.

3.1. Life cycle inventory analysis

3.1.1. Initial and recurrent embodied energy

The total initial embodied energy associated with the construction of the house was found to be 2,286 GJ (14.5 GJ/m²). The total recurrent embodied energy for the house over a period of 50 years was found to be 1,526 GJ (9.6 GJ/m²). These figures are in line with figures presented in other studies using a similar hybrid assessment approach, such as Fay (1999) and Crawford (2014). Figure 3 shows a breakdown of the life cycle embodied energy of the house by building element. It is clear from this that the substructure represents the overwhelming majority of the embodied energy of the house (62%).

![Graph showing life cycle embodied energy of original house, by element.]

3.1.2. Operational energy

The annual operational energy demand associated with the original house was found to be 29.84 MWh/year (107.4 GJ/year) based on the IES-VE analysis. After applying the constraint factors as per Section 2.4.2, the total operational energy over 50 years is 2,409 GJ. Figure 4 shows the operational energy breakdown by major use. The total operational energy of 15.2 GJ/m² compares closely to the figures presented in similar studies, including 14.7 GJ/m² by Crawford (2014).
3.1.3. Life cycle energy demand

The life cycle energy demand of the original house, combining initial and recurrent embodied energy and operational energy over 50 years, is shown in Figure 5. The total energy demand of the house over a period of 50 years was found to be 6,221 GJ (39.3 GJ/m²).

3.2. Life cycle impact assessment

3.2.1. Embodied energy-related emissions

The initial and recurrent embodied energy-related emissions were calculated to be 137 t CO₂-e and 92 t CO₂-e, respectively. Due to the substantial error range of ±40%, this results in a potential range of 82–192 t CO₂-e for initial embodied emissions and 55–128 t CO₂-e for recurrent embodied emissions.

3.2.2. Operational energy-related emissions
The operational energy-related emissions were found to be 179 t CO$_2$-e over 50 years (Table 1). A potential error of ±30% means that this figure could range from 125–232 t CO$_2$-e.

<table>
<thead>
<tr>
<th>Fuel type</th>
<th>Energy (GJ)</th>
<th>GHG</th>
<th>Emissions factor (kg/GJ)</th>
<th>GWP</th>
<th>Total GWP (kg CO$_2$-e)</th>
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<td>122,480.80</td>
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<td></td>
<td></td>
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<td>0.0013</td>
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<td></td>
<td></td>
<td>Sub-total</td>
<td></td>
<td></td>
<td>123,008.5 kg CO$_2$-e</td>
</tr>
<tr>
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<td>CO$_2$</td>
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<td></td>
<td></td>
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<td>0.0048</td>
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</tr>
<tr>
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<td></td>
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<td>0.000097</td>
<td>298</td>
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<tr>
<td></td>
<td></td>
<td>Sub-total</td>
<td></td>
<td></td>
<td>55,848.08 kg CO$_2$-e</td>
</tr>
<tr>
<td><strong>Total GWP (kg CO$_2$-e)</strong></td>
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<td></td>
<td></td>
<td><strong>178,856.58 kg CO$_2$-e</strong></td>
</tr>
<tr>
<td><strong>Total GWP (t CO$_2$-e)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>179 t CO$_2$-e</strong></td>
</tr>
</tbody>
</table>

3.2.3. Global warming potential

Figure 5 shows the breakdown of total GWP by life cycle stage for the house. This equates to a total of 408 t CO$_2$-e over 50 years. Operational emissions account for the single largest quantity of emissions (44%), followed by initial embodied emissions (34%) and recurrent embodied emissions (22%).

These findings suggest that the greatest effort in reducing the global warming impact associated with the original house should initially be on reducing operational energy-related emissions. This should be done in consideration of the effect that any improvement strategies might have on embodied energy to ensure that this does not increase at the expense of a reduction in operational energy demand.

4. House redesign

This section presents the energy and greenhouse gas emissions savings achieved as a result of the improvements made due to the redesign of the house. Based on the results of the life cycle energy analysis of the original house design (Section 3), the main areas for improvement were found to be...
Using life cycle assessment to reduce the energy use and global warming impacts of a detached house in Melbourne, Australia

reducing the energy demand for heating and equipment and reducing the embodied energy associated with the substructure.

4.1. Design changes

The redesigned house incorporates all of the strategies described below in order to reduce energy demand and associated GHG emissions.

4.1.1. Substructure

The substructure contributes the highest proportion of initial embodied energy which consists of A25 MPa concrete slab and polystyrene waffle pods. In comparison with a conventional raft slab with concrete strip footings, polystyrene adds significantly to the embodied energy of the flooring system. The redesigned house replaces the waffle pod concrete slab with a raft slab with 20 MPa concrete and edge insulation to prevent heat loss.

4.1.2. Roof

Due to the high embodied energy associated with corrugated steel sheeting, the steel roof cladding was replaced with terracotta roof tiles, lowering the initial embodied energy and providing longer service life for the roof cladding.

4.1.3. Ceiling and wall finishes

Plasterboard and paint used for ceiling and wall finishes contributes significantly to the recurrent embodied energy of the house. The redesigned house uses 10 mm plasterboard in place of 13 mm and a longer-lasting paint, estimated to be replaced every 15 years rather than 10.

4.1.4. Floor finishes

The original house uses ceramic tiles on the entire floor area which, which having a long service life, has a higher embodied energy as compared to an exposed polished concrete floor. The redesigned house uses ceramic tiles to all wet areas, but an exposed concrete floor to all others.

4.1.5. HVAC system

The HVAC system used in the original house (a split system with mechanical ventilation) contributed to considerable energy demands for heating. In the redesigned house this was replaced with central heating convector.

4.2. Life cycle inventory analysis

4.2.1. Initial and recurrent embodied energy

The changes made to the design of the house affect both initial and recurrent embodied energy demands. Figure 7 shows the life cycle embodied energy savings made for each major element of the house. The total initial embodied energy was reduced by 14% to 1,954 GJ. The total recurrent embodied energy was reduced by 13% to 1,318 GJ.
4.2.2. Operational energy

The replacement of the original HVAC system with central heating convectors resulted in a 27% reduction in operational energy demand over 50 years, down to 1,766 GJ.

4.2.3. Life cycle energy demand

The changes made to the original house in the redesigned house resulted in a 19% reduction in life cycle energy, down to 5,037 GJ. Figure 8 shows the comparison of life cycle energy demand for the original and redesigned house by life cycle stage.

Figure 7: Life cycle embodied energy of original and redesigned house, by element.

Figure 8: Total life cycle energy of original and redesigned house.
4.3. Life cycle impact assessment

4.3.1. Embodied energy-related emissions

The initial and recurrent embodied energy-related emissions for the redesigned house over a period of 50 years are 117 t CO₂-e and 79 t CO₂-e, respectively. Considering the potential ±40% error associated with the data used in calculating this figure, the initial embodied emissions may range from 70–164 t CO₂-e and recurrent embodied emissions from 47–111 t CO₂-e.

4.3.2. Operational energy-related emissions

The operational energy-related emissions associated with the house over a period of 50 years were found to be 120 t CO₂-e. Considering the potential error in the approach used for calculating this figure (±30%), the energy demand may vary from 84–156 t CO₂-e.

4.3.3. Global warming potential

The total life cycle greenhouse gas emissions/GWP associated with the redesigned house is 316 t CO₂-e. This represents a 22% reduction compared to the original house. Figure 9 shows the comparison of greenhouse gas emissions/GWP between the original and redesigned house, by life cycle stage. Considering the potential errors in the data used, the net benefit of the redesigned house may range from -168 t CO₂-e to +351 t CO₂-e.

![Figure 9: Total life cycle global warming potential of original and redesign house.](image)

5. Conclusion

This study demonstrates that appropriate design strategies can significantly improve the environmental performance of a building. It also highlights the importance of considering a building’s life cycle environmental performance during the early design stage, when the most critical decisions are being made and design changes are easiest to implement. Only a small number of strategies for reducing energy demand and related emissions were considered in this study. A more in-depth design approach should also include consideration of not only a reduction in energy demand but also the use of renewable, cleaner and less emissions intensive fuel sources such as solar or wind power. The use of a wider comfort band than the 21-24°C used in this study would also provide greater energy savings. This study also has a number of limitations, some of which include the results only being applicable to the house analysed and errors associated with the data used, including its age, source and reliability.
References


Construction, Materials and Technology
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A critique on on-going retrofit approaches to existing high mass historic building forms with heat sink capacity

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Abstract: The research presents a critique on unrealized heat sink capacity of Colombo’s historic British period buildings. The work discusses how on-going inappropriate retrofitting approaches to these buildings can hinder the passive heat sink capacity of high thermal mass envelopes. The research performed field investigations on selected renovated historic high mass buildings of which most of them are naturally ventilated. Results showed that renovated building interiors become overheated during daytime and night time due to direct and indirect heat gain due to newly introduced retrofit interventions i.e. courtyards and windows. Later, one renovated but critical building was simulated with its original status of physical characteristics by removing all newly introduced design interventions using Design-BUILDER software program. Results show that the original building performs better than renovated building in maintaining indoor air temperatures lower than outside ambient air temperature during daytime. The work illustrates the efficiency of heat sink effect of thermal mass in historic building forms and challenges the on-going retrofit approaches.

Keywords: Heat sink; retrofitting; thermal mass.

1. Introduction

Focusing on the debate on climate change and carbon constrained economies as a significant strategy for GHG abatement (IPCC, 2012), the paper considers how heat sink effect of high thermal mass envelopes found in historic building forms illustrate lessons on passive cooling in tropics and thereby improve energy performance of buildings and achieve emission reduction targets. This process involves an environmentally sensitive interaction between climate, occupants and building design. The work focuses on some significant building envelope characteristics of the British Period historic building forms found in Colombo. British Period buildings are built with high thermal mass envelopes. The work intends to explore opportunities and barriers associated with high thermal mass in these buildings for passive cooling.
2. Existing buildings as resources for retrofitting

Hughes (2012) argues that reusing existing buildings are far more effective than building a new in terms of sustainability. Langston, et al. (2008) support it by pointing out that the rehabilitation of a space can be achieved quicker than the construction of a new space, assuming there are no extensive structural alterations. It also emphasizes that rehabilitation will take half to three-quarters of time taken to demolish and re-construction of a building with equal floor area. Bullen and Love (2010) have also pointed out that there is a growing perception that it is cheaper to convert old buildings to new uses than to demolish and rebuild.

Langston, Wong, Hui, & Shen, (2008) elaborate on Chusid’s concept of ‘urban ore’ which suggests buildings that are ignored and left-out could be used as resources of raw materials for new buildings. But, reaching further, it is stated that, leaving the basic structure and fabric intact in order to change its use is more effective. This approach is called ‘adaptive reuse’ and is believed to breathe ‘new life’ into existing buildings in order to retain national heritage (in case of a historic building) while promoting environmental and social benefits. They further explain the negative impacts of destruction of buildings short of their physical lives due to mere economic considerations. (Langston, Wong, Hui, & Shen, 2008). Langmead (2009) has cited that, “the greenest building is the one that’s already built.” He supports this statement by pointing out that preservationists also promote reusing as much of the historic fabric as possible where the interest of sustainable design and historic preservation correspond (Langmead, 2009). Additionally, Love and Bullen (2010) assert that sustainable outcomes will begin to be realized only when buildings are treated as a reusable resource rather than a product that is consumed and discarded. (Love & Bullen, 2010)

Even though buildings are counted as being long lasting, they require frequent maintenance and restoration. Ultimately, buildings could become inappropriate for their original purpose due to obsolescence, or can become redundant due to change in demand for their service. It is at these times that change is likely to be introduced, mostly in the form of demolition to make the way for new construction, or as some form of refurbishment or reuse. (Waldron et al, 2013). Once an energy upgrading takes place in the form of a renovation, a refurbishment, or adaptive reuse etc. the building’s energy level can be elevated to a new level with a new efficient energy behavior pattern.

2.1. Prioritizing retrofitting for energy sustainability

A wide range of retrofit interventions and solutions sets are known for energy sustainability in existing buildings (Hyde et al, 2013). Literature suggests (Hyde et al, 2013) that non-technological interventions to user profile, user behavior and changing set point temperatures and technological interventions to envelopes, plan form, sectional form and mechanical systems are important areas of an existing building to be intervened for climate response and energy sustainability. However, appropriate applicability of these interventions may be prioritized depending on the thermal performance behavior of an existing building and expected energy efficiency level.

The diversity of retrofitting measures may create different impacts on associated building sub-systems due to interactive and collective impacts of each intervention suggesting that the selection of the retrofitting interventions become very complex (Ma, Cooper, Daly and Ledo, 2012). Dealing with these uncertainties and system interactions is a considerable technical challenge in any sustainable building retrofitting project.
3. Bioclimatic approach for retrofit and energy conservation

The bioclimatic design approach developed by Olgyay (1963), which considers the process buildings filter and modify the external climatic effects for occupants’ comfort, is seen as an appropriate way to deal with climate response, energy-efficiency and sustainability opportunities in retrofitting existing commercial buildings. However, the process and attitude of building design over the past 50-60 years has moved away from this climate responsive approach resulting in high energy use systems support building operation (La Salle, 2010).

Two main factors of bioclimatic approach to design contribute to the level of energy use of new and existing buildings. The first is the response to impacts outside the building to maintain thermally comfortable indoor air temperatures or avoid any indoor overheating situations. The second is the response to impacts from the components and systems inside a building for the benefit of occupants’ thermal comfort. In both these responses building design plays a major role involving its microclimate (climate around the building), plan form, sectional form and mechanical systems. Following priorities are significant for buildings in warm humid tropical climate;

- Reduction or avoidance of negative environmental impacts from outdoor radiant heat and elevated air temperatures in the form of heat gain.
- Optimization of cooling effect of both wind forced and stack force ventilation without the heat gain.
- Maximization of heat sink effect of building envelope with nocturnal ventilation and increase of internal heat loss from building interiors for maintaining lower air temperature than ambient levels.
- Optimization of daylight efficiency in building interiors without contributing to glare.

With bioclimatic retrofitting, these priorities are aimed at avoiding the potential for indoor overheating and maintaining indoor air temperature close to ambient or lower than ambient. The situation will then help to reduce the demand for energy in operation and any kind of air-conditioning. Selecting interventions are more case specific and relevant to performance characteristics of each existing building. A wide range of such retrofit interventions and solutions sets for exiting commercial buildings are known (Hyde et al, 2013). This approach has been examined through the use of case studies, which have been used to explore a number of issues in respect to four activities of the retrofit methodology. Hyde’s (2009) methodology has identified five main paradigms for design solutions in retrofitting.

- Paradigm 1 *External passive systems* – use of building external envelope as the third skin between human and climate in order to reduce solar gain and promote ventilation in summer, capture or retain heat gain winter and promote daylight in both seasons.
- Paradigm 2 *Internal passive systems* - use of building form/sectional characteristics and planning of spaces to support the paradigm 1, capturing optimum ventilation, day lighting and manipulating/controlling heat capture from environmental and internal loads.
- Paradigm 3 *Active systems* - efficiency of plant and equipment, reduction of air conditioned space.
- Paradigm 4 *Synergies between active and passive systems* - use of mixed mode where envelope/façade and air-conditioning system can be linked with human interaction for efficient control of systems.
Paradigm 5 Building occupants and non-technological aspects of building management and operation

This work primarily aimed at discussing the potential of thermal mass in the context of external passive and internal passive systems (Paradigms 1 and 2) for historic buildings found in warm humid climates. Other areas of interventions in Paradigms 3, 4 and 5 are not considered for this work but will be considered in future work.

4. Response to thermal mass effect

Thermal mass in the building envelope affects the process of heat flow from both environmental and internal loads and thus both indoor air temperature and internal surface temperatures. It is an important design component in bioclimatic retrofitting that dictates the thermal response of the building and assists with the means of storing heat for indoor climate modification and thus improves energy efficiency. Two important behavior patterns are;

• The thermal mass in the external and internal building envelope acts as a heat sink and reduces the amount of heat penetration through the façade and controls the peaks of the indoor air temperature. This modification improves indoor thermal environment and reduces the need for energy intensive space cooling during a typical hot day.
• The role of the thermal mass as a heat sink contributes to passive cooling and enhance stack effect when works with nocturnal ventilation and building section.

5. Heat sink capacity of building envelope

Building envelopes with thermal mass provides "inertia" against temperature fluctuations, sometimes known as the “thermal flywheel effect” (1973),Koenigsberger, Szokolay, S.V). For example, when outside temperatures are fluctuating throughout the day, a large thermal mass within the insulated portion of a house can serve to "flatten out" the daily temperature fluctuations. Thermal mass will absorb thermal energy when the surroundings are higher in temperature than the mass, and give thermal energy back when the surroundings are cooler, without reaching thermal equilibrium. This is distinct from a material’s insulative value, which reduces a building’s thermal conductivity, allowing it to be heated or cooled relatively separate from the outside, or even just retain the occupants’ thermal energy longer (Rajapaksha,I. (2004).

When an insulated high-mass building is ventilated at night its structural mass is cooled by convection from the inside. During the daytime, the cooled mass, if of sufficient amount and surface area and adequately insulated from the outdoors, can serve as a heat sink. It absorbs, by radiation and natural convection, the heat penetrating into and generated inside the building, and thus reduces the rate of indoor temperature rise. This is the process of passive cooling in hot climates.

This research employed a method to assess quality and level of reusability of historic building forms found in Colombo focusing on the role of thermal mass as a heat sink for indoor climate modification. Accordingly, the thermal performance of historic building specially the heat sink capacity of their envelopes were investigated using several on site thermal investigations in combination with simulation studies using Design-Builder software.
6. Research plan and hypothesis

A medical analogy is used in identifying main components of this research process to justify solution sets for renovation against obsolescence due to high levels of energy usage and for environmental purposes. The components of the research process are as follows;

• **Diagnosis** – climate analysis and climate change effects
Diagnosis phase challenge is to understand the negative climatic effects on building performance and then to mitigate the effects of climate change but also adapt our buildings and occupants. With the much of the existing building stock performing very inefficiently in terms of energy, diagnosing climate change effects will provide a critical analysis of climatic behaviours of macro, meso and microclimates and their negative effects on the design of buildings.

• **Building triage** – trend analysis of energy (and water) consumption of existing buildings
If we are to attack climate change we will need to know more of the internalities and externalities of buildings and design that affect the energy performance of buildings. This is required to identify interventions to improve energy performance.

• **Building surgery** – implementation of interventions
Integrating environmental retrofit strategies with the building design embracing technical and behavioural parameters in order to attack climate change effects and improve energy performance is targeted in building surgery. It is required to plan, act and reflect the interventions in a process of continued improvement for energy performance improvement in buildings.

• **Post-operative care** – findings evidence for future use.
Monitoring and modeling of performance improvements in respect to energy and thermal behaviour of buildings after the building surgery can become useful to assess the efficiency and effectiveness of interventions. Providing evidence from this stage will be useful to formulate tools to assess mitigation options when attacking climate change effects and energy obsolescence of buildings.

The paper adapts these “four stages” in assessing the effectiveness of new interventions to selected historic British Period building population. The work hypothesizes that heat sink capacity of these historic high thermal mass built forms have neither been properly identified nor enhanced with the renovation process that is being implemented at the moment in the country. The methodology makes an effort to investigate these facts involving the following;

**Step 1** _Identify historic building population:_ 28 historic buildings built during 1750–1940 were studied in respect to envelope characteristics, plan form and sectional forms. The study contributed to identify five main typologies as shown in Figure 1.

**Step 2** _Sampling of 28 buildings to identify 4 case studies:_ Due to limitations in time and available data resources five buildings were selected as sample case studies from the heavy mass historic building population, to examine their behavior as lasting built structures. The 3D form, plan form and sectional form were used as the main basis for the categorization. It was found that whole building EUI of most of these renovated historic buildings is higher than 120 KWh/m2/a which is a recommended good practice for conditioned buildings (Hyde, R et al, 2009).

**Step 3** _Identify and investigate the critical case study:_ Energy consumption data and building form typological characteristics are used for identifying a critical case study for a detailed investigation. The Tripoli building is found to be with more mixed modes of all other forms as shown in Figure 2. In addition, this building is found to be with free running office bays. Free running mode provides some good opportunities to investigate on-site thermal performance of
the building in terms of level of climate modification, air temperature and surface temperature behaviors. Further, the plan form and sectional form of this building have been altered by introducing a series of courtyards of which the intention was to promote more daylight. However, this research questions the effectiveness of these interventions on the heat sink capacity of thermal mass.

6.1. On-site investigation

Five British Period non-domestic buildings built between 1845 and 1920 were investigated in terms of EUI (Figure 1). These buildings which are high mass in physical character are currently undergoing a renovation process. Most of these old buildings are similar in architectural character with at least 0.6 m thick walls, linear in plan form with mixed mode in operation after renovation. It was found that Tripoli Market building is having the lowest EUI among them. This building consists of series of similar rectangular bays which can function as a separate entity if necessary. The objective of the on-site investigation was to understand the level of indoor climate modification in respect to corresponding ambient levels, surface temperatures of the external and internal building envelopes and thus the thermal performance of the building. The effect of newly introduced design interventions such as courtyards and windows on indoor air and surface temperatures was investigated. Data for physical properties were collected through drawings observations and interviews. Data for climate and thermal behavior were collected using instrumentation (see Section 6.3) installed at the site.

6.2. Simulation

A computer generated model was created using actual physical characteristics of the building and allowed to run under actual climatic parameters which were collected during onsite investigation and from main Weather Station of Meteorological Department which is located just 1.2 Km away from the case study building. The objective of this is to understand the heat sink capacity of the thermal mass and level of indoor climate modification. The process involved three stages i.e. i) developing the base case scenario with actual physical characteristics including additions like courtyard, glazed windows ii) calibrating the model by adjusting input data and comparing it with results of the on-site investigation and iii) creating a new model by removing added design interventions (courtyard and glazed windows) of the actual building.

The computer generated model is usually considered calibrated when the model prediction error is within 10% of the actual data during the calibration process (Hyde and Rajapaksha, 2013). As such a 10% deviation from the actual data can still be considered acceptable and validates the model. However, the calibrated results of this research are: Actual data range - 28.1\(^\circ\)C – 31.3\(^\circ\)C, 10% deviation range - 25.47\(^\circ\)C - 34.45\(^\circ\)C and Model data range - 27.9\(^\circ\)C – 32.5\(^\circ\)C which is below the 5% deviation range, thus the model is validated as accurate.
A critique on on-going retrofit approaches to existing high mass historic building forms with heat sink capacity

<table>
<thead>
<tr>
<th>Form Typology</th>
<th>Figure</th>
<th>Plan form</th>
<th>Sectional form</th>
<th>EUI with new usage/new interventions (kWh/m².a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shallow semi-enclosed plan form (Arcade building)</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
<td>240 (124,175KWh monthly energy consumption and AC load 61.84%)</td>
</tr>
<tr>
<td>Shallow linear plan form (Independent Square building)</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
<td>185 (64,220 KWh monthly energy consumption and AC load 42%)</td>
</tr>
<tr>
<td>Shallow top fully enclosed plan form (Dutch Hospital)</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
<td>167 (62,680 KWh monthly energy consumption and AC load 54%)</td>
</tr>
<tr>
<td>Deep plan form (Post Office)</td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
<td>228 (20,260 KWh monthly energy consumption and AC load 64.14%)</td>
</tr>
<tr>
<td>Mixed mode plan form (Tripoli building)</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
<td><img src="image15.png" alt="Image" /></td>
<td>135 (63,925 KWh monthly energy consumption and AC load 46.93%)</td>
</tr>
</tbody>
</table>

Figure 1: Five main building form typologies found within 28 historic building population.
6.3. Instrumentation

Two parameters, energy consumption and thermal performance in particular heat sink effect of thermal mass are, monitored. Hobo UX 100 temperature/RH 3.5% data loggers used for measuring hourly climatic data just outside the building. Surface temperature using K-alloy thermocouples and Wind velocity data using VelociCalc- model TSI 9565 were also taken in hourly intervals. Ambient climatic data were downloaded from the main weather station of Meteorological Department which is located just 2 km away from the case study building in Colombo.

Figure 2: Courtyards introduced in most bays increases heat gain and affects the heat sink capacity of thermal mass.

7. Revisiting to the retrofit interventions of the case study

Housed in a Colonial Era commercial precinct of 12 acres at the coordination of 6° 55' 48'' N, 79° 51' 41'' E with a 5m elevation from sea level at Maradana Ward in the Colombo District, this particular building was formerly known as the Tripoli Market and now known as Trace Expert City. There are rectangular shaped building blocks spread out within the premises at 50° of deviation from the North axis towards the East, resulting in a North-East, and South-West orientation.

The building is recently renovated introducing courtyards and large glazed openings to the plan form carried out by the Urban Development Authority in order to transform it into an IT park (Figure 3).

Figure 3: Plan form of case study building consists of 13 bays. Courtyards are introduced to Bays 2, 5, 9 and 12.
7.1. Internal wall characteristics

Internal walls have a high thermal mass similar to the external thermal mass with 350 mm thickness. Therefore it has the capacity to absorb internal heat loads, which are discharged from computers and other equipment. Though external walls have a high thermal mass, they are exposed to direct radiation. In order to perform thermal inertia efficiently there should be two design interventions.

- Shading the thermal mass.
- Coupling the thermal mass with nocturnal ventilation.

However, none of the above strategies has been applied to make thermal mass effective. The roof-overhang shadings and canopies for window-shading are not able to provide sufficient protection against direct solar radiation.

There are four courtyards built to accommodate 13 bays by cutting-out square shape openings from the roof of Bay 2, Bay 5, Bay 9 and Bay 12 and installing glass façades towards the North-West and South-East façade. The exposure of 4 façades which enclose the courtyard allows heat gain into the building while increasing the lighting level of the bay concerned. The 1m roof overhang is not adequate to support the reduction of direct solar gain through glass windows. Furthermore, the glass facade is not capable in resisting heat gain into the premises. Eventually, the courtyard generates a heat pool within the center of the bay and possibly increases the cooling loads of HVAC system.

7.1.1. Activity

The building is used as a new office complex consisting of 13 separate office bays of which 11 bays are occupied and Bays 6 and 7 are to be used as a gallery. Presently they are unoccupied spaces with complete interiors. These two Bays were investigated in order to find out indoor climate modification levels without people.

7.1.2. Occupied bay

Apart from the above mentioned bays the other 11 bays function during the week days from 8.30am to 8.30 pm. ‘Bay 02’ which is analyzed as a common bay, is occupied with 58 people (44- Male, 14 Female), 70 computers which run 24 hours both on weekdays and weekends.

7.1.3. Construction

The rehabilitation retains the internal and external wall construction of 14” thick brick work, while other building elements such as the roof, floor and ground condition have been replaced with new materials and insulation. The major retrofitting is the addition of 4 courtyards with 12mm thick tempered glass partitions.

7.1.4. Openings

The wooden doors which earlier covered the external openings, have been replaced with 12 mm thick tempered glass which is fixed to the structural opening without a hard frame unlike most other common methods of fixation. In addition, 4 light wells have been formed with the new courtyards.
7.1.5. Lighting

There are 26 pendent lights per bay with a capacity of 120W and they switched on after 5.30pm, since the day light distribution within a bay is adequate to satisfy the required lighting level of 350lux. Most of the bays are active till 8.30pm, therefore three hours of lighting demand has to be fulfilled in the night time.

8. Discussion

The study found that energy foot prints of all 28 renovated buildings are high as 135-240 KWh/m$^2$/a. On-site field investigations on the case study building carried out in February 2015 were aimed at identifying thermal performance behavior of the selected retrofitted building in free running mode. Bay 5 (see Figure 3) which has no air conditioning and runs on free running mode was selected in order to assess the new interventions with new usage. Air temperatures on all microclimates of the building, surface temperatures of all surfaces both inside and outside and indoor air temperatures were recorded every 15 minutes for several days using Hobo meters and thermocouples and compared with corresponding ambient temperatures for level of passive climate modification. Results showed that renovated building interior is overheated during daytime and night time due to direct heat gain form newly introduced courtyards when the buildings allowed in free running mode (Figure 4).

![Graph](image)

Figure 4: Renovated building shows indoor overheating throughout the day, February 19, 2015.

The pattern of increase of indoor air temperature during the daytime from 09.00 am – 18.00pm closely followed the ambient air temperature (Figure 4). The level of indoor overheating during night was 4 degrees C greater than daytime. The behavior suggests flywheel effect of thermal mass, lack of interventions to remove heat from the building interior and absence of nocturnal ventilation (Figure 4).

Despite indoor overheating, internal wall surface temperatures moved 0.5-1.5 degrees C lower than indoor air temperatures during the day time (09.30-18.00pm) suggesting heat sink effect of thermal mass is at work to a lesser degree (see Figure 5). The decrease of external wall surface temperature during midnight up to 26 degrees C suggests a potential of night ventilation with thermal mass for passive cooling. However, internal surface temperature remained high as 29-30.5 degrees C during nights primarily due to heat gain during the day from newly introduced courtyards and closer of roof level openings (Figure 5).
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Figure 5: Mild heat sink effect of thermal mass with lower wall surface temperatures than indoor air temperatures.

Actual thermal performance of this building was simulated using Design-Builder software program and then calibrated for accuracy as explained in sub section, titled ‘Simulations’ in Section 6 of this paper.

Figure 6: Calibrated thermal performance behavior of the building.
Function of the courtyards and new glass windows, which have been introduced with actual renovation program, were re-modified in order to avoid heat gain from courtyards. These new additions were removed from the computer generated model and simulated for the following solution sets;

A. Replacing new glass windows with 50% timber panes and 50% heat resistant glass.
B. A + Improving roof architecture by integrating roof level opening for heat removal and night ventilation through lower level openings.
C. A + B + removing the courtyard to avoid direct heat gain.

Figure 7: Design-Build computer generated model of the original building without new interventions.

Design-Build simulation outcome illustrates the effects of solutions sets, which helped to bring the renovated building to the older historic form. With the conversion of fully glazed windows to a much similar older original status where timber windows play the major characteristic, the indoor air temperature dropped further by 0.5 – 1.0 degrees C between 0.9 am and 18 pm than the actual situation of the renovated building. Further reduction of indoor air temperature was clear after improving and readjusting the roof design and plan form. Following positive results were observed (Figure 7);

1. Indoor air temperature moved 1.0 – 2.5 degrees C lower than the corresponding indoor air temperature in the actual building. It shows the effect of second solution set in lowering the indoor air temperature.
2. Indoor air temperature further moved further 1.0 – 4.2 degrees lower than the corresponding indoor air temperature in the actual renovated building. It shows the effect of third solution set in lowering the indoor air temperature.

The overall air temperature behavior shows that the original building design promotes a favorable indoor climate without any overheating situation. The indoor air temperature moved closer to or lower than the ambient but didn’t moved above the ambient, suggesting the potential of untouched historic high thermal mass building forms as climate responsive heat sinks in tropics (Figure 7).
Figure 8: Simulation results showing lowering of indoor air temperature after removing renovation interventions of the actual building.

Results further justify the potential of heat sink effect of thermal mass in lowering Energy Utility Index. Simulation I, II and III, which include re-modification solution sets to building design and bringing back the renovated status to the original status of the building form, show a 20.85 % energy saving (Figure 9).

Figure 9: Energy saving potentials due to solutions in removing new retrofit interventions.

9. Conclusion

The work highlights unrealized heat sink capacity of Colombo’s historic British period buildings. Findings show how new but non-responsive interventions can disturb this passive heat sink capacity of these unique building typology. The work presented a critique on the selection of refitting solutions and highlighted that they need to be selected after identifying the real thermal performance behavior of
buildings. Thus, solutions need to be case specific and context specific. In order to do this, a proper diagnosis of the thermal performance is essential. Findings show that renovated building interiors are overheated during daytime and night time due to direct heat gain which can be attributed to newly introduced interventions to the building forms. Despite indoor overheating, internal wall surface temperatures moved 0.5-1.5 degrees C lower than indoor air temperatures during the day time suggesting heat sink effect of thermal mass is at work. Heat sink effect can contribute to have a passive cooling effect inside a building and thus an energy saving potential. However, its benefit has not been experienced with negative thermal performance characteristics of new interventions. Actual thermal performance of these buildings was simulated using Design-Build software program and then calibrated for accuracy. Thermal performance of digitally undressed old building was found to be more efficient with heat sink capacity and insulating capacity of high thermal mass envelopes. This is an undesirable situation which can affect the designed and inherent passive influence of historic building forms.

References

A framework for the integrated cost-benefit analysis of the use of recycled aggregate concrete in structural applications

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Abstract: Recycled concrete waste in the form of recycled concrete aggregate (RCA) is presently used mostly as a road base filler replacing natural aggregate in Australia. However, instead of manufacturing Natural Aggregate Concrete (NAC) using Natural Aggregate (NA) as a constituent material to use in structural applications, there is potential to use RCA replacing NA to manufacture Recycled Aggregate Concrete (RAC). This paper presents a framework to estimate the costs and benefits of producing RAC, against producing NAC. The framework applies to the system boundary of production processes of RAC, NAC and the life cycle of their respective constituent materials. Cost-benefit assessment (CBA) is identified as an appropriate method to evaluate the internalised impacts as well as external costs concerning the use of both RAC and NAC. This paper proposes a framework to cover the primary impacts which are directly attributable to the RAC or the NAC, as well as the secondary impacts which results in the immediate boundary due to the proposed changes using CBA. The basic methodology for the evaluation of the above impacts considering technical, financial, environmental and social perspectives to obtain a comparable value is discussed in the paper.

Keywords: Recycled aggregate concrete; cost-benefit analysis.

1. Introduction

Concrete waste is recycled to produce Recycled Concrete Aggregate (RCA) which is currently used as a road base product in Australia. The research suggests that out of the entire world’s production of RCA, 99% is used for low value applications (Tošić et al., 2015), which include the use as a road base material or a filler material for pavement bases. The use of RCA in structural applications as a replacement material for coarse natural aggregate (NA) has gained wider interest as it suggests advantages in many fronts. These include 1) providing a sustainable end use to the concrete waste in the construction and demolition (C&D) waste stream, 2) addressing natural aggregate scarcity and 3) conservation of natural aggregate. Weighing the many advantages brought about by the promotion of the replacement of natural coarse aggregate in structural concrete, several investigations have been conducted over the
last decades to characterise RCA as a constituent material for concrete and to determine the level of performance of the resultant concrete, called as recycled aggregate concrete (RAC).

To produce RCA as a coarse aggregate, the fine aggregate needs to be separated following the typical two stage crushing process used to make RCA (Dosho, 2007). The crushing process results in micro cracks in the surface and produces a material that consists of two visible phases, namely the natural aggregate phase and the residual mortar phase. The parent concrete is crushed and the fine recycled concrete aggregate (FRCA) which are particles typically less than 5 mm are separated out in the process. The coarse RCA is generally identified in research as a material which is 1) porous, 2) non-homogeneous, and 3) of variable quality compared to NA. (Poon et al., 2004). One of the key challenges in using RCA for concrete is to deal with the high water absorption associated with the presence of a porous structure in the RCA, compared to the NA it replaces in concrete. The high water absorption primarily deteriorates the workability of the concrete (Behera et al., 2014).

Characterising the use of RCA in concrete, the research conducted so far, is more inclined to use it in low-medium strength applications (<40 MPa) and to adopt rates of replacement less than 30%. This is in line with the current Australian Standard, HB155:2002, which recommends the use of RCA for applications less than 40 MPa in strength at a maximum rate of replacement of 30% (Commonwealth Scientific and Industrial Research Organisation, 2002). Commercial production of RAC and the use of it for structural applications have not taken place so far at industrial scale in Australia, though industrial trials are reported. Amalgamating the findings of the research conducted so far, it is important to evaluate the position of the use of RAC in structural applications, against the current practice of the use of NAC.

2. Background

There are several studies which have evaluated the use of RAC against NAC, and RCA against NA focusing on different dimensions. Vivian (2008) has conducted an economic comparison of recycling of concrete and concluded that recycling of concrete is economically beneficial (Vivian, 2008a). The study has taken into consideration the avoided effect from landfilling considering the landfill to represent an economic cost. The study is limited to the recycling of concrete to produce RCA. Marinkovic et al. (2009) and Knoeri et al. (2013) conducted a comparative environmental assessment to compare the environmental impact of the use of RAC compared to NAC (Marinković et al., 2010; Knoeri et al., 2013). Estanqueiro (2012) have conducted a life cycle assessment of the use of RCA and NA in concrete (Estanqueiro, 2012). Duran et al. (2006) has presented a model for assessing economic viability of C&D waste recycling options (Duran et al., 2006). These studies have provided insights on evaluating one single criterion or part of the system boundary concerned, yet a complete analysis of the alternatives is still required.

Nicola et al. (2015) conducted a multi-criteria optimisation of NAC and RAC with the purpose of finding the optimal type of aggregate. The study used a normative multi-criteria optimisation method involving technical, economic and environmental aspects. NAC made with river aggregate resulted in the cheapest option, while RAC with RCA replacement of 50% was the overall optimal solution (Tošić et al., 2015). This is considered an important step forward in incorporating multiple disciplines simultaneously, to analyse the two alternatives. However, while the study used a specific case study, the detailed conceptualization of the problem in the general context was not present. Inclusion of commercial production complexities and valuing indirect and social components were also not addressed in this study.


2.1. The importance of an integrated evaluation framework

It is identified that a multi-disciplinary approach is required to compare RAC against NAC. This is due to the fact that, the assessment of material performance, environmental benefits and the financial viability individually, does not converge to provide a conclusive outcome; to decide between the two alternatives.

In general, RAC cannot be considered as a technically superior material compared to NAC for the purpose of using it in structural concrete. Unlike the other supplementary cementitious material (SCM), such as ground granulated blast-furnace slag (GGBS), fly ash (FA) and phosphorous slag (PS), that favours the pozzolanic reactions in concrete and improves the properties and performance, RCA as a replacement to coarse NA is not visibly advantageous in terms of the material performance of concrete (Wang et al., 2013). It brings complexity to the concrete mix as well as the processes of preparation (Li et al., 2012; Behera et al., 2014). Equally it provides little flexibility for adoption in the industry reliably as the applications are limited with the exclusion of higher strength classes and special concrete types and with a recommendation to apply in lower replacement rates (Limbachiya et al., 2000). Therefore, use of RCA in structural concrete is not driven by the purpose of providing an improvement to the concrete performance unlike for alternatives such as pozzolanic materials.

Considering the environmental perspective, the use of RAC is considered to provide multiple environmental advantages (Behera et al., 2014). However, when the direct environmental impacts are assessed in detail, the advantages were not clearly visible. Marinkovic et al. (2010) in his study comparing the environmental impacts of RAC and NAC concludes that the results depend largely on the transport distances and favor the use of RAC when the difference of transportation distance of RCA is 20 km less than that of NA (Marinkovič et al., 2010). The results are based on mixes with an additional 5% of cement. Knoeri (2013) extends the results by incorporating the avoided impacts of steel and fly ash and concludes that until RAC uses an additional 10% cement, the situation favors the use of RAC (Knoeri et al., 2013).

On the other hand, with the extent of processing required, and accounting for the changes in mix design and adaptation costs, 0-20% price difference between RCA may/may not make RAC a cheaper option. To make it further complicated, some elements affecting material performance are interlinked with other aspects, such as addition of supplementary cement to RAC. It would favor the material performance in terms of compressive strength enhancement, but compromises both the environmental and financial outcomes.

While some of the advantages associated with the use of RAC in structural applications are quantified in previous research, some are qualitatively evaluated. Therefore, an integrated framework which interlinks the design aspects of the material and the manufacturing process, to the environmental, financial and other qualitative aspects which are not quantitatively evaluated so far is required, in order to comprehensively evaluate the two alternatives. This paper proposes Cost-Benefit Analysis (CBA) to evaluate and bring the critical parameters concerned to a common base for comparison.

2.2. Aims and scope of research

The research presented in this paper aims to:
establish criteria to evaluate the use of recycled concrete aggregate (RCA) to manufacture recycled aggregate concrete (RAC); compared to the use of natural aggregate (NA) in manufacturing natural aggregate concrete (NAC); to use in structural concrete, covering all significant implications.

- propose a framework and outline methodology to evaluate the outcome of the above two alternatives using cost-benefit analysis (CBA)

3. Methodology

This section presents the research approach used to address the above mentioned aims of the study.

3.1. Proposed method for evaluation – Cost-benefit analysis

The common tools used for evaluation of alternatives as above are environmental impact assessment (EIA), strategic environmental assessment (SEA), life cycle analysis (LCA), risk assessment (RA), risk benefit assessment (RBA), cost effectiveness analysis (CEA), multi-criteria analysis (MCA) and CBA (Pearce, 2006).

CBA is selected out of the above approaches for several reasons. Firstly, considering the need to assess the monetary aspect, methods which disregard monetary aspects and costs such as EIA, SEA and LCA were not considered. LEA with life cycle cost analysis was not considered as the evaluation requires economic evaluations, in addition to cost analysis with environmental data. RBA is similar to CBA if the identified risks are monetised. CEA requires the assumption of a single indicator of effectiveness which would lack representation of all concerned variables. Multi-criteria analysis (MCA) is similar to cost effectiveness analysis yet involves multiple indicators of effectiveness. MCA differs from CBA with the distinction coming from the fact that not all criteria are monetised. The final outcome of MCA is the weighted average of the scores, relating to multiple objectives. MCA therefore offers broader interpretation, better transparency of the results against particular criteria and flexibility to make decisions considering one dimension as a more important one. However, MCA does not offer decisions on whether to carry out a project or not, especially if the results of each objective would offer different directions. Lack of cohesion of the decision variable is, therefore, a disadvantage of MCA compared to CBA.

As a basic analysis method which provides an absolute value for comparison integrating a number of different aspects into one result, CBA is chosen to evaluate the outcome of the study. However, CBA could be subjective in monetising qualitative aspects and is not transparent as to what would be the trade off with other dimensions, unless they are considered separately. The main outcome of CBA is the net present value (NPV), which is the difference between the value of all benefits and the value of all costs discounted to the present. A positive value of NPV indicates an economically viable project. A few important things to note in CBA are: 1) benefits to the wider society are considered rather just the profit of parties involved in a change; 2) non-financial perspectives are incorporated; 3) non-financial perspectives are monetised for comparison.

CBA measures the costs and benefits considering “an economic” point of view (e.g. benefit and costs to society) as well as “a financial” point of view (e.g. revenues and costs only to investors). It is important to highlight the difference in fundamentals between the economic and financial perspectives to understand this. “Financial” usually refers to money matters relating to transactions of some size or
importance, and it is generally associated with a specific party under consideration. The main bottom line indicator from financial analysis is generally given by profit, where;

\[ \text{Profit} = \text{Revenue} - \text{Cost} \]  

(1)

As an example, in evaluating a change such as the one associated with the RAC and the use of NAC, the financial implication can be presented as;

\[ \text{Profit from a unit of concrete (Contractor)} = \text{Price of a unit of RAC} - \text{Price of a unit of NAC} \]  

(2)

However, an economic system has a much broader definition. Economy is defined as the process or system by which goods and services are produced, sold, and bought, in a country or region (Merriam-Webster, 2015). The Government of a country is the regulator of a country’s economy and the primary purpose of the government is the well-being of the society. Hence, a change is evaluated from the point of view of change of a policy, project or an initiative and the bottom line indicator is the net benefit to the society, where;

\[ \text{Net benefit} = \text{Benefits} - \text{Costs} \]  

(3)

As an example, the economic implication associated with the use of RAC as opposed to NAC for a unit volume of concrete can be presented by;

\[ \text{NPV from a unit of concrete (Society)} = \text{Net benefit from a unit of RAC} - \text{Net benefit from a unit of NAC} \]  

(4)

While for some dimensions, readily estimated financial figures in valuing costs and benefits are available, some require valuation. Non-market costs and benefits, which do not have a readily available value for exchange in the market, require valuation using techniques such as willingness to pay (WTP) for a benefit and willingness to accept (WTA) a cost.

The basis of CBA is to establish that the costs and benefits would accrue over time as a result of a project or an initiative and to discount them to the present time to produce an absolute value. Therefore, CBA provides a net present value (NPV), taking into account the time value of money.

Therefore, considering the above example, RAC is viable to society if:

\[ \text{Net present value of RAC} > \text{Net present value of NA} \]  

(5)

However, the construction contractor would find it viable when,

\[ \text{Cost of producing RAC} < \text{Cost of producing NAC} \]  

(6)

Therefore, if Equation 6 is not valid, a construction contractor as a party conducting business for monetary gains would not be encouraged to buy the product. As a result the upstream supply chain
which involves the demolition contractor, recycler and the ready-mix concrete (RMC) manufacturer is not encouraged to produce the inputs for the product or the product itself. However, if Equation 5 is valid, society benefits from the manufacture of the product. In such a situation, intervention of the Government as the regulator of the economy would be required to incentivise production of the product.

3.2. Framework for economic evaluation of RAC and NAC

The paper proposes a framework for the evaluation of four variables mentioned in Equations 5 and 6 above. Application of the framework requires consideration of the boundary of two main operations and the cradle-to-gate life cycle impact of the constituent materials used for those two operations. They are, namely, 1) production of NAC using constituent materials for concrete with NA as a constituent material, and 2) production of RAC considering NA and RCA as constituent materials (with RCA replacing NA partially).

Moving to RAC could have impacts on the main operation of producing concrete, which are considered as primary impacts, and impacts on the related products, by-products and waste in the immediate boundary of operations considered as the secondary impacts. The primary activities covered in the system boundary of NAC and RAC are presented in Figure 1. The recycling operation of RCA as a road base material, and transportation of concrete waste to landfill, located outside the boundary are two operations considered as secondary impacts. The secondary impact arises as a material volume needs to be reduced from one option (concrete waste sent to landfill) in the immediate boundary for it to be used in another option (concrete waste recycled to produce RCA for concrete).

Figure 1: Boundary of primary activities of producing RAC and NAC.
Extraction of NA rock and aggregate processing are needed to produce NA; and NA needs to be transported to a RMC manufacturing plant and mixed with other constituent materials such as cement, fly ash, slag, water, fine aggregate and additives to make NAC. These are presented as primary activities of NAC production, inside the concerned system boundary in the bottom part of Figure 1.

The top part of Figure 1 presents the system boundary of the primary activities for RAC. The concrete waste would be recycled at a recycling plant to produce RCA suitable to be used in concrete. The RCA produced as a constituent material for concrete will replace x% of the coarse NA requirement in concrete, while the balance (100-x) % will be NA. The RAC would also be manufactured in a RMC manufacturing plant, but would use a different mix consisting of the same materials to account for the incorporation of RCA in the mix. The processes are also expected to be different to that of the typical NAC manufacturing process. With the change of the concrete mix in the two cases, the quantities of other constituent materials required will also be different, and their life cycle impacts must be incorporated. For simplicity, the upstream processes of the constituent material production are not presented in the two system boundaries presented in Figure 1.

3.3. Application of the framework

Figure 2 presents a framework for the evaluation of two main categories of implications associated with RAC as opposed to NAC. These changes are indicated by the changes in material flow within the mentioned system boundaries above. They are 1) internalised impacts and 2) externalities. Internalised impacts are the ones that have been accounted for monetarily in the pricing system, with the parties involved gaining or losing monetarily due to the change. Externalities on the other hand, are defined as an effect that production or consumption has on third parties who are not involved with production or consumption (Boardman et al., 2011).

In other words, internalised impacts reflect the financial value, either surplus/deficit whereas the externalities reflect external cost not captured by the pricing system. The next step is to categorise externalities into: 1) direct environmental, 2) indirect environmental and 3) social segments for the purpose of evaluation. The primary activities resulting from the change will give rise to direct environmental externalities, while the secondary activities will result in indirect environmental externalities. The sum of the above three elements will produce the net external cost/benefit to society with the production of a unit volume of RAC. The basic methodology for the evaluation of the above four impacts are stated in the next two sections.

3.4. Technical assessment for the manufacturing of RAC

In order to estimate the above impacts, the industrial scale production environment of recycling and RMC manufacturing operations has to be simulated. Firstly, a technical assessment is conducted for this purpose to state the changes required in the mix, manufacturing environment and the industrial material flows.

The evaluation of the manufacturing environment is based on the operations of a typical concrete recycling plant producing RCA to be used as a road base material and a typical RMC plant producing NAC, and assessing the changes required to manufacture RAC. In order to produce RCA to be used as a constituent material in concrete, which will have: 1) less contamination, 2) less fines, and 3) a different grading and size requirement, the operations of the recycling plant would need to change. While the crushing process would remain the same, size separation and quality control processes are assumed to
be different. In a RMC manufacturing plant, the material receipt, quality control, storage, material preparation and mixing processes are expected to change, requiring additional infrastructure and process modifications. Therefore it is assumed that additional cost and energy consuming activities will be required at the concrete recycling plant and RMC manufacturing plant.

![Figure 2: Main framework associated with cost-benefit analysis for comparing production of RAC against NAC.](image)

The concrete mix using RCA would be different to that of NA, to account for the different quality of the aggregate with attached residual mortar. The change of mix constituents involve inclusion of supplementary cement and cementitious material, addition of mineral and chemical admixture (Behera et al., 2014). In addition to altering the mix constituents in concrete, preparation and mixing techniques are suggested to improve the performance of the resultant RAC (Tam et al., 2007b). Based on the quantities required and the changes in the manufacturing environment, the material flow diversions are estimated next, as a result of producing RAC.

### 3.5. Evaluation of financial and direct environmental impacts

The financial impact is assessed as the incremental financial cost for RAC, estimated based on the changes proposed in the technical assessment. The incremental financial cost would include the incremental material cost (IMC) and the incremental processing cost (IPC), with a margin added to it. IMC of RAC results due to the change of mix, incremental pre-processing cost of RCA and the incremental transportation cost of RCA, whereas the IPC would result due to the incremental processing cost in RMC manufacturing. IPC is estimated via process based costing (PBC) method, based on the incremental process changes and infrastructure requirements.

The direct environmental is captured by estimating the embodied energy (EE) in RAC primarily. For this purpose, incremental EE of RAC compared to NAC is evaluated using input-output (I-O)-based hybrid method and is converted to CO$_2$ emissions, based on emissions per fuel mix assumptions. CO$_2$ emissions are monetised, based on a charge per MT, to provide the monetary value to the integrated result.
3.6. Evaluation of indirect environmental and social impacts

The secondary environmental impacts in the boundary presented in Figure 1, are identified as indirect environmental impacts. For example, concrete waste for producing RCA results due to diverting the C&D waste originally sent to landfill, and the replacement of NA by RCA, reduces use of NA, thereby reducing NA extraction. The avoidance of landfill of C&D waste and avoidance of NA extraction are therefore considered as indirect environmental benefits as a result of producing RAC, and evaluated using economic valuation methods. Adjusted transfer technique in benefit transfer method is suggested to evaluate the specific values of those, based on the previous evaluations conducted on estimating the environmental cost of these impacts separately.

Social impacts of producing RAC would be evaluated qualitatively under this methodology.

4. Results and discussion

The above concept, framework and basic methodology can be used to conduct CBA, to evaluate four main elements, to compare the use of RCA in manufacturing RAC against the use of NA in manufacturing NAC.

- The internalised impact estimates the financial cost/cost saving in producing a unit volume of RAC. This is evaluated by incorporating the incremental material cost and the incremental processing cost to manufacture RAC, resulting due to the changes in the production chain of RAC compared to that of NAC.
- The direct environmental impact is obtained by estimating the incremental EE of RAC compared to NAC. Using I-O-based hybrid method, EE of RAC compared to NAC is to be evaluated and the result is to be converted to CO₂ emissions and then to a monetary value.
- The indirect environmental impact is evaluated using economic valuation methods by considering the secondary impacts of manufacturing RAC. Avoidance of landfill, NA extraction etc. require evaluation using benefit transfer method, by obtaining previous values and conducting adjustments to match to the context.
- The social impact is to be evaluated qualitatively.

5. Conclusions

The following concluding remarks can be made from the above discussion.

- A comprehensive evaluation is required covering multiple dimensions to compare the use of RCA to manufacture RAC, against the use NA to produce NAC for the same purpose. This is because when the material performance, environmental benefits and financial viability are generally looked at there are trade-offs of one aspect or the other and there are complex interlinks within these.
- CBA is identified as an effective method to estimate the quantitative as well as qualitative aspects concerned with the use of RAC. CBA monetises the qualitative and non-financial aspects and brings them to present value terms considering the time value of money.
- The need to consider both the financial aspect which reflects the monetary gain to the concerned party as well as the externalities which reflect the benefits gained to the society is identified for this type of problem, as the pure financial drive may not lead to production of RAC.
A framework incorporating internalised impacts and externalities is proposed to evaluate the production of RAC against NAC. The internalised impacts are reflected by the financial gain/loss with the production of a unit volume. The external impacts are categorised into direct environmental, indirect environmental and social impacts. This paper proposes a methodology to evaluate each of them considering the concerned system boundaries for both cases. The framework and approach proposed in this paper are critical for evaluating and selecting of preferred concrete types for use in buildings as structural concrete. This is important information for building designers and engineers as they strive to reduce the environment impact of the built environment.

6. Limitations

The methodology requires adoption of different scientific methods, from different disciplines to evaluate each dimension. At the point of integration of the results, bringing them to a common base is a complex task. As an example, the results from economic evaluation would require the results to be brought to present terms, accounting for discounting and to be indicated by monetized value per unit volume of RAC. The results derived from environmental data (such as CO₂ emissions), especially under the direct environmental impact assessment would have uncertainty associated with the timing of effects, such as the emissions resulting from upstream processes. Equally, in evaluating the indirect environmental impacts, the subjectivity arising from the use of benefit transfer technique in economic valuations would affect the results. This is due to the inability to do adjustments to perfectly match to the context of the original study, and therefore, disregarding the key assumptions made in the original valuations.

7. Recommendations for further research

While there can be recommendations for further research suggested for each discipline considered, this paper would limit the suggestions made to the integrated framework. Firstly, in the technical assessment, different options for scaling up of the RAC manufacturing environment can be explored. Considering customized operations for the preparation of RCA as a constituent material in concrete, upscale impacts of having these operations as an extension to the concrete recycling or RMC industries need to be investigated. Secondly, dynamic material flow simulations with varying composition of concrete waste diverted to produce RCA as a constituent material for concrete could be conducted using a method such as system dynamic modelling. This study together with a demand-supply assessment on the requirement for RCA to replace NA would add value to understand the industry material flow impacts with the implementation of the initiative.

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References


A simulation-based model for evaluating the performance of ready-mixed concrete (RMC) production processes

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Abstract: The development of the infrastructure sector and the rise in the per capita consumption of cement and concrete over the years have triggered the rapid increase in the use of ready-mixed concrete (RMC) in India. The assured quality of concrete, accuracy in the mix proportions, faster construction, less workforce and improved workspace utilization make RMC advantageous over site-mixed concrete. This industry is turning out to be one of the most promising in terms of income and revenue that efforts have to be made to ensure that the RMC production processes are carried out in a timely and cost-effective manner. With the growing concern over the environmental impacts due to construction, its sustainability perspective should also be taken into consideration. This study presents a discrete-event simulation model to evaluate alternate RMC production scenarios and to assess its performance in terms of equipment (batching plant and truck) utilization rate, energy use and carbon emissions. A detailed review on the functioning of the RMC production processes is presented. Finally, this study presents a set of recommendations for improving the performance of the RMC industry.

Keywords: Ready-mixed concrete; discrete-event simulation; production performance; environmental performance.

1. Introduction

The arrival of liberalization principles into the Indian economy paved the way for large-scale investments in the industrial, infrastructural and agricultural sectors of the country. This led to the increased pace in the mechanisation of the construction industry and also to the advent of the usage of RMC in India (Jain, 2002). The use of RMC in the construction industry is significantly advantageous because of many reasons which include good quality concrete, precise mix proportions, faster construction, less number of labourers, reduced congestion at the worksite and improved workspace utilization (Indian Cement Review, 2014).

The size of the RMC industry has grown from USD 2.39 billion in 2009-2010 to USD 6.02 billion in 2014-2015 (Goyal, 2012). As per the earliest efforts to count the number of RMC plants in India, the total number of plants accounted to 27 in the year 2000. This was mainly concentrated to the major
A simulation-based model for evaluating the performance of ready-mixed concrete (RMC) production processes in metropolitan cities of India (Jain, 2000). In 2001, this increased to 47 (Jain, 2002) and further increased to 147 by 2005 (Ranganath, 2005). In 2013, the all India commercial count of RMC plants amounted to a total of 857 and the latest statistics as per January 2015 show that the total number of RMC plants is 1135 (Manjunathal et al. 2015).

Most of the plants have been set up in the major cities of India and they account for 30 - 60 % of the total concrete used in these cities. Its use is rapidly increasing in spite of the 12 - 20% higher cost as compared to site-mixed concrete (Alimchandani, 2007). On an average, the total concrete market in India is estimated at about 300 million cubic meters annually. Out of this, the RMC production is about 35 million cubic meters (Goyal, 2012), which is around 12 % of the total concrete production.

Since the country is witnessing a rapid increase in the use of RMC, a comprehensive framework must be set up to address the relevant issues relating to the production and environmental performance of RMC (Misra and Varsney, 2011). This study aims to present an understanding on the functioning of the RMC production processes and to develop a simulation-based model for evaluating alternate RMC production scenarios.

2. Literature review

As a large number of RMC plants are being set up in the country, the industry is turning out to be one of the most promising in terms of revenue and profit. Thus, this also means that the supply, delivery and in-house operations of an RMC plant have to be carried out in a timely and cost-effective manner (Park et al. 2011). To get the maximum cost and time benefit, proper vehicle scheduling and dispatching of the ready-mixed concrete should be maintained. Thus, the project management perspective of RMC has been quite a challenge for its suppliers.

One of the main factors that should be taken into consideration for this aspect is the lifetime restriction of concrete. Concrete is a material which possesses the perishable characteristic that it cannot be stored or produced much in advance. It hardens within a few hours (1 to 1.5 hours) and hence, it has to be delivered from the plant to the site within this time limit (Masten and Sherkow, 2012). This characteristic increases the complexity of the scheduling and dispatching of concrete (Zhang et al. 2011). The production process also depends largely on the distance between the RMC batching plant and the site (Park et al. 2011).

Furthermore, life cycle cost (LCC) has emerged as a significant element in assessing the economic performance of the industry in the long term (Hong et al. 2012). Life cycle cost is the total cost incurred in all the different stages of construction. With this concept, the project management perspective is slowly and steadily merging with the sustainability perspective of construction. There is immense pressure on the world’s environmental performance today that measures have to be taken to conserve the natural resources for tomorrow. It has been shown that humans are exploiting natural resources at a rate of about 20 – 25 % more than the rate at which the earth can replenish them (Gardiner & Theobald, 2014). This applies to the construction sector too as a large amount of raw materials are being used in this industry. Hence, there is an increasing demand in the construction sector, to understand and imbibe the concepts of sustainability in practice.

Many countries have made efforts to reduce the environmental impacts that take place due to construction (Hong et al. 2012). In India, almost 24 % of the total CO₂ emissions is due to the activities occurring in the construction sector (Parikh et al. 2009). It has also been found out that transportation is one of the most significant components which results in the emissions of green-house gases. The
transportation sector contributes to about 23% of the world’s total green-house gas emissions (IPCC, 2008). The transportation of ready-mixed concrete to site represents a major component of energy use and emissions during the on-site construction phase (Palaniappan et al. 2009).

The construction industry consists of complicated, dynamic and interactive processes and like most of the construction processes, the supply and delivery of RMC is stochastic. Thus, the production of RMC cannot be modelled deterministically using average input data. However, it can be efficiently modelled by means of discrete-event simulation (DES). Discrete-event simulation keeps track of the changes of the state of the system occurring at discrete points in time and builds up a logical model of the system to experiment with it on a computer (Lu and Lam, 2009). A lot of work has been done by means of DES to analyse the time, cost and sustainability aspects of earthmoving (Ahn et al. 2009) and road construction operations (Gonzalez and Echaveguren, 2012). In the context of ready-mixed concrete, the use of DES was undertaken in some studies to evaluate the production performance. A brief review of these studies is summarized in Table 1:

<table>
<thead>
<tr>
<th>Problems addressed</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trade-off between the transit mixer dispatching interval and queuing time on site</td>
<td>Park et al. (2011); Lu and Lam (2009); Zhang et al. (2011); Zayed and Minkarah (2004); Talin (2013)</td>
</tr>
<tr>
<td>Improving the concrete delivery performance by adjusting the pour start time at the site</td>
<td>Lu and Lam (2009)</td>
</tr>
<tr>
<td>Maximization of RMC productivity and minimization of cost</td>
<td>Smith (1999); Dunlop and Smith (2002)</td>
</tr>
<tr>
<td>Pump dispatching at the site to reduce the queuing and idle time</td>
<td>Zhang et al. (2011)</td>
</tr>
<tr>
<td>Maintaining the delivery time of RMC to site well within the time limit in order to sustain the best properties of concrete</td>
<td>Park et al. (2011); Zhang et al. (2011)</td>
</tr>
<tr>
<td>Minimization of the resource, market and policy risk associated with RMC supply and delivery</td>
<td>Zhang (2011); Azambuja and Chen (2014)</td>
</tr>
<tr>
<td>Determination of the time, cost and quantity relationship for a required distance from batching plant</td>
<td>Zayed and Halpin (2001); Zayed and Minkarah (2004)</td>
</tr>
<tr>
<td>Web-based quality control of RMC production</td>
<td>Arioz et al. (2006)</td>
</tr>
</tbody>
</table>

Since a lot of studies have been undertaken to take into account the project management perspective, this study aims to calculate the environmental parameters of RMC production processes, which have been relatively unexplored till date. The study aims to determine the truck and batching plant utilization rate along with the energy usage and carbon emissions associated with the RMC processes, while varying parameters such as the total quantity of concrete produced per day, number of trucks, distance travelled per trip and the speed of the truck.

3. Major phases of RMC production

Four case studies were conducted in order to account for the production and environmental performances of RMC processes. This comprised of several field visits to the RMC plants over a period of six months. The RMC plants are located within 100 kilometres of Chennai, the capital city of Tamil Nadu.
A simulation-based model for evaluating the performance of ready-mixed concrete (RMC) production processes in India. A detailed understanding of the RMC processes was developed. The field visits helped in demarcating the RMC processes into five phases and to assess the environmental performance. This was made possible through observations at the plant and interviews with the plant manager and other staff members of each RMC plant. The input for the simulation model was obtained from the analysis of data provided by the RMC suppliers. The RMC production processes are grouped into five major phases from the manufacturing of raw materials to site operations. The disposal of concrete is not considered in the scope of this study. Each phase consumes resources such as water, fuel, electricity, consumables, equipment, vehicles, instruments and human workforce. The details of these five phases are described below (Nellickal et al. 2015):

3.1. Manufacturing of raw materials

The raw materials required for RMC production include cement, sand, coarse aggregates, water, admixtures and flyash. Energy is utilised for the manufacture of cement at the cement plant for the extraction of raw materials, processing, clinker production, grinding and packaging. Coarse aggregates of sizes 20 mm and 12 / 10 mm are usually used for concrete production. Sand is mostly obtained from the riverbeds. Manufactured sand is used in cases when river sand is not available. Flyash is obtained as a by-product from thermal power plants. The admixtures are produced from a wide variety of chemicals. Water is usually obtained from a nearby natural source.

3.2. Transportation of raw materials to batching plant

The raw materials required for ready-mixed concrete production are transported from the supplier location to the batching plant by means of trucks. Cement and flyash are stored in large quantities in silos at the plant while the coarse and fine aggregates are stored in their respective storage yards. The admixtures are transported to the plant in cylindrical barrels which are usually directly connected to the batching plant mixer. Water is brought to the plant in tankers and are filled in the water tanks or is directly obtained from a natural source.

3.3. Operations at the RMC batching plant

The batching plant is fully automated and is run by diesel, electricity or both. The major sources of energy consumption at the plant include the diesel generator, site office operations, loader used for handling aggregates from the storage yard to automated belt conveyor, and the company vehicles. The batching plant is able to produce different grades and types of concrete. The mix proportions are already stored in the automated control systems of the batching plant. The plant uses either a pan mixer or a twin-shaft mixer of specific capacity.

3.4. Delivery of RMC using transit mixer trucks

The batched concrete is then fed into the transit mixer trucks which is transported to the respective customer sites. These are special types of trucks in which the final mixing of the concrete is performed in their rotating drums. For the best properties of concrete to be maintained, the concrete should reach the site within a time limit of 1 to 1.5 hours from the time of batching. This is hindered by heavy traffic on several occasions, especially in the major cities.
3.5. Construction operations at the site

Once the transit mixer reaches the customer site, the concrete is pumped to the required location by means of concrete pump. The placed concrete is further levelled and compacted. The surface is then given the final finish using appropriate tools in order to get an even surface of the concrete placed, prior to its curing.

4. Simulation model

The discrete-event simulation (DES) model takes into consideration the various activities and resources that are part of the RMC production processes. It is developed such that it runs for a period of one day, to deliver concrete from the batching plant to one site. The components of the model and its input and output parameters are shown in Figure 1.

The simulation model was tested for four scenarios by varying the quantity of concrete required per day, distance to site, number of trucks and the speed of the truck. The output parameters are batching plant utilization rate, truck utilization rate, energy use and emissions. Table 2 presents the input data used for simulation. This is based on the information gathered from several field visits. The energy use and emissions are calculated from factors which have been obtained from the field analysis. Energy use is calculated using the factor 6.35 MJ / cum / km one-way distance, whereas emissions is calculated using 0.48 kgCO₂ / cum / km one-way distance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>No. of samples</th>
<th>Mean</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantity of concrete transported per day (cum/day)</td>
<td>176</td>
<td>100.7</td>
<td>3</td>
<td>342</td>
</tr>
<tr>
<td>Distance travelled per trip (km/trip)</td>
<td>831</td>
<td>36.2</td>
<td>3</td>
<td>104</td>
</tr>
<tr>
<td>One-way distance travelled per trip per truck (km/trip)</td>
<td>364</td>
<td>18.2</td>
<td>2.7</td>
<td>66.2</td>
</tr>
<tr>
<td>Average number of trips per day per truck (trips/day)</td>
<td>364</td>
<td>2.2</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Fuel mileage for transit mixer (km/litres)</td>
<td>75</td>
<td>2.1</td>
<td>1.4</td>
<td>2.8</td>
</tr>
<tr>
<td>Waiting time at site for transit mixers (minutes)</td>
<td>268</td>
<td>150.7</td>
<td>0</td>
<td>397</td>
</tr>
</tbody>
</table>

The batching plant component in the model represents the pan mixer in which the various raw materials are mixed to produce the ready-mixed concrete. The capacity of the pan mixer is 1 cum per batch or 45.8 cum per hour. It usually runs for an average of 10 hours per day. Materials represent the storage of the raw materials which needs to be loaded into the pan mixer. The produced concrete is then loaded into the transit mixer trucks which have a maximum capacity of 6 cum. It takes approximately 8 minutes to complete one cycle of mixing the concrete and loading it into one transit mixer. The transportation to the site depends on the speed of truck and the distance of the site from the batching plant. The average speed of the truck is assumed to be 40 kmph over a mean one-way distance of 20 km. The transit mixer waits at the site depending on the availability of the pump and the time required for pumping. Pumping of concrete represents the unloading of concrete at the site by the transit mixer. The time required for pumping is assumed to be 15 minutes. Once the concrete is unloaded, the transit mixer truck returns to the batching plant, where they are cleaned prior to its next trip. The cleaning time is considered as 5 minutes. Based on the data gathered, there are about 8 to 14
transit mixer trucks owned by the supplier company. Their utilization depends on the amount of concrete required to be supplied on that particular day. The average quantity of concrete supplied per day is 100 cum.

5. Results

The results of the four scenarios tested using the discrete-event simulation model are shown in Figure 2.

5.1. Scenario - 1: variation of the concrete quantity produced per day

The quantity of concrete required at the site is varied from 50 to 300 cum. The number of trucks available is maintained at 10 while the one-way distance to the customer site is kept at an average of 20 km. It was observed that both the batching plant utilization rate and the truck utilization rate increases as the quantity of concrete to be produced increases. The batching plant utilization rate varies from 0.474 to 0.844 as the concrete required increases from 50 cum to 300 cum. The truck utilization rate increases from 0.521 to 0.859 for 50 cum to 300 cum of concrete. Similarly, the energy use and emissions increase as the concrete quantity increases. Energy use varies from 12693 MJ to 76519 MJ while the emissions vary from 968 kgCO$_2$ to 5811 kgCO$_2$.

5.2. Scenario - 2: variation of distance between the batching plant and site

The distance to the site is varied from 10 to 70 km and the number of trucks is kept constant at 10 in this scenario. The quantity of concrete required is also kept at a constant value of 100 cum. It was observed that as the distance to the site increases, the batching plant utilization rate decreases. This means that the plant has more idle time when the distance to site increases. The rate varies from 0.731 to 0.561 as the distance increases from 10 km to 70 km. However, it was observed that the truck utilization rate increases from 0.53 to 0.772 as the distance is varied from 10 km to 70 km. The energy use and emissions increase as the distance to site increases. Energy use varies from 12693 MJ to 88852 MJ as distance varies from 10 km to 70 km. Similarly, the emissions increase from 968 kgCO$_2$ to 6779 kgCO$_2$.

5.3. Scenario - 3: variation of the number of transit mixer trucks

The number of trucks is varied from 8 to 14 for a constant one-way distance of 20 km and a required concrete quantity of 100 cum. The batching plant efficiency decreases from 0.697 to 0.643 as the number of trucks used for concrete delivery increases from 8 to 10, after which it is constant at 0.63 when more number of trucks are used. The model showed that the utilization rate of the truck first increases from 0.708 to 0.716 as the number of trucks increase from 8 to 9 after which it decreases from 0.668 to 0.495 as the number of trucks vary from 10 to 14. Also, this scenario has an energy usage of 25386 MJ and emissions at 1937 kgCO$_2$. A constant value is observed as the energy use and emissions depend on the distance to site, quantity of concrete required and the number of trips undertaken, regardless of the number or trucks utilised.
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Batching Plant Construction site
Loading of concrete
Trasportation to site
Pumping of concrete
Return to batching plant

Materials

Transit mixer truck

Cleaning of trucks

Concrete pump

Truck waiting

Input parameters
1. Quantity of concrete supplied per day
2. Pan mixer running hours
3. Time for mixing and loading of concrete into transit mixers
4. Number of transit mixer trucks
5. Capacity of transit mixer trucks

Output parameters
A. Batching plant utilization rate
B. Truck utilization rate
C. Energy use due to transportation of transit mixer trucks
D. Emissions due to transportation of transit mixer trucks

Figure 1: Simulation model with input and output parameters.

a. Scenario – 1: Number of trucks = 10; One-way distance = 20 km

b. Scenario – 2: Number of trucks = 10; Concrete produced per day= 100 cum
A simulation-based model for evaluating the performance of ready-mixed concrete (RMC) production processes

5.4. Scenario 4: variation of the speed of transit mixer trucks

The transit mixer delivery speed is varied from 20 km/hr to 80 km/hr. The number of trucks is kept constant at 10 with a concrete quantity to be delivered at 100 cum. The batching plant utilization rate increases as the speed of delivery is increased. The efficiency varies from 0.593 to 0.731 as the speed is varied from 20 km/hr to 80 km/hr. The truck utilization rate decreases from 0.731 to 0.53 as the speed increases from 20 km/hr to 80 km/hr. Moreover, the energy usage was found out to be 25386 MJ and emissions at 1937 kgCO₂. The constant value is because the energy use and emissions are not considered as a function of speed in this scenario.

6. Conclusion

This study evaluated the RMC batching plant utilization rate, transit truck utilization rate, energy use and emissions using a simulation model. The following recommendations are presented to improve the production and the environmental performance of the RMC production processes: a) Proper monitoring of the transportation of the transit mixer trucks such that truck dispatching from the batching plant is in accordance to minimise the idle time at the plant and truck waiting time at the customer site; b) Integrate lean concepts into RMC production processes to eliminate the non-value adding activities and wastage at the plant and site; c) As transportation is one of the major sources of energy use and emissions, the determination of the optimal number of transit mixer trucks for efficient concrete production.
delivery can reduce the total impact on the environment; and d) Use of locally available or recycled raw materials such that the total embodied energy is reduced. This would be useful to improve the decision making processes of the RMC suppliers in terms of project management and sustainability metrics. Further studies can focus on considering the supply of concrete to multiple construction sites per day and the determination of the optimal scenario. Also, the effect of the truck speed on fuel mileage can be studied.

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**References**


A simulation-based model for evaluating the performance of ready-mixed concrete (RMC) production processes


Collaborative creativity: building envelopes and construction innovation

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Abstract: There is a trend in contemporary institutions to commission buildings characterised by façade designs of increasing formal complexity. Building façade systems are an area that demands specialist expertise and that has critical influence on overall building performance, marketing value and construction cost. These buildings can offer, at least in principle, a potential to promote construction innovation. By looking at a highly specialised area of the construction sector, this paper presents the findings from a pilot study that investigates industry perceptions and experiences on innovation through architecturally complex façades. The context of this study is a recently completed tertiary education project in Melbourne built with a novated ‘design and construct’ method of procurement. Semi-structured interviews with key project leaders engaged in the design and delivery of the façade systems offered an in-depth exploration of the differing perceptions about the interpretation of construction innovation among the participants. According to this pilot inquiry, in the context of novated contracts, the industry recognises the critical role of a design ‘gatekeeper’ engaged collaboratively with subcontractors while the prevailing industry mandate in Victoria, as shared by the participants, is to give priority to innovation opportunities that minimise on-site labour and reduce construction time.

Keywords: Innovation; institutional buildings; specialist subcontractors; building façades.

1. Institutional projects and innovation opportunities in building envelopes

Architectural design trends in recent Australian tertiary educational projects are displaying interest in multi-layered and geometrically complex building envelopes setting performance standards recognised through such criteria as those established by the Green Building Council of Australia. In this setting of apparent challenged ‘buildability’ (Hyde, 1995), are there opportunities to foster construction innovation? The target of this study is the role of specialist façade subcontractors in their capacity to take a pivotal role in the design development and the construction management of façades characterised by formal and technical complexity. Through this lens the potential available through cooperation between supply chain actors to bring into being that which otherwise would be standard
operative processes is investigated. This potential is described here as collaborative creativity, out of which innovation may be borne.

Tertiary education projects, given the privileged and the potentially illuminated role of their commissioners, may have an inherent potential to push construction innovation, but at what level does construction innovation happen, if at all, in these projects? Does the complexity and the challenged constructability of the façades of these project translate into new developments in construction process or production? Does it encourage the use of new materials, systems and components? Does it affect organisational structures and/or new methods of production? And lastly, do these highly complex building envelopes reflect an institutional push from the clients to achieve higher performance targets?

The Organisation for Economic Cooperation and Development (OECD) has set the benchmark for the definition of innovation that has come to be recognized by policy makers. It establishes innovation in terms of the creation and diffusion of new or significantly improved products (goods and services) and processes and methods supported by factors of research and development (OECD 2005, 2010, 2015). The full applicability of this definition to the construction industry has come into question, in challenging the low ranking of the construction industry in comparative industrial innovation performance data (Winch, 2003; Reichstein et al., 2005) and the nuances in innovation that apply to the project-specific problem solving characteristic of the sector (Slaughter, 1993, 2000; Winch, 2000; Tombesi, 2002).

Although literature abounds on identifying the sources of construction innovation motivation and obstacles (Whythe and Sexton, 2011; Blayse and Manley 2004) and the pressure on the Australian construction industry from a productivity innovation point of view (Ashurst, 2014), little investigation has taken place in relation to construction innovation grounded in the supply chain dynamics that apply to the project-based nature of the construction industry. There has been recognition of the importance of the role of sub-contractors (Gil et al., 2001), as well as studies from single specialist subcontractor perspectives (Holt and Edwards, 2012) and from component manufacturers (Larsson, Sundqvist and Emmitt, 2006). Loosemore (2014) has undertaken a study on Australian tier-one sub-contractors from a productivity perspective which briefly touched on the question of innovation, linking innovation opportunity to subcontractor productivity.

It is therefore pertinent to ask, how innovation is understood by the construction industry at consultant, contractor and subcontract level.

2. A pilot case study: methodology and approach

The aim of this paper is to gain insight into construction professional’s perceptions of innovation and how these perceptions may be exemplified through the building façade and envelope. At face value this building element offers innovation opportunity by its intrinsic design and technical requirements and in addition by being a key component on the construction critical path program. The building façade system as an environmental moderator potentially intersects with construction technical innovation but also with issues of broader significance for innovation in architectural design and construction management. It also offers an area of investigation for aspects of construction projects that require understanding of perspectives on collaboration (Hughes et al., 2012) in a context where design imperatives are more stringent (Fox et al., 2002).

The method of gaining information at this stage was not to investigate the façade components for their innovation outcomes but to obtain an understanding of how key stakeholders in the supply chain identified elements of the façade as being innovative within their own frames of reference and within
the context of the part they played in the project. The research takes a case-study approach where value is identified by providing insight into the very specific nature of project-based innovation dynamics that occur in the construction industry (Winch 1998; Tombesi, 2002) but which has remained unattended by recent studies.

The study adopted a qualitative research method. An open-ended interview based on the same set of questions being presented to each stakeholder representative was used to determine each viewpoint and perspective. The study methodology sought the participation of the primary actors in the façade design and supply chain by engaging with design, contracting and subcontracting teams. This afforded a holistic view of innovation from design to implementation. In total six senior leaders from six different professional and construction organisations were interviewed – two were key personnel responsible for architectural design and specialist façade consulting, one responsible for design management from the head contractor and three senior management representatives from three different specialist sub-contractors involved in façade delivery and installation.

The participants were asked six general questions in common and they were encouraged to expand their views on aspects of construction innovation in relation to the project. The key topics covered by the interviews can be summarised in three areas:

- The meaning and value of construction innovation from the perspective of the participant’s role in the process and in function of their position in the supply chain of the building envelope;
- The level at which opportunities for construction innovation originated in the project (e.g. at the level of new materials, fabrication processes and/or management resources) and the relationship of these opportunities with the complex nature of the architectural design of the façade;
- The opportunities and the restraints for the implementation of construction innovation in relation to the procurement system adopted – in this case a ‘design and construct’ contractual scenario.

The scope of this pilot inquiry was to test the effectiveness of the questions raised in the interviews, to identify patterns of perception and experience about construction innovation in the sector of architectural façades and to develop a protocol that can extend the interviews as a multiple case-study project that involves a number of similar projects located in other Australian States.

By targeting a small number of institutional projects with an embedded focus on building envelopes, the case study research methodology was chosen to explore in depth the mechanics of construction innovation. The aim of the investigation is to establish how and why construction innovation is introduced at a level of the façade sub-contractor in the supply chain of institutional projects.

The focus of this paper lies with the initial case study used as pilot for a larger research project that will investigate a number of tertiary educational projects completed in Australia in the last five years, with each having a project budget above fifty million Australian dollars. The pilot case study building is a six storey teaching and research facility of around sixteen thousand square metre gross floor area, procured under a novated consultant contract system, with a construction period of eighty weeks. Its façade system consists of a mixture of cladding components including precast reinforced concrete panels, aluminium framed glazing systems and metal screening. The building’s sustainability credentials have been recognised under the Green Star – Education V1 rating by the Green Building Council of Australia. A novated design and construct procurement method was utilised to offer the benefit of contractor input into the design management process to generate cost and time efficiencies in order to meet project budget and to deliver the project within the time requirements dictated by an academic
teaching calendar. The pilot study is not directed to investigate the efficacy of the procurement system or the façade system in meeting its intended outcomes but to consider these in relation to the question of stakeholder perceptions on construction innovation within the project.

3. Participants’ perceptions on construction innovation

There is consistent academic literature that defines innovation in construction (Slaughter, 1998; Winch, 1998) and another stream of studies that defines causes and sources of motivation for the implementation of innovation in the building industry (Seaden et. al, 2003; Hartmann, 2006). How innovation is defined and understood by the construction industry at consultant, contractor and subcontractor level is instead less documented. The participants of this pilot study were asked to define their understanding of innovation in relation to their role in their organisation and position in the supply chain of the project.

The architect and head contractor interpreted innovation chiefly in terms of market advantage. The architect saw innovation in terms of design creativity in interpreting programmatic requirements. The contractor saw the terms of market advantage instead as a capacity to deliver tertiary sector buildings outperforming cost and time parameters.

The architect saw a driver of innovation in the nature of the contractual regimes that are now the norm in the industry, design and construct, guaranteed maximum price and management contracting in particular. These contracting systems have afforded greater early engagement with the head contractors and partial access to subcontractors by being embedded within the contracting team, which is not facilitated by traditional forms of procurement prior to completion of contract documentation. This has not necessarily translated into material technology innovation but consideration for innovation in design, product and process innovation in support of on-site labour minimisation, construction program time and constructability. The architect saw this driving a shift from traditional construction methods to an engagement in building systems that lend themselves to prefabrication and unitised systems. The nature of these contract systems, it was argued, also held difficulties. The development of innovative façade systems in consort with specialist suppliers was seen as being difficult due to perceived project risks of losing competitive advantage in being tied to a single supplier. Furthermore the difficulty was seen in the contractor’s acceptance of risk by committing to untested building systems.

The architect also recognised innovation in terms of establishing bench marks for architectural design and building performance. These bench marks could, in the architect’s view, be achieved via the introduction of new building systems as well as by questioning and/or integrating existing construction materials and methodologies to achieve better design and performance outcomes. The architect identified the capacity to achieve complex design and performance outcomes as an innovative trait of the professional services offered. In the context of multi-storey institutional buildings the architect’s point of view on innovation was explained as the mastery of skill and awareness of the industrial reality while combining different building systems into a coherent design outcome. An approach of direct collaborative participation with sub-contractors and the necessity to engage in pro-active industry inquiries from the schematic design stage was identified by the architect as a critical aspect for the successful outcome of this process.

The perception of the value of innovation from the point of view of the façade specialist subcontractors concentrated instead on the ability to meet a wide range of different demands from the
designers in response to ad hoc performance requirements that can vary significantly from project to project.

The contractor's perspective lay in the mindfulness of meeting or improving on performance outcomes whilst being conscious of overall project responsibility related to cost and time. A key feature was an acceptance of the architectural design intent and building performance criteria. Innovation strategies therefore were seen as those generated in meeting or exceeding building performance criteria where the methodology of achieving these criteria were not clearly resolved and in those strategies directed to achieving early project delivery.

Subcontractor perspectives on innovation were in terms of internal systems and processes directed towards capacity development to demonstrate architectural design delivery at the system element level and to facilitate operational, fabrication or installation capacity to minimise project risk and project time.

The glazed façades subcontractor involved in the fabrication and installation of windows and shopfront facades explained construction innovation as the capacity to find the most effective solution to different design intents in terms of cost and time. In synthesis for this contractor the meaning of innovation was interpreted as effectiveness in delivery combined with a capacity to design and develop bespoke façades.

The architectural metal fabricator responsible for the fabrication and installation of external balustrades, metal sunshades and relative secondary steel supports interpreted the meaning of innovation as the capacity of ‘taking the normal stuff and turning it on its head’ in order to meet ever-changing design challenges posed by different projects. This subcontractor explained innovation as the ability to come up with ‘always something little cleverer’ by transferring hindsight from previous projects. However innovation in this trade was not related to a matter of questioning the basic techniques of metal fabrication (e.g. welding, bolting, folding et cetera) but rather as the ability to question everything else surrounding the production process. For this subcontractor innovation consists in essentially making fabrication simpler, updating and developing better finishes, and providing pre-assembled and modular solutions to reduce site work and manage delivery with better quality control in the factory. The subcontractor stated also that ultimately ‘most of what we change is what you don’t see’.

A key feature in common to all participants on this project was the notion of the importance of being proactive in developing a collaborative creative approach that fostered openness to innovative solutions in design resolution and project delivery.

4. Where did construction innovation occur in building envelopes?

The participants were also asked to comment in relation to specific instances where innovation occurred in the project.

The architect and façade engineer identified one of the primary design features of the building, its metal folded façade screening system, as being an element that required new product and process development. By being a frameless system, extensive research and testing was required in material technology and structural design to identify an appropriate material and support mechanism for these cantilevered screens. Research was undertaken in metal thickness and folding techniques to generate appropriate structural capacity in maximising sheet span to minimise fixing points. In being perforated, 3-D design modelling software was aligned with production manufacturing system capacity which was
itself modified to significantly reduce production times to meet construction program imperatives. Prototypes were developed which underwent wind tunnel testing to ensure structural integrity and to test noise generation in its future varied configuration arrangement across the façade.

The contractor also put forward the metal façade screen system as an exemplifier of project team collaboration in delivering this significant design feature within the contract obligations to meet time and cost.

The glazed façades subcontractor stated that the façade industry has now transformed into a highly bespoke trade practice where most systems used in medium-large institutional projects rarely contemplate the use of ‘off the shelf’ glazing suites. The professional design industry, from this trade perspective is now shifting towards a very high level of project specific production where ‘everyone wants something different, everyone wants a different appearance from their extrusions, everyone wants a different performance and everyone wants a different colour’. For this contractor the ability to gain flexibility including ex-novo aluminium extrusions in the delivery of the project is now paramount in order to gain competitive advantage in the sector of architectural façades.

The aluminium manufacturer has reinforced this view indicating that in some instances the bespoke nature of the glazing system required twenty extrusion dies to be cut for the project. This large variation of extrusion profiles was partially in response to a multitude of window alignments and in part in response to a more industry-generalised necessity to provide glazing pockets for a wide range of non-standard double glazed units. A current and local trend in the façade sector is that glass unit thickness can now vary significantly from project to project and also from system to system within the same project in response to structural, thermal and acoustic requirements set by façade engineering specifications. This non-standard, performance-based approach makes it necessary for subcontractors to develop a multitude of different extrusions with the effect of eliminating the use of ‘off-the-shelf’ framing systems outside the domestic market.

The glazed façades subcontractor produced in close collaboration with the aluminium manufacturer a set of specifically extruded window systems, louvres including relative brackets and a large prefabricated skylight system. According to this sub-contractor the project was symptomatic of a current trend where bespoke unitised structural glazing systems are transferred from high-end façade systems into smaller institutional project where finished-off products can be delivered pre-glazed directly from factory to site. The unitised approach, traditionally associated with large multi-storey curtain walls now provides significant cost benefits also at smaller scale due to increasing costs of site-labour and managing issues of dealing with construction management issues of building sites on a day-to-day basis. Beyond the immediate consequences for this sub-contractor to develop more extrusion dies in collaboration with the aluminium manufacturer the company had to accommodate for the project significant process changes in the layout of the factory, due to the necessity to have products completed off-site. While identifying production process changes as one of the modality through which innovation occurred in the project, this subcontractor highlighted the impact on employee profiles required in the factory by seeking different people with new skill-sets, for example with capacity to use cranes and slings. In this regard the pre-assembly of a glass roof element in large unitised sections was exemplary of this innovation mechanism at process level. The same sub-contractor also acknowledged an imperative to innovate that was generated by the design of the building, arising from its design form, geometry and size, as well as by requirements to achieve particular architectural and performance criteria such as glass set at different alignments. The sub-contractor recognised that working on these
types of building brings a marketing advantage for the company in a market where ‘the more you move from the norm, the more competitive you become’.

The architectural metal fabricator also identified changes in the processes of fabrication as one aspect induced by the project. The need to fabricate large Vierendeel steel trusses triggered the need to develop a new type of self-rotating rotating jig – the participant defined this the ‘spit-roast jig’ – where parts could be worked by the fabricator on both sides without turning it over, with the result of saving labour and handling time. Other items of innovation identified by the same sub-contractor were the need to modify initial connection details of the sunshade screens by using three-dimensional modelling. The use of three-dimensional documentation tools, however, was already in place in the company before the project in case.

5. Discussion

When facing the question to define their understanding of construction innovation the participants gave different examples as a demonstration of their capacity to be innovators in their respective fields. For those involved downstream in the supply chain it was difficult to define innovation coherently, revealing confusion between innovation as a process of substitution with elements of novelty and the inevitable creative problem solving associated with a project with a low level of standardisation. The word innovation was often misinterpreted as the capacity to meet project specific challenges indicating an incongruity with the more rigorous and broadly encompassing definitions adopted instead by academics, which more often define instead innovation as a process of substitution capable to extend its influence from one project to another and preferably from one project to an entire industrial context.

For this project, from the head contractor’s perspective, innovation was identified primarily as a process of improvement directed to meet performance standards set by the designers and to meet cost and time imperatives. Subcontractor interests were directed to component innovation to reduce on-site work and to improve productivity with more efficient factory fabrication methods. Another element that emerged within the perspective of the constructors was an idea of innovation not as a simple response in productivity directed to reduce construction cost. Innovation was claimed to be part of a more complex set of causes related with risk mitigation, programmatic pressures and opportunities to facilitate site management by minimising on-site labour.

A common understanding however was identified in the recognition of innovation as a means to obtain a competitive or a market advantage through increased efficiency and flexibility in production and delivery. The participants shared the view that the competitive advantages given by being perceived as innovators in their respective field is a key source of motivation to adopt innovative practice.

Two key considerations can be drawn from this pilot study and these allow setting a pathway for further research activity.

• The importance of having a ‘gatekeeper’ in the design team, which in this case was impersonated by the façade architect, was identified by the participants as an essential feature that ensures that the design intent and the performance requirements of the envelope could be carried out successfully from conception to completion of the project. The role of the gatekeeper was recognised by the participants significantly in the context of ‘design and construct’ procurement. In virtue of the constraints imposed by the design gatekeeping, the participants of this case study have suggested that the challenge to meet a design intent that is closely monitored by the designer can be a significant trigger of change from normal practice.
• Time-related pressures in the delivery of the project were identified recurrently by the participants as the primary source of motivation to engage in innovative forms of practice in construction. The need to speed up the building process was described as a make-or-break contextual condition setting the stage for improvements in fabrication methods and processes, the substitution of design elements or the introduction of new methods of installation. This scenario was deemed particularly effective in relation to items that were in the critical path towards what some participants defined as the ‘lock-up’ stage of the project, or in other words the time in the program when the initiation of the internal fit-out stage can occur in a weather tight environment. As one example of this form of time-induced innovation, several participants identified the process of maxi-prefabrication and redesign that was required by the timely delivery of a large atrium skylight, which in their experience resulted in ‘never done before’ building practice.

The participants indicated that the construction industry may find innovative benefits by working in a context where, at least in relation to the sector of building envelopes, the designers can work collaboratively in direct contact with specialist sub-contractors from the early stages of the project. This consideration leads to the need to understand the contractual dynamics that are established within a project.

This pilot case study suggests also that opportunities for innovation may not necessarily be excluded within projects that are procured with design and construct methods and where the designers are in contact, by virtue of the contractual necessity set by the novation, with the head contractor and potentially also directly with the specialist sub-contractors. These opportunities are however dependant on the specific modality of collaboration that is set in the project and by the attitude and the experience of the organisations and the individuals involved. In this case study, the head contractor and the architect have allowed a fruitful level of collaboration to occur weekly with intensive design meetings, where different sub-contractors, and at times product manufacturers, could enter in a direct relationship of collaboration with the designers.

The intensity of the collaboration is reliant on other variables related to the intrinsic nature of the architectural design of the building envelope. The gatekeeper in this case study took the role of custodian of the original design intent of the façade systems, which were conceived, developed, and agreed with the client following the successful outcome of an international design competition. During the design development and the subsequent documentation and construction stages of the project, design gatekeeping became the discriminant that ensured that the aesthetic design intent set with the client could be met. Gatekeeping implied, in this case, meeting not only specified performance requirements but also locked-in architectural appearance.

6. Conclusions and further research

There is an incongruity of meaning between the definition of innovation established by OECD definitions and the understanding of the meaning and value of the word innovation among a number of participants of this study at sub-contractor level. The difficulty within the building industry to define innovation seems to lie principally in the incapacity to recognise the different levels of intensity where innovation can occur. This study has shown that some of facets of the broader meaning of innovation are not always contemplated by the building industry. At a level of academic recognition, innovation would be considered as the adoption of non-trivial changes in process, component or systems which would go beyond the project specific challenges set by a bespoke component of the design. The industry
perception of the building industry seems to focus instead on the idea that to possess organisational flexibility and capacity to engage efficiently in project specific problem-solving is a sufficient condition to gain a market recognition as ‘innovators’ in their fields.

This pilot study suggests however that there are significant elements and patterns of change within the sector of façade specialist sub-contractors based in Victoria. The need to reduce on-site labour alongside with the imperative to reduce overall construction time is currently a robust driver of change which has the potential to make sub-contractors receptive of considerable innovative practice. In the sector of architectural façades, this time-induced motivation for change is favouring, for example, the adoption of bespoke design and fabrication of unitised façade systems also in medium-large educational projects by smaller and locally based façade sub-contractors, while traditionally these systems have been used as a prerogative of large multi-storey commercial projects by larger, and often off-shore based suppliers.

There are differences in the perception of the value of innovation which change according to the role taken by different participants in a project. Moving upstream in the supply chain, designers and head contractors seem to be more aware of the broader implications of innovation that can go beyond project-based practice. Designers and consultants, such as architects and façade engineers, may see as the chief driver of innovation the need to seek superior performance and the need to control design appearance through the different stages of the project. Head contractors may favour cost and time outcomes and subcontractors may seek benefits in efficiency and time-control as motivating factors for change. It is therefore necessary to engage with the contextual dynamics that are established by the method of procurement in a project and in that context it is also plausible to assume that these dynamics are related to the nature and the level of the risk taken by each participant.

It remains to be established how procurement systems can have an impact on the potential to introduce innovation in the construction sector, and more specifically in contemporary building envelopes in Australian tertiary education facilities. This consideration leads to the definition of a set of questions that should be analysed further with a multiple case study approach:

- Do design and construct systems of procurement preclude rigorous research and development activity in construction? Does competitive tendering require the actors playing downstream in the supply chain to withhold innovative strategies until certainty of contract is established? Was the outcome of collaboration unique for this case or related to the typology of novated contracts?

- Where does innovation capacity lie in the sector of specialist façade sub-contracting? Is it related to performance improvement or does it lie in construction management of a significant critical path item? Is it the critical path program that drives innovation?

- What mechanism is there to promote improved performance standards? Where are the incentives for innovation to improve performance standards? Is the lowest regulatory or rating regime becoming the benchmark?

- What role do bespoke projects in tertiary education sector play in being innovation incubators and is there evidence for this through multiple case study analysis?

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References


Erection of post-formed gridshells by means of inflatable membrane technology

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Abstract: This paper describes a new erection technique for post-formed timber gridshells based on an inflatable membrane technology. All well-known gridshell construction techniques are either based on the pulling/pushing up a flat grid of laths, or on the easing down of a grid of quads from a certain height. These techniques already suffer from shortcomings at the small scale; when applied to the large scale, the lack of a standardised and cost-effective erection method implies that new techniques have to be thought up each time. This is one of the reasons why gridshells are have only been designed for exceptional projects, such as the Downland Museum or the Mannheim Multihalle. Gridshells are not widely applied to common projects, even though they enable large spans to be covered with the minimum amount of material, they are fast to construct and are entirely recyclable. In this work, an inflatable membrane has been designed and used to erect a gridshell prototype with a footprint of 55m². Inspiration comes from the work of the architect Dante Bini, who, since 1964, has been realising hundreds of inflatable concrete domes around the world.

Keywords: Gridshells; inflatable membrane technology; construction techniques; form-finding.

1. Introduction

Shell structures carry loads through membrane action, and with reduced or no bending. This behaviour allows shells to feature an optimal stress distribution over the full cross section (Sasaki, 2014). Gridshell structures discretise the features of double-curved shells into a lightweight grid (Baverel et al., 2012). This allows, on the one hand, the structural self-weight to be reduced and, on the other (hand), the loads to be transferred only through compression forces (Bulenda and Knippers, 2001).

The term “gridshell” is broadly used to describe two categories of reticulated structures: post-formed gridshells and lattice structures. These categories differ as far as the materials, nodal configurations and construction methods are concerned. Lattice structures are generally made of steel and assembled directly in their final shape by bolting or welding rigid beam elements at the nodes - such as in the case of the court roof of the British Museum. Post-formed gridshells are timber products which are assembled by loosely connecting layers of linear laths in a flat grid of quads with hinge joints; this
grid is subsequently post-formed into a double-curved shape, and then stiffened by means of bracing, shear blocks and connection tightening (Knippers and Helbig, 2009). It is worth noticing that the laths run through the nodes; connections can either be made using bolts or clamps. Bolts have been used, for instance, in the Mannheim Multihalle, whereas clamps were designed for the Downland museum.

Gridshells have been widely studied in terms of form-finding and, more recently, optimisation; as the work of Frei Otto is the main reference for the design and erection of timber gridshells (Hennicke, 1974), so the work of Jörg Schlaich is for the design and construction of steel gridshells (Holgate, 1997).

Two main categories of erection techniques are explained in Quinn and Gengnagel (2014): the first one is called “pull-up”/“push-up” and the second one “ease down”; a third technique, based on an inflatable membrane technology, has recently been outlined as a promising research topic.

1.1. Current construction processes for gridshells

Post-formed gridshells generally undergo more stress during construction than during operation. Erection is thus a key phase for gridshell design, due to the high variations in bending, in the asymmetric load conditions and in the heterogeneous curvatures. The two best known techniques are illustrated briefly hereafter, and the advantages and complications of their usage are highlighted.

“Pull-up” / “push-up” construction techniques involve assembling the flat grid on the ground and then lifting it up, either by means of cables and cranes (“pull-up”), or using a static formwork and jacking towers (“push-up”) (Quinn and Gengnagel 2014). The first method draws benefits from the speed of construction. However, the nodes receive concentrated stress, and this can easily induce breaks; moreover, horizontal restraint cannot be provided and the use of cranes can be costly and require calm weather for their operation. The second method applies the same lifting principles, but by means of a low-cost technology. The Mannheim Multihalle is one of the largest and most relevant gridshells in this category (Burkhardt and Otto, 1978). The final form of the Multihalle was developed by means of scale-models; this allowed the most efficient form of pure compression to be determined for a model that was too complex and time-consuming to be calculated numerically at that time (Addis, 2013). The construction process started by laying the double-layered timber grid on the ground in a flat position. Holes and slots were carefully drilled for each one of the over 33,000 joints, thus providing them with hinge features (Harris, 2004). The initial choice was to use cranes for the erection, but eventually a system of jacking towers was used to reduce the costs (Happold and Liddell, 1975). In one year, the grid was lifted to its final position by pushing upward from below and pushing inward from the sides (see Figure 1). The construction phase ended with the joints being tightened and shear blocks and bracing cables being placed in position (Burkhardt and Otto, 1978). This erection technique, applied at a large scale, proved to be highly time-consuming and imprecise; moreover, a 1.5% lath breaking ratio was observed (Harris et al. 2003).

The “ease down” construction technique starts with a flat grid being assembled on a raised level and then its edges being bent down by means of modular scaffolds and mechanical formworks (Quinn and Gengnagel, 2014). The Downland Open Air Museum, by Buro Happold, shows how this technology offers, on the one hand, better safety for the workers and a lower breaking ratio, but, on the other hand, still involves high costs. Unlike the Multihalle, the flat lath mesh was laid on scaffolding at the shell hump top level and was post-formed to its final configuration by means of a scaffolding structure and forklift trucks (see Figure 1). After the lowering process, the gridshell was fixed at its supports and stiffened with a pre-stressed cable network (Harris et al. 2003). Adriaenssens et al (2014) have pointed
out that fixing the shell both at the sides and ends provides this erection technique with more precision, and that post-forming the grid under a gravity load leads to a more homogeneous distribution of the strains.

![Figure 1: Left: Mannheim Multihalle by Frei Otto and the “push-up” erection process (1973-74). Right: Downland gridshell and a description of the “ease-down” lowering process (2002).]

The aforementioned examples help to illustrate that, despite featuring a seamless integration between the material and form, shell structures still lack appropriate sustainable solutions for their construction and fabrication. The commonly used construction techniques for gridshells are highly demanding, in terms of resources and budget. These are among the reasons that generally discourage the use of shell structures. Moreover, the precise positioning of the joints in the correct final position still remains an open issue.

Fabrication-related shortcomings already arise at a small scale. When scaled to a larger scale, the lack of a standardised, cost-effective erection method implies that techniques have to be reinvented each and every time, and gridshells only become affordable for exceptional projects, such as the Downland Museum or the Multihalle in Mannheim.

2. Constructing with inflatable membranes

Historical examples show how membrane technology has provided an alternative means of construction through the centuries (Veenendaal et al., 2011). The potential of it is to seamlessly approximate ruled surfaces; moreover, the membrane’s flexibility allows fabric formworks to deflect and adapt under the weight of wet concrete. These features benefit membrane technology with an interesting potential in easily generating shapes of pure tension (compression if inverted), especially in comparison to traditional rigid formworks.
2.1. Inflatable membranes in shells construction

Early applications of the membrane technology to shell structures can be found in the work of James Waller. His patented “Ctesiphon” system relies on a set of catenary steel frames from which a fabric formwork is stretched; having a modular compressive catenary system allowed him to simplify the construction process, while minimising the use of steel reinforcement. (Waller and Aston, 1953).

Figure 2: Top left: Ctesiphon shell catenary frames (Credits: Waller and Aston, 1953); Top right: Binishell system during RC levelling. Bottom: one-day erection of the 1990 World Cup structure in Udine; inflatable flat stage in the morning, on the left, and in the evening, on the right (Credits: Bini, 2014).

Another technology applied to RC shells was proposed by Wallace Neff when, in the 40s, he pioneered the use of inflatable domes as formworks for concrete bubble houses (Neff, 1941). This technology was further explored by Dante Bini with his patented “Binishell” system for RC shells. Such a system relies on a rather intuitive form-finding / construction procedure (Bini and Fontana, 2014):

- after laying rebar, concrete is poured over a flat pneumatic preformed formwork;
- the membrane is inflated, and the shell is raised to its final position;
- after seasoning, holes for openings are cut.

Although providing RC shells with inflatable formworks was not an entirely new technique, Bini has had the merit of integrating them with James H. Marsh’s “Lift-Shape” patent to erect and bend reinforcements to the desired shapes (Marsh, 1961).

2.2. Inflatable membranes in gridshells construction

Dante Bini’s “Binistar” system involves applying inflatable pneumatic membranes to steel space frame structures. This automatic construction method was developed for pneumatically-lifting telescopic steel
spatial structures; an air-tight pre-shaped PVC-polyester membrane was used to lift the frame structure from the footing-level to its final position. At the end of the construction process, the membrane remained in tension, suspended from the nodal points of the structure as a leak-free final cover. The galvanised steel space frame was composed of a series of telescopic pipes which were mechanically fixed after completing the inflation (Bini, 1993). The various building projects include temporary buildings for sports, such as the 1990 World Cup Championship (see figure 2), or events, such as the 1992 Expo Pavilion in Seville.

3. Post-forming through inflatable membrane technology

The previously presented applications of inflatable membranes to shell structures showed promising potential in terms of automation, construction speed and shape control. This part of the paper describes the redevelopment of a timber gridshell by means of this technology. The case study is based on the post-formed Accoya timber gridshell built at the University of Melbourne in October 2014 (coordinators Pugnale, Colabella, Pone, www.karamba3d.com/accoya-timber-gridshell). The design of this gridshell arose as a variation of the Alida Woodome series, designed and constructed by Gridshell.it. Redeveloping a well-known structure first allows the construction technique to be focused on rather than the design; it also allows a comparison to be made of different processes that result in the same outcome.

Figure 3 shows the flat and post-formed configurations of the gridshell along with the Accoya timber properties (New Zealand grown Radiata Pine). The 11x11m² orthogonal grid is made of 50mm wide and 19mm thick timber laths, arranged in two layers in each direction. The lath spacing is 500mm for each layer.

Starting from the post-formed gridshell configuration, a physical model and a numerical model have been developed. Initially, the numerical model made it possible to determine the most appropriate membrane geometry to use for the post-forming of the gridshell. The physical model then made it possible, on the one hand, to understand the overall behaviour of the system and, on the other hand, to deal with technological issues related to the joints, connections and materials. Finally, a refined numerical model led to a better refining of the theoretical aspects of the problem.

3.1. Numerical model

The numerical model of the gridshell has been developed as follows. First, a flat configuration of the gridshell was drawn on the Rhinoceros CAD platform. Second, the two lath layers were parametrised by means of Grasshopper (Rhinoceros plugin). Third, the parametric model was translated into a spring system by means of Kangaroo (Grasshopper physical simulator plugin). Then, a preliminary bending process was simulated using the Accoya timber properties and the shape of the Alida Woodome by Gridshell.it (Pone et al, 2013). Finally, a more accurate bending was implemented by iteratively imposing displacement to the edge joints during the dynamic relaxation. Working with such a double-curved structure has allowed, on the one hand, to minimise the nodal vertical displacements and, on the other hand, to optimise the structural response to vertical and horizontal loads.

Once the double-curved post-formed configuration had been obtained, the inflatable cushion membrane shape and properties were determined. The cushion was made by welding two slightly convex square sheets at the edges. After running several inflation-collision simulations, the membrane that best fitted the post-formed gridshell was chosen (see Figure 3). Setting inextensible - rather than
rubbery - material properties made it possible to have a better control of the final shape of the membrane. Wrinkling was considered irrelevant as far as the overall behaviour of the system was concerned. A 7.2x7.2m² mesh was chosen as the most suitable solution; having a smaller cushion than the post-formed gridshell also made it possible to avoid self-intersections during the collision simulation.

Figure 3 shows how the inextensible cable and pulley system works in the initial configurations $t_0$, in the intermediate phase $t^*$ and in the final configuration $t_1$. Pulleys were positioned on the ground along the vertical projection of the cushion at $t_1$, in correspondence to the external and middle points of each free edge. Several assumptions were made to develop this system:

- to transform a vertical push into horizontal traction;
- to ground-restrain the free edges of the gridshell during the whole erection process;
- to allow a precise control of the final position of the joints;
- to use longer ropes than the laths to obtain an initial $t_0$ stress-free configuration.

Ground-stoppers were placed according to the post-formed gridshell configuration in order to control where to stop the bending process at moment $t_1$.

The traction and lifting forces were calculated, in Kangaroo, by approximating the cables and membrane with net force vectors. Given the final gridshell configuration, these force variables were determined by applying prescribed displacements to the flat gridshell.

The material and geometric properties were set and verified by means of both numerical and physical benchmarks.

3.2. Physical model

Figure 4 shows the 1:7 scale prototype that has been developed to simulate the system. The Accoya gridshell was modelled as a single-layer Poplar-timber gridshell. Continuous laths were connected at the joints with bolts and nuts; this allowed the 1:1 structure to be approximated with a reduced bending stiffness. An easier bending procedure was thus achieved.

The square membrane was fabricated as a PVC coated polyester strip. Vinyl Cement glue and duct tape were used to seal the strips together to prevent tangential forces from lacerating the membrane; welding two simple flat sheets together- rather than pre-curved surfaces – made it possible to facilitate the membrane fabrication process. A Halkey-Roberts valve was then placed on the PVC fabric and sealed. In order to seal the upper and lower halves together, a sewing-machine was first used and then duct tape was placed along the edges; this cautious solution has proved to be necessary to prevent tangential forces from tearing the two halves apart.

Implementing buttonhole-guides along the sealing led to a better control of the cable system. A 150g/m multifilament twisted twine was chosen for the cables. A trial-and-error iteration between the physical and numerical models made it possible to determine the geometry and properties of such a system (see Figures 3 and 4).

It has been discovered that swelling affects the membrane in two ways. During the first phase $t_0$-$t^*$, the membrane rises and shrinks horizontally at the same time; the gridshell only receives an upwards push from the contact. However, once the membrane reaches moment $t^*$, the cable system becomes tensioned; this triggers a secondary lifting effect in which centripetal edge forces induce bending and hence push the gridshell upwards. (see the bottom images in Figure 3 and the central ones in Figure 4).
The details were developed considering real-scale inflatable models (i.e. valve system, guides and d-rings, welding technology). The use of eyenuts as pulleys was crucial for several reasons:

- to transform the membrane vertical push into a horizontal traction for the gridshell, hence allowing lifting;
- to ground-restrain the gridshell edges during the lifting process, hence allowing an easy development of the ground-connections at the end of the process;
- to secure a precise final position of the free edges of the gridshell, hence making the whole process more controllable.

![Gridshell - Accoya timber properties](image1)

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<thead>
<tr>
<th>Gridshell - Accoya timber properties</th>
<th>Membrane - PVC coated polyester properties</th>
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<tr>
<td>5th percentile values</td>
<td></td>
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<tr>
<td>Bending strength $f_{b,k}$</td>
<td>Tensile strength Warp 2275N/50mm</td>
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<tr>
<td>Tensile strength $f_{t,k}$</td>
<td>Tensile strength Weft 2420N/50mm</td>
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<tr>
<td>Shear strength $f_{s,k}$</td>
<td>Elongation at break Warp 20%</td>
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<tr>
<td>Mean values</td>
<td>Elongation at break Weft 27%</td>
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<tr>
<td>Young’s modulus $E_{0,k}$</td>
<td>Density $ρ_m$</td>
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<tr>
<td>Shear modulus $G_{0,m}$</td>
<td>680 g/m$^2$</td>
</tr>
<tr>
<td>Density $ρ_m$</td>
<td>460 kg/m$^3$</td>
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Figure 3: Top: Gridshell and membrane properties; initial flat state and post-formed states of the system. Bottom: cable system before ($t_0$) and after ($t_1$) the inflation process. Cables tensioning occurs at moment $t^*$. The illustrated process is concluded before the bracing and shear blocks are installed.
Erection of post-formed gridshells by means of inflatable membrane technology

4. Conclusions

The idea of using an inflatable membrane technology for the erection of post-formed timber gridshells arose from a review of the issues of the existing construction methods, but also looking back at Dante Bini’s air structures. An inflatable membrane has therefore been designed to erect a 55m² timber gridshell, with the aim of increasing construction speed, safety and form control. An already existing gridshell was chosen as a case study to compare this alternative technique with a more conventional one: the Accoya timber gridshell, developed at the University of Melbourne in October 2014.

A numerical model and a physical model have been developed to simulate the erection process. The numerical model has been used to determine the geometric and structural properties of the timber, membrane and cables. The 1:7 scale model has instead been helpful to design the membrane/rope...
system and verify the results of the numerical simulation. The details of the physical model have been prototyped in order to be easily replicable at a full scale. It is worth noting that this technology focuses only on the erection phase; in order to provide the gridshell with structural stability, the installation of bracing and shear blocks on the final structure would also be required.

This new erection technique still requires further developments and tests on a few aspects:

- the numerical model needs to be refined in a higher-level FEM solver to extrapolate both lath nodal stress and membrane tension during the erection process. This step would be necessary to simulate the erection of a 1:1 scale model. A higher-end FEM software would allow the performance of different shapes and types of membranes to be compared. For instance, planar membranes can be cheaper and easier to fabricate, but double-curved membranes can stick better to the gridshell and hence reduce the lath breaking ratio while increasing the precision necessary to reach the final form;
- an internal cable system should be implemented and tested to link specific key-points between the upper half and the lower half of the membrane. This system would allow better control to be obtained of the membrane geometry and hence of the final gridshell configuration;
- this technique should be tested for the construction of different gridshell geometries, in order to verify its potential for standardisation;
- a more flexible system of modular membrane cushions should be developed, in order to allow application to multiple and different gridshell geometries, dimensions and configurations. As Dante Bini has pointed out (Bini et al. 2014), providing an erection system with a reusable technology is relevant to reduce construction costs;
- this technique should be tested on a full-scale prototype in order to obtain reliable data on its speed, safety and form-control. This would allow a comparison to be made between this technique and the current construction methods.

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References

Identifying performance parameters in public-private partnerships: gauging the stakeholder perspective

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Abstract: The definition of building performance may vary from different points of view. It could aim at performance targeted through a financial point of view, a user’s or a developer’s point of view. Can we have a project ‘on time’, ‘in budget’, that successfully delivers a 100% of its scope? Achieving the economic efficiency aims at achieving pre-determined objectives of the project with minimum expenditure of resources. PPP initiative is mostly taken to circumvent budgetary constraints, encourage efficiency and quality in projects. This paper investigates some of the sensitive parameters affecting the economic performance in Public-Private Partnerships through a stakeholder based intervention, to aid future study towards optimization. The intervention targeted both sides of the backdrop: the construction companies as well as the investment companies to understand the priorities of investors. Further study would encompass studying various forms of PPP, their sensitivity to project parameters and existing uncertainties affecting their performance. This parametric identification would aid us further in developing a business case for PPP in housing. Further investigation will be conducted through structured interviews, surveys and market case studies. Using the Sensitivity analysis and Monte Carlo simulation, a kit of methods for PPP application in social housing will be developed.

Keywords: Partnerships; parametric-identification; sensitivity analysis.

1. Introduction

PPPs are varied contractual arrangements between private and public parties for a project, with different measures of service delivery, financing and risks sharing models. Private sector involvement shows us the potential of investing in new technologies, having more transparent functioning, and possible innovations in delivery (Treasury, 2003). However, not all projects are suitable for adopting PPP. PPPs can be regarded as being a natural extension of the trends for outsourcing, contracting-out and privatization (CIB, 2011). However, their evolution has differed from country to country. Specific project conditions would decide if the incorporation of private sector in the delivery of services is viable for the respective project. This paper highlights the key findings of our survey and identifies
performance parameters in Public-Private Partnerships that will pave the way for future research focusing on PPP in housing.

Major Challenges with PPPs: Public Private Partnerships raise the following challenges in front of us:

- The complex long-term nature of PPPs and management of long-term contractual relations
- The performance of PPPs with respect to other range of options available (Eg. Traditional procurement, contracting out etc.)
- The management of PPPs with different interests and objectives of various stakeholders

Accountability is also a major concern in the context of PPPs and therefore a challenge in this regard, of limited transparency and poor adjustment to project specifications (Reeves, 2013). Transparency is essential to make PPPs more accessible and widely recognized and more assessable.

2. Methodology adopted: a focused group survey approach

A focused group survey approach, of 25 professional and academic experts in PPP, has been adopted to gather the concerns of stakeholders and understand the broad scenario of PPP. These participants were selected based on their involvement and work undertaken in the PPP industry. The major stakeholders that are involved in any PPP project include a public partner, in-charge of the designing, tendering and contract management; a private partner responsible for managing the project and development per the contract terms; and the financing authority responsible for providing financial resources. This survey extends to stakeholders beyond public, private or financing bodies that includes architects, contractors, clients or any personnel involved in PPPs. Detailed interviews including users as an important stakeholder, will be conducted in further investigation. The key themes of the survey include:

- Experience in number and types of PPP projects
- Drivers of efficiency in public private partnerships
- Major concerns and issues encountered in PPPs
- Key risk elements, & measures adopted to address the issues and challenges with PPPs
- The priorities of financers
- Strategies to improve the use of PPPs

3. Key insights gathered

Let us begin with the gathered results and move further to their analysis. This section illustrates some of the key findings of the surveys and interviews and throws light on various important factors in the PPP world. Figure 1 and 2 provide a broad insight into the various control variables for PPP and the drivers of their economic efficiency. Further, individual aspects have been emphasized.
The institutional environment

The institutional framework becomes a major aspect for the successful implementation of PPPs. There has been a varied view on the effectiveness of the legal framework governing the PPPs and the provision of resources and incentives by the government. Many participants have raised concerns regarding the failure of the project even before it commencement due to high cost of funding itself.

Risks in PPPs

Some of the main risk elements as identified in PPPs through our survey can be seen in the figure 3 below, with government policies, legal framework, and maintenance of long term capital being weighted as the highest. Often, contractual clauses and negotiations between the parties are used to deal with some of these risks (Flanagan and Norman, 1993). Good governance, reformed laws, reconsidered budget expenditures are some more strategies, however each project is required to be dealt on a project specific basis (Vose, 2008).
Re-negotiations in PPPs

It has been pointed out in the survey that re-negotiations continue to take place throughout the course of the project. They are observed more in case of inflation or when faced by public opposition. In large capital PPPs, re-negotiations are required to optimize contract terms as well as project approach and this demands a fair amount of flexibility in our PPP models (Egis, 2002).

Priorities of financers & investors

Some of the basic concerns of financers that have come across through this survey are low interest on funds, lack of transparency in financing and governance, having a positive debt-equity ratio, low risk and high demand, debt certainty and clarity of market returns, project viability, and an early involvement. However, we will have a deeper insight into the financing side, in the following section.

4. The financers’ perspectives

4.1. European Investment Bank

European Investment Bank highlights PPPs as an evolving framework. Today, EU PPPs are governed by standardization (Eg. standard contracts), holding dedicated teams (eg. specialist teams at banks or PPP task forces) and varied payment mechanisms with their focus on demand, performance and availability (Bain, 2009). They believe that the project size and its suitability to adopting PPP is essential to be investigated thoroughly. There may appear a maximum and a minimum size that may be viable for adopting the PPP approach.

Meaningful risk transfer along with private finance at risk are considered as some of the major attributes by EIB, for a PPP project. Procurement discipline, contract awarding criteria and having a long-term view by the promoters to protect asset maintenance are also essential to the efficient delivery of PPPs. Also, the stage at which EIB’s involvement is sought for, defines the reachability of the financial benefits to the public sector or the end user. The Bank, therefore, should be involved, preferably before the bidder is selected. PPPs are often condemned for being poor and inflexible in managing change (Bain, 2009). They work more in case of projects where the pace of change is slow and gradual (EIB, 2005). PPPs involving many stakeholders ensure due diligence, and they also promote design and technological innovation under certain circumstances. They also aid in generating efficiencies in projects.
with a genuine risk transfer. However, PPPs are considered politically fashionable to adopt and are being utilized by promoters as off balance sheet vehicles for some projects, which may otherwise be unaffordable for PPPs. This is considered a major threat by EIB.

4.2. World Bank

World Banks’ view of Public-private partnerships are arrangements based on pre-defined project assumptions about cost-estimate and demand forecasts. PPPs with long-term tenures involve greater amount of risks in their development, due to uncertainties such as technology, the macro-economy, or competition in the market to name a few (PPIAF, 2009). The output based approach of Public Private Partnerships enable more innovations and help to secure benefits such as technological efficiencies from the private sector. The aspect next to risks is the acceptability of the project, as success comes with its acceptance by the people.

Some of the major parameters essential to the functioning of PPPs as pointed out by World Bank are project costs and market fluctuation risks; demand risks; cost of debts vis a vis the movement in the variable interest rates, or the debt in a foreign currency; political risks vis a vis bowing to public demands or taking over of the project; and social unrest (Egis, 2002). Management of these risks rests on three pillars: Identification, Mitigation and Allocation. The major rule about allocating risk is allocating it to the entity or stakeholder who is best able to manage that risk. Forced risks would, otherwise, eventually be priced.

4.3. Asian Development Bank

Asian Development Bank has four major pillars of their Public-Private Partnership operational framework (ADB, 2012). These four pillars are:

- Advocacy and Capacity Development
- Enabling Environment
- Project Development
- Project Financing

From identifying the PPP potential to developing the regulatory and legal framework, aligning the project to the PPP development process, and financing and providing credit; each pillar plays a critical role in the project. And therefore, the performance parameters of PPPs are critical to the efficient functioning of the individual pillars. The following table highlights some of the identified key performance parameters and performance indicators for independent pillars of ADB:
Table 1: Identified Performance Parameters & Indicators for PPP Projects (ADB, 2012).

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<tr>
<td>Performance Parameters</td>
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<tr>
<td>a. Identification of the potential for PPP in various sectors</td>
<td>a. Suitability and preciseness of the policy, and legal frameworks of the projects in consideration</td>
<td>a. Alignment of the ADB project cycle to the PPP project process</td>
<td>a. Provision of credit enhancement</td>
</tr>
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<td>b. Development capacity of the government and AD Bank staff</td>
<td>b. Scope of alterations in the regulatory frameworks</td>
<td>b. Adequacy and expert support with regards to toolkits, funding or procurement, throughout the project process</td>
<td>b. Guarantee of credits and funds</td>
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<tr>
<td>c. Know-how and management links</td>
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<td>c. Adequate financial support to public sector</td>
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<tr>
<td>Performance Indicators</td>
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<tr>
<td>a. Supporting new countries to enhance the availability of PPPs through regional and national events</td>
<td>a. Number of new countries adopting the PPP framework or guidelines/toolkit or supporting processes at country/regional level</td>
<td>a. Number of countries pursuing PPP project development</td>
<td>a. Total project value created</td>
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<td>b. Number of PPP projects under development process</td>
<td>b. Total project financing provided</td>
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<td></td>
<td></td>
<td>c. Number of ADB supported PPP projects reaching financing agreement stage with either only public or private sectors, or jointly with both public and private sectors</td>
<td>c. Leveraging ratios of ADB funding</td>
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The Asian Development Bank believes that shifting to PPP requires redefining of the performance matrix to a great extent. For each of the above independent pillars, PPPs cut through boundaries between sectors and require coordination with many constituencies simultaneously.

5. Identified performance parameters in public-private partnerships

A partnership’s success is governed by many parameters that are structured as per the conditions of the particular project with an effective risk allocation, a stable regulatory framework and a transparent building process (Bain, 2009). The sections above and the literature gauged highlights some of the major parameters that affect a PPP’s performance; such as defined roles and responsibilities of public and private sectors, fund allocation, realistic forecasts, corruption and many more. Few of the main aspects that are critical to a PPP project’s success are as follows:

Risk allocation and transfer

Much of the literature (Li et al., 2005; Garvin, 2010; Mahalingam, 2010) stressed on the aspect of equitable allocation of risk as a key parameter to achieve value for money in public-private partnerships. However, the type of risk, its significance level and implications vary across countries and sectors. For example, demand risk becomes a major consideration for risks in road projects.
Project specifications and streamlined development

Quality of output specifications plays an important role in driving the design and operational innovation and an effective contract management. Involving all stakeholders specific to the project typology, at different stages, in development and review of the specifications, could ensure a thorough understanding of their needs and requirements. Clear client requirements and project briefs, certainty and well-defined objectives contribute to the success of PPPs (Akintoye et al., 2003).

Developing a business case & affordability of PPPs

Some of the literature demonstrates that many projects did not meet the expected outcomes due to ambiguity in the service need identification itself (Askar and Gaballah, 2002; Kalidindi and Thomas, 2003). It becomes essential to clearly identify the need of the service/project. It is very important to model a bid prior to its procurement, including the financing costs and life cycle assessment to have a realistic view on a project’s affordability. Also, it is essential to assess the repercussions of the PPP proposed project empirically, with the governments’ financial position. Figure 4 below highlights some of the major factors that govern the choice of PPP for a specific project.

![Figure 4: Governing factors for choosing PPP (Source: survey analysis).](image)

Contract management

All participants showed the need for effective administration of the contract, flexibility and increase in its ability to adapt to changes. Any PPP involves many contracts under the main PPP, for example, between the contractors, architects, or consultants. It is necessary to have an effective continual communication, specifically in events of changes and adjustments.

Governance structure & transparency

The need of having an effective governance structure within the public sector, and a transparent system throughout the planning and execution process has been a common issue raised by all participants.

Flexibility in PPPs

According to an Open Plenary Discussion in the two day conference ‘PPP days 2015’, about 70-80% PPP projects undergo re-negotiation (EBRD, 2015). There may always exist a substantial unpredictability with long-term tenured projects. Our survey results also show that the inflexibility in PPP contracts makes them very expensive and procurement can stretch over a period of time. And, this long-term nature
Identifying performance parameters in public-private partnerships: gauging the stakeholder perspective

The inflexible nature of PPP often becomes incompatible with the type of the project (Gibson, 2013).

6. Lessons learned

Some of the major lessons learned from the above survey, literature studies and especially from a few agencies including the UK National Audit Office (Controller and Auditor General, 2010), the UK Treasury, a UK policy think-tank (the IPPR1), the World Bank and an Australian PPP taskforce (Partnerships Victoria) can be summed up as follows:

- Project selection as a best fit with the PPP model, is the key
- Negotiation and procurement capabilities at the end of public sector should be made stronger
- Greater transparency and competitiveness is essential for PPPs to work at their best
- PPPs are more suitable to projects and sectors with gradual pace of change
- Risk transfer should be meaningful, and yet realistic for successful PPPs
- There will always be a minimum and maximum viable size for PPPs to work successfully
- Focus should be given on achieving value for money and quality service delivery
- PPP model should be adopted looking into the prospect of long-term affordability, both for the users and the government
- Early involvement of financers and soliciting the market interest is essential
- Sourcing of long term funds should be encouraged
- Involvement of stakeholders, and specifically users should be made essential for a smooth and efficient working of the project
- Model should be flexible to adapt to changing requirements and adjustments during the long-term tenure of the projects

7. Suggested measures for improved use of PPPs

Some basic measures that can be adopted in utilization of PPPs are:-

- **The choice of a delivery model** should be systematically assessed quantitatively, along with qualitative assessment and should be aligned with the government objectives, policies and frameworks.
- **A well-structured consortium** should be formed at the private sector end, considering the specific characteristics of the project, and have an effective governance structure for communication.
- **Risk allocation** should take into account the nature of the PPP framework, project-specific characteristics and the maturity of PPP market, both for public and private sectors. Equitable allocation of risks may give us the desired success and results. Also, essential is the assessment of the government support towards risks.
- **Financial arrangements should be transparent and streamlined**; with substantial capital investment provision from the government; equity provision or debt financing.
- **Sound Business Case** should be developed through a thorough cost-benefit analysis, with considerable involvement of stakeholders.
- **Robust tendering and flexibility** in the bid should be required. Bids should be evaluated focusing on the private sector’s capabilities and efficiencies.
8. Discussion & concluding remarks

This paper evaluates experiences of various stakeholders, academicians and practitioners about the performance of PPPs, identifies performance parameters affecting the success of PPPs and recommends few measures for improving the utilization of PPPs (Birnie, 1999). This study is a beginning step towards a focused PPP intervention. More attention is required towards the definitions of PPP, data quality and consistency. There will also be more stakeholder involvement required right from project inception. Stakeholders, especially users will be more insightful towards the implications and acceptance of the completed project. Frameworks such as demand based PPPs must involve users in the project development.

It is essential to acknowledge some limitations of this research as well. Though the survey was focused on practitioners and stakeholders across the spectrum, it did not involve the users of the projects. Also, it raises concerns about the general applicability of the parameters identified in different sectors. It is difficult to generalize the operational performance of PPPs as that would greatly vary to project-specific characteristics. The research gives an insight into the practical considerations for authorities planning to initiate new PPP projects and paves the way for further research in sector-specific variations. Being faced by a strong public examination, well carved out service identification and value for money project assessment will be undertaken before moving ahead with a PPP model.

PPP in Housing

In spite of many propagated benefits of PPP, its rare utilization in social housing sector is still a concern. Almost all the participants showed a willingness towards the possibility of successful adoption of PPP framework in housing (Hearne, 2009). Housing is a user based service. An ever rising demand in housing, and a 24% increase in building stock from 2013 to 2023 (Database, 2014), gives us an excellent opportunity to explore the PPP application in housing. Also, The PPP European Market Update 2014 (EPEC, 2015) highlights very little investment (<€300 million) in housing compared to other sectors (exceeding €2000 million). This brings us to question why PPP is still not widely adopted in housing when PPPs show us the potential of providing an alternate mechanism for meeting the needs of an expanding population, with the constraints of affordability (Brown and Yates, 2012). Some of the recommended cases are Single Occupancy Room accommodation in Down Town East Vancouver, Canada or Hong Kong Real Estate Industry or many cases in UK (Source: Survey Analysis).

9. Further work

This research lays the foundation to further analyze if PPP delivers economic benefits for planning and building in housing sector. Housing is a key typology in our built environment. The concept of Public-Private Partnerships is relatively new in social housing and has been adopted in very few cases across the world (UN-HABITAT, 2011). The propagated benefits of PPP and its distance from the housing sector strongly motivates me to question its feasibility and acceptability in delivering efficiency in performance in housing projects. This is a universal challenge in front of us. There is a need to understand the varying performance parameters across the sectorial spectrum and study the influence on housing (Frank).
Identifying performance parameters in public-private partnerships: gauging the stakeholder perspective

Key cases from Europe will be examined and stakeholder interviews will be conducted to gain awareness of the market scenario. The impact of the identified parameters and key issues will be tested through sensitivity analysis. This will help us understand the parameters, their input-output dependency and their affordability implications. Monte Carlo simulation will be carried ahead for continual assessment of the impact factors and to quantitatively assess the overall uncertainties and risks. The robustness of the outputs of a statistical model such as Monte Carlo simulation is heavily reliant not only on the validity of the assumptions but also the inputs. The above analysis will aid in developing an optimized parametric model for Public-Private Partnerships based on economic influencing factors. This will potentially facilitate decision-making in determining benchmarks for major uncertainties, and testing feasibility across unused sectors. The results and analysis will be combined together in developing a kit of methods for application of Public Private Partnership in housing. The kit will propose types of PPP for housing with all the governing factors. It will further aid in choosing the right option and metrics for a specific project, include major project characteristics required for PPPs, policy and contractual guidelines, and have provisions for a graphical analysis tool. This will be validated through providing the kit back to the stakeholders and users who will be involved in the initial part of the study.

Acknowledgements

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Saving the past: new challenges for earthquake prone buildings in New Zealand

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**Abstract:** The challenges facing heritage buildings in New Zealand will become all the more significant if legislation to strengthen building code requirements for these buildings is enacted. The strengthening proposals particularly affect old buildings constructed in unreinforced brick masonry. Many of these are “home shop” buildings with home accommodation above the ground floor retail space. Some have heritage value. The proposed legislation will affect all parts of New Zealand, regardless of the particular region’s exposure to earthquake risk. The implications of the upgrade are significant, both for owners and for townscape to which they belong. If the cost puts the viability of the building at risk, the owner will be in a position where demolition is the only feasible option. This could have far reaching implications for the social and heritage wellbeing of many small towns within New Zealand. This paper will report on the submissions to the proposed legislation, particularly as they relate to small-scale unreinforced brick masonry buildings. It will highlight strategies from those submissions that have the potential to enhance the life of some of these buildings, particularly in low risk earthquake zones, without unduly compromising cost and safety considerations.

**Keywords:** Unreinforced masonry; earthquake-prone; buildings.

1. Background

Legislation in the form of The Building (Earthquake-prone Buildings) Amendment Bill 2013 was introduced into the New Zealand Parliament on 13th December 2013. The aim of the legislation was to improve methods of managing New Zealand’s stock of earthquake buildings. The legislation arose out of the recommendations of the Canterbury Earthquake Royal Commission (2012), an examining body assembled to examine the reasons for the collapsed buildings following the two earthquakes that rocked the city of Christchurch. Christchurch, New Zealand’s second most populated city, suffered two significant earthquakes across a six-month period. An earthquake of magnitude 7.1 struck on September 4th 2010, followed by another on the 11th February 2011, this time of magnitude 6.3. The February earthquake caused extensive damage across the city and was responsible for the deaths of some 185 people, mostly as a result of building collapse.
Buildings affected by the earthquake included many small, unreinforced masonry (URM) retail buildings commonly referred to as “home shop” or “house shop” buildings, the main focus of this paper. (Figure 1) This building typology, so called because the shop owners retailed their wares on the ground floor and lived with their families in the upstairs portion of the predominantly two-storey building, formed the backbone of the many urban streetscape settlements that grew up around the larger cities in New Zealand, mostly between the years 1880+ to the 1920-1930s. In Auckland for example, such centres as Ponsonby, Grey Lynn, Herne Bay, Dominion Rd, Mt Eden, Otahuhu and Papakura have URM home shop buildings still gracing the main streets. External construction was single or cavity brick construction, often with protruding parapets elaborately adorned. Floors were constructed of timber, with strip timber tongue and groove flooring. Access to the upper floor, where the owner and family lived, was by internal stair. (Figure 2)
The proposals, if they are as expected carried through into legislation, will have a significant impact on the heritage value of many small towns throughout New Zealand, especially in older communities where many buildings within the local shopping precinct are constructed in URM, and as such regarded as “earthquake-prone”.

2. Criticisms of existing earthquake policy

Whilst the present act requires Local Authorities to develop policies around earthquake-prone buildings, there is, according to the Ministry of Business Innovation and Employment (MBIE) Consultation Document, large discretion in the present system as to “how actively they identify and deal with these buildings.”

Individual local authorities have very different approaches to implementing current policy requirements. Some local authorities are not actively identifying earthquake-prone buildings or requiring building owners to deal with them. Other authorities have taken some action, but have given building owners very long timeframes to resolve problems. A number of authorities have taken strong action, including requiring higher strengthening than required by law. (Ministry of Business (A), 2012, p16)

The MBIE suggested some 15000-25000 buildings would fall into the earthquake-prone category but acknowledged this figure was a very broad estimate as only a few local authorities “can provide good data”. (Ministry of Business (A), 2012, p6)

Of the 66 local authorities, only 23 were able to provide any information on the number of earthquake-prone buildings in their districts, and much of the information received was incomplete. (Ministry of Business, 2012, p120)

The call for submissions brought a substantial response; with MBIE indicating over 530 submissions received. These were from a broad cross section of community life, including a significant 42% from members of the public. Refer Table 1. (Ministry of Business, (B), 2012)

<table>
<thead>
<tr>
<th>Stakeholder</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Individual</td>
<td>42%</td>
</tr>
<tr>
<td>Building Owners</td>
<td>18%</td>
</tr>
<tr>
<td>Local Government</td>
<td>10%</td>
</tr>
<tr>
<td>Architects and Engineers</td>
<td>10%</td>
</tr>
<tr>
<td>Others</td>
<td>20%</td>
</tr>
</tbody>
</table>

3. Risk analysis and time frames

The proposed legislation originally treated the whole of NZ as a uniform risk, with the upgrading of URM and earthquake-prone buildings required within a specified time frame (15 years) applied uniformly across the whole of New Zealand. This stance has since been changed with the MBIE document acknowledging the original proposal had met considerable resistance from submitters.

Submissions from the Auckland Council, the largest Territorial Authority in New Zealand, helped to change this stance. They were based on a risk analysis survey from GIS Science, a research consultancy
commissioned by the Auckland Council, which looked at the statistical probability of a significant earthquake and the likely costs, number of collapses, and number of deaths that could result. (Cousins et al, 2014)

GIS Science suggested the risk levels to life from an earthquake were for Auckland statistically very low, even for earthquakes with a return period of 500 years or more (0.002 annual probability), with the number of deaths in the Region from this return period estimated as 7, with 2 deaths within Auckland city itself. Auckland, the location of many URM buildings has, suggests the GIS report, rarely experienced even low-level earthquake shaking “since Europeans first settled there in the early 1800s and there appear to be no historical earthquake casualties”. The Modified Mercalli intensity (MMI), an indication of earthquake intensity, has never been exceeded in excess of MM6, with only occasionally localized intensities of MM4 and MM5 shaking, and one instance only of MM6 shaking in 1891 (the Waikato Heads earthquake), located some 50 km south of Auckland near the mouth of the Waikato river. (Cousins et al, 2014, p23)

As it stands, the legislation now acknowledges different time frames for different zones, with timeframes for assessment and strengthening varying between 15 and 35 years, depending upon the risk zone.

Figure 3 indicates the three earthquake risk zones, low, medium and high. Wellington (the capital) is within a high-risk zone (the Wellington fault bisects the southern part of the city), whilst Auckland, the largest city, is within a low-risk zone.

![NEW RISK ZONES FOR STRENGTHENING](image)

Figure 3: New EQ risk zones (source: NZ Herald, May 2015).

4. Barriers to revitalization and enhancement of heritage buildings

4.1. Excessive strengthening requirements

Whilst the time allowances have been eased, the requirement remains for URM and other earthquake prone buildings to be upgraded to a minimum of 34% of the NBS, regardless of the location of the building. This, suggests researchers such as Tailrisk Economics, effectively means the safety standard for
a building in Auckland (a low risk earthquake area) is about “three thousand times stronger than the one applied in Wellington (a high risk area). (Harrison et al, 2013) What is more, suggests the Tailrisk report, compliance with the minimum standard for Auckland will result in a cost in excess of three billion dollars, (Tailgate’s own report puts it as high as $10 billion) “but is expected to take 4,000 years to save a single life” (Harrison et al, 2013, p6). The report suggest that the definition of what constitutes an “earthquake-prone” building should be urgently revisited and based on evidence of risk and not graded according “to their estimated strength relative to the new building code”. (Harrison et al, 2013, p8)

Other submitters responding to the Consultative document also criticised the excessive life safety standard applied to earthquake prone buildings.

Smoking alone kills 20 times as many people each and every year as were killed in Christchurch. The total number of Kiwis killed by earthquake is one tenth of those killed by smoking and the same for obesity... (Ministry of Business, (B), 2012, p12)

4.2. Insurance and financial barriers

Submitters responding to the Consultation document documented concerns of considerable importance. Comments included concerns about the lack of insurance for such URM buildings impacting on the ability to obtain bank finance to upgrade, assuming of course the loan-to-value ratios support a loan in the first place. Where they do not, and in many small provincial areas with low value and low rent properties, that is the case, financial support is required. The Auckland Council’s submission recognised this dilemma and suggested that “bank loans be guaranteed for owners needing to upgrade buildings and for the cost of a seismic retrofit (just that component) be deemed ‘repairs and maintenance’ rather than ‘capital expenditure’ for tax purposes”. [Ministry of Business, (B) 2012, p18] No financial support has been offered to date; yet there are considerable penalties for non-compliance. These include a fine of up to $200,000 if the seismic work is not completed by the deadline and a fine of up to the same amount for failing to comply with safety requirements imposed by a territorial authority. Such an approach is certain to cause wholesale demolition of the home shop in provincial areas, where values are relatively low and financial and insurance costs outweigh rental benefit likely from any strengthening. In large centres such as Auckland, the costs benefits would be mixed. High value areas such as Ponsonby or Devonport with a degree of heritage protection may survive. Areas of lessor value, such as Dominion Rd or Papakura would see at the very least most of the structures removed for new construction.

Where territorial authority or other government support is not forthcoming, demolition is likely as the only viable course of action available.

5. Conclusion

The MBIE Summary of Submissions document indicated a broad level of support for the government making improvements to New Zealand’s earthquake prone system. There was a lack of support for the “one size fits all” approach to risk, especially in low risk areas such as Auckland. Additional research is needed to develop and test alternative compliance processes, similar to the risk matrix assessment process used to determine cladding profiles and capable of being used, at least for low and medium risk zones, by non-engineer professionals. The aim would be to secure these small-scaled heritage building in such a way that fixes the most dangerous parts of a building and allows it to “fail safely” in a significant earthquake, but by the same token limits upgrading costs to levels where on-going
occupation of these heritage structures continues to be viable. Deaths from persons trapped within URM buildings in the Christchurch earthquake numbered 4. Mortality from persons outside and killed by falling debris, on the other hand, numbered 35.

The...biggest risk to public safety in Whanganui is from bits of building falling into the street in the central business district. (Maslin, 2015)

Many of these home shop buildings are small and have very low occupancy rates. Given the long return periods for even MM6 and MM7 earthquakes in low risk areas such as Auckland, there is a case for limiting the strengthening upgrade to securing protruding or dangerous elements such as verandas and parapets, and strengthening the balance of the parts to enable a “fail safe” situation to result.

Local factors such as wind speed are already a part of the National Building Code. The wind speed for any proposed building varies depending upon location such as proximity to the sea, whether urban or rural (open ground), or in a hill (exposed) or valley (sheltered) situation. The Building Code also acknowledges variations in general wind speed for different parts of New Zealand, resulting in different levels of bracing requirements dependent on assessed risk. Why should not a similar process apply to earthquake risk? Whilst regional variation introduces complexity into legislation, a suggested approach that takes into account such factors for an area as seismicity, economic profile (high value, high rent versus low value and low rent), local heritage issues and the likely impact of the legislation on the local community should be worthy of further scrutiny.

Cladding options differ in new residential buildings dependant on a risk matrix that takes into account the severity of local conditions and the type and complexity of building being constructed. Why cannot similar factors be used to mitigate the time frames and strengthening requirements of URM buildings?

The Financial Amendment Bill No 3 gave limited support to homeowners in New Zealand forced to repair their homes due to their buildings leaking through no fault of their own. Why not a similar financial scheme for the owners of heritage valued URM buildings forced by legislation to strengthen their buildings to an arbitrary value of the NBS, regardless of its location?

Historic buildings will always be at risk suggests Hassler (2009) because modern land-use planning and regulations “regularly lead to considerable losses of historic substance in areas close to historic city centres because potential financial returns on future use are compared with the proceeds of a change of use of existing buildings.” If however Government policy means mass demolition of street heritage – which will happen here in the parts of New Zealand towns and cities if upgrade costs are too prohibitive and owners exercise their rights to demolish - the very attractiveness of a neighbourhood will be diminished, and with it, suggests Hassler, the potential returns associated with that same attractiveness. (Hassler, 2009)

References


Slender waste: reducing the girth of construction and demolition waste to landfill in Alice Springs

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Abstract: Construction and demolition (C&D) waste is a critical issue nationally where it forms more than one third of the total waste generated. Several town councils and other regulatory authorities have developed policies towards construction and demolition material recovery and resource efficiency. However, the situation with C&D waste is very different in the Northern Territory, especially in remote regional centres such as Alice Springs. Whereas metropolitan centres are now able to recycle 40% of the C&D waste, Alice Springs only manages to salvage 2%. This paper argues that there is need for context specific approaches to construction and demolition waste management in remote regional centres because of barriers arising out of the physicality of the location. To this extent, this paper aims to identify the current building waste streams in Alice Springs as well as understand the stakeholders’ behaviour towards reducing building waste.

Keywords: Construction and demolition waste, remote regional centres, Alice Springs.

1. Introduction

The construction industry is the fourth largest contributor to the Australian economy, accounting for 6.8% of its GDP in 2008-2009 (ABS, 2010b). It is the fourth largest employer after retail, health care and manufacturing. This industry impacts the environment enormously, consuming more raw materials and energy than other sectors and producing more waste. Construction and demolition (C&D) waste is a significant issue nationally since it forms 38% of the total waste generated (ABS, 2010a).

Waste generation demonstrates poor use of resources, including a waste of energy and water used for the extraction, production and transportation of the product. Additionally, landfills are known sources for greenhouse gas production such as methane, and redirecting waste materials from landfills would lead to a reduction in greenhouse gas production (Campbell, 2008). Internationally, efforts are aimed at reducing waste from going to landfill, thereby conserving natural resources, reducing the production of waste and recycling and reusing waste that is produced.

In Australia, research on C&D waste focuses on generating statewide data, with a concentration on cities. What is evident from the various reports on C&D waste is that there is very little baseline data
regarding C&D waste for regional towns such as Alice Springs. The low landfill levies and lack of implementation of waste management plans, leads to an absence of initiatives towards waste reduction and recycling. It is more cost effective for builders to dump building waste on an empty site on the outskirts of town than attempt to separate it on-site and recover the materials.

Since the construction industry is a labour intensive industry, in order to bring about any change in waste reduction practices, it is fundamental that construction industry stakeholders are part of this discussion. Stakeholders in decision making roles such as clients, architects, builders, planners, engineers, project managers as well as trades people are all critical to the success or failure of any waste management plan. Especially significant is the fact that their behaviour is conditioned by their attitudes towards waste reduction, their resistance to change, their need to conform to new social norms and their perception of the problem. Therefore, it is essential to understand the attitudes of the stakeholders in order to recommend effective models of regulations and incentives.

This paper argues the need for context specific research on C&D waste in remote regional towns such as Alice Springs. It suggests mapping the waste streams generated, as well as using Ajzen’s theory of planned behaviour as a framework for obtaining insights into stakeholder behaviour regarding reducing and recycling building waste.

2. The case of Alice Springs

Alice Springs, located in Central Australia, is the second largest population centre (28,000 approx) in the Northern Territory after Darwin. The largest industry sectors of this region are mining ($552 million), Construction ($313 million) and Health care and social assistance ($240 million) (NTG, 2013). The construction industry employs the fifth largest number of people after public administration, health, education and accommodation and food structures. In this context, it is critical to pay attention to the reduction of construction and demolition waste in Alice Springs. At the same time, the issues related to C&D waste in Alice Springs are very context specific.

The primary barrier to C&D waste management in Alice Springs, as well as the Northern Territory, is the lack of baseline waste data. The only available data is for waste in Darwin City Council. Moreover, there is no current policy for procurement of recycled materials. Although there is a strategic policy through which the Territory is aiming for a 50% reduction in waste to landfill by 2020, there is lack of clarity around what the current volume/tonnes reduction to landfill are. Thus making it difficult to actually measure the success of this policy (Hyder Consulting Pty Ltd, 2011).

In the case of regional towns, such as Alice Springs, the cost of transport of even virgin materials is considerable and raises the overall cost of construction. All building materials have to be freighted by road or railway to Alice Springs. Additionally, higher fuel prices in Central Australia add to the cost of the building materials as well as to the cost of running construction machinery (Szava et al., 2007).

Due to limited or no C&D waste recovered, the reused materials have very little market and must compete with virgin extracted material market. Recycling of materials is very different in Alice Springs because of its remoteness and lack of access to recycling centers. Unless there is a local market or a facility to recover C&D waste materials in the vicinity, the C&D waste is likely to be landfilled. As stated in the report by Hyder Consultants, “Materials tended to be transported to the closest site, whether this was a landfill or reprocessor, due to the expense of materials cartage and the relatively low value per tonne of recovered product” (Hyder Consulting Pty Ltd, 2011). The other generic challenges towards recycling in regional towns are lower landfill levies than cities, non-availability of re processors,
availability of private land for illegal dumping, assuming waste is a by-product of construction and therefore lack of awareness of waste reducing approaches.

A feasibility study done by the Alice Springs tip operators in 2006 identified barriers regarding overall waste (not specifically C&D Waste) as low resale price of recovered materials, high transport cost of carrying recyclables to recycling centers and lack of financial incentives at the regional scale (Bowerbird Enterprises Pty Ltd, 2006). Although the Northern Territory Government, Alice Springs Town Council, and NGO’s such as ALEC have initiated schemes to promote the reduction and recycling of domestic and commercial waste (Eloise, 2009), no initiatives have been taken to reduce the C&D waste. Since context specific research on C&D waste streams is lacking, it is difficult to suggest solutions towards reducing or recycling waste. This study aims to fill that gap. Therefore, not only is it fundamental to raise awareness about regarding C&D waste in Alice Springs it is even more important to address the apathy in the construction industry towards reducing waste.

3. Sources of waste generation

Waste streams from a building are generated throughout the life cycle of the building involving new construction, renovations and finally demolition.

![Figure 1: Waste generated during the lifecycle of a building. (source: Cochran and Townsend, 2010)](image)

For long, waste was regarded as something to be collected and disposed of. Now a fundamental shift is occurring where construction and demolition waste is seen as a resource that can be reused and recycled. Lehmann (2010) suggests that the material life-cycle loop need to be closed by transforming waste into a material resource. He urges to “move the focus to waste avoidance, behavioural change, and waste reduction”.

Construction waste has been defined by Ekanayake and Ofori (2004) as” any material apart from earth materials, which needed to be transported elsewhere from the construction site or used on the site itself other than the intended specific purpose of the project due to damage, excess or non-use or which cannot be used due to non-compliance with the specifications, or which is a by-product of the construction process.”

The waste produced ideally should be reduced, recycled or reused rather than thrown in the landfill. So how do we reduce this waste in the building sector? One of the best ways to reduce waste is to stop producing it (Ekanayake and Ofori, 2004; Osmani et al., 2006; Wang et al., 2014). The process of construction waste is a complex one involving several stakeholders, numerous materials and different construction technologies (Keys et al., 2000). In their research assessing building waste in Singapore, Ekanayake and Ofori (2004) sorted the source of waste production into four categories - design related,
operational related, material handling and procurement related. Research by Osmani et al. (2006) concludes that although one third of waste generated can possibly be attributed to design decisions, architects do not perceive waste reduction as a high priority. In fact the common perception is that waste is largely generated through on site operations and not design and planning stage decisions. The operational wastes are attributed to errors by trades people and laborers on site, damages to work done due to subsequent trades and required quantities unclear due to improper planning” (Ekanayake Ofori 2004). Inappropriate site storage and damages while transporting materials lead to wastes generated from material handling. In addition, ordering too much or too little materials are also a source of waste related to procurement.

Literature on building waste generation is mostly from countries such as Hong Kong, Singapore and UK and very little from Australia. Additionally very few researches have been carried out on understanding the stakeholders’ attitude and its impact on their approach to waste minimization. Examining waste reduction in Australia, Crowther (2014) argues for focusing on designing for disassembly where materials and components are separated from each other easily. Study by Teo and Loosemore (2001) investigates the attitudinal forces that shape behaviour of the site operators. The research, however, concludes that it is more critical to assess the attitude of the decision makers that are at managerial levels in the construction process. Lack of information on sources of waste in Alice Springs as well as attitude of professionals involved in the construction industry identifies the need for future investigations in this area.

The above mentioned sources of waste production are generic for cities and remote towns, but the difference between cities and remote towns lies in solutions targeted towards reuse and recycling of building waste.

4. Reusing and recycling building waste

Other ways of avoiding waste going to landfill is by reusing or recycling it. The primary considerations when reusing construction and demolition materials would be acceptance and demand in the market as well as their compliance of specifications. Reusing and recycling waste from construction and demolition can be very context specific. The issues of C&D waste in smaller regional or remote towns can be quite different from those in cities. In order for any waste management plan to be implemented, it is critical to map the waste streams generated. Sorting of waste into categories such as demolition materials, wood, concrete, asphalt, plastic, metal, packaging materials, glass and others allows the adoption of specific techniques in dealing with each type of waste effectively (Shen et al., 2004)

A study conducted into the C&D waste markets in Perth Metropolitan areas revealed that the C&D recovered markets have to compete with the virgin extracted material industry (Edge Environment Pty Ltd, 2012). The construction market requires basic raw materials for construction activities. If the recycled materials are comparable in cost and quality then they can be readily used. Construction companies cite “materials cost, transport costs, specifications and usability” as the key parameters in the use of any construction material (Cardno, 2008). The virgin extraction of materials is successful because there is economy of scale there which implies that the industry generates large volumes of materials with efficient machinery thereby reducing the cost of the product. It is observed that massive materials such as concrete, asphalt and bricks have higher recycling rates in cities since these materials are heavy and cost more to dispose at landfill. Additionally, the technology to reuse concrete, bricks and asphalt is uncomplicated and well established. Crushed concrete and bricks are in sub bases for roads and pavement, replacing virgin crushed rock (Edge Environment Pty Ltd, 2012). The high landfill costs in
cities such as Melbourne and Sydney, act as deterrents when disposing heavy materials. Adelaide not only has high landfill levies but also prohibits dumping of unsorted materials in landfills which further encourages recovery of materials (Hyder Consulting Pty Ltd, 2011). Although Perth increased the landfill rates, the site operators in some cases have absorbed the difference and it does not reflect as an increase in levy.

In absence of cost being competitive, the markets for recovered or recycled materials can be expanded if the governments pushes uptake of the diverted materials through appropriate legislation and polices.

5. The role of government in reducing of C&D waste to landfill

While the government’s intention is to encourage C&D waste reduction to landfill, there has been little organised effort in Australia to facilitate this. In contrast, several European countries demonstrate best practice examples by achieving very high rates of C&D waste recycling. Although the EU has no specific legislation for the disposal of C&D waste, certain directives have helped to reduce the waste going to landfill. Firstly they have suggestions on using excavated soil which constitutes a large percentage of the C&D waste. Secondly the directives provide goals for C&D waste which led to initiatives on C&D waste recycling (Malia et al., 2013). Regulations such as pre-separation and high landfill levies are the other policy mechanisms that have had a significant impact on waste management and in some extent to increase recycling of CDW (Poon et al., 2003; Rocha and Sattler, 2009; Michael Hiete, 2011; Poon et al., 2013).

In the UK, the Landfill Tax is the main legislative tool used to support an increase in recycling and to even promote reduction of waste production through design (Sassi, 2004). Denmark is cited as the success story for achieving a 92% recycling rate for construction and demolition waste (Danish Environmental Protection Agency, 1999). The two instruments for achieving this high ratio in Denmark are: state tax on non-recycled waste and ‘agreement with Danish Contractors’ Association on selective demolition of building materials which aided pre-separation of materials (Montecinos and Holda, 2006). Similarly, the Netherlands achieved its goal of recycling 90% its C&D waste by 1990 in 1999 and since then has aimed to achieve 95% recycling of waste produced (European Topic Center on Sustainable Cosumption and Production, 2008). Germany produces the most C&D waste in Europe but also recycles or reuses 85% of this waste (Weisleder and Nasseri, 2006). The Construction and Waste Disposal Charging scheme (CWDCS) in Hong Kong has also had a large impact in terms of reducing the construction waste both on site and in landfill sites (Lu and Tam, 2013).

However the situation is more ambiguous in Australia with states and local councils responsible for regulation of waste. The National Waste Policy, (DEWHA, 2009) which sets the direction for Australia for the next ten years aims to support development of best practice across all states and territories. With regard to C&D waste, Strategy 11 in the National Waste policy states, “All governments continue to encourage best practice waste management and resource recovery for construction and demolition projects.” With the current rate of recovery of C&D waste at 55% (2008-2009) (Hyder Consulting Pty Ltd, 2011), Australia has a long way to go before it catches up with the C&D reduction targets of other developed countries. Although Western Australia, South Australia, Victoria, New South Wales and Canberra have put in successful measures to recover C&D waste materials, Tasmania and Northern Territory are far behind, with even baseline data regarding C&D waste being unavailable.
6. Using theory of planned behaviour as a framework for understanding behaviour of stakeholders

Maloney and Ward (1973) argue environmental problems cannot be solved by technology but need change of behaviour. Environmental issues such as waste reduction and recycling issues, therefore, need to be addressed by first understanding human attitudes towards waste and then attempting solutions through regulations, incentives and education. Maycox (2003) in his seminal paper demonstrates that understanding behaviour is the key to the success of any solid waste management program. The outcomes from Maycox’s three year study demonstrates research design based on well-researched cognitive psychology can lead to significant waste reductions. Often projects encouraging waste reduction are not successful due to lack of any theoretical underpinning of the research design (Barr et al., 2001; Tonglet et al., 2004).

Ajzen’s Theory of Planned Behaviour (Ajzen, 1993) can provide a cognitive framework to understand and explain behaviour and to get insights into factors that underpin stakeholders’ behaviour towards waste reduction. The Theory of Planned Behaviour (TPB) has been widely tested, providing new insights into range of factor’s influencing people’s behaviour in an environmental context such as recycling behaviour and green marketing (Taylor and Todd, 1995; Chan, 1998; Harland et al., 1999; Teo and Loosemore, 2001).

The theory which developed from the earlier Theory of Reasoned Action (Ajzen and Fishbein, 1980), assumes that people have a rational basis for their behaviour, in that they consider the implications of their actions. It considers three aspects of influencing behavioural intentions - attitude, subjective norms and perceived control. The attitudinal behaviour is predicated on a person’s evaluation of a certain type of behaviour and is based on personal beliefs or knowledge of the outcomes of it. It could be based on, for example, a positive experience of working on a project that had successfully implemented a waste reduction plan. The second aspect is the social norms which are an individual’s perception of the social pressure to perform or not to perform certain behaviour. The third is perceived control, which refers to an individual’s perception of his/her ability to perform or not perform that behaviour. This reflects past experiences as well as anticipated obstacles in doing so.

This project builds upon the work done by Teo and Loosemore (2001) investigating attitudinal forces that shape behaviour at the operations level in the construction industry using the framework of TPB. Their study only took into account the attitude of the operational staff and identified the importance of examining attitudes of other groups for achieving higher rates of waste reduction and recycling. Therefore, this study concentrates on understanding the attitude of a range of stakeholders from the building industry towards decreasing volumes of C&D waste going to landfill.
The aim in this research is not to test Ajzen’s theory of planned behaviour but using it as a framework for revealing operative’s beliefs and perceptions of difficulty or ease towards building waste recycling. This would provide a rigorous set of evaluation criteria to determine the individual’s knowledge base and awareness of their role in the waste generation process and what they consider impediments to effective adoption of waste management strategies.

As Stern (2000) explains that there needs to be a combination of interventions for any behaviour change. There is a need for combination of incentives and information for achieving successful outcomes. He gives the example of investment in home insulation. “To promote investments in home insulation, for example, it is necessary to reduce the financial barriers, provide accurate information on which actions would be effective, and reduce the difficulty of getting the information and finding a reliable contractor. Programs that did all these things were vastly more successful than programs that only did one or two.” (Stern, 2000)

7. Research design

The aim of my project was to identify context specific approaches towards recycling and reducing waste in Alice Springs. These approaches are examined under two categories- how the remote location of Alice Springs is impacting efficient recycling of various streams of building waste and the other is the attitude of the stakeholders within the building industry towards building waste recycling.

A two fold qualitative research approach was adopted for this study. First, a thorough literature review was adopted to obtain insight into the waste minimization and recycling debate in construction as well as assessing the role of stakeholders in improving waste reduction. Secondly, 22 semi structured interviews were scheduled to be conducted with professionals related to the building industry as well as those involved in recycling building waste. The stakeholders selected were from the following categories; Builders (10), plumbers (2), electrical contractors (2), civil work contractors (2), recyclers and landfill operators (6). The building related participants were randomly selected from the yellow pages. It was decided to use interviews rather than postal survey since the participants were more likely to spend 20 minutes answering questions than filling in a survey and posting it back. Also since Alice
Springs is a small town (25,186 population), it is easy to get introductions and to organise meeting times for interviews.

The interview questions are designed to map waste streams generated, examine reasons for low level of building waste recycling and get insights into attitude of stakeholders towards waste. The interview questions were tested in a pilot study to ensure ease of understanding and clarity.

The first set of questions related to identifying the waste streams generated and their disposal methods during the construction of buildings in Alice Springs. The next set of questions contained questions on recycling attitudes, perception of social pressure to recycle waste and factors which may facilitate or inhibit recycling behaviour. Most attitudinal surveys are usually conducted through a Likert-type scale for questions. However in this case, since the target population is small, open ended questions gauging stakeholders attitude were included within the interview questions. The focus was on getting insights into behaviour rather than making generalizations.

The analysis will consist of using the collected data to map the existing flow of waste building materials from the construction site. This would identify different waste management practices prevalent and types of waste. This information is essential before any recommendations leading to increased recycling are made. The second set of analysis will use the data collected relating to stakeholders attitudes towards building waste. This data will be categorised into themes that emerge from the interviews.

The interviews will be carried out in October and November 2015 and the preliminary results will be presented at the time of conference in December, 2015.

7. Conclusions

In this paper, the primary argument is that solutions regarding C&D waste cannot be generalised to cities and regional centres alike. Cities have the critical mass of recycled materials along with a demand for recovered products. Regional centres suffer a disadvantage because of small population and distances from major recycling centres. The cost of transporting virgin materials to remote regional centres adds to the cost of construction considerably and can be resolved to an extent if the C&D waste is managed efficiently and recovered in sufficient quantities to supply to the local market. The other major deterrent to recycling and reducing C&D waste are the low tip fees and available land on the periphery of towns. If the tip fees are increased marginally, there is an increase in illegal dumping in the bush or on vacant lands rather than more efficient on-site waste sorting or increase in recycling.

Often stakeholders do not realize that waste management can be a cost saving measure. There is a lack of awareness of waste generated at the design stage or how a life cycle waste can be minimized by designing for disassembly. The town councils are unaware that not providing specifications for reused materials can be a deterrent for recycling as well as not setting specific targets for waste reduction. Until perceived obstacles are not identified, it is difficult to suggest specific solutions. It is this situation that the theory of planned behaviour can help get insights into. Results from a research using theory of planned behaviour can then help formulating effective policies and incentives for waste reduction which are context specific.
Acknowledgments

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References


Abstract: A majority of universities occupy expensive campuses that incorporate outdated designs and low utilization rates while campus users can conduct working and learning activities from a distance. For instance, Massive Open Online Courses and totally virtual universities allow self-education virtually free of charge. In this complex environment, campus managers face a strategic alignment problem between supporting research, education and societal impact. Strategic alignment in corporate real estate is an act of aligning the services with the core business. To outline the dynamic conditions of campus management processes, this paper explores two cases in the University of Melbourne main campus. It aims to answer: 1) What kinds of challenges does campus management encounter in strategic alignment? and 2) How do the explored cases aim to tackle the challenges? The literature overview discusses strategic alignment. Thereafter, ten campus management organization interviews are reported based on analysis in a qualitative research analysis software Atlas.ti. Conceptual guidelines of strategic alignment are drawn. University campus process challenges can be tackled by, for example: real time Big data of built environment for future foresight; Integrated services for economical paucity; Cross-pollination for institutional sharing; and Open access to information services for functional flexibility.

Keywords: Campus management process; added value; new ways of working and learning.

1. Introduction

Share of private expenditure for universities is increasing globally (Van Damme 2012) and competition between universities is tightening (Barnett, 2013; Poon and Brownlow 2015). Consequently, universities are increasingly run like highly branded market-driven businesses rather than guild-like institutions (Bernasconi, 2013; Drori, 2013; Levy 2013). Multiple scholars play with future university scenarios ranging from absolute meltdown through virtually open mass-learning to traditional elite ivory tower visions (Maassen et al., 2012; Den Heijer, 2011; Tapio et al., 2011).
New ways of working and learning are affecting the ways in which facilities are used and designed as these actions are disseminated around city structures and scattered in online environments. Totally virtual universities are also emerging allowing anyone to educate themselves virtually either free of charge or with a clearly smaller cost than accompanying a physically-based education (Lambert and Carter, 2013; Carr, 2012; Evans et al., 2013).

The changing environment and pressure to be highly ranked globally leave campus managers with a strategic alignment problem. Strategic alignment in real estate can be seen as an act of aligning the services with the core business of an organization (Heywood and Kenley, 2013). In between the university management strategies, school, faculty and user demands, campus managers need to facilitate a variety of internal and external stakeholders.

Earlier research on university campus management suggests that business models and processes have a core role in regards to the resulting campus (Rytkönen et al., 2015; Rytkönen, 2015). As units of analyses, business models and processes interlink the strategic and the operational levels of an organization which argues for the rationale of applying them in strategic alignment. To outline the challenges of this complex decision making act, this paper reports on two cases in the University of Melbourne Parkville campus: a faculty-specific building project and a thematic collaborative building project. It reflects on ten thematic semi-structured interviews conducted with campus management professionals from operational, tactical and strategic organizational levels.

First, the literature overview outlines the decision-making field from the strategic alignment aspect of campus management. Second, the methodology chapter explains the qualitative methodology, data collection and analysis. Third, the results are introduced. Fourth, the limitations and implications are discussed. Finally, the concluding chapter highlights the main message of the study.

2. Literature Overview

Jensen (2011) argues that while core business should add value to external customers, Facilities Management (FM) must create value for internal customers by supporting the core business. Accordingly, Corporate Real Estate Management (CREM) should be conceived as an act to align the services with the core business of an organization (Heywood and Kenley, 2013; Dewulf et al., 2000).

Facilities form the second largest cost of universities after HR ranging between 5-15% in Europe (Den Heijer and Zovlas, 2014) and around 20% in Australia (AAPPA, 2000). Multiple studies indicate that university facilities have high vacancy but utilization rates as low as 20-40%, for example, SMG, 2008; OECD, 2012; University Herald, 2013; Neary et al., 2010; Harrison and Les Hutton, 2014. On the other hand, the majority of university facilities in Europe, for example, were built in the 1960s and the 1970s and appear in poor technical conditions with outdated designs (Den Heijer and Zovlas, 2014).

Kamarazaly et al. (2013) concluded that inadequate funding is the toughest challenge university facilities managers face in Australasian universities. A shortcut to economically viable pedagogical arrangements is arranging part of the education virtually which some scholars perceive to decrease pedagogical quality and others as a huge opportunity. Yet, even though the costs of the education are seen as a major attraction factor of the virtual experiments (Cheung, 2013), White (2013), for instance, suggests their biggest potential lies in flexible access, tailor-made education curriculum and lifelong learning possibilities.

Universities are interested in Massive Open Online Courses (MOOCs) as R&D platforms for pedagogical experiments and data gatherers. Wappett (2013) sees two fundamentally different
demographics taking part in educational activities – on the one hand the diploma-seekers who tend to be mid-20s and need their diploma to conduct their career, and on the other hand the lifelong learners who are interested in the subject and self-education but do not emphasize the value of the diploma. MOOCs seem to provide flexibly accessible knowledge for professionals on-demand, which is different from the diploma-seekers who prioritize the value of the degree and need a certification to conduct their career. (Wappett, 2013)

Alongside multiple other stakeholders, students are a focal representative group of the demand side of Corporate Real Estate (CRE) practices in universities. The major decision rulers when students search their future university are: programs, student satisfaction, teaching quality, tuition fees and university rankings (Go8, 2014; Poon and Brownlow, 2015; Price et al. 2003). Especially international students are charged increasing tuition fees (Margison, 2007; OECD, 2012; Wilkins et al, 2013; Dunnett et al., 2012) an increasing part of which is allocated to university supportive services and facilities (Maassen and Stensaker, 2015).

At the same time, university management aims for high rankings to attract students, which requires focus on research activities. The time per student by an academic staff member is steadily decreasing due to constantly growing student intakes (De Vries et al., 2008; Larkins, 2015) and proportionally smaller increase in academic staff numbers (Maassen and Stensaker, 2015). The value of a degree is dropping due to larger student intakes, while tuition fees are growing (OECD, 2011; 2012). Universities have been criticized of becoming increasingly research-intensive with less emphases on education and societal impact (Barnett, 2013; Berner, 2015) even though they are increasingly funded by the students either straight or later in forms of taxes (Maassen and Stensaker, 2015; Larkins 2015). The funding systems can be divided in three main categories in OECD countries usually dictated by national legislation: high-tuition fee –, progressive tax – and low tuition fee –based model (OECD, 2012).

We can simplify the challenges that university campus managers encounter in strategic alignment under organizational levels of strategic, tactical and operational as described in Table 1.

Table 1: The challenges in strategic alignment from campus manager perspective according to reviewed literature.

<table>
<thead>
<tr>
<th>Level</th>
<th>Decision rulers from student perspective.</th>
<th>Challenges from campus manager perspective.</th>
<th>Challenges from university management perspective.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategic</td>
<td>University rankings vs costs of education vs value of a degree.</td>
<td>MOOCs and virtual universities vs increasing demands vs inadequate funding.</td>
<td>Attract talents vs aim for high rankings vs funding systems dictated by legislation.</td>
</tr>
<tr>
<td>Tactical</td>
<td>Programs and courses.</td>
<td>How to facilitate programs and courses while adding value to education, research and societal impact?</td>
<td>Synergies and balance between core tasks.</td>
</tr>
<tr>
<td>Operational</td>
<td>Satisfaction and teaching quality.</td>
<td>Ineffective campus utilization and outdated campus design, poor technical building condition, requirements for investments.</td>
<td>Level of pedagogy, number of students, number of staff.</td>
</tr>
</tbody>
</table>

The reviewed literature has not touched the tactical level of campus management organization which links the operational and strategic levels, and the tactical student and university management
Tackling the challenges of university campus management processes

The analyses of the interviews focus on identifying first, the challenges, and second, how the processes of the state-of-the-art case projects try to tackle the identified challenges.

3. Method

This paper employs a qualitative case study with embedded units approach as described by Yin (2009). We consider this method valid, because we are particularly interested in not only examining phenomena in university campus management processes in one context but between two sub-cases which follows the description of the method by Baxter and Jack (2008). The applied research instrument is semi-structured thematic interviews.

3.1. Case Selection

The two cases explored were selected based on four criteria:

- They are located in the same campus and are initiated and managed by the same university;
- They have been recently developed representing the state of the art of university facilities;
- They can be assumed to differ in terms of their processes due to the nature of the cases; and
- They both aim to facilitate interdisciplinary collaboration.

The selected cases are the new development for the University of Melbourne School of Design (MSD), Faculty of Architecture, Building and Planning which has the faculty and the university as tenants, and the Carlton Connect Initiative which aims to attract multiple tenants from university, public, government and industries to encourage collaboration and drive innovation.

The MSD building, covering an area of 14,320 square meters, replaced a poor-condition 1960’s-built building. In the end, the entire project cost 129 million $AUD. First and foremost it was designed as a new home for the MSD promoting interdisciplinary collaboration between the MSD’s disciplines, and a place for meeting and working for the whole university community in the centre of the Parkville campus.

The Carlton Connect Initiative occupies an old hospital building covering an area of about 50,000 square meters located on the eastern edge of the campus along a major street in Melbourne. The building is being planned, updated and retrofitted step-by-step during of this study, and the aim of the project is to facilitate problem solving of major sustainability challenges of our times through encouraging cross-organizational and interdisciplinary collaboration.

3.2. Informant selection

The informants were initially selected based on their occupation in the university campus management organization on three levels: operational, tactical and strategic. Students and university management were not interviewed because this paper focuses on exploration of the challenges that the campus managers encounter in their processes. A snowball approach was applied meaning that the initial informants were allowed to suggest other informants to be interviewed.

3.3. Interviews

The interviews were semi-structured and divided into three themes: General questions on the present and future of university campuses; Business models; and Management processes. The general questions
handled a larger perspective of campuses in general whereas the business model and the process questions were targeted to a specific case that the informant had been involved in.

3.4. Analyses

The interviews were transcribed and uploaded into the qualitative analysis program Atlas.ti. The aim of the analyses was to understand first the main challenges of campus management, and second how the two projects tackle the challenges.

Each interview was analyzed without formal lenses allowing the evidence to emerge from the data resulting in 106 codes. The most often referred codes were taken into a closer examination and integrated with alike codes that were referred to more seldom. They were then clustered into major challenges that the campus management organization faces in its work resulting in four interlinked thematic entities of Future foresight (42 codes), Institutional sharing (38 codes), Economical paucity (32 codes) and Functional flexibility (30 codes). The challenge clusters were then observed from strategic, tactical and operational levels of the management organization.

4. Results

The results of the analyses suggest that the major challenges can be clustered under four interlinked themes as illustrated in Figure 1: Future foresight, Economical paucity, Institutional sharing, and Functional flexibility. The social interaction of the university community was seen to be the focal aim to be supported with physical and virtual environments as a result of campus management processes.

Figure 1: The challenge field of university campus management processes.

Foresight was seen as a challenge because the very moment a building is completed, it is a product of the past no matter how future-oriented the development process has been. Economical challenges arose from inadequate monetary resources which some informants suggested to be tackled by taking a
wider portfolio approach to assets in the long-term combined with a short-term view on execution in a minor scale.

_institutionally_ speaking, the organizational structures and discipline-specific projects were seen to create barriers for sharing and collaboration between units. On the contrary, identity building through placemaking was seen as a very important means of engaging students with the faculty. The trade-off was considered problematic because barriers between disciplines maintain low utilization but high occupancy rates. Then again, inviting the whole university community in by effective building design and shared spaces was seen as a potential way for improved utilization.

The main _functional_ challenges related to designing for flexibility in an ever-changing university organization in both virtual and physical environments. Virtual environments were seen as only a supporting layer of the face-to-face pedagogies and as a way of reaching a totally different student market who were not after a certification but rather interested in continuous life-long learning. However, the evolving virtual pedagogies were increasingly seen to affect campus and building designs – the curriculum must be matched with activities most suitable for virtual and physical formats. The main means of tackling the identified challenges are listed in Table 2 and practical guidelines visualized in Figure 2.

| Table 2: The ways of tackling the challenges in the studied cases based on the interviews. |
|---------------------------------------------------------------|-----------------|-----------------|-----------------|
| **Challenge** | **Carlton Connect Initiative** | **MSD** |
| **Strategic** | **Future foresight** | How to foresee what will be needed in the future? |
| Strategic framework | Step by step experimentation and iteration | Bottom-up activity creation |
| Constant development | Strategic campus framework | Strategic campus framework |
| Process linked to intellectual capital of the unit | Placemaking | Top-down collaborative planning |
| **Tactical** | **Economical paucity** | How to get enough money to do all that is needed in a limited amount of time? |
| Renovating the old considered more viable economically | Attracting tenants from the outside |
| Monetary incentives to seed-fund collaborative research | Fund raising and donations |
| Facilitating emerging action step-by-step | Faculty and university funding |
| Careful financial planning | Short-term sacrifice for long-term advantage |
| **Institutional sharing** | How to arrange the organization to utilize the assets effectively? |
| Thematic cohesion of multiple stakeholders | Inviting in industry, government and municipalities |
| Recruiting platform | Exhibitions and event |
| Sharing spaces | Placemaking |
| Events | Focal location |
| Highly visible building | Shared spaces |
| Encouraging bottom-up research | Design for people flow |
5. Discussion

Seemingly, the major challenges incorporated in university campus processes can be tackled by: collecting and sharing real time *Big data of the built environment* for future insight; providing user organisations with *Integrated services* for economical paucity; encouraging *Cross-pollination* for institutional sharing regarding the variety of learner, worker and community types with differing and similar demands; and providing *Open access* for functional flexibility regarding information and infrastructure services.

These challenges call for more interlinked and cross-disciplinary approaches than the existing university campus management literature suggests, for example, Den Heijer (2011), and Den Heijer and Zovlas (2014). In order to effectively manage the built environment and foresee the demands of the future, the management focus needs to shift from managing quantifiable empty facilities walls, roofs...
and floors towards facilitating the user communities that act inside the facilities. As the users act increasingly in both virtual and physical environments and have greater decision power over the ways in which they learn and work the best, effective campus management becomes increasingly complex and tailored. Therefore, real time Big data on space use patterns need to be collected, shared, followed and analysed to create evolving standards on the go.

Because of Economical paucity, which was also identified as a focal challenge by Kamarazaly et al. (2013), the results suggest a holistic portfolio approach to the campus as a series of precincts rather than a single building approach. As discussed by Den Heijer (2011) assessing the existing assets is crucial before commencing with new projects but the whole campus should be considered as a pool of potential assets. Economical paucity also calls for collaborative business models.

Regarding Institutional sharing and Functional flexibility, the tactical level of campus management gains more importance through potential of shared use and externally accessible facilities. Spatial standards that define ‘right’ amounts of allocated space per a student of a faculty, such as AAPPA (2000) are losing their relevancy as spatial management tools. However, tackling the institutional sharing challenges require more proactivity from the users, and a more supportive, dynamic and agile approach from the campus management, administration and information systems of the university. The campuses that embrace shared use designs and cross-pollination call for an integrated approach of HR, Communications, IT, Real Estate and other services which is similar to what Joroff (2002) and Materna (2007) suggest for corporations.

This research is based on a preliminary literature overview and 10 thematic semi-structured interviews on two cases. Due to the small amount of interviews in just one organization, the validity of the results is limited. The interviewees represent the internal organization of only one university which might result in bias regarding the reliability of the data. Further research should compare the findings with similar national and international cases under different circumstances to increase the reliability of the results.

6. Conclusions

Campus management is a complex decision-making act during the process of which user activities and clients’ strategic aims are aligned and implemented to support working, learning and living in physical and virtual environments. The process outcome affects multiple stakeholders who contribute to and demand from the project. This study suggests that the major challenges incorporated with university campus processes can be tackled by: collecting and sharing real time Big data in the built environment for future insight; providing user organisations with Integrated services for economical paucity; encouraging Cross-pollination for institutional sharing regarding the variety of learner, worker and community types with differing and similar demands; and providing Open access for functional flexibility regarding information and infrastructure services.

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Design Education and Design Research
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Built pedagogy and architectural design in the architecture library of the Melbourne School of Design

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Abstract: The Melbourne School of Design (MSD) located at the University of Melbourne’s Parkville campus aspires to be a ‘pedagogical building’, with built-pedagogy a driving aspiration behind its design and construction. This paper reviews one programmatic component of the building, the library, and how notions of built-pedagogy were interpreted by the user-group and the project design and management team in the design of the library as one of the key learning spaces in the building. It investigates the nature of current thinking about tertiary education learning spaces and their design from the perspective of those tasked with delivering the Architecture Building and Planning Library as a response to the understanding of built pedagogy developed by the design team, project managers, and library management. It suggests that the notion of built pedagogy contains multiple interpretations, influenced by current tertiary education shifts towards student-centred pedagogic practice, consideration of campus spaces within their social settings and the facility for buildings to engage as reference exemplars in teaching and learning which is generating opportunities for campus-centred student experience within increasing availability of online and digitally enabled education.

Keywords: Built pedagogy, library design

1. Introduction

In November, 2014 the Melbourne School of Design (MSD) located at the Parkville campus of the University of Melbourne opened its new building to house the Faculty of Architecture, Building and Planning. The building, as articulated in the initial international architectural competition brief, aspired to be a ‘pedagogical building’, with built pedagogy as a driving aspiration behind its design and construction (Faculty of Architecture Building and Planning and University of Melbourne, 2009). The library component of the MSD building provides an interesting study for investigation as programmatically and organisationally it operates independently from the Faculty whilst directly supporting it. Embedded within a purpose-designed faculty building, it offers, therefore, a case study for a point-in-time investigation of the translation of pedagogic strategies into tertiary education facility
design from an institutional level, current library design responses to support teaching and learning and in this case, by being embedded within a Faculty building dedicated to built-environment education, consideration on the role this played in forming its final design. It also offers a format by which one can investigate user and designer reflections on the understanding of built pedagogy and how these may be interpreted in the built form. Implicit in the use of the term by its inclusion in the competition brief is the notion that buildings have the capacity to convey meaning. This idea has been much debated in architectural discourse (Weber, 1984; Eco, 1997) and the framework for this paper lies in the use of the term as applied in tertiary education and libraries in particular.

The Architecture, Building and Planning (ABP) Library housed within the MSD building presents a germane microcosm for investigation into the question of built pedagogy and how this unfolded in the most recent development of a new building in the centre of the University of Melbourne’s Parkville campus. It has been argued that libraries play a part in aligning with institutional goals and outcomes (Matthews and Walton, 2014), with the advent of a “learning landscape”, which places the library in a holistic model of campus-level interaction (Appleton, et al 2011).

Monahan (2002) and Oblinger (2006) speak about the role of built-environment design in communicating institutional educational approaches and the capacity of space to influence how one teaches, defining this as built pedagogy. Academic library learning space attributes have been discussed in related research (Bailin, 2011; Cunningham and Tabur, 2012; Delaney and Bates 2014) with a great deal of literature directed to the pedagogical drivers of change in library design and the impact of socially constructed learning on library space requirements and design (Beard and Dale, 2008; Chan and Spodick, 2014; Gayton, 2008; Matthews and Walton, 2014). Fisher (2005a) outlines a rubric for linking pedagogical activities to spatial qualities and types. Little research has been undertaken, however, in how such literature and discussion has been interpreted and utilized by design and project delivery teams in new campus facilities. This paper aims to tease out how the notion of built pedagogy was interpreted by the design team and user group involved in the design of the ABP Library.

2. Methodology

To discover how the design process and aspirations were interpreted and implemented, a qualitative research method was adopted by undertaking a series of interviews with design professionals, project managers and library management. Qualitative methods were particularly useful in this research, as such analysis allowed for a deep level of engagement with the issues being investigated, uncovered the varying perspectives of the participants and allowed for the validation of themes from multiple sources who had a role in shaping how the building project evolved (Merriam, 2014).

Using a qualitative research methodology of in-depth open-ended interviews, two members of the research team participated in all interviews. Participants were selected due to their involvement either in the brief formulation process, the design development stages or project delivery stages, an equal weighting of interviews were given to represent the end-user group and architects. A total of thirteen interviews were undertaken, representing six members of the architectural briefing and design team and six members who represented the client end-user group, one representative of the project management team was also interviewed. All participants were asked the same series of open-ended questions which covered individual’s perceptions of the key factors that inform library design, precedence study undertaken, the role of library professionals in the architectural design process, formulation and interpretation of the design brief, libraries role in pedagogic practice and the lessons learned for process and library design outcomes. All interviews were recorded and transcribed, with the
transcriptions analysed following qualitative methods of analytical induction through a process of coding and thematic analysis that involved the entire research team (Corbin and Strauss, 2008). This permitted comparative investigation, regarding professional perspectives and interpretations of the language used in the aspirations for the building, as well as the approach taken in the methods adopted in formulating a design response for the project - especially as it related to pedagogy - within the contexts of built environment, project management and librarianship.

3. A pedagogical building and the pedagogical framework

The planning and design of the building and its library coincided with a critical and significant change for the University of Melbourne. The introduction in 2005 of the Growing Esteem strategic plan proposed significant changes in pedagogic strategy in undergraduate course structures, the establishment of graduate schools and a focus on the on-campus experience of students (University of Melbourne, 2005). A ten-year strategic plan, by Dr Kenn Fisher, drafted in 2005 for University of Melbourne libraries, coincided with the changes proposed by Growing Esteem (Fisher, 2005b). Fisher identified changing teaching modalities and the demand for flexible library spaces responsive to digital resource access as drivers for change in library service provision. Libraries had an opportunity to be defined in terms of broader educational and social space provisioning rather than information transaction exchange (Fisher, 2005a). The further refinement in the University of Melbourne Plan 2008, saw the establishment of an Information Futures Commission with the mandate to examine information management and systems and develop a ten-year strategy, known as the Melbourne’s Scholarly Information Future: a ten-year strategy to enhance learning and library precincts.

The Plan identified a new building for the Faculty of Architecture, Building and Planning as a major priority in the provision of new facilities (University of Melbourne, 2008). In concord with these strategic directions, was the 2008 commissioning of a new campus master plan drafted by architect Daryl Jackson to guide development of the Parkville campus. This document articulates the learning approach to be taken by the University in terms of the built-environment towards “a student-centred model”, emphasising the “on-campus experience for students” accompanied by consolidated infrastructure support (Jackson, 2008). To advise and shepherd the development of future student spaces throughout the campus Associate Professor Peter Jamieson was appointed as Strategic Advisor on Learning Environments Design in 2009 operating within the Office of the Provost. The architects identified this role as being an important one in providing input across a range of design responses ranging from space planning to the detail of furniture type that was consistent with overall University built-environment design approaches across campus.

Jamieson (2013, p.145) argues that the role of the library has expanded with the adoption of constructivist pedagogies. He posits that universities have so far been largely unsuccessful in providing informal learning spaces, and that libraries have stepped into the breach to be “critical source[s] of space for student learning”. Fisher (2006) argues that campus based students still require physical spaces, where they can become “a community of learners’.

4. Interpreting built pedagogy

The genesis of the building in 2008, therefore, occurred during significant change within the University academic environment, tracking alongside much of the policy development initiatives and roll-out to provide the framework for the new Growing Esteem strategic direction.
The University of Melbourne selected a shortlist for a building design consultancy team for the new MSD building via an international open architectural design competition process, establishing in its competition briefing document six evaluation criteria in its selection of entrants. The first of these criteria was identified as ‘Built Pedagogy’ describing this in terms of the project being an exemplar in its learning environments, as a work of architecture, urban and landscape design as well as mandating outstanding construction, structural and servicing techniques (FABP, 2009). This articulation of built pedagogy as a model or pattern underplays the broader use of the term in the academic literature and which has informed student-centred pedagogical approaches in contemporary planning and design.

Monahan (2002) views built pedagogy as architectural embodiments of educational philosophies, arguing that the design of space has the capacity to influence behaviour. He goes on to argue that built pedagogies can enable flexibility in the behaviours around the usage of space. Oblinger (2006, p.1) defines built pedagogy as “the ability of space to define how one teaches”, whilst Luz (2008, p.5) establishes built pedagogy as being “the ability of space to define how one learns, teaches, acts or responds”. Fisher (2006) links pedagogy to a spatial paradigm, arguing that the learning space has to adapt to a “range of pedagogical delivery approaches”.

The MSD building, therefore, aspired to be a ‘pedagogical building’, with built pedagogy a driving aspiration behind its design and construction. What then did this mean to the various participants of the project delivery team who were tasked with implementing the aspirational component of the building and library, and how did the designers interpret this? A number of themes were identified in the research interviews, these have been summarised under those related to institutional legibility, those related to evolving pedagogic practice and the socialisation of academic and campus space, programmatic adjacencies and aspects of design to allow building elements to engage as models or examples in teaching and learning practice.

4.1 Institutional legibility

The Dean, Professor Tom Kvan identified built pedagogy as playing a role across a number of streams of tertiary education (T Kvan: 2014 personal communication). First, amongst these was the interest in campus planning to remove perceived barriers between the University as an institution and the general community. Built environment design was seen as playing a key role in supporting institutional legibility in becoming more open and engaging public institutions by being assessable, permeable and transparent. This extended to internal engagement between University disciplines, given current inter and multi-disciplinary approaches to teaching and research, which needed to be reflected in its new building stock. Professor Kvan identified University libraries as early adopters of this shift, with library services becoming increasingly student focussed, and the approach to the provision of services and spaces incorporating a social constructivist pedagogical approach.

In interview, Nader Tehrani, one of the principle architect design directors, expanded this to include the positioning of Universities within the global environment via online education and the influence this potentially has on campus planning and facility design. Making a distinction between online access and physical access to the campus, consideration of the nature of the spatial, environmental and experiential features of the physical campus, he argued, takes on far greater prominence as the physical facilities provide resource capacity and interactions not possible via online education. He observed, “now that the virtual world has freed us from physical contact the idea of destination becomes even more important. So the physical access to the campus is like a bonus, the physical campus is no longer a mere backdrop for education; it is a destination for education”. (N Tehrani: 2014 personal
communication). He saw the building and the library playing an important role in terms of institutional legibility. Transparency of the internal functions of the building was seen as the key component, with glazed components to the three public faces of the library offering views into its inner workings and operating as a metaphor for making knowledge accessible. Institutional legibility also lay in the “transformation of a library from a quiet space of scholarship, only for higher levels of study into a place that reaches out even to the younger age. Part of the success of this building is to find a way in which this transparency, this accessibility, becomes manifest in the public it draws”. (N Tehrani: 2014 personal communication).

4.2 Pedagogic practice and socialisation of space

The retention of a library within the MSD building ran counter to the University’s policy of resource consolidation, particularly within library services, as advocated in the ten-year library strategic plan which proposed the establishment of precinct learning hubs servicing multiple faculties. A major argument for the retention of the ABP library, co-located with the Faculty, was presented on pedagogic grounds. It was argued this discipline cohort use library material differently to those of other disciplines. Professor Kvan argued that library space needed to accommodate the particular manner of study in the simultaneous use of multiple sources. He identified built-environment education as being ‘heavily focussed around teamwork, collaboration and group work’ and that this needed to be reflected in the design of spaces. He saw the library as encapsulating tertiary education’s move “from the predominance of didactic instruction to other forms of engagement and enquiry, libraries have followed lock-step with that” (T Kvan: 2014 personal communication).

The architects suggested that a design-based education has always operated with a different form of pedagogic practice generated from the design studio teaching method. Tehrani argues “that the design field is one of the only pedagogies whose main vocation and classroom context is not top down education – it is a round table which is focused on drawings and where criticism and debate are an essential part, to flatten the hierarchies between students and professors” (Cassell and Russell, 2015).

This notion of the socialization of space and the role it plays in the situated nature of pedagogical practices, though, was not seen by others as particularly unique to a built-environment education. The Deputy University Librarian and Director of Scholarly Information Jenny Ellis identified an increasing demand for shared and collaborative spaces in libraries as reflective of a pedagogic shift where students work collaboratively with increased peer-to-peer learning (J Ellis: 2014 personal communication). This with the greater use of online resources has reduced library lending and increased the requirement for the provision of technology-rich social spaces where collaborative learning can occur. This pedagogic shift is recognized by the designers, with architect Stefan Mee explaining the complex nature of contemporary learning spaces providing for flexibility within an increasingly domestic approach towards interior design:

The student is more the centre of learning rather than the teacher. You start to think about designing spaces differently. It’s about how the students might learn within that space, it’s not necessarily about delivery information within a library or bookshelf - it’s about how they grapple with that and how the architecture might allow that to happen in a different way. The spaces are much more social and interactive; it is providing a lot of choice. We like to provide students with a range of different ways to occupy space. You’ve got students living nearby, in often quite small accommodation, where they are sharing, so
the library becomes their lounge room. You’ve got to be aware of that and that makes an opportunity for the library to reinvent itself, reverse of how it used to be with library space. (S Mee: 2015 personal communication).

Anne Thompson, University Project Manager, observed “it’s all about socialising within the framework of learning and providing spaces for students to do that”. Recognising the need to accommodate the students who make up the ‘community of learners’, Thompson says, “the University is providing spaces so students stay on campus so that they’re actually participating in the University environment. And the spaces that are specifically designed for that need to be flexible” (A Thompson: 2014, personal communication).

4.3 Programmatic adjacencies and transparency

The prominent location of the library on the ground floor adjacent to a main entry point of the building, and the role it played as a public expression of pedagogic approach was an important consideration, commented on by the research participants. This centered on the programmatic adjacencies relative to the library and within the library space and the linkages that could be generated to reinforce these adjacencies by architectural devices of transparency and connectivity.

The architects identified the placement of the workshop areas directly opposite the library on either side of the primary internal access route as exemplifying the bifurcation of the teaching and learning approach of built environment education. Architect Stefan Mee explained:

That’s the kind of interesting relationship across the internal street, you’ve got scholarship, if you like on one side and you’ve got making on the other. Which creates this interesting relationship between the two and it’s all very transparent, you can see what going on in the library sitting there making a model on the other side. (S Mee: 2015, personal communication).

Mee also identified a new type of library space, influenced by the social-constructivist pedagogical input of Peter Jamieson, which has the capacity to operate as public space, student-use study space and library space. Located at the eastern end of the ground floor level of the library, this collaborative space is glazed on three of its facades with an outlook onto the external public and landscaped areas adjacent to one of the primary entry points to the building. With different floor levels and offering a variety of seating and study arrangements it offers configurable access to operate independently of the library.

This is part of the built pedagogy discussion, the idea of drawing out the activity into external spaces. It is an extension of what the library would otherwise do because the library is typically ring-fenced by the security of not allowing the book outside of its perimeter. (S Mee: 2015, personal communication).

The idea of removing visual barriers between programmatic zones and promoting transparency and connectivity to promote a student-centred approach in service delivery was commented on as applying to the design of library staff workspaces. The open plan staff office is surrounded on three sides by glass, which allows the staff to be visible and connected to users of the library, and vice versa. The architects explained Professor Kvan’s interest in “exposing faculty activities to the campus community” was consistent with locating staff areas behind clear glazing and within the lower level student study areas. Dwyer explained “I think it’s the transparency to the staff area that probably makes the staff presence more readily felt” (M Dwyer: 2014, personal communication), with interior designer Jeff Arnold
explaining “we made an attempt to open up the office space and make it fairly transparent and visible for the library spaces” as a demonstration of an “open relationship between staff area and the student areas” (J Arnold: 2014, personal communication).

The notion of programmatic adjacency as against program separation was also seen in the internal relationship between book stacks and study tables. Jenny Ellis points out, “our students do seem to read more print and borrow more than other students”. (J Ellis: 2014, personal communication). As a result, the design of the ABP Library allows connections to collections. There are study tables adjacent to the journal compactus, and spaces for individual study integrated with the shelves. Jeff Arnold, talks about “activating the stacks, which is having more student activity and liveliness within every sort of available space within the library” (J Arnold: 2014, personal communication). Strategies included generating sight lines through book stacks by apertures, seating areas within the stacks and integrating display elements into the stack areas.

### 4.4 Learning support exemplars

The original competition brief established an implied requirement for the demonstration of built pedagogy throughout the building, and for it to act as a direct teaching tool through the exemplification of architecture, construction and servicing techniques. Professor Kvan saw this as a link to the tradition of architectural education via precedents and references; one of the roles of the building was to support built-environment education by also providing an avenue for reference as a direct teaching tool (T Kvan: 2015, personal communication). Participants identified a number of examples as representative of direct teaching tool mechanisms of architecture, construction and servicing techniques. These ranged from such items as direct visual access to service areas from the library to mechanical service rooms, to the modelling of urban design concepts such as ‘active frontages’ in the relationship of the library entry and glazing to the internal circulation spine of the building.

The design item that was seen by the majority of participants as encapsulating the buildings ‘built-pedagogy’ approach is the ceiling of the lower library level, which has come to be known as ‘the wishbone ceiling’. As one of the main architectural features in the library, exposed reinforced concrete wishbone-shaped beams support a concrete lawn over the lower library level. The architects identified this feature as not only defining the space architecturally but also as a visible lesson in design precedent, structural ingenuity and construction technology. They inform design teaching in referencing the work of the Italian engineer and architect Pier Luigi Nervi; offer a demonstration of high-level concrete design and construction; as well as provide a talking point for construction supply chain engagement in the production of concrete formwork and achieving Class A finishes in concrete construction.

Professor Kvan identified a window located within the main collection area that provides a view into a plant room normally concealed as the capacity of the building to act as reference material:

That’s a clear statement to the students as are the wishbone beams that run across. These are statements to the students saying - use your eyes, this is physical material, it’s a one-to-one model, pay attention to it! And, the library professionals here can do that which other libraries don’t offer. The transition from paper based to physical material. (T Kvan: 2014, personal communication).

He also explained that such items as the wishbone beams, which have cost attached to them, come under scrutiny during reviews in meeting project budget targets. An approach adopted on the recommendation of the quantity surveyor early in the project development was to quarantine a sum of
money which could be awarded back to the project when it was identified that an item enhanced the research or pedagogical value of the building. The library ceiling structure was one such item that the project team felt enhanced pedagogic value and was the beneficiary of this early cost planning exercise.

5. Discussion

A primary interest in undertaking this research was to utilize the opportunity presented by a library facility which was embedded into a new tertiary education building whose explicit design intention was to deliver a building which engaged with built pedagogy. This is of particular interest where the relevance of physical campus spaces is being questioned within the framework of information and communication technologies and an educational environment engaged in global competition for students. The opportunity therefore lies in investigating one institution’s approach in utilising library design in presenting its educational approach and demonstrating the capacity of library space to influence how one teaches. Given that the library and the building has not been operating for a full academic year much of this remains untested and lies for future study. The investigation, therefore, sits within the front-end of generating a design response – what did the stakeholders in the building process understand as being built pedagogy and how was this interpreted?

The project briefing documents, although establishing it as one of the key design criteria, did not explicitly define the term built pedagogy, but expressed its use as the building being an exemplar. This in part reflects the lack of a clear accepted definition made manifest in the literature review. Participants in this project suggested that communication between the design team, project reference group and user group workshops obviated the need for explicit definition and allowed for such aspirational goals to evolve through the development process. When asked specifically to define built pedagogy interview participants did not provide a definition of the term, but in place gave examples of where it was felt that engagement of ideas dealing with built pedagogy were expressed. This approach appeared to work well for this particular project given the commonality of themes expressed by participants. A key factor was the two-stage competition consultant selection process, which provided a reasonable gestation period for stakeholders and the design team to work through project aspirational objectives. Where such extended lead times prior to formal consultant engagement or user-group work shopping is not embedded into the project program, explicit outlining of project objectives may need to be considered.

The summation of participant responses under the broad headings identified carry implications for library and built environment design in tertiary education. International and local competition for students amongst tertiary educational institutions, it may be argued has been a contributing factor in the reassessment of campus-based facilities in meeting the needs of students. Institutional legibility and branding of universities are increasingly being overtly expressed through built form in support of a global profile in a competitive education market. Academic library spaces have become an important part of the campus based experience and in being increasingly unbounded to individual faculties, provide a flexible campus asset conduit in the promotion and delivery of broad service agency. This service agency for library design links to pedagogic practice through the approach of the creation of an immersive learning environment, where programmatic adjacencies and transparent connections bring not only students, but also academic and professional staff, to the centre of learning practice. Built pedagogy, as seen in this case study, relates to the building or space as a direct and in-direct learning tool. Although the library in this case study caters to built-environment design and practice, there is opportunity for academic libraries to engage in the consideration of how their spaces offer a capacity to act as a learning tool.
Pedagogic shifts away from didactic instruction towards collaborative and self-directed enquiry have led to a reconsideration of library space as technology-rich social spaces for learning. The progression in engaging with the challenges and opportunities generated by information and communication technologies and the impact on education delivery via these mechanisms on the physical campus setting is looming large. The notion of a built pedagogy will need to engage with multiple permutations of interpretation presented by virtual/physical education delivery. Library facilities being the common denominator in information access for students have already been impacted by this shift and will continue to be at the forefront of response strategies to these evolving pedagogies.

6. Conclusion

Academic libraries play a part in supporting the research, teaching and learning activities of their institutions. University policy documents will provide the framework and an outline for strategic direction of the institution, with the implementation of these often left to the operational departments, faculties and consultant teams. The provision of new, and refurbishment of existing campus buildings provide an opportunity for the institution to articulate the expression of what it means to design a learning space in the 21st century. The communication and interpretation of briefing documents that guide the design of these facilities, however, invariably fall on individuals, project reference groups and the consultant teams who workshop and convert policy, institutional approach and spatial requirements into built form. It is, therefore, important to reflect on the issues that such parties identify as being important in this conversion process. This paper has sought to investigate, in this particular case study project, what key issues were identified in guiding the translation of educational pedagogy and student support into built form. Client reference and user groups have the important task of translating institutional policy and operational aspirations into cohesive instructions to allow the design and project delivery team to generate a design response. Designers and project implementation parties then have a key role in interpreting institutional strategic policy and in formulating and workshopping not only design responses for facility planning but also aspirational intent.

The MSD building has been operating for less than a year; however, anecdotal evidence indicates that library patronage has increased dramatically over all spectrums of client engagement. It is appropriate to now investigate how the pedagogic underpinnings of the library, as identified by the project delivery team, have met their designed intent and whether the issues seen as responding to the built pedagogy mandate of the brief align with library services requirements and client use through a post-occupancy study.

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References

Colourful language: researching architects’ knowledge and use of colour

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Abstract: The development of architectural materials and technology is transforming the colour palettes and identities of cities by juxtaposing or replacing vernacular colours with global and often contextually meaningless colours. As Built Environment designers have significant roles in determining city colourscape, it might be expected that these professionals have considerable knowledge. However, there is largely an absence of colour training in the majority of built environment degree programs. While colour has been studied in a broad range of disciplines, very few studies have focussed on architecture and even less on colour in architectural education. This paper reports on the early findings of research into what informs architect’s understanding and use of colour. Data was analysed from a survey of 33 practicing architects, academics and postgraduate students from Melbourne, Australia. The findings indicate that built environment designers see the need for increasing their colour knowledge. In line with previous studies, there was no evidence of correlations between gender and age, but findings suggest cultural differences in the level of colour education depending on country of architectural study. The wider research that this study is a part of ultimately aims to inform education around the use of colour in the built environment.

Keywords: Colour; colourscape, architectural education.

1. Introduction

Colour has been the subject of ample research in different disciplines during the past few decades, in relation to colour perception, theory and measuring methods. However, there have been few studies on the use of colour in architecture and even less on colour in built environment design education. It is argued that a misuse of colour from lack of knowledge among architects and urban designers has raised the issue of the ethics of colour use (Minah, 2013). Little research has considered in any depth the relationships between education, the power of the architects in making colour decisions, and city colourscape. Thus the goal of the study is to investigate the role of educational and personal
experiences in informing architects’ understanding and use of colour. This paper reports on the findings of a pilot survey developed to elucidate this goal completed by practicing architects and built environment PhD students and academics in Victoria, Australia.

2. Context and Background

Colour has been described as a spirit of life that can express the human soul (Wright, 1995). It connects the realms of architecture, history and culture through its impact on moods, feelings, interpretations and perceptions. In contemporary life colour plays a key role in determining the visual hierarchy of urban space, informing human understanding of their surroundings (Feldsted, 1962; Eduardo, 1974), and emphasizing unity and continuity (Boeri, 2010). It not only plays a crucial role in preserving city identity, but can also initiate urban and social regeneration. It follows that designers’ knowledge and experience in colour selection has an impact not just on design outcomes, but also on the quality of city colours and the wellbeing of city dwellers. It can be argued that colour ought then to have a significant place in the education of architects and urban designers. Unfortunately, colour is still rarely a subject of serious inquiry in design practice and education, where it is considered as secondary to architectural characteristics such as form, line and structure and thus as more of supplemental consideration — as a matter of personal expression and manner (Durao, 2002; Minah, 2013). As Jasper suggests in the editorial of a 2015 edition of the Architectural Theory Review dedicated to the subject of colour,

“Today, colour has been dispensed with. Not only dropped from the core curriculum of architecture schools... it has been exiled from the professional domain of architecture. Colour is an a-conceptual decorative choice that sits in a theoretical limbo between urban planning and interior design: “interdisciplinary” in the sense of “fallen between stools”. Colour is a secondary design decision at best—one that is resolved usually only after the important decisions have been taken.” (Jasper, 2014)

A review of Australian architectural curricula and the criteria of course accreditation bodies (Wise and Wise, 1988; NCSA, 2008; AIAP, 2009) reveals, perhaps unsurprisingly, an apparent absence of adequate colour training in most built environment degree programs. Moreover, review of the literature reveals very few studies have dealt with colour in architecture, and even fewer with colour teaching in architectural education. Janssens and Mikellides, in a cross-cultural study of three Swedish and two UK design schools, have investigated the colour knowledge of architecture students. The study, which was restricted to undergraduate students, found a deficiency of colour knowledge, with complaints from the cohorts “about a lack of coverage, of the subject area in lectures, seminars, or studio work, with very little theory and only few practical exercises” (Janssens and Mikellides, 1998). As the degree of colour knowledge amongst Australian graduate architects has been even less studied, the research reported here focuses on the impact of higher education on Australian graduate architects’ knowledge and use of colour. The survey of practicing architects, and built environment academics and postgraduates investigates the relative impact of personal and educational backgrounds on colour understanding. In developing the survey, the structure of Janssens’ and Mikellides’ survey (Janssens and Mikellides, 1998) was used as a basis. As the focus of the study reported here is architects’, rather than undergraduates’ use and understanding of colour, the Janssens survey has been augmented.
3. Method

The instrument was an online pilot survey that will be used to inform a national survey circulated in 2015. Items in the survey were informed by a literature review on what informs designers’ colour choices. The review was carried out as a part of a broader PhD project investigating the impact of a wide range of factors on colour knowledge and use in the built environment, such as, in addition to education, culture, personal practice experience, colour preferences and attitudes, stakeholder influences and the practice context. The study reported in this paper is restricted to analyses of questions directly focusing on two factors: the role of higher education and of personal experiences in informing architects’ colour choices and knowledge.

3.1. Survey description

As noted, the survey instrument was informed by the Janssens and Mikellides study. While the previous survey was composed of six blocks plus a comments section, the current survey has 9 blocks in three sections, as summarized in Table 1.

<p>| Table 1: The structure of questionnaire |</p>
<table>
<thead>
<tr>
<th>Blocks</th>
<th>General content</th>
<th>Focus</th>
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<tbody>
<tr>
<td>Section I</td>
<td>Block 1</td>
<td>Demographics</td>
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<tr>
<td>Section II</td>
<td>Block 2</td>
<td>What you think you know about colour?</td>
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<td></td>
<td>Block 3</td>
<td>What you actually know about colour?</td>
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<td></td>
<td>Block 4</td>
<td>Source of your general colour information</td>
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<td></td>
<td>Block 5</td>
<td>Detail question about colour theory and use</td>
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<tr>
<td></td>
<td>Block 6</td>
<td>Source of colour research information</td>
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<td>Block 7</td>
<td>Preferred source for colour research information</td>
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<td></td>
<td>Block 8</td>
<td>What is expected from colour research</td>
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<td></td>
<td>Block 9</td>
<td>Expectations from colour education</td>
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<td></td>
<td>Block 10</td>
<td>Suggestions about colour education</td>
</tr>
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Section I and Section III repeat the Janssens instrument, while Section II is an additional series of questions on the level of participants’ knowledge about colour and the factors that inform their colour choices. In total, the survey has 120-items consisting of 5-point Likert scale questions asking participants to rate their colour knowledge, with open ended questions seeking elucidation after each block of Likert-scale questions. 24 questions (15 Likert-scale and multi-choice and 9 open-ended questions) were related to the role of higher education in informing colour choices. Table 2 shows the summary of the survey in schematic diagram. The first section of the survey includes multiple types of questions about participant’s personal and educational demographics. The second section asks about the level of
participant’s knowledge of colour, and was designed to examine the impact of four factors on participants’ colour understanding and use: (1) Personal background and ability, (2) Knowledge and education, (3) Experience in practice, (4) Environmental and human needs. These factors were drawn from the literature as those that may impact on colour understanding. In this section, participants were asked to rate on two different forms of 5-point Likert scales: (1) (from 1 = not at all, to 5 = very important) and (2) (1= strongly disagree, 5= strongly agree). These are followed by open-ended questions allowing for qualitative answers expanding on issues raised in this section. Finally, the third section is dedicated to participant’s expectations from colour research and education, and concludes with space for their further suggestions and comments.

Table 2: Schematic table of 24 selected questions of survey

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<tr>
<th>No #</th>
<th>Parts of Sections</th>
<th>Type of Questions</th>
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<tr>
<td>Section I</td>
<td>7</td>
<td>Part 1</td>
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<td>2</td>
<td>Part 2</td>
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<tr>
<td></td>
<td>3</td>
<td>Personal Background &amp; Ability</td>
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<td></td>
<td>5</td>
<td>Knowledge &amp; Education</td>
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<td></td>
<td>3</td>
<td>Experience in Practice</td>
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<td></td>
<td>1</td>
<td>Environmental &amp; Human Needs</td>
</tr>
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</table>

3.2. Participants

The survey was given to two groups based in Victoria, Australia. The first group consisted of architecture postgraduates, and the second was of academics and practicing architects. From the 55 questionnaires that were distributed, 33 completed questionnaires were received. The gender distribution showed a marked discrepancy between the two groups, with more men (76%) than women (24%) in the cohort of architects and academics, and more women (82%) than men (18%) in the postgraduates. The data shows that both genders demonstrated generally similar positive response on the importance of colour in architecture. 100% of females see colour as very or moderately important (M=4.5, SD=3.6), with a small difference for males – of which 92% see colour as important. Only 8% of the rest chose somewhat for the level of colour importance (M=4.3, SD=3.2), with no respondents seeing colour as unimportant to architecture. The ages of respondents varied, with 70% of participants in the age range of (31-50), meaning most had considerable experience in the study and/or practice of architecture.
4. Results and Discussion
The following section reports on the analysis of the quantitative and qualitative data from participants’ answers to the twenty-four questions relating to the role of personal experience and higher education in colour understanding and use. Grounded theory has been used as a codifying method to reveal the major themes from comments. Unlike the Janssens study, statistical testing of comparison of variance has not been used because the small sample size would not give meaningful results.

4.1. Educational Background
53% declared that their highest completed degree is a masters, 24% a bachelors and 21% a PhD. The range of participant’s graduation years are various, but half graduated in 2000-2009. Half of the participants stated that they did not have any colour related course in their education, while the other half claimed they had studied colour. The comments suggest that none of the participants had studied a course specifically on colour use or theory, but that they had merely received basic information about colour theory as a part of another course with a different focus. It appears that colour related courses were mostly offered in the first year of a bachelor’s degree or as an elective course. Participant responses to “state the colour related course name” reveals that colour had been studied in a number of different courses, such as “form analysis”, “the elements and principal of design” and “ambiance” and most commonly introduced via an “architectural studio.” Thus knowledge of colour was most commonly learned through the process of designing or as an aspect of the design process.

As the literature suggests that educational system and the country of study can have a significant impact on the importance and place of colour knowledge in architectural curricula (Madden et al., 2000), participants were asked to declare the country of their undergraduate and postgraduate degrees. As one might expect from the multicultural population of Australia, responses show a wide range of countries in addition to Australia e.g., UK, Iran, Spain, India, Japan, Kingdom of Saudi Arabia, Egypt, Libya, Indonesia, USA and Romania. Due to the small sample, it is difficult to draw conclusions about the relationship between colour education and country of architectural study, but the results suggest that the prominence of colour in the architectural curriculum has a relationship with the cultural importance of colour in the country of study. As an example, participants who studied in the UK, Japan and India see colour as very important, claiming they have good colour knowledge from colour courses in their education. Moreover, participants studying in these countries were able to name a studied colour course and its content. In contrast, the most dominant comments of participants who studied in other countries such as Australia and Iran rated the importance of colour with more variability. They were less certain about whether they had colour courses, and most could not remember the name of the course. The last question of this section sought level of agreement with the statement: “The higher education that I received in colour theory was thorough.” More than half of the participants disagreed or strongly disagreed with the statement, while 32% answered neutrally, leaving only 16% who agreed or strongly agreed that they had received a thorough colour education (M=2.48, SD=3.1).

4.2. What you think that you know and what you actually know about colour
The Likert scale questions of this section aimed to examine knowledge and understanding about colour in four areas: (1) Personal background and ability, (2) Knowledge and education, (3) Experience in practice, and (4) Environmental and human needs. The answers showed that while only 59% of participants chose the neutral option 3 or higher (from Likert-Scale (1=Don’t know, 5=Expert)),
indicating that they had at most an average level of knowledge (M=3.11, SD=6.61), 46% agreed that ‘the knowledge of colour is important to architectural design’ (M=4.2, SD=5.3). This suggests a significant gap between what architects are taught and what they feel they ought to know.

To investigate in greater detail what participants thought was the role of colour in architecture, they were asked to rate the importance of colour as: (1) decoration, (2) part of the design concept, and (3) a functional element. The results show that: 64% of the participants thought that colour was of average or above importance as a functional element (M=3.8, SD=3.74); 48% thought that colour was of average or above importance as part of the design concept (M=3.96, SD=4.7); and 28% saw that colour was of average or above importance merely as a decorative component (M=3.2, SD=2). This suggests architects most commonly view colour as an integral element of design rather than merely as applied decoration. In line with common opinion about the comparative importance of colour use in interior and exterior spaces, the next question asked participants to rate the importance of colour use in three contexts. While 64% (M=4.6, SD=7) felt that colour is highly important in interior spaces, nearly half believed that colour has a highly important role in building facades (M=4.3, SD=5.3), with 72% feeling colour is moderately or highly important in landscape (M=4, SD=4.3).

Five questions were dedicated to the role of higher education and practice experience. The results reveal that while nearly half of the participants agreed that ‘higher education should play a role in informing knowledge about colour use in architecture’ (M=4.125, SD=4.92), only 48% agreed or strongly agreed that ‘higher education had an impact on my understanding of use of colour’, 28% neutral and 24% disagreed or strongly disagreed with this statement. It seems that the educational culture of schools had only a minor influence on colour preferences (M=3.08 out of 5, SD=2.82), with only 12% feeling ‘that the design aesthetic/philosophy/stance of school has impacted the way of use colour in their designs” highly. When answering “how do you rate the impact of practical experience on use of colour in your design process?” almost 52% felt their practical experience had a moderate impact on their colour use (M=3.76, SD=4.94), 20% highly, 20% Some-what, and 8% Not at all.

To investigate what factors inform architects’ colour choices, participants were asked to rate answers from not at all to highly for three questions examining colour in the design process. The first question was “how important are the following factors when choosing colour for your designs?” The eight proposed factors had been identified through the literature review. Figure 1 shows that, except for ‘surrounding built environment’ (M=4.04, SD=4.1) and ‘climatic and geographic conditions’ (M=4.03, SD=4.81), which were identified as highly important design considerations by 42% of participants, all other factors bar one received a moderate level of importance (from 31% to 38%). Decoration, was the least influential design consideration (M=2.92, SD=1.64)). Interestingly, the ‘meaning of colour’ is only just ahead of decoration (M=3.1, SD=1.92), which might be said to reflect an apparent lack of knowledge of this area due to a lack of teaching of colour theory.
Figure 1: The percentage of the impact of eight factors on choosing colour for architectural design

Figure 2 shows participants’ responses to the four options offered for the question “how do you rate the importance to your colour use of the following socio-cultural factors?” As can be seen, all four options reached a moderate level of importance, with the aesthetic taste of clients (M=3.84, SD=4.65) seen as the most influential socio-cultural factor informing colour choices. The other three themes: Designer’s personal traits, Cultural and religious value of colour and symbolic meaning of colour respectively received 38% (M=3.5, SD=4.2), 35% (M=3.5, SD=3.03) and 31% (M=3.6, SD=2.6).

Figure 2: The level of socio-cultural impacts on architects’ colour use

The third question on what informed colour choices indicated that the physical and cultural context of the design, with 64% (M=2.54, SD=6.1), is the most important factor in colour decision making, with designer cultural background and colour preference seen as equally as unimportant as design education (M=1.9, SD=1.15), with both lagging well behind physical and cultural context.
4.3. Expectations from education

To investigate expectations from architectural education with regards to the teaching of colour knowledge, three open-ended questions were asked. The qualitative data gathered was analysed by coding the comments via the grounded theory method (Glaser and Strauss, 2009; Charmaz K, 2014). Codifying the most dominant responses to the question “what kind of colour information and training is it necessary to receive in architectural education?” revealed four themes: ‘introduction to colour theory’, ‘colour use in architectural design’, ‘influence of colour on community’ and ‘colour, industrial and natural material’. The comments suggest that participants believe that architects should have at least a basic knowledge of colour theory, its role in design and impact on the community, and how to use colour in architecture. The second question “in which courses/units do you think colour study should be taught?” reveals a variety of suggestions. The most dominant course suggestion (Figure 3), with (43%), is ‘Architectural design,’ and the second highest is ‘Architectural design theory’ with nearly 15%. 10% of participants stated that the course should be offered in communication subjects, or that its place of offer depends on the needs and context of the discipline.

![Figure 3: The courses containing colour knowledge and training in architectural education.](image)

The third question “who should make decisions for cities about the architectural use of colour?” elucidated particularly interesting results. The comments reveal strong agreement (80%) on the belief that it is architects who are responsible for colour decision-making. However, only 35% believe that the architect is the only professional who should make colour decisions (Figure 4). Thus, 48% believe in collaboration between architects and other professionals to make group decisions about the colour of the built environment, with the most dominant comments citing architects in collaboration with ‘Urban designers and planners’ (32%) and with ‘community groups and clients” (11%).
Thus, we see that the findings of this study are very much in line with that of Janssens and Mikellides, who in 1998 concluded that while architecture undergraduates perceived and evaluated colour as one of the most important concerns in their professional careers, they received little teaching on the subject. Similarly, nearly 20 years later, while our own study sees a clear recognition amongst practicing architects, academics and postgraduates of the central role of colour to practice, it contrasts sharply with a severe lack of taught colour knowledge. Other similarities and some differences can be seen between the two studies. Like the previous study, we also did not find evidence of correlations between gender, age, and recognition of the importance of colour. But unlike the previous study, we did find suggestion of cultural differences. Although the Janssens and Mikellides study (1998) is a cross-cultural one, cross-cultural differences were not discussed by them, an omission we might speculate could be due to a lack of difference between Sweden and the UK.

5. Concluding remarks

The findings from the pilot survey reveal that there is a clear gap between levels of knowledge perceived as required on colour in architecture, and the educational training that is received on colour. For although the results show an overwhelming interest and agreement about the importance of colour in architectural design, none of the participants received sufficient and thorough education on colour, and majority of them claim that they have just an ‘average’ level or less of colour knowledge. The data shows that, commonly, architectural education offers no specific course about colour theory and that colour knowledge if mostly taught through the process of designing or as a part of another course with a different focus. Thus, while participants saw colour as an integral part of the design process and as an integral design element, not just applied decoration or for interior design, it seems that colour is still considered a secondary concern in an architectural education that plays merely a minor role in informing the colour knowledge and understanding of architects. Thus there is a need identified for better colour education, with architectural design and theory courses seen as the most appropriate points in the curriculum for this. Comments revealed the most desired areas of learning for architects being a fundamental introduction to colour theory, and the impact of colour on community.
The data also reveals that the design aesthetic/stance of design schools and practical experience in architectural design respectively have minor and moderate influence on the use and understanding of colour. Thus, while personal background, culture and design education have impacts on colour use, it is likely that the influence of client/stakeholder preferences and the physical and cultural contexts of each design are of far greater importance. Indeed, unpacking the relative impacts of all these factors on colour use in the built environment will be the prime focus of a national survey to be distributed in the winter of 2015. As the findings also suggest that the colour content of architectural curricula has a relationship with the cultural importance of colour in the country of study, further research is also needed in this area. While architects believe that they should mediate all these influences, the pilot survey reveals that they should do so in collaboration with other professionals. This of course suggests that architects are not the only professionals who require a more complete education in colour theory and use. It can be concluded that in order to achieve sustainable city colourscape, there is a strong need to improve colour education in architectural curricula to teach architects about the ways of colour use in design and its impact on community.

References
Constructing a professional education: a new architecture degree at Unitec 1994

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Abstract: In 1994 Unitec Institute of Technology welcomed its first cohort of enthusiastic students into the new Bachelor of Architecture programme within the School of Architecture and Construction. This new programme, a second architecture programme in Auckland city, was reportedly initiated by professional dissatisfaction with the lack of work preparedness of the graduates from the existing architecture programmes in the country. Little has been written, to date, about the origins of this new programme. Architecture programmes globally are evolving to meet contemporary needs and the discourse surrounding the beginnings of this programme may shed light on current trajectories. Situating the programme within a School of Architecture and Construction was part of a strategy to produce an architectural graduate who was more practice focused. But how was this intention manifest in the programme organisation and what were the distinctive features of this new programme that were designed to meet this objective? This paper will examine the originating documents and the context in which this programme was developed. It argues that, while the proposed curriculum and course structure contain elements that meet this professional, practice focused need, there are other elements embedded within the course that have a more expansive vision.

Keywords: Architecture; education.

1. Introduction

Writing at the turn of the nineteenth century, Arthur Cates, long-time campaigner for formal architectural education described the traditional system of pupillage where apprentices were practically instructed by a skilled master as under pressure from;

...the stress and struggle of modern life, the wide range of knowledge and acquirements now necessary to ensure success and the changed relationship between master and pupil.
(Cates, 1900, p.394)

He stated that the pupil’s learning was “limited to what he may ‘pick up.’ As a result he saw the need for a ‘systematic course of strictly professional education.’ His views were echoed by William Emerson
(1901, p.1) RIBA President in 1900, who called for a ‘better and more methodical system of Education for our students in architecture’ to counter what they saw as a potentially piecemeal education in the professional office. While we now have had professional degree programmes in architecture worldwide for almost a century there remains an ever-present tension between constituent elements of architecture as to how a ‘methodical, systematic’ course might be constructed. Within the New Zealand architectural world there is a persistent narrative that suggests the establishment of the Architecture degree programme at Unitec Institute of Technology in 1994 was a response to the architectural profession’s dissatisfaction with the work preparedness of graduates. This paper reviews the development and establishment of the degree (1991-1994) and argues that, while the proposed curriculum and course structure contain elements that meet this professional, practice focused need, there are other elements embedded within the course that have a more expansive vision.

2. draft INTERIM SYNOPSIS

In April 1991 R.F. (Bob) Matthew, Head of the Architectural Studies Department at Carrington Polytechnic delivered a memorandum to the Academic Board requesting their approval to proceed with the further development of a Bachelor of Architecture degree programme. The memorandum, which was one and a half typewritten pages, briefly outlined the proposed (rather optimistic) time frame and noted that it was an opportune time for the start of a new architecture programme as there was:

...considerable goodwill and support in principle. In particular we have support from Professor Helen Tippett in her role as President of the New Zealand Institute of Architects and as a senior academic at the Victoria School of Architecture. (Matthew, 1991)

The memorandum additionally argued that there was already a cohort of 20 draughting students who annually entered the architecture degree programme at Auckland University and these students could be diverted to this proposed new programme. A ‘draft INTERIM SYNOPSIS’ of the proposal (Matthew, 1991) was attached to the memorandum and I will return to that shortly.

There are several local factors that background this proposal. The Education Amendment Act of 1989 opened the way for polytechnics to offer degree programmes. This legislation made possible new opportunities for the polytechnic sector but that ever-present tension between architectural practice and the academy was again rising to the surface. The memorandum quoted above refers to the support of the NZIA. Undocumented personal narratives regularly refer to industry dissatisfaction at the time with the work readiness of graduates from available course offerings. Lindsay Wood summarised the particularities of this dissatisfaction.

There was a perception that the two schools of Architecture (Ak [Auckland] and Vic [Victoria University of Wellington]) were not catering well for practitioners – Ak was seen as having a ‘purist’ design focus and Vic a building science one. (Wood, 2014)

The view was held that because of Carrington Polytechnic’s engagement with industry through the provision of its Bachelor of Building and Bachelor of Quantity Surveying along with an array of Certificate and Diploma courses for the construction industry it would be well placed to offer a Bachelor of Architecture degree that was concerned with the everyday issues that confront architectural practice.

There is another element of influence that may have impacted on this degree proposal and that involves architectural theory. Gevork Hartoonian (2002) has suggested that architectural theory came to prominence in American Schools of Architecture in the 1970s. He argues that the protagonists of the
Whites vs the Greys debate dominated the discourse within the universities and then, through the dispersal of their students by the late 1970s, these same theories and critical practices dominated the work of the profession. While the same processes cannot be directly translated to New Zealand there is a reported narrative or a version of that narrative that identifies staff and students conversant with this new contemporaneous theory and critical practice at the Auckland School during the 1980s. (Austin, 2014) The New Zealand architectural climate is not as receptive to theory as its American counterpart or put more bluntly as David Mitchell pointed out in the same period ‘Amongst New Zealand architects pragmatism is still the most morally defensible critical position.’ (Mitchell, 1984, p.7) The identification of at least parts of the Auckland school with what were perceived to be deeply theoretical positions may account for Wood’s description of Auckland as having a ‘purist design focus.’ This theoretical bias was another significant factor in opening up a space for a new programme that was perceived to privilege the pragmatism that Mitchell acknowledges.

3. Architectural education is in a sorry state

The draft INTERIM SYNOPSIS (Matthew, 1991) identified seven themes in the ‘ongoing debate about the education of Building Professionals generally and Architects in particular.’ These themes were supported by a list of references to recent articles and reports on the state of the industry and education. There were three themes that specifically relate to architectural practice. The first was the ‘need for increased skills in management and communication.’ The academic setting of most schools of architecture has always been a difficult place to practise the kinds of management skills required for the construction industry. The proposal argued that the proximity to existing Construction Management and Quantity Surveying courses and the ability to share elements of these courses with the Architecture degree programme constituted a better environment for significant learning in the management area. The penultimate theme spoke of;

active integration of professional experience with academic programmes and the reinforcement of the historical notion of Architect as master builder. (Matthew, 1991, p.1)

The first phrase was an appropriate statement of difference for this new programme. The reference to ‘the historical notion of Architect as master builder,’ however, seems awkwardly tacked on to the first part – an uncomfortable conflation of professional experience with a contested role. This notion may have owed its revival to an article that described the late Sir Ian Athfield’s experience of a recently completed, two-year Visiting Professorship at Victoria University of Wellington where he promoted this traditional model. Athfield’s quoted statements demonstrated his belief that;

sound building knowledge... is the key to architects earning the respect and place they expect in today’s building industry (Ross, 1989, p23).

Again the setting of an architectural degree programme within a polytechnic already teaching construction seemed to provide the opportunity to strengthen the relationship between design and construction. The master builder notion however has connotations beyond that person being the master of her/his craft and could be construed as romantic yearning for the notion of the architect as leader of the building team. This is perhaps why it sits so awkwardly in a proposal that argues for responsiveness to change.

The final background theme identified on the first page of the SYNOPSIS was ‘the “Building Team” approach.’ Again we can turn to the above-mentioned reference list that backgrounds these selected
themes. The 1989 *Architectural Review* Education issue contains a damning diatribe by Peter Buchanan titled (on its first page) WHAT IS WRONG WITH ARCHITECTURAL EDUCATION? On the second and facing page he replies to his own question ALMOST EVERYTHING. (Buchanan, 1989, p.24-25) Buchanan’s article begins with his statement that ‘Change of all sorts [list] has been rapidly transforming much of the building industry and its procedures.’ He accuses architectural education of not only refusing to take up the challenges brought about by these changes but instead ‘they are ignored as being compromising, even distasteful, in an idealistic flight into irrelevancy.’ In the changing building industry world of his dystopic vision ‘...the Architect is being reduced to simply another member of the building team.’ Buchanan also laments the lack of attention to the understanding of construction.

Both of these criticisms are echoed by Diane Ghirardo (1989, p.50) in another article in the same magazine. Ghirardo describes the ‘number of projects pinned up at the end of term with no reference to materials and structural systems’ as ‘staggering’ and argues for the necessity for architectural education to imbue an understanding of;

the craft of construction: hands-on experience, learning to work with and understand materials and teams of people to put up a building. (Ghirardo, 1989, p.50)

She expands this last team reference to include the necessity for students to understand;

architecture as an institutionalised practice set within a network of political, social, economic institutions. (Ghirardo, 1989, p.50)

Both writers are seen to reinforce not only the need for the sound construction knowledge that Athfield speaks of but also an understanding and engagement with broader roles within networks of construction practice, financial management and socio-political aspects of inhabitation and ownership in its broadest sense. The issues articulated by the writers of the SYNOPSIS (Matthew, 1991) are the same issues that permeate the writing in the AR Education issue. While we can identify them in this context as issues of the time we can also see that they are part of the ongoing discourse about how to construct a methodical and systematic course to learn about the discipline.

A similar characterization of ‘the crisis in architectural education’ occurs in Mark Crinson and Jeremy Lubbock’s (1994, pp. 180-183) history of architectural education in Britain. They identify the narrowing role of the architect as, increasingly, property developers and other professionals take over the role as leaders of the building team. They argue for broader access to an architectural design education so people from other disciplines such as civil engineers and traffic engineers might qualify and for a parallel introduction of multi disciplinary projects within the academy which privilege the construction and craft ethic of architecture. The opinions expressed in this publication might suggest that a trend towards the pragmatics of practice is a particularly British phenomenon but as mentioned above the American Ghirardo (1989) also takes this position as does the Australian Rory Spence (1989). The apparently contradictory trend towards an increasingly theorised architectural education is also present in discourse from the period. Templer (1990) and Mayo (1991) identify the pressures, globally, for research and publication to become part of accepted performance within Schools of Architecture. Necdet Teymur (1992, pp.23-31) articulates some of the issues around this new pressure in his chapter “Research in/on architectural education” where he discusses alternative modes of research and the newly evolving discourse on design as research. The overseas influence is complex and often contradictory.
4. Local ambition

But the aim to develop a degree programme was not just driven by overseas influence. As mentioned earlier the ambition arose from the local context with strong support from the local architectural profession. The draft INTERIM SYNOPSIS lists the planned consultation which includes the statement;

Architectural Advisory Committee to be reconvened and briefed with a view to obtaining both guidance and detailed input over the next 2-3 months. (Matthew, 1991, p.7)

The 16 person Committee was chaired by prominent Auckland Architect Tom Dixon and made up of members of architectural and associated professions in Auckland including John Sutherland (later to head the new programme), Professor R. Aynsley (Dean of the Faculty of Architecture, Property and Planning at Auckland University), Peter Rutland (Dean of the Carrington Faculty of Architecture and Design) and Lindsay Wood. (Supporting Document, 1994, p.26)

Wood seems to be the person who is most strongly associated with the academic development of the course. (If you speak to those around at the time, Lindsay Wood is the name that is the first to be mentioned.) This narrative is borne out by his listing as Programme Director of the Development Team, as joint Study Leader of Integration and his appearance as Strand Leader of Design Theory and Process, Integration and Negotiated Study/Electives. Wood had also been the developer and subsequently Leader of Bachelor of Building and Bachelor of Quantity Surveying Programmes. Academic Board minutes during 1991 and 1992 record his co-option to the Academic Standards Committee to assist with the degree development. His resignation from the Academic Standards Committee was tendered just before the first day of the first term of the new Bachelor of Architecture programme commenced. His role as leader of the Programme Development Team for these three degrees was done. Now came the task of putting those ideas into practice. But that is another story beyond the scope of this paper.

5. The Curriculum concept

5.1. The Drawing

We have already discussed some of the general themes identified in the original SYNOPSIS where the principal aim of the programme is to:

provide students with an effective academic foundation for Architectural practice and for ongoing personal and professional development. (Matthew, 1991, p.3)

The Curriculum Concept drawing, Figure 1, from the Definitive Document (1994, p.16), explains the intended relationships between the four study areas with the Professional Ideal (the imperative), Discipline Base (the skills and knowledge) and Practice (the processes) all coming together in the Integration Study Area where they are implemented through the application of Creativity, Holistic Design, Special Activities and [Negotiated] Studies, Professional Experience and “Building.” It is an art meets construction process list with Special Activities and Studies as the meat in this pedagogical sandwich. The proposal is for an architecture degree so there is a conventional logic that locates the art end of the spectrum above that of processes and pragmatics.

There are tables and charts setting out management structure and course study patterns but this is the only drawing in the Definitive Document. It could be read as a bubble diagram for a plan for a degree. It is the kind of diagramming style that was learnt in architecture schools internationally from
the forties to the seventies where they were considered ‘integral to design education’ (Eammons, 1998, pp. 420-425).

![Figure 1 Curriculum Concept drawing. (Source: Definitive Document, 1994, p.16)](image)

The central Integration bubble is constructed with the heaviest line weight and is punctured and pressured from the outside by the attendant Practice, Discipline Base and Professional Ideal bubbles. The Practice bubble seems to have the most impact distorting the Integration bubble into a kidney shaped vessel. But these walls do not hermetically contain. They are pressured and they leak. The authors of this weak-walled bubble diagram were conscious they wished to avoid the hermetic model that characterized the architectural education of their peers. They understood that to make good work you need strength to resist but, equally, they were inviting pressure and influence as co-habitants.

5.2. Special Activities

The bubble diagram communicates a process where integration of the attendant study areas is realized. Within the central Integration bubble Holistic design that harnesses creativity and engages with Professional Experience and “Building” is enriched by a category called Special Activities and Studies. There is an interesting contradiction in the formal inclusion of the Special Activities part of this category. The Special Activities strand, assessed on participation only and worth 3% of the total course credits, was an optimistic attempt to institutionalize those events that could constitute a rich architectural culture; exhibitions, debates, social events, conferences, seminars... The designers of this new degree structure wanted to;

Inspire and extend students and enrich their learning through involvement in a diverse range of planned and impromptu activities which are primarily experiential. (Definitive Document, 1994, p.134).

This attempt to formally embed this culture within the course structure could be construed as a failure of ambition or, at the very least, a lack of confidence in the ability of the core course structure itself to produce this kind of fertile architectural atmosphere.
5.3. Negotiated Studies

Negotiated Studies are part of this same grouping (Special Activities and Studies) within the Integration Study area. They could be considered to be the middle of the middle of the diagram. I would argue that this location is significant and that they are pivotal in the new programme structure. Negotiated Studies are identified in the Document as;

...a distinctive feature of the programme which promotes independent capability and provides scope for considerable flexibility in the development of individual study patterns.
(Definitive Document, 1994, p.136)

The words ‘independent capability’ are crucial here for they reflect an influence that grew out of the English discourse on education during the 1980s. Professor John Stephenson was the director and ardent promoter of Higher Education for Capability at the Royal Society of the Arts in the United Kingdom. Stephenson was in New Zealand in 1990 addressing that year’s HERDSA (Higher Education Research and Development Society of Australasia) Conference and was invited to run a half-day seminar at Carrington. The 1991 proposal and the 1993/94 Definitive Document both reference the Education for Capability movement and Stephenson himself. The Definitive Document (1994) specifically includes it in the section 3.0 PHILOSOPHY AND NATURE OF THE PROGRAMME as Part 3.7 Independent Capability.

The concept of Independent Capability is increasingly recognised as central to effective personal and professional performance. It combines competence with other qualities, such as the ability to work independently or in a team, to cope with uncertainty, and to explain to others what one is doing. ((Definitive Document, 1994, p.23)

The Pattern of Study section that follows reveals that the base-level Negotiated Studies required by the programme comprise 16% of total course credits. But a further 12 of the twenty design credits at levels 300 and 400 (Years 4 and 5) were negotiable giving potentially 28% of the course over to this study method.

It is clear that the trajectory to provide a situation for independent study, a kind of de-institutionalised format within an institution, comes out of the Education for Capability movement. But the large extent to which those principles are embedded in the curriculum indicates strong pedagogical belief in the outcomes possible from this form of study. The need for graduates who could work independently or in teams, could cope with uncertainty and talk convincingly about what they did was established early in the original SYNOPSIS (Matthew 1991) and the Definitive Document (1994, pp.11-14) but the method by which this could be achieved was less clear until the last pages of the Definitive Document which outline the potential extent of negotiated studies within the programme. This belief in this method of (individually, student directed and negotiated) enquiry permeates the proposed Architecture course structure.

Additionally, the Education for Capability campaign had a significant architectural ally in Donald Schon. His 1985 book The Design Studio, referenced in the original 1991 SYNOPSIS, was commissioned and published by the RIBA Building Industry Trust. The book strongly links the design studio approach outlined by Schon with the development of capability. In the preface Trust Chairman Keith Ingram advocates the wider use of the design studio teaching model to avoid the ‘polarisation of the arts and the sciences.’ He goes on to state;
Such an education produces young people with much greater all round capability, of great value to them and society. Such people are also just the kind that a diverse industry such as building needs in all its facets. (Schon, 1985, preface)

While the provenance of the Negotiated Study may be traced back to the influence of the Education for Capability movement, its real significance was that because of its extent it provided the potential for enormously diverse areas of study. Judicious and responsive negotiation between staff and student could have resulted in graduate cohorts with architecture degrees of widely differing composition. The principle of large areas of study available for negotiated enquiry introduces a component of uncertainty in the course. This degree of openness potentially moves the course away from being described as vocational (systematic, methodical, practice focused) and more towards that end of the spectrum usually characterised as broad, innovative and exploratory.

6. Conclusion

In 1991 two major local factors supported the establishment of a new degree in architecture in Auckland; the ability for polytechnics to offer degree programmes as a result of the 1989 Education Act and an architectural profession in search of a more practice focused graduate. The support from the NZ Institute of Architects and the issues raised in that original 1991 proposal, canvassed earlier in the paper, all point to the primacy of architectural practice. The principal aim stated in that proposal is;

...to provide students with an effective academic foundation for Architectural Practice and for ongoing personal and professional development. (draft INTERIM SYNOPSIS, 1991, p.3)

However, in March 1994 when the programme greets its first cohort of enthusiastic students the equivalent section in the Definitive Document records that:

The Primary Aim of the Bachelor of Architecture at Carrington Polytechnic is to provide society with accomplished graduates capable of ongoing effectiveness and adaptability both personally and (author’s emphasis) in the discipline and practice of architecture.  
(Definitive Document, 1994, p.11)

This change, this reversal in order evident between these two documents (draft INTERIM SYNOPSIS 1991 and Definitive Document 1994) is, I believe, a result of the development of the Negotiated Study, in this period. The Negotiated Study was seen as a means to provide opportunities for students to independently develop a personal and particular relationship with the discipline driven by their own interests; 'students are encouraged to assemble distinctive individual patterns of negotiated study" (Definitive Document, 1994, p.137). The list of six aims for the Negotiated Study area in the Document link it to the acquisition of skills of initiative, negotiation and critical enquiry. But embedded in this list there is a more powerful idea of the impact of Negotiated Study upon the course. Number 5 aimed;

To enrich the academic programme generally though direct and indirect feedback from the diversity of negotiated studies. (Definitive Document, 1994, p.136)

It is clear that the developers of this programme saw the Negotiated Study as that course element most capable of producing both individual and collective benefits. They saw it as a means not only of developing individual capability to enquire, act and reflect but also that it contributed to a broadened, a diversified programme of architecture study. Hence in the 1994 Definitive Document we have the Primary Aim locating those core skills in the foreground.
The Primary Aim of the Bachelor of Architecture at Carrington Polytechnic is to provide society with accomplished graduates capable of ongoing effectiveness and adaptability both personally and (author’s emphasis) in the discipline and practice of architecture. (Definitive Document, 1994, p.11)

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Economic benefit of increased architectural involvement and design quality on the improvement value of prime commercial assets

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Abstract: A quantitative and qualitative analysis, measuring the relationship between Architectural Involvement, Design Quality and the Improvement Value of Sydney’s Prime Commercial Assets. A sample 12 projects from prominent domestic and international architects are selected and assessed for design quality and compared with existing and publically available property valuation, construction and design fee information. The indicators were then compared to establish correlation between Architectural Involvement and Design Quality against the Improvement Value of the Asset. Correlation was measured through the existence of any linear relationships by correlation coefficient.

Keywords: Architectural; quality; value; fee.

1. Key Findings

As expected, a greater the level of architectural involvement, in the development of Prime Commercial Assets, results in an increased improvement value for asset owners. Similarly, the greater the architectural design quality, the greater the improvement value. This is however in contrast to architectural design fee and design quality comparisons, whereby a negative relationship is exhibited. That is, the greater the level of architectural fee, the lower the design quality. Based on the data set, encompassing 12 of Sydney’s prime central business district commercial assets, the key outcomes of this analysis is as follows;

- There is a clear, positive correlation between architectural fee and the improvement value of assets;
- There is a clear, positive correlation between architectural design quality and the improvement value of assets; and
- There is a clear, negative correlation between architectural fee and design quality.

This infers that whilst Commercial CBD developments aspire to both high value and high architectural design quality, paying a higher design fee may not necessarily achieve both outcomes.
This may be because those architectural practices deriving lower architectural fees, potentially as a result of lower overheads are achieving greater levels of design quality through a focus on innovative design, and maintaining competitiveness.

2. Research Problem

Within the local context, generally accepted standards for defining, measuring and valuing architectural design quality are diverse and fragmented. There is currently little available evidence that draws a link between architectural design quality and the valuation of assets. The lack of clearly defined criteria for design quality in the built environment does not adequately encourage investment in architectural excellence, innovation in construction and environmental sustainability.

This has resulted in the short-sighted, box-ticking approach to architectural design quality and value for money by developers and commissioning bodies. Demonstration of the added value of good design is inherently complicated. The contextual issues that have led to this research include;

- Lack of data available on the provision and economic value of architectural services outside broader macro industry data;
- Inadequacies in current valuation methodologies and quality rating systems to adequately provide the framework under which design excellence can be fulfilled;
- The subdivision and erosion of a traditional scope of architects services;
- Increasing specialisation of architectural services (building types and services) versus the perceived value of an architect’s training; and
- Industry assumption that design excellence means high quality assets thus higher returns.

3. Methodology

Existing data has been collated for a sample of 12 Sydney Prime Commercial Assets (“the Sample Assets”). The Sample Assets were selected on the basis of their variety in completion dates, architectural design quality, levels of architectural involvement and project value (>100mil). The Sample Assets were derived from a variety of well-established Australian property groups who had engaged the services of prominent domestic and international architectural firms. A listing of the Sample Assets is shown in Table 1 below.

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample Assets</th>
<th>Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>1 Bligh Street, Sydney</td>
<td>2011</td>
</tr>
<tr>
<td>2.</td>
<td>Barangaroo South Building C4, Sydney</td>
<td>In progress</td>
</tr>
<tr>
<td>3.</td>
<td>Barangaroo South Building C5, Sydney</td>
<td>In progress</td>
</tr>
<tr>
<td>4.</td>
<td>Darling Quarter, 1 Harbour Street, Sydney</td>
<td>2011</td>
</tr>
<tr>
<td>5.</td>
<td>161 Castlereagh Street, Sydney</td>
<td>2013</td>
</tr>
<tr>
<td>6.</td>
<td>40 Mount St, North Sydney</td>
<td>2010</td>
</tr>
<tr>
<td>7.</td>
<td>30 The Bond, 30-34 Hickson Road, Millers Point</td>
<td>2004</td>
</tr>
<tr>
<td>8.</td>
<td>126 Phillip Street, Sydney</td>
<td>2005</td>
</tr>
<tr>
<td>9.</td>
<td>52 Martin Place, Sydney</td>
<td>1996</td>
</tr>
<tr>
<td>10.</td>
<td>200 George Street, Sydney</td>
<td>In progress</td>
</tr>
<tr>
<td>11.</td>
<td>No.1 Martin Place, Sydney</td>
<td>2001</td>
</tr>
<tr>
<td>12.</td>
<td>1 O’Connell Street, Sydney</td>
<td>1991</td>
</tr>
</tbody>
</table>
Actual project costings and publically available valuation data was compared to establish correlation between Architectural Involvement and Design Quality against the Improvement Value of the Asset. Correlation was measured through the existence of any linear relationships by correlation coefficient.

![Project Selection > Data Collection > Correlation Modelling > Drawing of Inferences](image)

Figure 1: Process Methodology.

Rigorous control measures have been implemented to ensure quality and consistency of the data including adjustments, escalation and exclusions. This has involved independent quality assurance reviews and benchmark testing of construction cost, fee and valuation results.

Any inconsistencies regarding the basis of valuations, construction costings and architectural fees were reconciled where possible. Refurbishments or refurbished components are excluded from this analysis. These components are assessed on the following basis;

### 3.1. Level of Architectural Involvement

Architectural Involvement is measured by architectural fee as a proportion of the construction cost (as a percentage) as at the date of the contract. The level of architectural involvement for each of the Sample Assets is deemed to be comparable, with fees categorised into the following project phases;

- Development Application;
- Construction Certificate;
- Construction Documentation;
- Construction Attendance; and
- Defects Close Out.

The Sample Assets have been compared on an all-inclusive fee basis. Approved variations, fees both pre and post consultant novation, for both in-house and external architectural consultants are included in the calculation of architectural fees.

Fee information has been sourced from a variety of project consultancy agreements, final progress claims and architectural invoices.

An assessment by fees split by project stage, or the levels of claimed / approved fee variation are not considered in this phase of the research.

### 3.2. Design Quality

The assessment of Design quality is based on the designer’s ability to address the site constraints from first design principle for the best outcome, relative to the developers brief. The existing Property Council Australia Innovation and Excellence Award assessment criteria and International Standard 15686-5:2008 Whole of Life were utilised as both robust and existing frameworks.

An independent analytical framework, based on these existing assessment criteria was then developed to assess the direct (economic) and indirect (social and environmental) benefits that good
design can contribute. The following attributes were identified to play a significant role in adding economic value to commercial assets:

<table>
<thead>
<tr>
<th>Design Attributes</th>
<th>Weighting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rental values - Producing high returns on investments</td>
<td>5%</td>
</tr>
<tr>
<td>Sustainability</td>
<td>5%</td>
</tr>
<tr>
<td>Placing developments above local competition at little cost</td>
<td>5%</td>
</tr>
<tr>
<td>Excellence and integration of landscape design</td>
<td>5%</td>
</tr>
<tr>
<td>Interior quality</td>
<td>5%</td>
</tr>
<tr>
<td>Tenant efficiency (layout, circulation and escape routes)</td>
<td>5%</td>
</tr>
<tr>
<td>Helping to deliver more NLA</td>
<td>5%</td>
</tr>
<tr>
<td>Workplace productivity</td>
<td>3%</td>
</tr>
<tr>
<td>Supporting the 'life giving' mixed use elements in development</td>
<td>3%</td>
</tr>
<tr>
<td>Spatial Renewability / Flexibility</td>
<td>4%</td>
</tr>
<tr>
<td>Facilities Management cost saving</td>
<td>4%</td>
</tr>
<tr>
<td>Operation cost</td>
<td>2%</td>
</tr>
<tr>
<td>Overall savings on rent and occupancy level</td>
<td>2%</td>
</tr>
<tr>
<td>Accessibility</td>
<td>2%</td>
</tr>
<tr>
<td>Lobby / Foyer</td>
<td>4%</td>
</tr>
<tr>
<td>Addressing the Character of the surrounding</td>
<td>4%</td>
</tr>
<tr>
<td>Access to views, daylight and fresh air</td>
<td>3%</td>
</tr>
<tr>
<td>Internal courtyard</td>
<td>3%</td>
</tr>
<tr>
<td>Façade compositions of neighboring buildings / surrounding</td>
<td>3%</td>
</tr>
<tr>
<td>Identity / civic pride</td>
<td>6%</td>
</tr>
<tr>
<td>Place vitality</td>
<td>6%</td>
</tr>
<tr>
<td>Inclusiveness</td>
<td>6%</td>
</tr>
<tr>
<td>Connectivity</td>
<td>5%</td>
</tr>
<tr>
<td>Vertical Village</td>
<td>3%</td>
</tr>
<tr>
<td>Total</td>
<td>100%</td>
</tr>
</tbody>
</table>

3.3. Asset Valuation

Property Valuations are derived from a combination of publically available valuation reports, investment property trust Annual Financial Reports and recent transactions occurring at arm’s length. CBRE’s National CBD Capital Value index is utilised to escalate capital values to 31 December 2014 for comparative purposes. Valuations had been escalated on the basis that the assets have been maintained in accordance with the design specification and the relevant standards. No allowances have been made within the current estimates for the following:

- Lease expiry profiling;
- Macro-economic factors;
- Changes in design trends and tenancy requirements; and
- Asset Condition.
3.4. Unimproved Capital Value

Land Values are derived from the New South Wales (NSW) Valuer Generals Unimproved Capital Values provided by Land and Property Information (LPI). Land Values are publically available and represent a broad range of sales comparable to reflect the subject property value as at 1 July 2014 in the valuing year for that entire financial year. The median of that period of assessment, being 31 December 2014 is adopted for the purposes of this assessment.

3.5. Improvement Value

The Improvement Value is derived from the Asset Valuation (Section 3.3) minus the Unimproved Capital Value (Section 3.4). The improvement value represents the value of buildings, other structures and any relevant public domain assets.

3.6. Construction Cost

Construction Costs were sourced from a variety of final progress claims, contract prices, depreciation capital allowance and insurance replacement cost assessments. Construction Cost values are adjusted to include approved variations and to remove demolition cost, remediation cost, sitewide infrastructure costs and contingency allowances. Construction Costs are escalated using Rider Levett Bucknall’s Tender Price Index.

3.7. Improvement Value: Construction Cost Ratio (IV:CC)

The metric for assessing the Improvement Value for the sample projects is the Improvement Value: Construction Cost (IV:CC) ratio. The Improvement Value divided by the adjusted Construction Cost reflects the value of the physical assets as a proportion of the cost to physically construct the said asset, escalated to the 31 December 2014 for consistency in each comparison.

\[ IV:CC = \frac{\text{Asset Valuation} - \text{Unimproved Capital Value}}{\text{Construction Cost}} \]

52 Martin Place, Sydney and 1 O’Connell Street, Sydney have been excluded from the IV:CC calculations as the current day valuations are not reasonably comparable with the more recent Sample Assets. This is because the remaining effective life and asset condition progressively diminish as the buildings age.

4. Design Quality

Within the Australian property market, the “the quality of assets are typically measured under Property Council of Australia for Commercial Office Standards. This type of analysis is bound by the physical attributes of the assets as opposed to the particular qualities of the asset in relation to its urban context. In 1999 the property Council of Australia undertook a “Design Dividend” research to test whether design excellence translates to high financial returns. The research concluded that design excellence does not cost more to construct than the industry norm, and the design fee component did not vary greatly from industry standard. There was also little evidence that better design took longer to build.

The commercial sector is driven by strict profit calculations, putting considerable pressure on the cost-efficiency of the project.
MacNeil (2005) argues, architectural design value added are reflected in higher rents including brand enhancement, workplace productivity or retention of skilled employee through the communication of the firm’s status.

It is suggested that International architecture firms are engaged as a means of lubricating the planning approval process, especially in sensitive urban contexts. Allegedly, international architects add value through the reconciliation of urban context and architectural typology with commercial development rationalities and in the letting of interior space of the building to prospective tenants (MacNeil, 2005, p487). The study by Fuerst et al (2010) has shown that, compared with building in the same submarket, office buildings designed by signature architects have received 5%- 7% higher rent, and sell for prices 17% higher.

However, this research does not distinguish between high quality architectural design as a result of the involvement of international architecture firms. While good office design can deliver higher performance and greater longevity, the greatest value is created by the totality of the place itself and its correlating desirability. Of the 24 drivers of design quality for Prime Commercial CBD Assets, the following 7 attributes have been identified as key:

- Integration of landscape design;
- Vertical village;
- Place vitality;
- Identity and civic pride;
- Lobby / foyer finishes;
- Workplace productivity; and
- Floor layout, efficient on-floor circulation and logical travel routes.

This analysis implies that higher architectural fees do not necessarily exhibit higher quality spaces even though they may comply with City of Sydney Design Excellence under Sydney Local Environmental Plan 2012. While design excellence itself cannot secure a higher rental yields, poor place vitality can still result in a financially successful project, it is evident that the seven drivers of design quality facilitate the asset’s likelihood of achieving higher financial returns in the longer term as a result of high design quality. Table 3 demonstrates attributes that can have a negative influence on the perceived quality of commercial asset.

<table>
<thead>
<tr>
<th>Asset</th>
<th>Negative perceived attribute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barangaroo Tower 2 Sydney</td>
<td>Close proximity to proposed residential towers – risk to asset value due to loss of view and daylight.</td>
</tr>
<tr>
<td>Barangaroo Tower 3 Sydney</td>
<td>Base building and tenancy finishes and fabric creating inconsistencies with the overall project brief.</td>
</tr>
<tr>
<td>200 George Street Sydney</td>
<td>The design not achieving the minimum NLA and efficiencies as required by the developer. The lobby finishes not achieving PCA premium specification</td>
</tr>
</tbody>
</table>
Due to the commercially sensitive nature of the Design Quality Information, the Sample Assets have not been identified at this time.

5. Level of Architectural Involvement

There are a multitude of factors that impact upon the fee derived by an architectural firm for a project. RAIA Advisory Notes (2001) guides practitioners to build-up their fee quotation based on the estimated hourly resource, personnel and their applicable dollar rates required to deliver a project, in addition to overhead requirements and estimated levels of productivity within a work breakdown structure. The RAIA Advisory Published Fee Guides then serves as a check-method, providing information as to the range of fees that might be applicable.

It today's market, there is little consistency in fee outcomes on major commercial projects. Wider macro-economic factors and competition between architectural firms substantially influence fee quotations at any given time. The scope of services included or offered as optional extras also vary, as well as the approach to the provision of the design and documentation. The complexity of the project and the level of prominence and prestige also has an influence.

Recent times have seen a shift from traditional engagement of architectural services, i.e. the architect is engaged directly to the developer, to the novation of the architect under a Design & Construct contract arrangement i.e. the architects engagement is passed on to the contractor. According to Greenwood (2008), at the start of the 21st Century, architects find themselves in a world in which development is trending towards contractor-led coalitions, having significant implications for fee levels and the profession as a whole.
6. Results

The Sample Assets display a positive linear relationship between both Improvement Value and Architectural Design Fees; and Improvement Value and Design Quality Scoring. Correlation between Design Quality and Architectural Designs Fee is however inconclusive. The strength of the linear association between the variables is measured through by correlation coefficient. A correlation coefficient of +1 indicates a perfect positive correlation, a correlation coefficient of -1 indicates a perfect negative correlation and a correlation of 0 indicates no correlation. P-value hypothesis testing to quantify the significance of results has not been undertaken in this phase of the research.

Due to the commercially sensitive nature of the construction cost and architectural fee detail, the Sample Assets are not been identified within this results section.

6.1. Level of Architectural Involvement Relative to Improvement Value

There is a positive linear relationship between the Level of Architectural Involvement, measured by Architectural Fee and Improvement Value for the 10 relevant Sample Assets (52 Martin Place, Sydney and 1 O’Connell Street, Sydney excluded). The variables display a correlation coefficient of 0.284, a low positive correlation, indicating that an increased level of Architectural Involvement may cause an increase in the Improvement value for Sydney Prime Commercial CBD Assets.

![Figure 3: IV:CC Ratio vs. Architectural Design Fee (%)](image)

6.2. Design Quality Relative to Improvement Value

An equally positive linear relationship exists between Design Quality and Improvement Value for the 10 relevant Sample Projects. The variables display a correlation coefficient of 0.288, a low positive correlation, indicating that an increased Design Quality may cause an increase in the Improvement value for Sydney Prime Commercial CBD Assets.
Figure 4: IV:CC Ratio vs. Design Quality Scoring (weighted).

6.3. Design Quality Relative to Level of Architectural Involvement

Interestingly, there is a demonstrated negative linear correlation between Architectural Design Fee and Design Quality. When comparing the 12 Sample Projects, the variables display a correlation coefficient of -0.444, indicating that a higher Architectural Fee can cause a reduced Design Quality for Sydney Prime Commercial CBD Assets.

Figure 5: Architectural Fee vs. Design Quality Scoring (weighted).
7. Conclusions

This research provides a framework for assessing the relationship between the Level of Architectural Involvement, Architectural Design Quality and Asset values. It has addressed how Architectural Design Quality is measured and the impact of varying levels of architectural involvement on asset value.

Significantly, this research has concluded that higher architectural fees do not necessarily exhibit higher quality spaces. There is no apparent correlation between high quality design as a result of the involvement of international architecture firms. It suggested that whilst Commercial developments aspire to both high value and high architectural design quality, procuring greater levels of architectural involvement may not necessarily achieve both outcomes.

The outcome promotes the value of increased designer continuity, the ultimate implication being, traditional design services procurement results in a better outcome than design and construct (D&C) type procurement.

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Educational architecture and architectural education: through Dar al-Fonun to Iranianised modern universities

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Abstract: The European impact upon modern educational buildings started with the establishment of the Dar al-Fonun in 1851 and flourished in the architecture of the University of Tehran in the 1930s. In the late Pahlavi period in the 1960s and the 1970s, international styles were dominant in the architecture of university buildings. The first signs of returning to local vernacular forms and materials can be traced from the early 1970s. Regionalism started to shape the architectural mainstream of Iranian universities since then. This paper aims to trace the main architectural stylistic features in Iranian higher education buildings in the last two centuries. To provide a clear understanding of this, the first Iranian modern college, the first (European-style) Iranian university and a number of subsequent university buildings are chronologically studied to identify and categorise the prominent architectural styles in conjunction with main upheavals in architectural education in the past two centuries. The architecture of selected university buildings of this period exemplify both modernising and localising approaches toward which the pendulum of Iranian higher education architecture has swung.

Keywords: University building; architectural education; regionalism, Iran.

1. Introduction

‘Through its physical estate, a university can reinforce the high ideals of scholarship and institutional values to create a unique and defining sense of place’ (Coulson et al, 2011). Through educational buildings, and university buildings in particular, secular and modern education were brought to Iranian society and locally trained Iranian architects had the opportunity to learn from these buildings, which were intended to represent the most progressive ideal architecture of the time. Higher education buildings promoted and accelerated architectural changes in society. The transformation from traditional educational buildings in the early nineteenth century to modern university buildings in the turn of the millennium are discussed in this study. Educational buildings are treated in a chronological order to convey the evolution of their architectural styles. In the following, the transition from the traditional structures, such as Maktabkhanehs and madrasas, to secular ones, such as modern colleges
and universities, is shown to project how the process of the transformation from eclectic Irano-Islamic buildings of the nineteenth century to abstract concept-based ones of the late twentieth century came about.

2. Maktabkhanehs and madrasas

Porter (1821) said that education in Persia was ‘far from being neglected by any class of the people’.

All persons of high rank have their children instructed by moullahs [religious instructors], and other preceptors, who attend their pupils at the houses of their parents. The lower orders, and often the considerable Persians, who are under the condition of nobles, send their sons to the public schools; which are planted in every town. They are commonly held in the mesjids [mosques], and sometimes in the houses of the teachers, who are mostly moullahs (Porter, 1821).

That is why almost no Iranian secular school in the early nineteenth century was recorded in foreigners’ accounts or in official reports. The education was religiously based, and was imparted either in religious spaces, such as mosques and madrasas, or in private spaces, known as Maktab or Maktabkhaneh (which were usually integrated in the houses of the religious teachers), in which ‘the scholars sit round their master on the matted floor all conning their lessons aloud’ (Porter, 1821).

Madrasas were the higher level for Maktabkhanehs to provide further studies, and they usually had a mosque built next to them. Beside Islamic teachings, madrasas covered a wide range of purposes when there were no hospitals, modern observatories and modern schools in Persia in the first half of the twentieth century (Bayani, 1972). As Daniel (1897) points out, to reach the highest level of education (Mujtahed) in madrasas, students had to further their Shia Islamic studies in Iraq.

3. Dar al-Fonun: the first secular college

Mirza Taghi Khan Farahani (Amir Kabir) was the mastermind behind the establishment of the first secular college in Iran, the Dar al-Fonun. Amir Kabir ordered Sir Davoud Khan to recruit German or Austrian instructors in preference to British, Russian, or French so as to prevent the increasing influence of those European powers upon the Persian government (Haghighat, 2007). By the time one Italian and the six Austrian teachers arrived at the Dar al-Fonun in November 1851, Amir Kabir was no longer in power. There was some hostility toward this modern technical school posthumously. Although the Dar al-Fonun was not strongly supported by his successors, the provided possibilities for members of royal family to study in a modern school sustained and strengthened the situation of the Dar al-Fonun to be supported by the government for about a century. The college later became a place for improving royal arts such as painting and, in particular, photography, which was one of the main interests of Naser al-Din Shah, and the technical and military aspects, which were Amir Kabir’s main purposes in establishing the college, became less importance than the artistic aspects. There was no course in architecture in the curriculum of the Dar al-Fonun during the Qajar period, and that is why the main upheavals in style of Naseri buildings are due to the revolution in other arts, like painting, rather than architecture itself. Therefore, for understanding the influence of the establishment of the Dar al-Fonun, as a modern institute, on Persian arts, it worth studying briefly the situation of Qajar painting, as one of the most important artistic aspects of Qajar buildings.
4. Dar al-Fonun: promoting European art

Wall painting was always a narrative means for their ambitions, dreams, and beliefs. Painting was mainly used in Qajar architecture for decorating walls while Qajar tilework was also affected by painting. During the second half of the seventeenth century, a number of Iranians sent to Italy to learn the techniques of European painting. There are different opinions as to whether Safavid painters were taught in Iran by European teachers or studied in Europe. However, there is no doubt that there were some Iranians in Italy during the late seventeenth century studying painting. They were sent by the Christian Armenian community in the Julfa district in Esfahan to learn religious paintings required for Armenian churches, and probably by the second Safavid Shah Abbas. Safavid rulers became fascinated by European paintings brought by European travellers into Iran. Oil painting firstly emerged a result of the increased relationship between the Safavid dynasty and the European countries during the seventeenth century, and oil wall painting was first used in Iran in the second half of the century. The pictorial wall paintings were not only ornamental elements in their palaces, but also narrating the victories of the Iranian rulers in the battles, hunting scenes, their portraits, and also important events (Utaberta et al., 2011). Displaying paintings with the subject matter of violence and killing enemies was not by chance. The main purpose was to impress the visitors with the power of the dynasty. The use of these themes continued until the second half of the nineteenth century. The Western influence on the early Qajar paintings was only the oil technique, which was indirectly derived from Europe through Safavid paintings, and the main themes and subject matters in this era were quite Iranian. A group of forty-two Iranian students were sent to Europe in 1859, which had been the largest group by the time (Mohseni and Saradehi, 2011). Austrians and trained Iranians in Europe were the first teachers in this European based academic system. Until the late nineteenth century, ‘There was no distinction between the fine arts and the decorative arts as there was in Europe’ (Mohseni and Saradehi, 2011). Artists were trained traditionally, and they worked as members of their guilds. Naser al-Din Shah was a key factor in the advancement of new arts. The emergence of photography was coincided with the first decade of the Naseri period. He was considerably keen on photography as he himself took about 20000 photos out of 40000 photos of his collection in the Golestan Palace. Painting was also interesting for him, and he had a regular yearly visit of the Dar al-Fonun to check the students’ works and new achievements. A strong tendency toward the West led traditional architects to think of creating a sense of being European in buildings, but they did not have the necessary tools and also necessary academic knowledge even for duplicating European buildings. All they had for their inspiration was an ambiguous image of the West illustrated on postcards, wrappings, and any imported goods such as even soap covers which might convey a pattern, a scene, or a view of a European building. Painters amongst the team of decorative artists for a building were in a better position in rather than other traditional artists because of the possible chance of studying either abroad or in new established colleges.

5. Dar al-Fonun: architecture

In the Dar al-Fonun, all the classrooms were arranged around the central courtyard (Karimian, 2002), which was not an unfamiliar way of the organisation of spaces, but the Western influence was in the means of access to the classrooms from the corridor behind. However, architectural elements of the college remained Qajar in design, as the gables, arches and openings. The geometrical pattern used in the design of the pathways in the courtyard is European as well. Like St. Peter’s Square in the Vatican City, a cross and a saltire superimposing on each other were used unprecedentedly in the design of the courtyard of Iranian building, instead of following chahar bagh (literally means four garden) Persian...
order. The Iranian architect Karim Teherzadeh Behzad, studied at the Istanbul Academy of Fine Arts and then the Berlin Academy of Architecture, left Germany and returned to Iran in 1926, despite getting admission to PhD in architecture in Polytechnic University in Berlin. Behzad’s proposal for the establishment of an architecture school was accepted (Shafei et al., 2006). However, the architectural programmes did not last more than a year and a half, for there was no longer any financial support from the government, seeing no priority in educating architects while having lots of uneducated traditional ones available. Nikolai Markov, a Russian architect, and Teherzadeh Behzad seem to have been the only architecture teachers at the Dar al-Fonun College at the time of the first intake of Iranian students in architecture in 1927, according to an announcement in the Ettelaat newspaper (24 September 1927). Markov diverged from Qajar architectural characteristics in his work during the reconstruction and renovation of the Dar al-Fonun in 1929. Here, he had no opportunity to blend a European plan with an Islamic elevation, as in his other works, but the combination of different Irano-Islamic architectural elements, ranging from the pre-Islamic to the Safavid period, is characteristic of his eclectic style. Behzad and the French architect Roland Dubrulle later proposed a programme for the reestablishment of architecture course, this time, in the Fine Arts School, which was successful (Shafei et al., 2006). The architecture classes were later transferred to the Higher Academy of Arts (Shafei et al., 2006), and finally to the Faculty of Fine Arts of the University of Tehran in 1940.

6. The University of Tehran

The impact of the Beaux-Arts and then of the Bauhaus School is apparent in the architecture of the University of Tehran during the first half of the twentieth century designed by the European trained architects André Godard, Maxime Siroux, and Mohsen Forughi. The Faculties of Literature and Humanities, Science, and Law in the University of Tehran are examples of the use of European architecture by Mohsen Forughi, the Beaux-Arts trained Iranian architect. The classic modern style of these buildings, in which there is no sign of decorative details of European classical styles, is reminiscent of the Palais de Chaillot built for the Exposition Internationale of 1937 in Paris. The use of this type of Stripped Classicism in Iran was most characteristic of government buildings in the 1930s, of which all of the architects were of course European-trained. In the Faculty of Fine Arts, designed by the French architect Roland Dubrulle and the Persian American architect Eugene Aftandilian (Masoud, 2009), the influence of the Bauhaus style can be seen. The faculty apparently differs from its other contemporary faculties in the campus in which, instead, the architectural system of Beaux-Arts classicism were used. Function seems to have been the main concern of the architects, and the appearance of the faculty rather contradicts with its title, as the building does not have much to say about Fine Arts. Unlike traditional Iranian educational architecture in which a central courtyard provided an isolated place for contemplation, university campuses of the twentieth century in Iran were designed to fit in a grid. The idea of courtyard, however, was revived in the planning of some universities in the late twentieth century, such as Imam Khomeini International University.

7. A shift towards Irananity through firmly established European-based architectural education

While apprenticeship in the office of practising architect had been the most common way of becoming a professional architect in Europe and United States, The École des Beaux-Arts (School of Fine Arts) established in 1819 was a unique academic institution in Europe which had no parallel in the nineteenth century (Watkin, 1986). The prestige, continuity and high seriousness of the architectural education
system made France a centre of new architectural debates during the eighteenth and nineteenth
centuries (Moffett *et al*., 2003). Therefore, a number of foreign students were attracted to the school
and, after returning to their home countries, created local variations on the Beaux-Arts curriculum. The
flexibility of the method of composition which was taught in the school institutionalised a group of
styles instead of being limited to one particular style, and ‘Beaux-Arts’ denotes not a style, but a number
of techniques which helped to design in an appropriate way after a century of architectural turmoil
(Zanten, 1977). Compared with European countries, Iran fell far behind in modern education of
architecture. The first architecture schools in Iran were established in the second quarter of the
twentieth century long later than those in the West. For example, Germany alone had near forty schools
of architecture in 1876 (Blake, 1867). Beaux-Arts methods were abandoned by avant-garde architects
with the advent of modernism in the early twentieth century (Moffett *et al*., 2003). However in Iran,
Beaux-Arts influence was mainly reflected in the educational architecture during the first half of the
twentieth century when European trained architects were commissioned to design modern schools and
university buildings across country. Amanat (2013) describes a shift in architectural education towards
learning from Iranian architecture by site visits, initiated by Seyhoun in the mid-1960s (Tiven, 2013).
This approach in architectural education, focusing on the local architectural heritage, must have
accelerated the emergence of a regionalist trend amongst Iranian architects in the 1970s and
subsequent revivalist movements.

8. **International style is fading away**

By the early 1960s, a group from the University of Pennsylvania had outlined the first pedagogic
programs for Shiraz University (known as Pahlavi University before 1979), and Minoru Yamasaki had
been selected as the main architect (Kooros, 1962). This high-rise dormitory with long ribbon windows
and concrete slabs on its facade, designed by the architect of World Trade Center towers (Darton, 1999),
on a foothill of the university campus, remained unfinished for some time after the Islamic Revolution in
1979. The modern concrete student residence in Shiraz resembles another work of Yamasaki: the Pruitt–
Igoe blocks which were demolished about twenty years after its construction in 1954. This marked the
symbolic failure and the end of modern architecture according to Charles Jencks (1984). By the mid-
1970s, international styles had lost their popularity in Iran as well.

Despite the astonishing view overlooking the city of Shiraz and the neighbouring gardens below, the
dismay of today’s Iranian students at their outdated modern residence is apparent, and a tradition of
strange harassing behaviour has been established in this building by which new residents or visitors are
welcomed by a falling plastic bag of water from the upper storeys. In international styled box buildings,
the physical characteristics seem to have intensified social misbehaviour, not the social variables

The international style of modern architecture of the Iranian universities during the 1960s was
supplanted by an emerging trend of revivalism in the early 1970s which aimed to return to native
architectural elements.

9. **Regionalism, action!**

The process of the localisation of the university buildings first can be seen in the 1970s, when
regionalism suddenly became the main architectural theme. Nader Ardalan’s regionalist work built in
1972, the Centre for Management Studies with Harvard University in Tehran, was a turning point in
Iranian architecture during the last century. He created an ensemble of neo-vernacular buildings
meeting specific requirements of the brief and yet invoked Safavid architectural language in the geometrical patterns of the design. The courtyard and the pavilion in Persian gardens inspired him. Ardalan still admires the use of courtyard in architectural practices across the world, and he strongly believes in the necessity of reviving them even in the multi-storey apartments, like Moshe Safdie’s Habitat 67 in Montreal (Ardalan, 2014). Ardalan committed himself and his team in the use of local materials and techniques in design of what has been known since 1979 as Imam Sadegh University. Ardalan’s local solutions to the modern demands of the government opened up a wide range of possibilities of regionalism for the next generations of Iranian architects. It is quite difficult to find evidence of modernism in his work, and a spiral staircase in the central hall of the library seems to have been the only use of modern architectural language as discussed in A Critique of Contemporary Iranian Architecture (2007). Tehranian (2004), like many other political researchers, attempts to relate architectural movements to the most powerful figures of government. Upon this basis, Reza Shah would have been responsible more than anyone else for the neo-Achaemenid style during the 1930s and the Prince Farah Diba for the Irano-Islamic revivalism of the 1970s. Tehranian surprisingly names Ardalan’s Centre for Management Studies as an example of this. Ardalan’s biography demonstrates the consistency of his architectural practice and theory, and his book with Laleh Bakhtiar: Sense of Unity (1973) shows how influential he was in introducing and defining the notions of geometrical symbolism in Islamic, Iranian architecture. Therefore, positioning Ardalan as a subaltern architect, as does Tehranian in attributing this ‘new turn’ to Farah, seems quite illogical. Tehranian (2004) clarifies his point of view by referring to a proverb that ‘people emulate the style of their rulers’ and without presenting any evidence surprisingly concludes that ‘the Iranian upper and middle classes have similarly adopted the imperial or Islamic style in their personal homes and consuming identities’. In fact this was not the case, as the buildings commissioned by the private sector and even by Reza Shah himself, such as his palaces, were not Neo-Achaemenid, but eclectic, European, or modern. This gap between the architectural styles of officially commissioned buildings and the residential and commercial work of the private sector is apparent in also other periods, such as after 1979. Architecture was not necessarily the sole result of ideological stance of the Iranian governments in the twentieth century, and it was shown that other factors such as upheavals in architectural education and the presence of western trained architects in Iran were also (if not more) operatively important in shaping architectural movements (than rulers’ desires). The International Style ‘failed to meet human cultural demands, or to address the climatic and environmental issues, which became even more important in the late 1970s, when the price of energy increased significantly (Hassan Pour, 2013). In addition, the emergence of localising approaches in the architectural education of Tehran University in the mid-1960s and the successful works of Iranian architects, such as Amanat’s monument at the Azadi Square, in introducing innovative Iranian architecture opened up new horizons in modernising Iranian architecture in the early 1970s and paved the way for its spread over the subsequent decades.

The main regionalist trends in Iranian university architecture can be divided into three main streams imitative/imported regionalism, iranianised regionalism and innovative regionalism. These are described below.

9.1. Imitative/imported regionalism

The subtraction of circles from the brick cubic forms in Jondi Shapour University by Kamran Diba is a reminder of Louis Kahn’s Indian Institute of Management in Ahmedabad, India. A comparison between the other buildings of the Jondi Shapour University and other works of Kahn reveals further connections.
Kahn’s Phillips Exeter Academy Library in New Hampshire, completed in 1972, was probably the main inspiration for Diba in the design of the Administration Building of Jondi Shapour University.

Designed by Moghtader and Andreef Architects, yellow brickwork embellishes parts of the central library of Shiraz University and creates a contrast with the concrete fins between the windows. The local decorative element does not affect its dominant late-modern monumental character. Brutalist architecture was fashionable at the time, and the style was common in university buildings in the third quarter of the twentieth century. Another work of Moghtader and Andreef Architects is the restaurant of the campus. The pitched roofed arcade in front of this building in its use of old familiar forms in a modern way recalls the way in which the modern concrete vaults characterised the Kahn’s Kimbell Art Museum in Texas.

Amanat in Sharif Technical University in 1975 displays his artistic sensitivity in the creation of ambiguous motifs in the brick relief on its plain homologous brick background. They seem quite innovative in design. The brick relief at the entrance of a school near Stockholm, Sweden, however, indicates that the use of these artistic brick reliefs in educational spaces was not novel, if not common. Regionalist works of the 1970s present a mingled brew of imitative and local architectural elements.

The School of Visual Arts in Karaj, designed by Ali Akbar Sarami in 1993, seems to have been originated in the architectural language of Post-Modernism, except for the outside staircase which resembles that of the Achaemenid Persepolis.

The use of brick as the dominant material in the university buildings emphasises the sense of locality. Nonetheless, the geometrical arrangement of the façades of these buildings sometimes followed the aesthetic principles of late modern and post-modern architecture, and apparently, there were no local decorative details in the design of these buildings.

9.2. Iranianised regionalism; adopting Iranian architectural heritage

The Faculty of Engineering, the Faculty of Science and the dormitories of Imam Khomeini University in Qazvin in 1989 by Sheikh-Zeyneddin and Kalantari show an unprecedented use of the Neo-Qajar style in the design of a university. The architects adopted Qajar motifs and principles in shaping the façade of the buildings and the gates while being reluctant to use of tilework or other decorative details of the Qajar period. This minimalist interoperation of Qajar architecture has made their work a unique architectural reference to a period which was apparently most neglected by Iranian architects.

The return to the past and the reuse of its architectural details to embellish a modern structure became even more popular after the Islamic Revolution of 1979. Historical and postmodernist motifs used in this trend created ‘a thoughtful eclectic design’ (Hassan Pour, 2013) what Ozkan (1985) describes as Concrete Regionalism. Traditional characteristics, such as the use of arcades and colonnades, courtyards, decorative patterns, and the use of brick as the dominant material, gave these buildings a local character.
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9.3. Innovative regionalism: abstract symbols

The mosque of Jondi Shapour University is probably the most distinctively innovative building of the campus in its bold approach to redefining traditionally invariant architectural parts of a mosque, like the minaret and the dome. In fact, Diba integrates these two elements together. ‘By its refusal of traditional architectural elements, this is a determinedly modern mosque’ (Khan, 1992).

The mosque of the University of Kerman, by Youssef Shariatzadeh and Mohsen Mirheydar in 1983, deconstructed the traditional image of a mosque. ‘Its cubical shape makes reference to the Ka'baa at Mecca’ (Diba, 1992), and the conventional idea of the dome and the minaret was challenged in this modern, yet familiar-to-Muslims, design.

Seyyyed Hadi Mirmiran, who is famous for his unique Iranian Neo-modern style, designed the Sport Complex of Valiasr University in Rafsanjan in 1995. In this project, the function was compromised in favour of the colonial form (Hallaj, 2004). The colonial part of the complex slightly resembles that of another educational building: American Heritage Centre and Art Museum in Laramie, USA, in 1993 by Antoine Predock. The latter had also had its references to the locality, here to ‘a mountainous volcanic shape’ (Mostaedi, 2000). Mirmiran, graduated from the University of Tehran in 1968, borrows his main
concepts from Iranian traditional forms, local icehouses in this particular project, yet his design is creative, expressive and innovative. The forms are pure, combined simply, and do not comprise function. Mirmiran, himself was interested neither in the imitation of traditional architecture nor in modern architecture, which was ignorant of the local architectural heritage with its spatial and formal concepts and lessons (Sayar, 2012). In Mirmiran’s neo-modernism, ‘history belongs to the past’ (Arbabiyazdi and Zeraat Pisheh, 2012), and he creates new forms which are not historical, but seem local, not of international modernist or postmodern styles, but which seem modern. The conical form of the building has an iconic character, by the use of which and its reference to the yakhchal the architect won the design competition. Mirmiran’s interpretative Iranian architecture illustrates an abstract design in the range of Iranian regionalist university buildings, which started with Ardalan’s work in 1970.

10. Conclusion

The establishment of the first Iranian secular college Dar al-Fonun in 1851 with its European teachers galvanised the formation of a new class of Iranian artists and craftsmen. This resulted in freedom from Orthodox Irano-Islamic art and architecture which have been well established and promoted by hereditary artists and artisans. The Naseri artists combined Iranian and European motifs and radically exerted a naïve style in decorating Qajar buildings. The shift form the Safavid revival styles of the first half of the century to European influenced and free styles of the Naseri period, however, was not sharp, but gradual. The new styles coexisted with the old ones and were not iconoclastic to the traditional designs.

The faculties of the University of Tehran in the 1930s exemplify the architectural dominance of the Beaux-Arts school over the already-forgotten Iranian architectural heritage at the time. In the second half of the twentieth century, the enthusiasm toward international styles gradually gave the way to regionalism. The 1970s became the decade of the emergence of brick university buildings, in the design of which Iranian architects borrowed some architectural elements from the works of western architects, such as Kahn. In subsequent projects, the innovation and symbolism found place beside imitation, as symbolic architectural interpretations of Iranian culture and architectural heritage have emerged.

Over the last two centuries, the architects who took up the challenge of being interactive in reconciling the architectural embodiments of tradition and modernity in Iran projected the possibilities and opened up horizons in designing with consideration of the local heritage while being modern. These regionalist experiences and the course of architectural styles in modern Iran will be informative and instructive for architects in other developing countries in which similar solutions could be applicable to reestablish a balanced relationship between modernity and local identity in architectural design.

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Exploring methods to increase the efficiency of the integration between design process and environmental systems: an education and design research experience

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Abstract: This paper explores the integration between environmental systems design and architectural design process. The integration of these two processes is essential from the very early stages of the design process, both to improve and/or efficiently preserve the environmental, and architectural quality of spaces. The paper presents the design teaching and research experience carried out with the students of final atelier of the Master of Sustainability, at the Polytechnic of Turin in the second semester, 2014. The aim of the atelier was to design an institutional educational building by applying sustainability concepts throughout all the stages of the design process delivery. This latter was applied from design conception to construction detailing process, by utilizing a set of tools – such as climatic and microclimatic analysis - to maximize the environmental and sustainability performance of the projects. In particular, this paper analyzes tools such as the site microclimatic matrix, as support to the climatic considerations about different technological choices for heating and cooling systems; and to the architectural approach definition. This paper synthesizes and presents guidelines that can contribute both to the educational and professional design experience.

Keywords: Education, design research, environmental systems, architectural design.

1. Introduction

The scientific progresses achieved in the studies of environmental systems and technologies in the last decades seem to be different from the debate about the aesthetic of sustainability, which seems to have fallen behind the interest of professionals and academics. The projects categorized as ‘sustainable’ are often defined either according to the number and type of environmental systems and technologies utilised, as well as their efficiency, rather than their architectural design approach (Brown and DEKAY 2001). Furthermore, in several cases, the ‘sustainable’ label is associated with not-integrated juxtapositions of elements on already designed buildings, reducing the quality of interventions (e.g. technological, esthetical, and operational) and increasing the cost for their inclusion (Chiesa, De Paoli, 2014; Pagani 2014; Kiviniemi 2012).
The contemporary examples of ‘sustainable’ architecture show a number of different aesthetic approaches that designers seem to have undertaken. These approaches span from the more literal design solution of ‘environmentally aware’ buildings, in which the relation with the natural resources was conceived as a design tool; to the more technology oriented approaches, where technologies and environmental artificial systems became expression themselves of an architectural aesthetic (Grosso, Chiesa, Nigra, 2015). The dichotomy between these disciplines, especially between architecture composition and building technology – both in the profession and the academic world – reflects its characteristics on the design education processes. In spite the fact that, by-and-large, having an ‘environmental awareness’ is perceived as an obvious approach to design, the ability of merging technical environmental knowledge to the design process as a integrated design enriching tool seems to be far from being a consolidated approach, at least in the current educational system in Italy. This paper presents a methodology, which was applied and improved in several years of both didactical and professional practice (Chiesa, Grosso 2015; Nigra, Marfella, 2014; Grosso, 2011; Grosso, 2005), that aims at integrating these different aspects since the building programming design phase. This method reached very good results reducing the friction between esthetical and technological requirements, the design time (everything is more integrated since the programming phase), and increasing the quality levels of the final building. These results were confirmed by the very high appreciation levels reached by this course.

2. The challenge of teaching architectural design in a changing world – theory versus reality

During the preparation of the final design studio titled Sustainable Design of a Building and its Services (SuDBuS), carried out during the first semester of the academic year 2014 – 2015 at the Polytechnic of Turin for the Master of Architecture and Sustainability, it was clear that one of the goal to set was to educate the students to consider environmental technical knowledge as an embedded aspect of the design decision making process. A sequence of the phases characterizing the design process in relation to environmental and technological aspects is shown in figure 1.

Specifically, the challenge that was posed was answering the following question: ‘Is it possible to tease out aesthetic design alternatives based on and informed by microclimatic site analyses, rather than merely comply with normative framework and economic conditions? Is it possible to utilize a ‘technique-follow-form’ approach today?’ The novelty of this approach - at least for the Polytechnic of Turin - was to show the students how the use of their technical knowledge as a contribution not only to the creation of fit for purpose projects, but also as a tool that can help define an aesthetic direction in the design decision process, and enrich their compositional skills, which are often left behind the technical priorities in the design studios.
3. The experience on the atelier in Turin

The Final Design Studio Sustainable Design of a Building and its Services (SuDBuS) intended to offer to students an experience of design development of a building and its services according to environmental compatibility and energy conservation approaches as well as using advanced innovative technologies. This Final Design Studio comprised the contribution of three disciplines: Architectural Design, Advanced Environmental Technology, and Environmental Control Systems. These three disciplines were treated as a single integrated subject that could enrich the design process among all the technical requirements that the students were asked to answer to.

3.1. Program and objectives

The program of the design studio called for the design of a complex iconic building design project, to test the ability of the students in both proposing innovative design solutions, and managing the complexity of the environmental systems required. To this end, an existing competition brief was selected as an occasion to test the ability of students to deal with real and challenging program requirements. The brief selected was the one for the New ABP Building Faculty for The University of Melbourne. This brief was selected because it called for a complex project characterized by outstanding design solutions, and environmental sustainability awareness. The complexity of these characteristics allowed establishing the following objectives: 1) the exploration and understanding of the multi-layer meaning of the concept of sustainability in the design and delivery of a complex project; 2) the development of an appreciation of the processes of design development and its relation to advanced technologies and sustainability concepts; 3) the understanding of multidisciplinary role of sustainable research and development during design development to achieve high quality design solutions.
3.2. Methods

The method utilized to achieve the objectives defined six connected assignments across the three disciplines treated in the subject and assist the project development progressively. These six assignments were: 1) the analysis and design of social and functional sustainability of the spatial organization; 2) microclimatic and wind analysis on the site to assist the volumetric alternative definition and design; 3) technological system research and architectural design definition; 4) façade, envelope, shading and solar systems design definition and analysis; 5) natural and assisted ventilation and evaporation system definition in conjunction to construction system design definition; and 6) construction details definition for the relation between architecture and technological systems. For each of these assignment, the students had to undertake research on existing built projects, understanding systems and design solutions, and to design an innovative solution for each part, answering to the following questions: ‘Does your design propose innovative design solutions? How does your design decisions seek passive solution to the energy saving issue? What is the aesthetic of sustainability that your design propose?’ These questions were posed for each assignment as reflection of each phase of a project design development. The significance of this method is that it allowed the students to merge the design process with the technical knowledge and data learned as a system to define creative guidelines to establish a direction for the definition an aesthetic of sustainability, on the top of the ability of proposing project solutions fit for purpose and energetically sustainable. Beside a number parameters - such as meeting of the agreed deadline, scope and completeness of information; degree of legibility; and engagement of technical problems and sustainability principles - the work produced by students was critiqued by assessing the ability of their projects answered to the following questions: 1) Does the work stem from a progressive sequence of rational decisions to develop the initial design proposal, based on the microclimatic analyses undertaken? 2) Does the work provide efficient technical design solutions developed on the basis of the results of the initial microclimatic analyses? 3) Does the work express a clear cultural, socio-economical or aesthetic statement through technology and sustainability principles? 4) Does the work incorporate awareness of ESD and/or reasonable economic decision-making based on sustainability initial analyses? 5) Does the work show an autonomous personal initiative to express strong design intent?

3.3. Project outcomes

The outcomes of the applied method in the design studio were the achievement of a number of outstanding projects that demonstrated the ability of the students to understand the posed tasks, and to propose design alternatives that respected the technical call for sustainable systems as well as the ability of exploring the aesthetic aspects of sustainability as general design approach. The first assignment allowed the understanding during the preliminary phase of the project of the implication of social sustainability in early design decision-making. The second assignment allowed the understanding of the areas of the site in which the function required the users needs were more suitable for the requirements.

The environmental aspects were analysed using the site microclimate matrix in order to localise correctly the building to be designed, considering solar radiation and seasonal prevalent wind flows. Figure 2 shows an example of this analysis.
On the basis of the data analysed a number of volumetric design alternatives were explored and defined in relation to the spatial distribution in the building.

The third assignment lead the students to study compositional aspects — such as geometries, shapes, volumetric design, balance, harmony, et cetera — in relation to technological systems used, in such way that students could propose an architectural language that can represent a design language for sustainability.
The fourth assignment allowed the students to utilize the wind and site analysis to define design solutions that can both optimize the site conditions and create spatial design challenges and opportunities, such as the use of atriums, vertical circulation spaces not only as a design opportunity but also as solar chimney, wind tunnels and evaporative towers.

Figure 4: Design proposal based on the wind analysis data and proposed ventilation systems (proposal by Mamak P.Tootkaboni, Danial Mohabat Doost, and Xiaochen Song).

The fifth assignment focused on the use of the climatic analysis to determine the performance and specifications of the main façade components defined in the project proposal. Specifically, glazing characteristics, shading devices, and ventilated façade rain screen were selected ad-hoc for each façade, according the exposure and characteristics, elaborated in the micro-climatic analysis.

The sixth and last assignment allowed completing the project by offering the students the opportunity to develop construction details that both became essential for the overall design and architectural language definition (see roof design in figure 6), and defining ad-hoc technological solutions that could contribute to the technological sustainability of the project.
Figure 5: Example of design process to establish modules, patterns and shading devices in a façade design proposed according to the solar analysis on the façade, based on the micro-climatic analysis (study by Mamak P. Tootkaboni, Danial Mohabat Doost, and Xiaochen Song).
Figure 6: Example of construction detail as design opportunity. The roof design was achieved in conjunction with the development of an ad-hoc drainage construction system that could slow the drainage process and reutilize the rain water (proposal by Michele Giannini, Samuele Marino and Giacomo Pillitu).

4. Reflecting on the experience

The first interesting project outcomes was to notice the different – and sometimes diverging – architectural characteristics between the recently built ABP Faculty Building of The University of Melbourne, and the projects proposed by the Final Design Studio in Torino, from the orientation of the building to the final technologies selected. Moreover, the ability of using a site-climate based analysis, design phases and design parameters represents a design methodology that can be applied through all the phases of project delivery. This methodology could assist in both considering technical parameters, and optimizing design solutions, without impinging on the creativity side of the design process, which instead informed on a number of potential design alternatives. Moreover, this methodology could assist the development of specific requirement schedules for each technical element, and support the testing of the quality of design choices and their optimization (Grosso, Chiesa, Nigra 2015). From this experience, it is possible to underline that: 1) site analyses have to be performed before sketching, in a pre-design phase; 2) activities-needs analyses can be developed in parallel; 3) results from these steps can be integrated in a “virtual building organization” that aims in helping designer to develop their creativity without forgetting technological and environmental aspects connected with the specific project.
5. Conclusions

Environmental building programming and site-climate analysis can provide the students of architecture with the ability of open an informed discussion on the role of design within the sustainability approach to buildings. Having a number of design alternatives directly informed by the environmental context could contribute defining a new architectural language that consider all the approaches that have been taken so far in the history of architecture until now, and implementing them toward an integrated language between design and technology. This language could potentially produce a variety of buildings that, not only try to limit energy consumption and resources depletion, but that are able to express the identity of those buildings. At the same time an environmental and technological approach to design, by using the performance-driven approach since the preliminary design phase, is essential for considering these issues in the design process evaluating different compositional solutions and suggesting possible optimization procedures.

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From model to drawing and back: reversing the design process

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Abstract: This paper rethinks the role and the position of an analogue model within the design process, in the design studio setting, at the earliest stage of architectural education. The main argument set by this paper is that by altering the conventional organization of the design process, students’ abilities to generate complex spatial configurations and demanding geometries significantly improve. By starting the design process with an analogue (physical) model instead of with a two dimensional drawing, students are early on equipped with an instrumental method that introduces them to the realm of genetic architecture, algorithmic thinking and the idea of analogue computing. This research is conducted within a regular design studio (level 1) where the coursework formulates the basic parameters. The result of this research is students’ work analysed and evaluated by a defined set of criteria and documented in this paper.

Keywords: Design process organisation; design methods; analogue modelling; analogue computing.

1. Research motivation

Most of the written material for this paper comes from notes taken on prevalence and effectiveness of tools and methods used at level one design studio, the author was involved with in semester 1, year 2014 at the Xi’an Jiaotong-Liverpool University in China.

One specific observation - that students at this level, being effectively digitally incompetent, are actually in a dichotomy with a current architectural discourse that endorses the use of digital tools and computational logics - is the underlying motivation to do this paper. However, the intention of this paper is not to question whether digital skills ought to be acquired as early as in the foundation level, it is rather about questioning whether a different kind of pedagogical approach could stretch the limits of the analogue setting these students are operating in, by bringing in some of the fundamental principles of parametric design and in that way bring students closer to algorithmic design thinking paradigm.

2. Research aim and questions

The above said clearly opens ground for a number of questions to be raised, which are to be addressed within the further body of the paper: How this can be done? Why would that be important, and how
would students benefit from it? What is the parametric design really about and what kind of intelligence can the analogue inherit and take on from the digital?

Contemporary shift in the design medium from the analogue to digital design processes, is sometimes giving a false indication of analogue model as a traditional design tool. This paper argues that we cannot be speaking of traditional tools; we can however speak of the traditional approaches or mind-sets or of conventional methods. Analogy can be drawn here, that we can be using computational logic, or be thinking parametrically while still be working with analogue tools, or as Whitehead puts it, in the foreword of Woodbury’s Elements of Parametric Design, parametric design is more about “an attitude of mind which seeks to explore and express relationships than any particular software application.” (Whitehead, 2010)

Grounded in the findings from the design studio experiment, that are to follow, the aim of this paper is to investigate whether higher level of complexity of students designs can be achieved through employing computational logics through the analogue modelling process, while still maintaining the benefit of having a direct contact with the physical, from the very conception of the design, through the material and structural experience, toward realisation.

Figures 1-3: Living space for the Panda _student Bowei Liu (1302138)_ Module ARC105_Level 1.

2.1. How this can be done and how would students benefit from it?

As already stated, this paper is pedagogically motivated to help level 1 students go beyond their limitations, using a method that would not burden them with having to absorb new skills instantaneously (such as having to learn a new software application). What this is paper proposing is a simple re-organisation of a design process that I believe carries a great potential that has not yet been sufficiently addressed. The idea originates from working with students on very different levels of architectural education, where I have detected that introduction of an even minimal change into the organisation of a design process, can give positive effect on their designs.

The academic setting I am acting from, or more specifically the setting of a design studio, came as a true supporting ground for pursuing my research interests: to study, monitor and evaluate the effects and the results of the reversed design process methodological approach. If expected sequence in the design process can be identified as: from a drawing to model, this research paper sets a stage for a
pedagogical experiment, where we will be able to see the results of shifting these sequences into: from a model to drawing and rethink the position and the role of a physical model in a design process.

Postulation set by this research is that by altering the standard organisation of the design process, students, especially those who are at an early stage of their architectural education would benefit greatly. Moreover, their lack of design studio experience and low competency in design methodology and digital design technique will possibly work in their advantage. Due to their lack of skills necessary for mastering available digital tools, while following the conventional order in the design process - starting with sketches and 2-dimensional drawings – level 1 students find it difficult to go beyond planar way of thinking or referring to the prevailing historical references (Roudavski, 2011), that can lead them towards unoriginal, superficial architectural concepts, and moreover towards spatially underdeveloped and geometrically unchallenged design solution.

On the other hand, as this experiment intends to show, when starting design process with an analogue (physical) model instead of with a pencil and a paper, students are timely equipped with an instrumental method that allows them to create spatial experiences and complex geometrical structures that would otherwise be inconceivable and unreachable to them. This comes as no surprise, as a design tool (as in: “what is used?”) and a design method (as in: “how it is used?”) are really the means of setting the framework within which a designer, or in this case a student is operating, i.e. thinking and creating; a framework that can come to be a limitation or a window to experimentation and reaching new insights. The strategic role of tools and methods within the design process was given recognition long time ago by Konrad Wachsmann in his book "Milestones in the construction", where he suggests that focus instead of on the building itself, should be on what has influenced the way in which it was made - on the techniques, materials and tools, believing that their role is yet to become even more important in architectural education and research in the future. (Wachsmann, 1959).

This paper argues that by introducing students to from model to drawing design method, we are navigating them towards exploratory and experimental design thinking. We are encouraging them to embrace the culture of experimentation, risk and critical evaluation early on, which is to be a milestone for their further education and the direction they will take on as future professionals. Angélil and Hebel are among those that are stressing the importance of encouraging students to take risks “even if it means being vulnerable.” (Angélil and Hebel, 2008).

By reversing the design process, by telling students to conceive their architectural ideas through the process of analogue (physical) model-making, rather than through the means of two-dimensional drawings, sketches or diagrams, what we are really doing is exposing them to the world of genetic architecture, algorithmic thinking and the idea of analogue computing – computing complex geometries and spatial structures without the use of digital tools or computers.

Kostas Terzidis writes on the subject: “Algorithms are not necessarily dependant on computers [...] This distinction is very important as it liberates, excludes and dissociates mathematical and logical process used for addressing the problem from the machine that facilitates the implementation of those processes”. He indicates that there is a distinctive difference between the term “computation” - implying a way of resolving a problem, and “computerization”- suggesting a way of storing and processing data with a computer. (Terzidis, 2006) In other words, understanding and applying computational logic may be done with the use of analogue means such as physical models.

The idea of computing without computers is not new and can be outlined though the work of Gaudi, Otto, Isler and others. Gaudi’s use of suspended chain models for computing the geometry of arches for La Sagrada Familia in Barcelona is a well-known analogue computational method and a subject to many
From model to drawing and back: reversing the design process

contemporary researches (Jos, 1989), as is the work of Frei Otto. Otto, who certainly holds the very central place in working with analogue modelling techniques, was almost exclusively relying on experimentation through spatial or physical models for researching on form-finding process (Roland, 1965). Otto basically used analogue modelling techniques to transfer natural intelligence processes to the process of a design and construction of spatial forms (Barthel, 2005).

Analogously to the above said, we can assume the possibility of transferring digital intelligence to the design process driven by analogue means. This is getting us back to the main objective of this research, that is: to reinforce abilities for generating complex spatial organizations, structures and environments for the purpose of architectural education, by employing computational logic in an analogue setting.

![Figures 4-5: Peacock and Lillies _student Li Jiaxu (1301782)_ Page 1_Module ARC105_Level 1.](image)

2.2. What is the parametric design really about and what kind of intelligence can the analogue inherit and take on from the digital?

Parametric design is essentially operating on the basis of algorithmic principles that require for their each step to be precisely defined, as Knuth points out, and continues: “the actions to be carried out must be rigorously and unambiguously specified for each case” (Knuth, 1997). Accordingly, in order to understand the underlying principles of parametric design, we need first to understand the algorithmic nature of it.

As defined by Terzidis:

“An algorithm is a process of addressing a problem in a finite number of steps. It is an articulation of either a strategic plan for solving a known problem or a stochastic search.
towards possible solutions to a partially known problem. In doing so, it serves as a codification of the problem through a series of finite, consistent, and rational steps." (Terzidis, 2006)

Barrios is on the other hand pointing out that parametric model can be defined “as a group or cluster of geometrical components that have attributes (properties) that can vary and other attributes that are fixed.” (Barrios, 2011)

The promises of the contemporary digital processes are grounded, as much in the close relationships to materialization (though fabrication), as in the precision and a level of control over the design process (Aish, 2005).

What this paper suggests is that, by reversing the design process and repositioning the making of the physical model within, we can transfer some of the key aspects of the digital processes and algorithmic thinking into the analogue setting. Firstly, we would need to identify the essential characteristics of the digital intelligence that analogue should try to inherit and learn from.

According to Aish, there are three essential characteristics of computational design that can be distinguished - Geometry, Composition and Algorithmic thought:

Geometry: “We need to start with a fundamental understanding of geometric primitives: points, planes, coordinate systems, line arc, curves, surfaces and solids. We need to understand what the ‘order’ of a curve means, how curves and surfaces are parameterized.” .. “We need to use these primitives and operations to define relationships.
We need to understand the stability of these geometric relationships under certain modifications and configurations.” ...”By building and exercising these systems of geometric dependency we are able to explore variation in design, indeed to explore the solution space, and to discover and validate the configuration that will finally be constructed.”

Composition: “What is certain, is that developing and refining compositional strategies is a key aspect of design skills.”

Algorithmic thought: “Essentially this geometry cannot be drawn. It has to be computed. If it is to be computed, then there has to be an algorithm. To be original and to be in control, the designer has to understand, if not originate, his own algorithm” (Aish, 2005).

3. Evaluation of students’ work – case studies

The basic assumptions set by this paper were tested through evaluation of students’ work performed within a seven week long (from Oct 27th to Dec 14th 2014) design studio module in Level 1 at Xi’an Jiaotong-Liverpool University in Suzhou, China. Module ARC105 (Small Space design) was led and coordinated by Ciro Marquez, with a team of 16 tutors, an author being one of them, each having a group of 12 students. It is important to acknowledge that this was these students’ first architectural assignment. The brief has set a flexible framework and allowed for diverse pedagogical posits to be taken by any of the tutors involved.

For the purpose of performing the intended design studio experiment and testing the reversing the design process design method, I have given a set of very simple instructions to my group of students:

1. to start envisioning their design concepts by working with a physical model directly and not as what they were used to - by doing sketches or drawings on paper first.
2. to engage in a bottom–up design process, by firstly defining the components with material properties that would allow manipulation and ‘trial and error’ to happen along the way, but that can also add to the structural strength of the configuration.
3. to think about the relationships between the components, rather than thinking about the final form.
4. to define the set of rules for assembling the components together.
5. to be clear and consistent with the geometrical language they are using (to state if they are working with triangles solely, or with a variety of polygons, or with circles, and so on..)
6. to be free to change the variables of the geometrical entities they are using (lengths of the components, proportions etc.)
7. to be exploratory and not be afraid of the geometrical and spatial complexity they are achieving.
8. to draw the architectural plans and sections after the final physical model is done.
The above mentioned three essential computational design characteristics as identified by Aish and labelled by him as key to future design - geometry, composition and algorithmic thought (Aish, 2005) will be used as criteria in evaluating the rate of success of students’ work in terms of reaching the set research objectives.

Figures 1-3 show the work of a student centred on a self-supportive physical configuration constructed with a use of wooden sticks - linear elements that student is putting together for defining a set of triangular and polygonal planes. These basic geometric entities are branching out furthermore, into more intricate patterns that are built in a multi-layered envelope folded around an inhabitable interior womb-like system of voids. Obviously, student is working with a very complex algorithm, achieving a spatial configuration of equal complexity, but manages it well, and in consistency with geometrical rules he has set.

Configuration is manipulated along the way by varying the parameters of the polygons. This was done for fine tuning of the sophisticated spatial experience student wanted to achieve, and for the articulation of the architectural, material and structural properties. Another reason for working with a variety of polygons was to optimise the material use while achieving the structural strength. Student has shown remarkable geometrical and compositional skills, and has demonstrated a high-level of understanding of the rule-based (algorithmic) thinking.

Figures 4-5 show work of another student working with linear elements. This student has chosen to work with plastic sticks that have elastic properties to some extent that he intended exploit in his design. Contrasting the previous student, where we always had two straight linear elements meeting in a point, this student works with straight lines and curves, by setting a simple rule: line-arc-line, so that lines within one component would always join radially, rather than by forming an angle. The set rule, as well as the material properties, have largely defined the geometric language student operates in, giving an impression of a continuous line drifting back and forth through space in an unpredictable rhythms. This spatial configuration is much less dense, and the emphasis is rather on the elusive linear inscription of space, than on the volumetric nature of it. Another difference is that unlike the previous, this structure is partly self-supported, and partly supported by the topography it is embracing. There is a lot
of freedom undertaken by this student in varying the geometric parameters, yet there is a clear strategy in using the geometry for a fine outline of a subtle, well-rounded spatial composition.

Figures 6-7 show work of a student using the same material as the first one – wooden sticks. Student is working with triangles and quadrilaterals, putting an emphasis on the pointy and linear nature of these elements - lines are always straight and meeting in a point, most often forming a sharp angle. When assembling the components, student has aimed in reaching compositional hierarchy, rather than a high complexity of the compositional framework. Space occurs between the patterns that are reduced to a minimum number of elements. The formal tectonics is resulting from the functional and structural consideration and the hierarchical relationship between the parts and the whole. The formal outcome of the process in this case clearly holds less complexity, yet it demonstrates geometric clarity, and the compositional consistency within its own internal logic and according to its own rules.

Figures 8-10. Student is working with triangular components that are supporting one another and composing three distinctive spatial latticework structural segments - two vertical and one horizontal - that are then being joined into a whole. The triangular patterns vary in length of the elements and the proportion. Student has modified these through the form making process, aiming towards a somewhat predefined spatial composition that was to fit in the context set by the student- the structure was to be attached to the two trees that are few meters apart. This work demonstrates perhaps less experimentation, and more intentionality, but student has developed a well-balanced spatial composition, within a controlled set of conditions.

What is I believe is apparent in all four case studies is that the design studio experiment have put student through an exploratory process, where they had the opportunity (and have used it) to work with free-forms in a more systematized and controlled manner. The process was controlled by themselves, and the rules they have set previously. Through this process they have developed substantial awareness and understanding of geometry and of design decisions making in the ruled based environment, in an algorithmic framework that they have set and that they are responsible for.

4. Conclusions

Evidently, many of the potentials of the digital design processes can never be achieved when working solely with analogue means. Firstly, analogue process and its outcome can never be as precise and as controlled as a digital one. It is also important to mention that, when working with analogue means there is a limit to a number of variant design solutions, that digital processes do not necessarily have to meet.

However, one must acknowledge that there are other capacities of parametric design that are conditionally true, but in reality are quite hard to achieve, such as efficiency and continuity of the process, that many researches are pointing to. In parametric modeling it is a commonplace that designer has to remake the parametric model over and over again (Gerber, 2007) or that he will have to go back to the relational graph many times for editing or for a complete remodeling (Burry, 2007).

On the other hand, parametric modelling requires substantial technical knowledge on mathematics, geometry and computation (Aish, 2015) and this is not something that we can expect easily to be acquired and mastered by level 1 students.

Case studies show that, even though students were unconscious of having been employing the logics and principles behind the digital processes, they have developed a worthy understanding of the design process and gained a better sense of the control over it. Having to manage very demanding geometries,
students have demonstrated considerable geometrical awareness. Through the application their own set of rules they have exercised algorithmic thinking and have managed to generate spatial configurations of certain complexities. This approach has turned their focus towards what really matters in the design, the exploration of the new materials and forms (Aish, 2005) rather than on the appealing appearance of the formal outcome.

Aspiration of this research is perhaps best reflected in Terzidis’s view of an algorithm as not being “about perception or interpretation but rather about exploration” and “extension of the human mind” (Terzidis 2006). Likewise, this paper is not suggesting an ultimate pedagogical approach; it rather wishes to demonstrate one design studio experiment and to test its effectiveness for a level 1 design studio.

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References

Games and Chinese gardens: an equivocal experimental approach to a complex and subtle design genre

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Abstract: The object of a non-project, non-studio, graduate architectural design approaches and methods course is for students to investigate their own predilections in designing. Among the many topics to which students respond, the design of private Chinese gardens has proved popular. In 2013, the Homework and Workshops exercises were replaced with six board games. These Chinese Garden Games differed in their focus on ingredients, geometry, canonic situations, Chinese traditions (Wu Xing, Yijing), numbers of players, sequential, iterative or simultaneous play, sequence in which classes of design decisions were to be taken and the contour sets and tessellations of the Game boards. Entries in Reflective Journals, responses to the university’s semester-end course Student Experience Survey and the one Questionnaire returned together with fifteen more or less complete garden plans provided data. Students generally found the instructions far too complicated, differed in their enjoyment of play, but generally participated helpfully in the experiment. Interestingly, as with results from an earlier set of instructions, garden designs were nearly always two-dimensional. This may result from the emphasis in the Games on that distinguishing feature of the private Chinese garden design tradition: the number of simultaneous systems applying to the total site layout.

Keywords: Design approaches; Chinese gardens; board games; design pedagogy.

1. Introduction

An accurate diagram of the design process would be more like a board game than a straight path ...

Susana Torre (Shoshkes, 1989, 10)

This paper examines the most recent in a series of experiments employing the private Chinese garden tradition both as site of and tool for investigations of design approach and method. In this case, the direct investigators were graduate students mostly of architecture, participants in a non-project, non-studio, elective design course, Design Approaches and Methods (DAM), aimed at getting students to be much better informed and clearer about their own predilections, strengths and weaknesses as
designers. The course is based on the belief that you cannot strengthen nor prune poor growths from what you cannot grasp nor understand.

I have a long-standing fascination with board games, from playing competitive chess in my teens to discovering *wei chi* (gow) much later. Here, games arise, in part, as an homage to the fictional Joseph Knecht’s *Chinese House Game* in Herman Hesse’s *The Glass Bead Game* (1946) perhaps reinforced by Bill Hubbard’s (1980) discussion of games as possible models for architectures of complicity. And, an underlying impetus derives from the attempt to provide a universal description of games in M A Foster’s *The Gameplayers of Zan* (1977).

Equally, I am fascinated by the simultaneous complexities and subtleties of the private Chinese garden tradition and the cross-cultural issues that arise with its contemporary development (Missingham, 1999 and 2007; Missingham and Selenitsch, 2002).

In the past, the Topic on the design of traditional Chinese private gardens proved a pleasing revelation to many students. To explore what was raised in the lecture, as the associated Homework and Workshop Exercises for the Topic, various ways of laying out a Chinese garden were provided in the form of sketch instructions. In 2013, those instructions were replaced, as an experiment, with six board games. Indeed, board games might be useful design approaches to complex repeatable situations from other traditions. (Tschumi’s recent book on his design thinking includes two instances of such experiments (2014, 76-79 and 251-252).) Games have been used before in landscape architecture design and urban design education (Kent, 1997; Morris, 2013, reviving the mid-1950s game played at Austin, Texas, respectively), and board games have frequently been used in art education, if rarely at tertiary level. (See Bain & Newton, 2003; and Patton, 2014, on the history of educational games; Cox, 2014, on role-playing games). The arguments for the use of games include enhanced memory (Goff, 2010), student engagement and developing increased capacity for handling complexity (Patton, 2013; Han, 2015; Leaning, 2015) and fun.

Six sets of rules for Chinese Garden Games were devised with different emphases, incorporating different principles for sequences of moves, simultaneous or serial play, and different numbers of players or playing teams. Teams of students attempted various of the Chinese Garden Games (sometimes more than one), provided feedback on their experiences with the Games and provided their worked examples, annotations and sketches.

The paper discusses the lessons learned. How successful were these Games as collective designing approaches? What was learned about Chinese gardens? Compared with results from the sketch instructions in earlier years, dutiful teams probably learned rather more but the effort entailed in comprehending the Notes and Rules for the Games and for actual play required very much more time. For any next time, Chinese Garden Games should be simpler – especially in terms of their instructions and the level of information provided. Pedagogical gain could better be served with some loss of art historical detail in what was issued to students.

### 2. Chinese garden exercises, previously

There are at least four reasons for a Topic on private Chinese gardens:

- they are a particularly sophisticated spatial design genre of non-European origin (Liu, 1979; Johnston, 1991; Rinaldi, 2011);
- they entail design of a whole site, boundary to boundary;
- the many compositional principles should act simultaneously; and
architecture students faced with landscape projects as Workshop exercises cannot so easily rely on current magazine fashions.

2.1. Previous Homework / Workshop Exercises

Figure 1: Mnemonic diagrams underlying four of the Six Ways of Laying Out a Chinese Garden: a. Designing from the Main Hall’s Main Scene Outwards, b. Following the Ten Steps, c. the Mnemonic Diagram, d. Design Issues.

In previous years (from about 2007 to 2012), the Homework set at the end of the Chinese Gardens lecture was for students to try one or more of Six Ways of Laying Out a Chinese Garden, set out as ten sheets of relatively simple instructions based mostly on one or more mnemonic diagrams that structured Lectures in earlier years (Figure 1):

- Elaborating a Scroll from an initial Scene,
- Designing from the Main Hall’s Main Scene Outwards,
• Following the Ten Steps (Missingham and Selenitsch, 2001)
• Using the Mnemonic Diagram (itself including several alternatives)
• The Grided Garden (Missingham, 2005b)
• Design Issues (Geometry and Materials).

Figure 2: 2005 samples of garden designs from the *Six Ways of Laying Out a Chinese Garden*: left: Elaborating a Scroll from an initial Scene, right: The Grided Garden (by the same student and exceptional in both being unusually three-dimensional images).

3. Chinese Garden Games 2013

In 2013, I thought that, as games depend on group work, both competitive and collaborative, and to capture the fun in designing that students in groups obviously had trying out various Chinese garden design exercises, why not test the possibilities explicitly? The experiment tested board games played in small groups

1. as a design approach,
2. as a tool for students investigating their own approaches to designing and their own design thinking (the point of the course, itself),
3. as a tool for better understanding the design of traditional private Chinese gardens, and ...
4. as a test of a draft chapter of a proposed book on generic design approaches, *The Garden of the Cool Change*.

At the Lecture, student teams were issued with packages, containing:

• Overview notes on traditional private Chinese gardens (28 pp., the draft chapter)
• Rules for the six Chinese Garden Games (10-15 pp., averaging just over 12)
• Notes on the Game Boards (19 pp., 13 of images)
• three different Game Boards at A3
• appropriate polyhedral dice (six-, eight-, twelve- and/or twenty-sided)
• Plain Language Statements, Consent Forms, Questionnaires.

Playing the Games was to be that week’s Homework, to be followed up at the ensuing Workshops.

3.1. The Games

The six Chinese Garden Games were:
G1 Constituent Ingredients Game – emphasizing site planning through decisions about major classes of materials: Architecture, Water, Rocks and Planting, first at the level of Space-cells across the garden and then within each Space-cell. ‘Space-cell’ is Keswick’s (2003) excellent term for the usually bounded subsections of a private Chinese garden. (Think of “garden room”.) In this Game, both Space-cells and Scenes are fuzzy areas. The Game also makes use of stacks of twenty-two cards, determining items to be located on a move, one stack for each class of materials and one for Chance (including additional, rarer items from the classes of materials). Naming garden features completes play.

G2 Points and Lines Game – focusing on positioning objects first (key buildings, rockeries, a lake), paths and boundaries, axes and alignments (and their avoidance), an approach suggested in Johnston (1991). Space-cells and Scenes were to be constructed on linear bones. The key idea is of Stations from which to view Scenes (from Zhao and Kvan, 1984). Deciding where walls are needed completes play.

G3 Wu Xing Game – focusing on balancing the five energies: Wood, Fire, Metal, Water and Earth, both materially and poetically. (Plaks, 1976, 45-53) A key idea is the quincunx of key Space-cells. Moves of the five players are simultaneous and each is expected to play in the spirit of one of the energies, oscillating from waxing to waning phase for each round. Resolution of conflicting moves is resolved by reference to the Chinese theory of cycling energies. Naming completes play.

G4 Yijing Game – with decisions driven by reference to the Book of Changes, its eight trigrams and sixty-four hexagrams. (Feuchtwang, 1974; Deng 2006) Much of the play concerns overlapping regions shared by Space-cells and themes of Space-cells. Naming completes play.

G5 Ten Steps Game – The Ten Steps cover three levels of increasing particularity (Poetry & Concepts, Places & Experiences, Forms & Making – respectively, Finding, Composing and Designing) and pairs of themes, linked. (The same Ten Steps referred to earlier. See Missingham and Selenitsch (2001).) Allegory is important. Play is cyclic through the Ten Steps (though not all need be played in any round) and is completed at players’ discretion after Livelinesses have been decided often enough.

G6 Canonic Situations Game – focusing on designing for a selection from twenty-six characteristic vignettes (Situations), emphasizing lyric interpretation of imagined events, behaviours and their accommodation, spatial and temporal. The key idea is the Situation. Here, play is conducted on the lines and points of the tessellations rather than in the spaces (tesserae). Naming completes play.

The Overview notes with which teams were supplied mostly consisted of a description of principles underlying decisions common to the six Games, regarding: Fields of Play, Locations of Space-cells, Locations and Orientations of Halls, Internal features of Space-cells, Boundaries, Planting, Paths and Naming. There were two Appendices: a table of functions of Halls, and a table of the architectural natures of built elements.

The Game rules were designed to allow teams generally, through play, to develop their designs in top-down sequence, from larger, site-subdivision decisions to locating scenes for viewing and then to details of path or wall layout. The locations of lakes, Principal Halls and Entrances were pivotal strategic decisions in each case. In Workshops from previous years, Naming the parts always added a fun element.

3.2. The Game boards: tessellations, contour sets

Sixty-four Game boards were devised, combining eight tessellations (red) with eight sets of contours and levels (in black), printed at A3 and assuming a scale of 1:100, modeling an area of very nearly 2500 m². This is smaller than the median 3300 m², and a third of the average 7500 m² size of the fifteen gardens.
discussed in Liu (1979), the canonic source text, which includes the more famous, larger gardens in Suzhou.

The contour sets were modified from those available on the WWW of three North American and two Victorian mountain areas, a Melbourne suburb and two areas of Mars, with height differentials set to a maximum of eight meters and scales usually greatly differing from the originals, including one left-right reversed. These contour sets represented: a plain crossed diagonally by parallel ridges (below, left), a shallow valley with three marginal hills, a deep valley with flat banks, a soft slope with one hill at the top, a deep V-shaped valley (below, right), a wide, central ridge with slopes to both sides, a shallow plain with narrow valleys to left and top, and multiple ridges around a lake intruding at top left.

The tessellations included a fractal rectangular, four semi-regular and three Penrose non-periodic tilings of the plane. Figure 2 shows sample Game boards.

Figure 2: Sample Game boards (BGM: contours from Bear Garden Mountain, Appalachia; OS1: Octagons and Squares semi-regular tessellation; NM: contours from North Melbourne).

4. Outcomes

From comments in students’ Reflective Journal/Workbooks (and the one completed Questionnaire received), teams took between two and four hours outside and two within Workshops to play their games, much of this taken with reading and understanding the Game Rules.

From the seventy-seven students enrolled, across five tutorial groups, fifteen gamed gardens were received from twelve groups of students ranging in size from three to six people, involving a total of thirty-six students. All five tutorial groups were represented. Two teams each provided two gardens, one from Homework, one in the following Workshop. Two teams provided no illustrations, so their designs are not included in the fifteen. Two original Game boards were returned, anonymously (but, probably, both from individuals), one marked up, one quite incomplete (locating only Main Hall, forecourt and Lake) and one well-developed design. Three additional students provided Workshop illustrations of sketches for their own, single-spaced gardens not on any of the Game boards, and one produced a completely different set of names for the team’s garden, as a separate piece of work. That is, forty-one students contributed to these results, if imperfectly.
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Figure 3: Sample gardens designed in play

Figure 4: A garden conceived in three dimensions.

Of the fourteen substantial garden designs, another had got only as far as an external wall in the time spent, with an entry gate, and only one student provided a perspective view of the garden her team designed. One of the individual students provided three postage-stamp sized vertical perspectives illustrating borrowed landscapes from his individually designed Ten Steps Garden (though site-less and not located on any Game board provided). That is, the garden designs were plans of gardens.

Based on internal evidence or comments in Journals, no teams played either the Constituent Elements Game or the Situations Game (the most ‘phenomenological’). Four gardens derive from G2 the Points & Lines Game and three each from the G3 Wu Xing, G4 Yijing Games and G4 Ten Steps Games. One team managed to play the G3 Wu Xing game twice, changing the Game board and adding another team member in the Workshop. The team that played the G4 Yijing Game twice changed only the Game board. And, one student played in two entirely different teams for Homework and Workshop.
5. Discussion

5.1. Game boards

Providing tessellations had two purposes: to speed up play by providing a variety of potential sizes of space-cells and varieties of indicative boundaries, and to provide ready-reckoners for distances and areas (supported by a table of these in the issued *Notes on the Game boards*). Given that the players were architecture students, setting the scale of game boards at 1:100 should have sufficed. For some teams, providing the tessellations was a mistake, especially aesthetically when three of the garden designs included ugly acute angled spaces. These do not occur in private Chinese gardens. This could be fixed through precluding tessellations that include triangles or banning acute angles in Space-cells.

5.2. Instructions

In Journals and written remarks in the Student Experience Survey, the instructions were generally regarded as too complicated, often exasperatingly so, and clearly too long. Compared with the ten pages of the *Six Ways of Laying Out a Chinese Garden* (including diagrams and illustrations), the 107 pages of instructions and information and fourteen of illustrations issued this time, after the Plain Language Statement, Consent Form and eight item Questionnaire, were obviously too much.

There were various responses to this, including teams making up their own rules for play/design, forgetting to follow the Game rules (and, therefore, presumably also making up their own, possibly derived from the information in the lecture or provided on the University’s Blackboard-based Learning Management System), disregarding the tessellations and, in one case, the Game board. One team made clear its exasperation by naming their garden *The Garden of Perpetual Struggle*. Students from mainland China often apparently had little trouble, enjoyed the novel encounter with their own culture and, when perplexed with the instructions reverted to their own knowledge.

A number of students complained that better instructions for setting up Games, what they needed for play and what to do first could have helped. This was the most annoyed (from the university’s Student Experience Survey):

> The Chinese Garden game exercise was totally a nightmare for all of us ... A game should be understandable and feel joyful to play not like we can’t even understand how to play the game after 4 hrs of reading through the instruction.

Nevertheless, if only implied in the tenor of some comments, many teams obviously were trying to help with the research project, despite these difficulties.

5.3. Summary of outcomes

5.3.1. Games as a design approach

This is an equivocal result. Complaints about the complexity of the Game descriptions cloud the issue of playability. It is clear that the *Six Ways of Laying Out a Chinese Garden* were previously better received. From the Questionnaire returned (and that so many gardens were actually designed directly refutes the second point) ...

> It was quite fun – but I think would have been fun a second or third time around when the game flowed a little better.
I struggle with the idea of it as a design approach because it does not lend itself to the complexities of a design brief.

Now, I have had a few students in graduate design studios that have used game engines as part of their investigations, so the discrepancy could both be a matter of personal preference or it could be because these particular Games were simply unattractive as games.

5.3.2. Better understanding the design of traditional private Chinese gardens

This was a success. However, whether the positive comments were related to the playing of a Game or to the supporting lecture and materials is an open question.

The predominance of two-dimensional designs might suggest that there is something in the very nature of the Game rules that doesn’t help, perhaps the emphasis on that distinguishing feature of the private Chinese garden tradition: the many techniques simultaneously applicable to laying out the garden as a whole. More obviously, it is that the generating systems were board games, after all.

Further, the designs being confined in their representations to the one, overall scale meant that much of the detail work within Space-cells could not easily be illustrated nor was it necessary to describe and account for in the Game rules. Despite this, it was a major feature of the G4 Yijing Game and none of the members of the three teams that played that Game made any comment on this issue (though it could have been disguised in the general annoyance exhibited by members of one team).

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References


Investigating the digital/analogue/cognitive collision through codified CNC mill watercolour painting

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Abstract: This research explores the convergence of digital tooling and manufacturing with cognitive and metacognitive learning processes, framing pedagogical possibilities through the discourse of metacognition. Currently there is as much uncertainty about environmental futures as there is existential unease regarding automation and the perceived gradual or abrupt loss of human control. In that context however, it can be argued that the process of codifying complex non-linear systems can reveal insight into how the human brain operates and perhaps how society can better cope with uncertainty and other changes we will face, informing how we live and learn and ultimately how a better built environment can be envisioned/manufactured by the relationship we have with machines. This paper discusses a unique codified process of learning through a discussion of metacognition and the exploration of a unique teaching-learning process that involves programming a CNC Mill to paint effectively with watercolours. In illuminating the nuances of the trial and error process of cybernetic pedagogy, this focused case study ultimately proposes critical questions concerning the impact of technology on teaching and learning in design.

Keywords: Automation, pedagogy, design, watercolour.

1. Context: object and systems levels

This paper explores a cybernetic design research framework as outlined by Glanville (1997) to expose key stages of cognitive and metacognitive processes in design. Metacognition has been referred to as “the knowledge about and regulation of one’s cognitive activities in learning processes” (Veeman, 2005; Flavell, 1979; Brown, 1978) or in other words, knowing how one knows something. While metacognition is itself an umbrella-term, specific derivative terminologies describe key cognitive actions at secondary levels. Some familiar terms include learning strategies, self-regulation, theory of mind, etc. Nelson (1996) unifies many of these subordinate terms by describing a two level system of classifications. He distinguishes an “object level” stage, at which cognitive activity takes place, from a “meta-level” which
effectively governs that object-level cognition. Flavell (1979) describes the most common distinction in metacognition as separating metacognitive knowledge from skills; on one hand, referring to a person’s declared knowledge about interactions between people, their tasks and strategies for success, and on the other hand, referring to our procedural knowledge for how we regulate our problem solving and learning activities (Veeman, 2005; Brown & DeLoach, 1978).

Metacognitive knowledge is largely perceptual; and it can be objectively correct or incorrect. Metacognitive skills however tend to operate within a feedback loop, just as computational or controlled design methods. As Andrew Kudless (2011) observes, the gathering of information begets the need to gather more information. This can be traced back to the core of learning, and the fundamentals of intelligence that lie in the circular actions of perception and action (Brooks 1999). The act of making, including the process of repetition, subsequent failures and eventual success that results through a continuously increasing precision, speed and craftsmanship lead to an incredible range of discoveries. We (the experimenter and the machine) act iteratively until reaching fidelity or grotesque (Headley & Bussiere, 2014). And, as Drittas and Yeo (2013) assert in the reproduction of historic sculptures and buildings, it is noteworthy that the reconstruction of technique is limited in a practical sense by the resolution of the equipment being used. Taken together, the emergence of new tools, procedures and relationships between human and non-human cognition offers glimpses into potential forms of enhanced and engaged learning.

2. Process: recursive cybernetics + Deus ex machina (or, God in the machine)

Here we pose a question. Can expertise be codified? And specifically, can the design process, as opposed to objects, be measured and organized sequentially to enable the reproduction of holistically minded and reproducible techniques and how is reflection, a core dimension of metacognition, acknowledged and embedded within the programming? Beesley and Seebohm (2000) have suggested the notion of a digital tectonic by scaffolding traditional construction methods with design software. They observe that much of architectural design is an abstraction that emphasizes visuality and spatiality rather than tangible material and construction methodologies. This aligns with Glanville’s (1999) framework for research as the simplification of variables in the search for pattern. It further suggests a correlation between craftsmanship and the process of discovery.

The term Deus ex Machina, which refers to a common plot device in theatrical performances, proves useful in answering the question. In such a case, suddenly, and in a way that seems out-of-nowhere, some new event, character, object or ability appears and solves a critical and previously impossible problem. The solution advances the story, usually comedically transitioning to some point of narrative resolution. In this way, it can be argued that key moments of discovery in the recursive testing process can offer similar evolutionary prompts for the designer, student or researcher as they struggle through the learning process. In this case, programming a typical CNC mill to watercolour paint is the Deus ex Machina in a search for metacognitive value.

In a close examination of watercolour painting techniques specifically, brush size, brush angle, colour density, stroke approach, stroke retraction, stroke speed, stroke pressure, as well as other situational factors such as the water content in the brush, or the process of adding water and subsequently removing it on the edge of the paint tray, or the capillary effect of the paper against the water loading can potentially be systemized. Beyond human-controlled technical processes, the speed at which the air removes or dries water molecules in varying volumes or other atmospheric changes that indicate when
the painter can return to different areas of the work, or how paint is gradually built up in layers, ultimately determines the image resolution. The process is non-linear, nuanced, ambiguous and therefore very difficult to codify. However, to reiterate the core argument the circular and recursive actions performed within the above stated cybernetic framework, inherently reveal opportunities, leading to continued scrutiny and continued learning. The assumed steps within the non-linear and ambiguous act of creative making, typically at first using simple media such as pen and paper (or watercolour in this instance), becomes clearer through identifying, organizing and programming more complex media, methods and interrogation.

Through the exploration and production of watercolour drawings utilizing CNC technologies, the artists (researchers and students) are simultaneously the experimenter and the experimented. This does not conflate the process and product but instead reveals how they themselves process experience through revised operations. By radically simplifying and coding the complex variables in the production of an explicitly nuanced painting technique, the admittedly mechanical process is searching for clarity and ultimately replicability. The creation of a rule-based foundation that is repeatable or recursive steps fosters enhanced and focused learning.

Figure 1. Programmable variables.
The tests first isolate each potentially adjustable factor \( x \). Next, those factors (variables) \( x \) are combined \((x + x + x)\) to produce desired effects. Variables are tested in multiple combinations, sequenced and modified under a range of conditions. (Figure 2.) Next, various technical effects are achieved through each equation. We can speak to what was learned in each test, with each adjustment, a new layer of understanding is achieved, etc. Finally, the incremental increase in complexity allows for enhanced legibility and comprehension, and thus replicability. Defining programmable variables allows for greater levels of control despite limited initial understanding of both the painting process and the end results. (Figures 3 & 4.)
3. Hacking the process

The codification of the processes requires the interrogation of the function, both in terms of how it is done and why it is done, for each action at any moment within a given process. Simultaneously, it requires hacking– technologies, and their limits, must be challenged and catechized, and the programmers must reflect on what we know and what we think we know.

CNC milling technology is primarily designed for the removal of material. The action of inverting its relationship with its primary directive (shifting the machining type from subtractive to additive) embeds a logic, at the onset, that engages the programmer in a critical discourse with the machine. At every step in the process the machine challenges the programmer as the programmer questions themselves. Automated processes that are taken for granted by the typical user must be comprehended and subsequently manipulated to control the outcome of the process. This is the very core of design thinking.

As the dialogue between the machine and the programmer ensues, we observe that the task itself has too many contingent factors to be absolutely knowable. Unprogrammable variables challenge the process. Humidity, air flow, machine vibration, and temperature for example can all be measured and controlled to an operational limit, but absolute control will never be achieved. Similar to building construction methods, where weather effects the curing of concrete and the speed at which masons assemble brick wythes, certain contingent spatio-temporal conditions reveal themselves to be outside the control of the programmer or architect. It is however through the embracing of these variables and the parametricising of programmable variables that evolutions are feasible. Each variable presents a motion which combines with the coordinated motions of other variables to produce the action.

In addition to hacking the hardware, the software processes must also be hacked to develop a functioning workflow to take the conceptual processes and actions into tangible numerically controlled values. Understanding how light is interpreted by Photoshop, how Illustrator deals with colour volumes to map raster content into vector data and finally the translation of the vector areas into codified toolpaths through Rhino and Grasshopper all force the programmer to rethink the tools, their limits/boundaries and their potential relationships with each other. This is particularly noteworthy since the actions of programming the skill necessitates the compression of the senses into bites that are digestible by the computer processing.

Within the metacognitive framework, the foundation of specific knowledge is rattled by the nexus of interactions within the various processes: from the programmer to each piece of software; the software’s interactions within the digital environment; and the software communication to the hardware. In performing these actions the programmer enables both the digital and physical tooling to become extensions of their own body enabling a new form of mastery (Figure 5).
Figure 4: Graphic shows one of the results of the in progress research. There is notable impact that the machine embeds into the developed image that is a representation of much of what was observed by the programmers of masters painting. The processes of building up areas for example, when performed by masters appears almost simplistic in the execution. We see the conceptualization of patterns within the programming of the actions and ultimately the failure to fully comprehend all the variables in play for the said technique.

4. Conclusion

The work here supports design knowledge for practitioners who are pushing toward a greater understanding of design thinking through a more technologically integrated design process, or for design educators who sometimes feel like they’re teaching “robotic” students. This research, through a meticulous understanding of process - both in linear and holistic indexes of cognition – offers greater insight into the impact of technology on design pedagogy. Perhaps more importantly, it also raises questions about education, and the future of design practice. The more this work advances, the more questions will be raised, and the more we will be able to shed light onto those questions. What are some potential impacts of technology on design education? What is the frontier of design knowledge? If we’re not there yet, what must we do as a field to enter that frontier? And so on...

This methodology bounds the pedagogical value of the programming since the programmer must simultaneously interrogate the tools and the process. Each action is performed in concert and the programmer makes choices regarding the outcome which in turn sets the parameters and their limits. We no longer seek to achieve pretty pictures but instead seek to understand the fundamental and excessive variables. As noted by Hoadley and Cox (2009), in the context of design knowledge, ‘experts indisputably “know” the subject but often have great difficulty explicating what they know for novices/apprentices’. Within this method set these issues are resolved by virtue of the process – Thinking is not doing, Doing is thinking.

With students, an educator can quickly note whether each learns a certain way and adjust his or her approach. With machines, however, success is entirely up to the “teacher”, or more directly, the programmer. A programmer can prescribe object level functions, which are fairly straightforward, step-wise and often exact – but because there’s no erasing permanent ink, no correcting the “mistakes” made in the mechanical and irreversible testing process. The authors of this paper contend that there is great value in technology’s imprecision as a means of understanding human cognition. In other words, what is objectively knowable (as opposed to what is thought to be known in a subjective sense) and expressed through unambiguously coded forms may hold critical allusions to what is not yet known and
what has not yet been considered. That these revelations are, in fact, what lead to new evolutions within each designer.

Lastly, as technology continues to penetrate design practice and, more globally, our lives, there is considerable uncertainty about environmental futures as well as existential unease regarding automation and the perceived gradual or abrupt loss of human control. However, based on the research presented here, it can be argued that the process of codifying complex non-linear systems can reveal insight into how the human brain operates. We force ourselves to interrogate how we learn by teaching the machine. The impasse between the human mind and the robotic action is circumvented through the metacognition of both the machine (knowing about how the machine knows) and ourselves (knowing how we know). Additionally and by extension, this perhaps enlightens how society might cope with this same uncertainty and the other changes we will face; informing how we live and learn and ultimately how a better built environment can be envisioned/manufactured by framing the relationship we have with machines of production.

References


Mapping a classification system to architectural education: investigating the relevance of classification systems in creative education

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Abstract: This paper examines to what extent a new classification system, Cuneco Classification System, CCS, proves useful in the education of architects, and to what degree the aim of an architectural education, rather based on an arts and crafts approach than a polytechnic approach, benefits from the distinct terminology of the classification system. The method used to examine the relationship between education, practice and the CCS bifurcates in a quantitative and a qualitative exploration: Quantitative comparison of the curriculum with the students’ own descriptions of their studies through a questionnaire survey among 88 students in graduate school. Qualitative interviews with a handful of practicing architects, to be able to cross check the relevance of the education with the profession. The examination indicates the need of a new definition, in addition to the CCS’s scale, covering the earliest phases of architectural work. This paper will suggest a possible approach to these revisions of the CCS.

Keywords: Education; profession; classification.

1. The introduction of standards

Before implementing a new classification system, such as the cuneco CCS, into the education of architects, it is necessary to uncover the actual overlaps between the classification system and the whole education program. This paper explains that process of uncovering and how it ties into a fundamental discussion about the aim and purpose of an architectural education, and the balance of producing graduates, in the face of industry needs, with both practical and aesthetic skills. Through a discussion of the implementation of a specific classification system, this paper will raise a general architectural education discussion seen from a Danish architectural-educational point of view. The CCS tools cover areas in the building industry e.g. Classification and Identification etc. CCS potentially opens new possibilities of establishing a complete information tool for the building process. However, does the rigor of the system add value also in the context of education?
1.1. Cuneco Classification System – CCS

CCS is the abbreviation for Cuneco Classification System, a set of tools developed by cuneco (centre for productivity in construction) between 2012 and 2014 in Denmark. The CCS is a revised version of the now abandoned DBK classification system – a system which was intended to replace the Swedish SfB, but never actually functioned. The CCS tool covers nine areas: Classification, Identification, Pricing, Property data, Levels of Information, Measurement rules, Purpose Grouping, Classes of Information, and Standardized Tender lists. The tools are developed with the intent of facilitating a more structured communication through common standards for enhanced exchange of data throughout all construction processes from initial concept and design over construction to operation and maintenance (Cuneco, 2013).

The work with CCS has been initiated due to a Danish government decree (ICT regulation, 2013), requiring all public construction with a budget above 5 million DKR, roughly 750,000 US$, and applies digital tools for coordination, handling and communication of the digital models and other information connected to the construction project. These digital tools can be cuneco CCS or equivalent tools.

1.2. CCS in the education

An examination of the use of digital tools in the student projects in the architectural education was performed during the spring 2014. The examination focused on the two schools of architecture in Denmark: The Royal Danish Academy of Fine Arts Schools of Architecture, Design and Conservation – School of Architecture, KA, and Aarhus School of Architecture, AAA. The examination was a part of a larger EU Regional Fund project about implementation of new digital standards in education. The examination aimed at finding the level of relevance for an implementation of and teaching in the cuneco CCS tools.

The examination has led to a concrete discussion about the level of implementation of CCS in the schools of architecture, and a general discussion about the relevance of classification in creative educations.

1.3. The Danish schools of architecture

The Danish training of architects meets the European qualification criteria, which among other things provides for the ability to create architectural designs that satisfy both aesthetic and technical requirements (EU, 2013). The education in the two main Danish schools of architecture categorize as artistic educations (UG, 2014) and distance themselves from related educational offers in the universities because of the heightened focus on the aesthetics and reflective practice. This is regarded as a necessary requirements for a fundamental architectural understanding and is the foundation to eventually be able to work creatively in a professional office, municipality or elsewhere. While the purpose of the education is to prepare the students for individual reflection, and find their own momentum in the architectural field, it is not always the case that the content and form of the education are reflecting the more concrete premises of the architectural profession. The education lasts for five years, while the professional phase lasts for the rest of the working life. This gives a relatively short time span in the education, to learn the basic skills and competences for creating architecture. On the other hand, one has the rest of one’s life to train the skills needed for working under the conditions of the construction business. Therefore, there is traditionally an amount of business related training for architects in the professional life after graduation. That divides the training of architects into the
education and post education training, where the former is mostly concerned with the generation of ideas, artistic work, and sketching techniques, and the latter is more concerned with technical, economical, and feasibility aspects. In these circumstances, is necessary to define if, or how and when, the CCS classification system should be introduced.

2. Motivation for the investigation

The use of CCS will require an additional workload for architects in the beginning of the building project phases, e.g. when the classification of building elements and components must be applied, while the actual savings from its use will appear only subsequently in the lifecycle of the building – thus extra work which does not benefit the architects directly. This extra work can be substantial because projects in the design phase often change a lot during the sketching, and therefore would require re-classification in CCS each time a change is made.

On the other hand, the progressive aspects of implementing a new toolset could also be beneficial for the dialogue between the educations and the profession. Ideally spoken, new dynamics and closer relations could be a result, if a parallel implementation could be done sufficiently meaningful in education and profession. Perhaps an implementation of CCS in the construction sector could also sharpen the focus of the different professions, and actually assign the task of classifying to other professions to whom it is more obviously useful.

3. Methods

The method used to examine the relationship between education, practice and the CCS was divided in a quantitative and a qualitative exploration: A questionnaire survey among students in graduate school, and a handful of qualitative interviews with practicing architects.

The survey consisted of 26 questions that were sent out online and collected online through the service Survey Monkey. 88 students from the two schools of architecture completed the entire questionnaire. Over 90% of the replies received came from students who are partaking in the master’s program of study.

The qualitative interviews with five Copenhagen based architects had a supportive function in relation to the survey, to be able to cross check the relevance of the education with the profession. The questions for education and practice focused on allocation of analogue and digital work, information level of study assignments, working methods, loss of information through study assignments.

We have analyzed the processes and traditional forms of work existing in respectively education and profession, while we have also performed an exploration of the CCS tools.

4. CCS tools in relation to existing work methods in education

Of the CCS tools: Classification, Identification, Property data, Classes of Information, Levels of Information, Purpose Grouping, Measurement rules, Standardized Tenderlists, and Pricing, the last four can be screened out, since they are not included in the curriculum and have currently no connection to the work with study projects at the schools of architecture. Below is an introduction to the remaining tools and a mapping of the overlap with education.
4.1. Hierarchical classification of buildings, spaces, and building components

The tools Classification, Identification, Properties and Classes of information enables a standardization of the classification of structures, spaces and buildings for architects. If one views classification hierarchical, with buildings at the top, spaces in the middle, and building components at the bottom, the architect's work typically begin in the top of the hierarchy and then move down. As the figures in the survey show, for example that 48% of the students have not used a detailed design drawing during the study; it will probably be rare for architecture students to go deep into this hierarchy. On the other hand, there is a rich activity in the top of the hierarchy, as the work with structures and spaces and their properties occupy a significant part of the study tasks. CCS supports the work with space programs and space requirements that could be a connection to the space programming, which is a typical and indispensable parameter in many study assignments. However, 30% of the students organize their own study tasks, and thus even develop delivery requirements themselves.

4.2. Objective and subjective properties

Properties in CCS can be divided into two principal main categories, objective and subjective. The objective can be verified from a measurement (e.g. weight or length) or from an associated custom code, such as life cycle phase or project ID. The introduction of the intended subjective features in CCS are very remarkable and highly relevant for architects, though not yet developed. This could be attribute categories such as sensory properties, experienced spatial quality or experienced comfort. It seems in line with the surveys that education and profession supports this part of CCS, develops and explores how to get the most benefit from these property categories. These categories can be defined at a very early stage. It may also well be that these are subjective features together with objective characteristics could be listed as requirements from the client to the architect, or in architectural competitions.

4.3. Levels of information and classification of projects

The CCS Levels of Information divides the building process into seven information levels from IL 1 to IL 7, representing the process of the building project from the representation of an idea to the fully detailed specification of a physically feasible solution (Cuneco CCS, 2014). In several of the interviews, it was stated that it is most natural to begin the project classification at the end of the sketching phase. But, as shown in the survey, this phase ends only after a thorough shaping and clarification which stretches across 58% of the students' time. The architecture students will thus inevitably work at an information level that is prior to IL 1, an IL 0 if you will. As it is today, this shaping phase is a safe haven where a non-linear creative process is ongoing, and classification does not make much sense. It is therefore the question whether this discipline should be exercised in an environment where the project classification has already begun.

4.4. Mapping between CCS and education

The figure below (Figure ) shows a mapping between cunecos CCS tools and the study work in the schools of architecture. The overlap is limited to the relatively few study assignments in the schools of architecture that moves beyond information level three. It is a minority of study assignments, which reach beyond this level of detail, because the whole education’s aim is inclined towards presentation of the principal architectural idea and not the professional offices’ self-evident focus on building technology, feasibility, and economics.
An interesting point is the subjective properties, which could probably be very relevant in the early phases of a study project. Unfortunately, these subjective properties are not being developed at the time, and is therefore work that needs to be (re)initiated – possibly in collaboration with both education and profession.

Figure 1: Overlap between the CCS tools (light blue) and a typical student project in the Danish schools of architecture (dark blue) mapped sequentially with the Information levels. The graph illustrates that the overlap is relatively small, but could be expanded, if the CCS ‘subjective properties’ were developed.

5. Student questionnaire investigation

The student survey consisted of questions in relation to their working methods addressing

- Distribution between analogue and digital working methods
- Level of information in the study assignments
- Linear versus non-linear working processes

5.1. The distribution between analogue and digital working methods

The part of analogue work in relation to study assignments, as opposed to digital work, represents 45 % (Figure 2). Analogue work includes both analogue drawings and analogue models.

Figure 2: Analogue versus digital work in student projects.

Alternating between analogue and digital work in relation to study assignments is one of the characteristics of the education of architects as an artistic education. That the students are working like this is in good agreement with the curriculum (Curriculum BA/KA, 2014), which over the years has incorporated a balance between analogue and digital approaches. It is of fundamental importance that the students cultivate their perception of space and form based on the mixture of tangible models or drawings and their counterparts in the virtual models or abstract systems.
5.2. Level of information in the study assignments

The CCS Levels of Information from IL 1 to IL 7 spans from idea to fully detailed specifications. The students’ work, however, is very often initiated at an even earlier stage than the CCS IL 1. We had to include this in our survey, why it was necessary to add our own terms to the information levels, namely shaping and clarification. While clarification will correspond roughly to CCS IL 1, shaping occurs prior to this, outside the CCS information level scale, because there is usually no classifiable building information at all. We suggest the term IL 0, information level zero, to meet the CCS terminology.

- Shaping is defined as the timespan from when the assignment is given until a set of drafts are created and available for further contemplation. This phase is characterized by exploration, analysis, and experimentation.
- Clarification is defined as the timespan from when a set of drafts are available until a clearer idea of the building can be described in regard to function, light and material conditions. A draft project pointing in one specific direction.

The survey tells that graduate students spend an average of 58% of their time on shaping. This means that 58% of the study related work done at the schools of architecture, is placed outside the CCS information level scale. Of the remaining 42% of time, which is subsequently used for clarification of the drafts, around 33% is analogue work. In reality this means that, out of 100 study days, only 28 have a relevance in relation to CCS. In the remaining 72 days it will not make any sense to introduce classification at all, since the work performed is either analogue or on an information level below 1 (Figure 3).

![Figure 3: Days of study work relevant in connection to the cuneo CCS tools.](image)

Approximately 93% of the students are not using Revit, which is the most common object oriented software used in the schools of architecture, in shaping their student projects (Figure 4). Approximately 90% are not using Revit in clarification of the projects (Figure 5). More than half of the students answer that they have never made a detailed design drawing, or anything resembling a detailed design drawing, in relation to a study project (Figure 6).

![Figure 4: Use of Revit in shaping of project.](image)

![Figure 5: Use of Revit in clarification of project.](image)
Though this might seem disturbing to a more technically based school of architecture, it is nevertheless consistent with the goal of teaching in the main Danish architectural educations. In the schools of architecture, students are trained extensively for proposal making and not necessarily for actual detailed design (Curriculum KA). There are other schools focusing exactly on detailed design, but none other than the schools of architecture are focusing on the preconditions for creating architecture, as an artistic discipline.

5.3. Linear versus non-linear working processes

Identifying whether the individual student's work process is linear or non-linear was investigated to see whether the students experience a continuously increasing level of information during a study task or whether the process is rather a fluctuating curve where information loss frequently occurs as a natural part of the creative process (Figure 7).

When this graph is compared with the next question about redrawing (Figure 8), it could indicate that having a continuous process is not necessarily considered equivalent to being more efficient and therefore something desirable. It could indicate that sometimes there can be a real value in redrawing and going back in the process in both shaping and clarification during the development of study projects.

When asked about redrawing and redefining of objects due to changing from one software to another, the majority indicates that it is not a big problem. This indicates that the use of several types of software for most students is considered a condition and a necessity for architectural study work. That
only very few don’t know, indicates that there generally is a high use of digital tools and that most students have experience changing from one software to another.

6. Interviews with the profession

Five Danish sketching architects were selected and interviewed. They were from the offices Hplus arkitekter, Zeso arkitekter, C. F. Møller, and BIG. One of the premises for the interviews were that we could only anonymously use them.

The interviews with the professional architects have a supportive character in relation to the survey among the students. The students are usually not given credit for including economics or constructability in their projects compared to presenting an architecturally coherent overall concept. It is therefore clear that the students focus on communicating their overall architectural idea, since that is what they will be assessed on. There is a difference between the projects in education and the profession; thus, the interviews help to determine whether there appears to be a connection between the students’ answers and the attitude in the professional offices. Some benchmark quotes from the interviews are selected to illustrate the professional attitude towards CCS, in the profession, and in the education.

All architects had been working in teams in relation to specific sketching projects. The sketching phase varied from three to eleven weeks, which is equivalent to an average of 7 weeks. An average of 20% of the sketching work was analogue sketching.

Two out of four answered yes to being Revit in the sketching phase, and everybody were positive to the suggestion that analogue drawing is important for the generation of ideas. It was also the common understanding that information transfer between software was labour-intensive and lowered efficiency.

6.1. Selected quotes from interviews with the profession

“The proportion of analogue drawing in the sketching phase is about 20% - but it is the most important part of our profession, I mean. Its significance for the architecture corresponds to 70-90%. I never directly sketch into the computer. Analogue sketches are faster and brings me quickly to something good” (Architect 1).

“I think it is obvious that young architects come from the school of architecture with a knowledge of cuneco and an understanding of how cuneco code can facilitate the procurement procedure for both client and architect. One could well imagine courses in cuneco towards the end of the study” (Architect 2).

“Overall, I think that the architect education in Denmark should be more technical and furnished with a better eye for what is going on at the offices and in the construction industry. It is as if the architecture education has fallen behind on a technical level, the past twenty years” (Architect 3).

“One must be very careful that you are not going to waste time on something that really does not matter. It may take time to sit down and define these codes. One must be very careful ... In any event, I do not see why there should be taught cuneco at schools of architecture. It does not seem appropriate” (Architect 4).
“Architecture Schools must of course teach BIM [Building Information Modelling, ed.]; it is obvious and very important. However, I think regarding CCS, you can just inform and tell what it is, and give some examples of when and how it can be used. I do not think you have to teach the code language, etc. It does not make sense” (Architect 5).

7. Discussion

As we have seen, the average number of days where students might involve the use of a classification system such as the CCS is only about 28%. When compared with the fact that more than half of the students have never created a detailed design drawing throughout the study, and have had no need to, and that less than 10% work with Revit during shaping and clarification of study projects, it seems that the extension of an introduction to CCS must be very limited. The overlap between student projects and the CCS is simply very small. A brief introduction to classification would be appropriate in equivalence to the current working methods in the student projects.

If one takes the offices’ point of view though, there is a more obvious need. Two out of four use Revit in the sketching phase, and as a design tool. Since analogue drawing in the sketching phase, in our study, only accounted for 20% of the time used, it seems that a link between Revit and other types of sketching software is a good idea to support the implementation of CCS in offices. This could indeed be a task for the education.

Of course, architects must know about classification to some extent, the question here is when and where they will need to learn it. From our investigation, we find three possibilities: 1) During the education as a mandatory course; 2) During the education as an open offer; 3) After graduation as a part of the vocational training in the professional offices.

There is also a need for the development on the software side of the plug-ins between CCS and other common applications. Revit has a plug-in for handling CCS. A similar plugin for e.g. Rhino could be desirable. Such plug-ins may potentially be an important part of the specific handling of CCS for architects, since it will be possible for the sketching architect to communicate important overall classifications and characteristics prior to release for design. This will facilitate communication between architects and designers, and expand the potential for CCS to the other types of software architects use in sketching. This, however, will only really benefit the education if actions are taken to develop and incorporate the use of subjective properties into the CCS. This could be developed as part of the additional information level 0 that includes the shaping definition from our division of the sketching phase.

Subjective property data in a project allows commenting on shapes, spaces and architecture - or even benchmark the experience of these. This could presumably be done, cleverly using building information modelling with virtual reality simulations.

8. Conclusion

From the investigation we have learned that the overlap between education, in the two Danish schools of architecture, and CCS is relatively small, while the profession has more obvious needs for implementing CCS. Therefore, we suggest broad but brief (2 hours) introductions to CCS within the education, in line with the curriculum and expectations of the students. The actual skills in using the CCS is suggested to take place after graduation in a collaboration between the education and professional studios. We suggest that the CCS expands the definitions of the information levels with IL 0 for the
shaping of projects. Furthermore, we suggest a collaboration project between Cuneco and education on developing the subjective properties in a combination of BIM and Virtual Reality. A proposal has now been submitted in this respect.

The above mentioned conclusions have been noted and already applied in changing the education.

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Melbourne School of Design Building Archive: a unique learning resource

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Abstract: The construction of the new Melbourne School of Design (MSD) Building offered a unique opportunity to capture and document the entire building design and construction process. Documentation was collected from every stage of the project, from the initial design competition held in 2009 to data generated during the current operational phase. This information has been captured in the Melbourne School of Design Building Archive and made available to staff, students, researchers and the broader university community in order to provide a comprehensive resource for future teaching, learning and research. The archive contains tens of thousands of images, documents, drawings and other items of information generated throughout the life of the project. The aim of this paper is to describe what was learnt from the process of creating an archive of a building project in real time. The major challenge as well as greatest opportunity faced in the process of archiving the project was the live nature of the project. The archive represents an important resource that very rarely exists for building projects and its establishment and the processes involved can be seen as a useful model for the production of similar resources for other building projects in the future.

Keywords: Melbourne School of Design; building archive.

1. Introduction

The University of Melbourne’s new Melbourne School of Design (MSD) Building was completed in 2014 and represents a unique example of a ‘Living and Learning’ building. The building’s design creates a pedagogical resource for students and visitors alike. Elements of the building that would normally be hidden have been left exposed, including services and structural elements. This enables the building to be used as a teaching resource, with students not only learning within the building but also from the building itself. This pedagogical approach to the building’s design is supported by a digital archive documenting the building design and construction process. The development of this digital archive was guided by an archival documentation strategy (Samuels, 1992) geared to meet the pedagogical requirements while not compromising the underlying principles of archival practice. These principles
focus on the documentation of the operational context surrounding the creation and initial uses of the records with the goal that they will be interpretable by those not involved in their creation, especially those in the more distant future, or those from different cultures. The documentation of context results in a contextual information framework identifying all the major agents (people, organizations, activities, events, stakeholders etc.) and the relationships between them. Importantly, the contextual information framework enables the documentation of change through time.

This paper describes establishment of the archive through the collection of born-digital material from a range of sources and discusses the major obstacles encountered. From the perspective of archival science, this project pushed the bounds of conventional practice by purposefully collecting records and documenting the creation of a new university building as the building’s design and construction unfolded. As a rule, archival processes are enacted once an activity is fully complete. The paper utilises an autoethnographic research method (Ellis et al., 2011) to take a close look at how this archive was produced and how the challenges and opportunities that arose were addressed.

2. Melbourne School of Design Building

The new Melbourne School of Design Building, located at the centre of the University of Melbourne’s Parkville campus, is a state-of-the-art academic facility, designed by John Wardle Architects (Melbourne) and NADAAA (Boston). A large-scale laboratory for built environment education and research, the building sets a new standard for design education in the Asia-Pacific region. The project commenced in 2009 with an international design competition. This was followed by the demolition of two existing buildings and construction of the new building from early 2013 until August 2014 (Figure 1).
Figure 1: External and internal view of the MSD building. (source: Peter Bennetts (L) and Peter Ashford (R) (2014))
2.1. A pedagogical resource

Construction projects are one of the most complex human endeavors. They also offer an ideal opportunity for learning and knowledge development that can be used to inform future projects and educate construction industry professionals to help improve the building process. However, the tight budgets and timelines on most construction projects allow little scope for documenting the material to allow learning and creating knowledge both during and after the design and construction process.

Two of the key design drivers for the MSD building project were ‘The Living Building’ and ‘Built Pedagogy’. This focus very rarely exists in building projects and allowed an opportunity to capture knowledge and learn from a real-time project for future use, expanding the broader industry knowledge base of building design and construction processes, especially in the context of an educational building.

In relation to ‘The Living Building’ focus, it was envisaged that the building would ‘…act as a laboratory, providing opportunities for staff and students to control, adjust and monitor environmental systems such as sun-shading or natural ventilation’.

Central to the pedagogical approach to the new MSD building was the development of knowledge of the processes, issues and challenges associated with its design and construction. The material generated from the building project, documented in the MSD Building Archive (2015), provides a useful resource for understanding these aspects and allows a comprehensive insight into the building development process. Although the material was mostly generated by parties external to the university, the Faculty of Architecture, Building and Planning (ABP) aimed to create a learning resource, while at the same time meeting the key design objectives for the new building – The Living Building, and Built Pedagogy. This context needed to be strongly considered in creating the digital archive.

The subsequent documentation strategy, which focused on the construction process, was influenced by Samuels’ (1992) functional approach to documenting the activities of academic institutions. In her analysis of American university archives and their records appraisal (inclusion) policies, she outlined seven high level university functions. Only one – the governance and administration function, serving to sustain the institution – had to that point been considered generally as defining the collection policy of a University archive. Samuels was controversial in challenging conventional wisdom. Her view of the university as an organism evolving and adapting through time supported the use of social science techniques to plan a documentation policy, including the collection of entirely external (non-institutional) material (Cook, 1994, p. 396).

3. The MSD Building Archive project

The MSD Building Archive project involved capturing, collating, organising and documenting as much of the material generated from the design and construction of the building project as possible, as the project unfolded. The aim was to make this material available and easily accessible to the broader university community for teaching, learning and research purposes. This would ensure that this living and learning building could be used as a resource indefinitely into the future, even well beyond the life of the building itself. As most of the records or information objects created as a consequence of the design and construction process were digital, the focus of the archive project was on the assemblage, documentation and curation of the digital materials. The management of the paper surrogates of the records was deemed out of scope for this project although it is acknowledged that some of these records may contain valuable annotations and be a more accurate record of what actually transpired on the building site.
3.1 Project team and stakeholders

In June 2012, before the demolition of the existing buildings, the Faculty of Architecture, Building and Planning asked the University’s eScholarship Research Centre (ESRC) (2015) to assist in archiving the information and material created as part of the MSD building project.

The ESRC, established in 2007, has a research agenda and practical experience focused at the junction of archival science, social and cultural informatics and the humanities. Up until this project the Centre addressed the challenges of documenting records to create archival collections after their operational use had been served. The major risk here being the lack of access to personnel involved in the project with intimate knowledge of the story of the records. The creation of the contextual information framework in which to situate the records was done after the fact and contingent upon the records that survived. Archival work in this context was more akin to archaeology with a happenstance salvage aspect. For the Centre, archival projects involve the two distinct but entangled processes of documenting records and documenting context. To enable this, the Centre developed two related but independent electronic systems, the Heritage Documentation Management System (HDMS – for documenting records) and the Online Heritage Resource Manager (OHRM – for documenting context). As the MSD Building Archive project was running concurrently with the design and construction process and records were being generated in multiple places, the OHRM, with its more flexible open network functionality, was selected as the primary focus for the MSD Building Archive with the goal of documenting the context of the project as it happened rather than after the event.

Other stakeholders and collaborators included The University of Melbourne Archives and the University’s Records Services, who provided advice on appraisal and present and future storage of the digital material. ABP were designated as the owners of the material from the design and construction process and provided copies of the digital material to the ESRC. The original sources of these resources included ABP itself, the builder Brookfield Multiplex, architects NADAAA and John Wardle, and university staff, who contributed thousands of images.

3.2 Scope of data assets

The resources contained within the MSD Building Archive cover every phase of the project, from the initial design competition, to the design process, pre-construction activities (demolition of existing buildings, services redirection, propping of an existing heritage façade and asbestos removal), construction and post-construction. All the material provided to the ESRC for archiving was in digital format. There were a range of resource types provided, including images, videos, sketches, drawings, documents, presentations, WebEx screenshots, renders and data. The archive also includes images of the previous buildings in which ABP was housed (Architecture and Old Commerce buildings).

3.3 Archives and records assumptions

There are various attitudes that are considered in this paper and frame the following discussion. Firstly, the traditional and narrow view of archivists in the academic context, according to Samuels (1992), had been that universities exist to sustain themselves as institutions and that the selection of records only needs to support that function. This is a perspective inherited from government archivists who tend to operate on the assumption that only a small percentage of records created during day-to-day operational activities has value in the longer term and are worth the investment of archival documentation. This assumption dates from pre-digital archival practice and was partly driven by the
limits of physical storage and the budgets available for manual documentation activities. However, this view reflects a bureaucratic perspective and does not take into account alternate perspectives and value propositions, for example the specific needs of the MSD Building Archive. While the advent of digital technologies and their use in records creation processes has opened up possibilities for more extensive archival collections, as a rule archival policies and practices are still dominated by a pre-digital mindset.

Secondly, at the other extreme, the advent of the digital world has created a general community sense that it is possible to keep everything, that a ‘Google’ style search will allow users to easily find what they are seeking, and that those materials and their supporting systems will be miraculously preserved into the foreseeable future. Sadly or perhaps fortunately, this knowledge utopia has failed to materialise. The digital world has significantly disrupted managed and effective record-keeping practices. For example, the ease of duplication and sharing via email of other means has led to massive duplication of materials across multiple distributed environments. In this world a Google style search is likely to reveal vast numbers of de-contextualized copies. Assessing the value and meaning of any particular record has proved to be problematic.

The pedagogical purpose of the MSD building meant the archival record of the design and construction process had to be, as much as possible, the whole record and the capture of the project materials needed to occur concurrently with the design and construction process to optimise the capture of related contextual knowledge through direct access to people and systems. This entanglement of the archivists, records managers and architects in the documentation and preservation process from the outset meant that the diversity of assumptions and understandings of what the archival process actually involved had to be confronted.

3.4. Systems for data capture

The Online Heritage Resource Manager (OHRM) system and methodology were selected to develop the MSD Building Archive. The OHRM utilises relational database technology and is capable of producing a range of standards-based dissemination formats including xml and html. The OHRM has been used to make online encyclopedias or registers, and manage related information from archival, bibliographic, audio and video sources, as well as photographs. Data is captured in the OHRM to document entities (primarily people, organisations, concepts, places and events) and resources (information objects and cultural artefacts) based on archival and related cultural informatic standards (International Standard Archival Authority Record for Corporate Bodies, Persons and Families (ISAAR (CPF), 2011) and Encoded Archival Context for Corporate Bodies, Persons and Families (EAC-CPF, 2012) (2012)). For this project, the design and construction activities were mapped by making connections between related entities to build a network of information around a subject, for example, a project stage can be related to archival and bibliographic references and digital resources such as multipage digitised documents, images, sound files, and movies, and to other related or sequential processes. The OHRM can produce web pages and exchange data with other digital resource repositories and search engines, such as Trove (2015).

HP TRIM (Total Records Information Management) (2007) is the University’s Electronic and Records Management System supported by Records Services. It is available to all University departments to manage their records, regardless of format, and meet their recordkeeping obligations. HP TRIM was initially proposed as the repository for much of the data in the Archive. In contrast to the OHRM, HP TRIM is essentially a flat file system with a primary focus on operational records management and is not geared to capture the broader context of the records and the multiple time and location-based relationships between entities. HP TRIM was also deemed unsuitable as the content in TRIM could not
be easily accessed by unauthorised users. The decision was made to focus instead on contextual data and curated subsets of the documents and images in the OHRM.

Aconex (2015), a commercial project content management system, was used to store and transfer documentation between project participants during the design and construction phases of the project. This web-based communication platform was designed to facilitate the management of a building construction project and was not geared to meet archival needs. Aconex, as a massive repository of all documentation generated from the construction of the building, was appraised as a valuable source of records that could provide the information on the construction of the MSD building in a useable form.

The initial plan was that the OHRM would hold a description of the attributes (the metadata) of a digital information object, and map these to other related resources and entities. The digital material received from ABP – images, drawings, videos, etc. – would all be registered in HP TRIM. In this way, it was thought that both the interest of Records Services in keeping the project records (legal requirements), and the MSD Building Archive project objectives could be served. It was hoped that Saffron, a third-party web interface developed for HP TRIM, would provide a web mediated link or citation point for each digital object described in the OHRM, so that archive users would be able to access (view and download) files kept in HP TRIM. However, this capability was not available during the first phase of the project.

Using the OHRM to categorise the distinct project phases allowed the Archive to grow responsively as the construction of the building unfolded. This categorisation also supported subsequent access to the materials. A key requirement of the Archive was that the documentation contained within it was organised in a way that not only reflected the way the building project developed but also aligned with the accepted structure of the processes and components of a building design and construction project. This helped ensure that individual items or groups of items could be easily found by users of the Archive and that relationships between items could be easily seen and explored.

3.5. Disposal, storage and access

The University of Melbourne’s Records Services, Archives, Property and Campus Services and Legal Services in conjunction with the architects and contractors contributed to discussions on the appraisal and disposal of the materials and the user obligations associated with access and use. There was a particular focus on material that is usually destroyed. As a rule, access conditions are determined according to categories of material, rather than on a document by document basis. There was some uncertainty about the architects’ contractual arrangements, particularly regarding copyright, for which Records Services offered assistance with locating relevant contracts.

Discussions about access protocols for MSD Building Archive documentation aimed not to hinder access, but to establish protocols and clarify the obligations of those who are granted access to documents. Records Services drafted an Access to Records and Archives form and an Access checklist to assist with this, currently on trial by the University’s Property and Campus Services.

4. Results

4.1 Archive structure

As noted in Section 3.4, the system used to create the MSD Building Archive, the OHRM, was historically used to map contextual information from a wide range of sources, such as archival and published
material, photographs, audio and video. The conceptual model and the derived informatics of the OHRM were based on entity and resource types and concepts from archival science. The entities and resources are interconnected by defined relationships which can be richly annotated and spatio-temporally constrained as required. This ‘relationship-as-entity’ model enables the creation of a contextual information network or framework that can be geared to meet specific purposes. It is also well situated to contribute data to the emerging Linked Open Data frameworks.

In addition to the network approach to discovery, to gear the use of the Archive for teaching and research, a faceted search capability became a key requirement for accessing and displaying the content of the Archive. This required a search functionality that could return a display of images and other documentation as a visual search result rather than as a simple list. Selecting an image from a grid view, accompanied with minimal text, opens it on screen and allows the user to scroll, zoom in and view the image and its related information in detail. This information (metadata) has two purposes: firstly, to inform the user of key attributes such as title, date taken, creator of the image or document, and rights of attribution and use. Secondly, the metadata extracted from the digital objects maintains links to the source material, and helps categorise the material.

4.2. The MSD Building Archive web resource

The first iteration of the MSD Building Archive online resource was launched on 11 December 2014 as part of the official opening ceremony of the new MSD building.

The online archive developed provided access to more than 8,000 images and hundreds of other documents in the archive in what is intended to be a useful and meaningful way. Alignment with user needs was a major consideration in this phase of the project. The focus on highly structured data and curated subsets of documents and images led to the development of the faceted search interface (see Section 4.1 and Figure 2), supported by a more traditional encyclopedic approach to presenting the contextual data.

In addition to searching, the Archive content can be browsed by selecting any of the pre-established search categories. The key categories are the project phases of the MSD building project, adapted from the construction program. There are six project phases: 1. Old ABP building and pre-existing conditions, 2. Design competition, 3. Design, 4. Pre-construction, 5. Construction, 6. Post-construction.

Other search categories or filters are: Resource type filters – a list of all the types of data (i.e. images, videos, drawings, renders, WebEx, sketches, data, documents, audio, 3D models); Entity type filters – digital object, publication, archival resource; Repository filters – a list of repositories for the data processed in the OHRM: HP TRIM (Records Manager), University of Melbourne Archives; Date – shows a list of date ranges, for example: 2000-2001, 2002-2002, 2009-2009, etc..

Most of the project phases also have sub-categories corresponding to the construction program, traditional building design and construction activities or building elements. For example, the Design phase has four sub-categories (schematic design, detailed design, construction documentation and tender) and five sub-sub-categories, which in this case are resource types (Figure 3). The online archive can also be searched via keyword or phrase, entered in the search box. The results are shown in a grid view in the centre of the screen (see Figure 2). Results can be interrogated further by selecting one or more of the resource type filters, and other sub-categories.
Figure 2: MSD Building Archive search interface.

Figure 3: Design phase sub-category and sub-sub-category filters.
5. Discussion

The creation of the MSD Building Archive was a unique application for the OHRM which had previously been used for historical, text-based research data and was developed using archival data standards. The MSD Building Archive was created using only digital materials. The challenge was that the OHRM, initially conceived as a tool to produce encyclopedic and archival descriptions, was useful to produce descriptive, detailed documentation of an entity, but lacked the capacity to display large sets of images well, which became one of the main objectives. It soon became clear that a grid-view and full-screen view of images and a targeted search for accessing the Archive was needed. This resulted in a complete redrafting of project priorities and the development of an application to act as an image display as well as a search tool.

All the material provided for archiving was in various digital formats. The data was made available as each stage of the project concluded. The live nature of the building/archive project and large volume of the data, particularly digital images, drawings and audiovisual material added more complexity to the management and processing of the digital assets. Assumptions had to be made about the likely number of documents to be included and their arrangement within the Archive structure. These unknown and unspecified elements made budgeting and forecasting time and staffing difficult. It is clear that it is easy to underestimate resources required.

Aconex was anticipated as a useful source for all the project data. It was thought that the large amount of information created and stored in digital format would make the process of creating the Archive easier. Regrettably, the Aconex system created a collating and archiving challenge that proved to be out of scope for the first phase of the project. When a sample of the data was analysed the team identified potentially useful data and metadata, but omissions in content were also noted. The structure and categorisation of the vast number of information objects within Aconex were not immediately usefully for the purposes of the Archive. On examination, the data mining necessary for extracting relevant documentation and placing it within the structure of the Archive would have exceeded resources. The task would have been to transform that data into a format transferable between systems, such as the OHRM and HP TRIM. Additionally, the extraction of the data required specific proprietary applications. Aconex offered API enablement and developer network access to suitable application interfaces to download the data, however the purchase price exceeded the initial Archive budget. The University’s Records Services team investigated whether anyone had successfully integrated Aconex data with HP TRIM and no examples were found. While apparently possible, time and money precluded attempts to do so in the initial phase of the project.

According to a report of a 2004 interview of Australian preservation specialists, an effective digital preservation strategy should not be based on proprietary data formats or systems (Harvey, 2011, pp. 105-106). Clearly, a mixture of proprietary and in-house systems was used, which shows that the curation process was highly adaptable, as well as highly challenging. A positive outcome was that all data formats were considered, successfully documented and preserved in the digital archive.

Additionally, there were queries about the intellectual property in this information and the need for traditional archival and records practices such as disposing of certain classes of records (tender documents), and making clear distinctions between what records had ongoing corporate business uses and which records had immediate broader use in the Archive. The University’s Records Services and University Archives provided valuable broader support in managing copyright and granting authorisations for
access to the material, and with decisions on which material to publish. Discussions on long-term storage for the material have commenced, and are ongoing.

Long-term storage and future accessibility of the material posed further challenges. How would future system changes or upgrades affect the ability to retrieve and view the existing material? Would the raw material have to be migrated to a different resource format so it could be accessed? Hardware and software should be maintained in working condition, so that the digital materials can be accessed in future (Harvey, 2011, p. 132). How much data storage would be needed? For example, the time-lapse material, shot on three cameras, consists of approximately 1,200 high resolution images per camera per month (approximately 10 GB per month per camera). At the time of writing it was stored on a server of the company providing this service with back-ups in Melbourne and Singapore. The entire collection of images requires storage of more than 1 TB and was beyond the capacity of the ESRC server hosting the MSD Building Archive website. A future storage location under the control of the University needs to be negotiated. These discussions have been started, and concerns only partially resolved.

6. Conclusion

Understanding the nature of the documentation available, its structure, its value, how it would ultimately be used and the relationships between different aspects of the project were some of the greatest challenges faced in the development of the MSD Building Archive. This is something not typically considered for construction projects.

The creation of the MSD Building Archive has been a complex undertaking, with much work remaining to be done. The successful completion of the project entailed challenges requiring changing scope and direction as it evolved. The successful outcome depended mostly on the clarification of the purpose of the Archive (as a learning and teaching and research resource), how the material was to be accessed and viewed (search and image handling), and the ability to trace each data item back to its source. This in turn defined the practical tasks of the participants.

Alignment with user needs was a major consideration in this project. The focus on highly structured data and curated subsets of documents and images led to the development of a faceted search interface, supported by a more traditional encyclopedic approach to presenting the contextual data. While the HP TRIM and OHRM systems had their specific applications for this project, adaptation and further development was necessary to satisfy the purpose of the Archive and accessibility of its content.

Discussions on data management, including addressing storage of data, future maintenance and system compatibilities are important to maintain data integrity and the ability to track back to the original source, and need to be ongoing.

It is difficult to perceive this project as final. The Archive has potential to become a living and growing resource, with material added as the new MSD building continues to evolve. Often, the means and support required for establishing and maintaining such a resource is significantly underestimated. A plan for ongoing data management and funding for resources required to perform the ongoing maintenance are key considerations.

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References
Rethinking architecture as a catalyst for sustainability

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Abstract: This paper proposes an alternate approach to considering the role of the architect against a backdrop of climate change, urban expansion and evolving technology, as the remit of architects is increasingly marginalized by other professions. Using the case study of architectural design studio investigations for the Master of Architecture at the University of Technology, Sydney on conflicted sites in Australia, the paper address the implications at two levels: 1. Opportunities where architecture and strategic urban interventions become catalysts for sustainable practices. 2. Insights and outcomes from this pedagogical approach to sustainable architectural design education. Developments on conflicted sites are laden with social, ethical, political and environmental concerns that intensify the environment and often contradict with sustainable development and intelligent environmental performance. The design studios explored in this paper challenge the traditional approach (in both academia and practice) of considering efficiency or technical building environmental performance in isolation. They offer opportunities for deploying design thinking in a strategic manner to develop resilient architecture in the context of climate change and current debates.

Keywords: Resilience; agency; architecture; education.

1. Introduction

The central role of the design studio at the core of architectural education is universally accepted across most schools of architecture (Oh et al., 2012); as is the potential for a studio teaching approach to encourage reflection (Schon, 1985; Green and Bonollo, 2003). Against concerns to integrate environmental studies into studio teaching, and make the discipline area more appealing to students (AIA, 2006), Thomas (2009) has argued for the value of an alternate approach to architectural design studio teaching where the objectives of the discipline are primary drivers within the studio.

Questions of sustainability and environmental consequences pervade most aspects of our lives. In architectural practice, they influence our building regulations and our energy codes. They are embedded in our criteria for architectural awards, and of course our education policy and school curricula. At the University of Technology Sydney (UTS), the building blocks of architectural science are delivered through a suite of three core compulsory subjects (each a quarter of a full semester load). The strand begins by
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facing global imperatives for sustainability, and progresses to develop an understanding of human comfort, climate responsive design, advanced environmental control, lighting, acoustics, and integration of building services. Students learn to work with specialists from different disciplines and reconcile the competing environmental and program requirements in their design projects. This approach where technology courses operate to extend the resolution of the concurrent design studio project is not uncommon in many architectural schools. While the principles of architectural science are considered to be done and dusted on completion of the core subjects, a few schools offer specialist design studios with an environmental focus. Traditionally, dedicated environmental studios have looked to the tectonic integration of elements within architecture to ensure energy efficiency or technical building environmental performance. As digital tools for performance analysis in engineering and construction gain prominence, studios such as Hensel (2013), Guzowsk (2013) and Thomas (2009) have also sought to emphasise digital processes beyond mere form making into the realm of performative design.

A purely techno-centric focus on facades in green buildings or water and energy efficiencies often continues to fuel growth and consumption. It turns out (surprisingly for some) that technology cannot fix every one of our problems. A more holistic view of sustainability recognises it to be a WICKED problem. Wicked problems as characterised by Rittel and Webber (1973) have complex interdependencies with no “solutions” in the sense of objective or definitive answers. This issue is further intensified in the context in which architecture operates, where the production and design of objects including buildings generates further consumption. Nevertheless the potential exists for design thinking to influence the way we approach this conundrum (Papanek, 1995; Hocking, 2010), enabling us to posit questions such as: How do we embed sustainable practice in our buildings? Can design motivate or instigate sustainable habits or expectations? How do we future proof our cities and our buildings?

While the remit of the architect is being increasingly marginalized in favour of other professions (Bennetts, 2008), this paper argues that addressing questions such as those posed above is crucial for the future of the profession especially in the context of climate change, urban expansion and evolving technology. Using the case study of architectural design studio investigations in the Master of Architecture course at UTS on conflicted sites in Australia where urban, economic, social, environmental and climate challenges are intensified, the paper address the implications at two levels: 1. Opportunities where architecture and strategic urban interventions can become the catalysts for sustainable practices. 2. Insights and outcomes from this pedagogical approach to sustainable architectural design education.

2. Studio Approach and Framework

The selective studios in the Master of Architecture at UTS emphasise modes of practising in architectural design with specific sub discipline objectives (such as technology, environment, and urban) as well as broader ambitions around the creative processes of architectural design. UTS has more recently framed studio investigations under a school wide theme (Burke, 2012). This paper discusses the pedagogical framework developed by the author for four recent studio iterations (2011-14) within the environmental studies theme offered at UTS. The first three of these iterations were developed and offered as part of an EU-Australia Joint Mobility Project1 “Designing the New World: Developing Architectural Education in Response to Climate Change” (DARC).

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1 During 2011-13, UTS was part of DARC - a 6 university consortium (led by RMIT, with UTS & QUT from Australia & ETSA Barcelona, ENSA Toulouse, and Politecnico di Torino from Europe) that was awarded the mobility grant for staff and students.
2.1. Studio approach – the notion of the contested site

A core theme of the studios under discussion was the focus on conflicted sites in Australia. Developments on such sites are laden with social, ethical, political and environmental concerns that can sometimes contradict with sustainable development. Analysis of these conditions has the potential to provide critical insights for preparing for and responding to change. In addition they serve as a vehicle to drive research and design for sustainability at regional and precinct level.

From a pedagogical perspective, the real context of the site serves to encourage students’ engagement with the multi scalar and trans-disciplinary nature of sustainable design. Previous studio iterations that focused on everyday situation in the city had led to valid and competent outcomes. However a reflection on those outcomes indicated that many students were content to mirror tried and tested solutions and struggled to challenge the status quo or posit an alternate future. By directing attention to conflicted sites with a remit for sustainability it was hoped that they would address pressing and contemporary concerns that affect all Australians – issues that appear daily in the news. More importantly the extreme, intensified nature of the condition was intended to push student thinking beyond the comfort of the “mixed use development and transit oriented design” framework to understand and respond innovatively to the conundrum of sustainability.

A key question for the studio was whether or to what extent an architectural intervention or proposition could be a catalyst for sustainability. The studio aimed to answer this from the context specificity of the condition, as well as through wider research and application of alternate possibilities. The contexts of two sets of iterations around the notion of contested sites are discussed below.


The first studio focused on Roma, a small agricultural based town with a population of 6000, in Queensland. The town was facing a powerful rupture in economic and social continuity, through unprecedented rapid investment in coal seam gas (CSG) mining and large-scale recruitment of a fly-in, fly-out (FIFO) workforce of approximately 2000. A second studio iteration focused on the other end of the gas pipeline at a section of Curtis Island (near Gladstone). The island is part of the Great Barrier Reef marine park and soon to be the site of four LNPG plants where extracted gas is refined before being shipped offshore. The two studios investigated how architectural agency and research can drive opportunistic approaches to developing long-term sustainability of the towns whose economy was suddenly becoming heavily dependent on a booming energy intensive yet limited lifespan industry.

2.1.2. Refining Kurnell 2013 and Refuelling Kurnell 2014

The return to the city as the site of resource consumption generated two iterations of a studio focused around the now decommissioned Caltex Oil refinery at Kurnell Peninsula in Botany Bay. Situated at the fringe of the city at Sydney’s busiest marine transport hub, it is flanked by national park and industry sitting alongside expanding residential communities and remnant infrastructure. Both studios were framed on the premise that in the short term Caltex’ stated plans to redevelop parts of the refinery site for refined oil storage would continue. With input from real world stakeholders at Caltex, Sutherland Shire Council and community and action groups, both iterations required students to formulate a position for the future of the precinct and develop supporting design proposals.
2.2. Studio framework

Within the framework of investigative research the studios developed mapping as a design tool for the first five weeks, leading to student development of a comprehensive ‘intelligent brief’ and detailing of an architectural intervention in the remaining nine weeks. Each studio cohort comprised 18-19 students who worked with two studio tutors including the author.

2.2.1. Design and research in the studio

Salomon (2011) in his discussion on the rise of the research studio in architecture schools proposes that they have an ability to simultaneously engage with extra disciplinary issues while combining design and research to produce creative processes and artefacts. He suggests they need to commit to “practicing rigorous systematic and self-conscious methods and to producing results recognised as original and significant beyond their immediate context.” The UTS studio used the process of mapping as an investigative tool to enable documentation and understanding of the site in different ways, leading to strategic propositions. Mapping processes required both an analytical and suggestive practice (after Corner, 1999). Students worked in sub-groups of 4-5 to develop a detailed understanding of the stasis flux and possible futures of the project using a series of lenses appropriate to each studio. A key outcome was a comprehensive set of critical diagrams and drawings to synthesise and explain the complexities of the site and its relation to the immediate precinct and region/metropolis. In her essay reflecting on the Refining Kurnell studio, co-tutor Holliday (2014) describes how maps were used in the studio environment.

“Maps for our purposes were considered useful when they offered an opinion, when they suggested an argument or a way forward in order to identify an opportunity for architectural intervention. Maps were… lenses through which… projects would emerge”.

![Figure 1. Student analytical mapping of Kurnell Peninsula, showing land use, conflicts and opportunities. (Source: M.Arch Studio Project - Salinas, E., Yeoh, J.L., Yeung, C.A., Chow, L.H., Gatesoupe, A., 2013)](source)

A major challenge is how to encourage students’ engagement with the trans-disciplinary nature of sustainable design given their limited experience of many of the issues at hand within the constraints of the 13-week semester. A process of careful design and preparation prior to commencement was implemented to alleviate this. This involved extensive background research, engaging with and attracting the right stakeholders, experts and resources to facilitate student learning as well as staging the studio through weekly learning activities, stakeholder workshops and specialist lectures.

2.2.2. Towards the idea of the “intelligent brief” or “strategic intervention” and design development
Rather than focus on a large scale “master-planning” of the “site”, the studios worked at the scale of strategic architectural interventions that could be instrumental in achieving the aspirations of the studio. Commencing in the latter part (Week 4 onwards) of the mapping and research phase, individuals or groups of students worked to develop their position on the condition and formulate their proposal.

Students were encouraged to harness organizational, environmental, social, programmatic and spatial intelligence when framing their proposition and developing their architectural design. They were challenged to rethink the nature of environmental performance, and shift from considering building efficiency in isolation to the nature of resilient architecture and urban interventions. Questions they grappled with included: What is the nature of the “intervention” and “program” that can harness opportunities and constraints to redress the imbalance seen at this contested site? How can one achieve more by building less? How does a better understanding of stakeholders and their requirements affect program, zoning, layout, form across the multiple components? How can we innovate and explore new ways of working, shared programming and precinct level strategies for water, waste and energy? This interrogation led to the formulation of “an intelligent brief” for diverse and creative propositions. Students presented their return brief with schedule of areas, program uses and performative criteria to measure the success of their individual development at the midpoint of the semester.

As students responded to the challenges of social and community needs, renewal, growth, consumption and climate change, they were expected to formulate criteria to satisfy key objectives for performance, resilience and sustainability. While core considerations included site sensitivity and appropriateness, building performance, safety, comfort and ‘quality’ indoor and outdoor space, students also detailed at least one of the following: life cycle and flexibility, ecological impact of materials, water conservation and reuse, net Zero Carbon Energy and eco-positive solutions, sustainable transport and pedestrians.

3. Studio outcomes

As a result of the studio methodology, outcomes were both unexpected and provocative. Students explored questions of valuing environmental and social capital and sustainability, and forged projects that can be catalysts for change in the communities in which they were situated.

At Roma, stakeholders (local government and mining companies) had assumed the emerging studio projects would be about low embodied energy or energy efficient/comfortable worker accommodation, or medium density housing proposals to combat the town’s housing shortage. However the mapping and (offsite) research uncovered the flow and carbon footprint of the FIFO cycle, the limited spatial interface between temporary workers and permanent residents, a sense of two-speed economy affecting the social fabric and the extreme condition of flood and drought in the region apart from its remoteness from other centres. This yielded a number of sophisticated proposals, with funding models capitalising on the obligations of mining companies and governments to provide social and environmental infrastructure. As an example, one project developed simple infrastructure for the year-long activation of the local showground (typically used twice a year) to promote interaction between locals, tourists and FIFO workers and provide an emergency services base during the region’s recurring floods. Programming events enabled transition from small group education and training to large regional crowd events. The built form integrated shading, energy generation, water management and flood mitigation.

In the Kurnell studios, students developed a narrative for the precinct by overlaying independent research findings with reflections from their interactions with stakeholders. The mapping exercises
uncovered hidden layers of Kurnell - its history, geography, unique biodiversity and a strong sense of community rarely found in other parts of Sydney. Significantly, the studios allowed particular examination of post-industrial brownfield sites and the largely untapped opportunity they offer to reimagine the future of our cities. As industry shifts off-shore and large tracts of land become available for alternate development, pre-existing infrastructure at such sites ensures ready-made access to roads, energy water and other services. The growth of the city often engulfs sites within proximity of the CBD and attracts large investment in medium and high-density housing. Thoughtless developments on such sites are critiqued (Langhorst, 2014) for using the sustainability banner of regeneration and renewal to rationalise neoliberal development and fuel further consumption. These sites themselves are not without challenges, particularly toxic contamination of the land from previous industrial use.

Figure 2. Studio project for hydroponic fish farm and market garden at Kurnell. (Source: M.Arch Studio Project - Oh, S., 2013)

The mapping and research served as a platform for further investigation of urban themes to shape individual propositions for the site. Project outcomes demonstrated the opportunity to remediate remnant refinery infrastructure and contaminated land, and reimagine a sustainable future for the Caltex site by introducing new uses and community focus spaces within the precinct. In the 2013 iteration, a number of projects explored ideas for energy and food security such as algal biofuel farms, fish farming, and an aquaponic farm with microbrewery and biogas plant (Figure 2). Other proposals promoted sport, recreation and cultural performance by linking the Caltex precinct to neighbouring national park, wetland and tourist sites such as Captain Cooks Landing and whale watching outposts. While projects for scientific research facilities harnessed the existing intensity of high-tech infrastructure onsite, a few provocative projects sought to negotiate the tricky terrain of the contested edge, mediating restricted access to concurrent Caltex operations while affording substantive opportunities for passive surveillance of contained processes for remediation.

The 2014 iteration emphasised the importance of the site as high value employment land with a core brief for a research centre of excellence to trigger co-programs. One comprehensive proposition (Figure 3) used a premise of increased population density and reinstatement of the ferry connection to close the loop from Little Bay and connect the precinct to other centres of growth. The campus proposal was placed as the catalyst at the core of the former refinery, positing the post-oil transformation of the fuel import site into a high tech employment research/residential precinct supported by on-site bio-energy, food production and waste treatment. Other groups explored redevelopment that was integrated with a carefully staged process of bioremediation and constructed wetlands, the concept of the outdoor city and questions of blurring the contested edge between the existing Kurnell village and institutional use.

Individual projects (Figure 4 and Figure 5) enabled an exposition of the overarching propositions through architectural development. The imperative for architectural and aesthetic resolution of the
brief emphasised metrics such as reduction of floor space (and embodied energy) through shared programming, sizing of food production or bio energy potential, flow charts for inventive co-production workshops, integrated bio remediation, water and site sensitive design and material selection over energy simulation or heat balance calculations.

Figure 3. Student group precinct strategy for the post-oil transformation of fuel import site at Kurnell. (Source: M.Arch Studio Project - Capparelli, J., Ferriere, M., Kacha, K., Trudeau, T., Zarsav, S., 2014).

Figure 4. Individual designs for Kurnell, showing art galleries, public omni theatre (left), exploratory walkway and scientific research facility (right). (Source: M.Arch Studio Project - Caparelli, J., and Kelly, J., 2014)

Figure 5. Student design for solar powered car factory at Kurnell, including detailed scheme for the co-production of manufactured goods flowing through multiple structures. (Source: M.Arch Studio Project - Trudeau, T., 2014)
4. Reflection on studio process and outcome

4.1. Evaluation of effectiveness of student learning

Criterion referenced assessment was used to assess the effectiveness of the learning outcomes throughout the studio. Milestone submissions via design jury with internal staff and guest critics were supplemented with staged process submissions, a reflective journal and final portfolio exposition. In addition to formal and informal assessments, final studio outputs in the first three iterations were subject to charrettes as part of the 6 university DARC Mobility grant. This provided an opportunity for a two way learning process for the local and exchange students and staff from the six participating universities. Through the charrettes, staff and students were able to separately disseminate the outcomes to company, council and community stakeholders. Outputs were well received by the stakeholder groups, particularly the use of mapping and precinct strategy as a method for understanding and visualising stasis, flux and future(s). The quality of outputs prompted production of a booklet showcasing them for future students, and the stakeholder group.

Student feedback on their learning was positive with objectives, assessment, feedback, resources, overall quality and teaching generally averaging over 4.0 on a 5 point scale (1=Strongly Disagree and 5=Strongly Agree). Students by and large found the studio and its framework “interesting and challenging” “intellectually stimulating” and “outside the box”. In the first iteration, students noted their early struggle with the quantum of research and mapping “quite a lot for one week to investigate about the whole ecology”. This was remedied in subsequent iterations through more carefully design (see 2.2.1) to facilitate learning and leave adequate time for detail design development. Students noted “To think beyond architecture and at a precinct scale definitely made the learning experience of the studio much more interesting where design decisions were based on satisfying both the micro and macro scales”. In the author’s view, the emphasis varies with each iteration - given the constraints of the 13 week semester, a first iteration on a complex condition of this nature calls for different kind of project expectations compared to a second studio on the same site that builds on the research of the first.

4.2. Collaborative and designerly approaches for integrating sustainability

The collaborative benefits of working in groups and managing this are well recognized. Group work was critical to effectively manage the swathe of background research in an investigative studio of this nature. It also enabled students to develop and contribute specialist skills within the team and more importantly benefit from teaching and learning from one another.

With current concerns regarding climate change and the ever widening scope of architectural curriculum content, the argument for colocation of disciplinary content within the studio is compelling. However an aspect of integration that is less talked about centres around teaching staff and expertise. In too many schools, teaching staff with sustainability expertise come in as specialists and their view does not always have buy in from all design tutors. In contrast, a key feature of the studios presented here is the complementary expertise of the teaching team - in each instance, both tutors had architectural training and a strong interest in sustainability and design process. While one specialised in environmental performance evaluation and user studies, the other came from an urban design architectural practice background. This was augmented with specialist expertise sourced from outside (see 2.2.1). Although this appears to be a resource intensive way of teaching, it is valued in the school as means of engaging in research and debate about the role of architecture in the future of our cities.
If questions of sustainability are to be taken seriously, it is important that students see and know this - not only through stated brief requirements and assessment criteria but also in terms of how the issues are naturally part of the day to day concerns of the studio. In the author’s view, expertise in the field must be intrinsically located within the studio. In other words “architectural science” staff must not be reticent about offering and directing serious studio options. However as Lawson (2004) notes, students will find it hard to “connect and use the theoretical knowledge when actually designing” (p 105) unless knowledge has been taught in a way that is designerly. If studio options are to be valued by students, the studios must adopt a designerly approach to sustainability and capture their imagination even if it does throw students out of their comfort zone. The studio framework as set out in section 2 aimed to achieve these objectives, and in the authors’ view demonstrates one way in which this can be pursued.

4. Concluding discussion

An integrated approach to architectural design pedagogy is needed in order to produce graduates capable of synthesising the array of complex considerations they will confront. From a disciplinary perspective, the studios subscribe to the importance of using design to effect an eco-positive future (Birkeland, 2008). The outcomes did not sit squarely in any one of the six competing logics of sustainability, from technology to cultural and social, as characterised by Guy and Farmer (2011), but aimed to mediate these boundaries. The approach concurs with their position that

“If the future direction and success of sustainable architecture strategies relies on the abilities of architects to act as moral citizens by engaging in an open process of negotiation, criticism and debate… it’s vital that students are encouraged to become more sensitive to the range of possible logics of innovation that may surface in design practice.”

It is acknowledged that some aspects of the studio model described are not easily replicable everywhere – as noted, resource implications can be onerous and must be supported by the schools. Additionally, outcomes can be enriched and workload can be managed by capitalising on groundwork and results of the past studios to develop subsequent iterations, as well as fostering a team of teaching staff able to work collaboratively. Furthermore, encouraging academics to develop research-led teaching programs in their area of expertise can mitigate competing demands for teaching and research outcomes while exploiting design studios as potential sites for real and speculative investigation.

This paper argues that analysis of the specific conditions of conflicted sites, where urban, economic, social and environmental and climate challenges are intensified, offers the opportunity to prepare graduates able to respond to change. The design studios explored in this paper simultaneously serve as a vehicle to drive research and opportunistic approaches to sustainability at regional and precinct level and challenge the traditional approach of considering efficiency or technical building environmental performance in isolation. The studio model highlights opportunities for deploying design thinking strategically to develop resilient architecture in the context of climate change and current debates.

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References


Wicked deliberations: research and design studios

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Abstract: The paper discusses a graduate architectural design studio emphasizing designing as a research practice. Students chose their own Wicked Problems. They were initially supposed to employ their usual design approach, one suggested by the problem and one “at right angles” to those, then to determine a preferred approach, chosen or hybrid. Finally, they were to present argued recommendations in report form to a hypothetical committee interested in those recommendations and any rejected experiments. Thereafter a summary of relations between projects and theory in PhD design research, studio problems, projects and research methods from the three years’ running of the studio are discussed. Projects were developed for eleven countries, on urban, suburban, rural and remote sites. Apart from numerous design approaches and conventional research techniques (demographics, observations, interviews), research methods included versions of linear programming, animal suits, www avatars, role-playing games, storybooks, ethnographic investigations and various sensory and physical disablings. Outcomes included everything from scattered installations, more or less conventional buildings to train carriages, publicity campaigns and complex precedent networks. The paper concludes with evaluating the successes and shortcomings of the studio based on examination of the assessment rubric developed with students, commenting on design research, and noting an irony.

Keywords: Design pedagogy; research by design; studio teaching; wicked problems.

1. Introduction

Few schools of architecture teach research skills and fewer yet insist upon critical reflection and learning based on research findings. Kieran (2007, 28)

Varnelis (2007) traces modern interest in architectural design research from the Eames and the Smithsons, through to the publications coming out of studios run by the Venturis (1977) and Koolhaas (1978, with AMOMA, 2004). Later publications of academic-led, collective student design investigations include Gandelsonas (2002). (In designing practice, these research-design studios are quite different
from the design-build studios discussed in Hinson (2007) where the learning is predominantly of teamwork, construction and materials.)

Pressure on studio time within curricula and the shift to graduate programs at universities for professional entry in Australasia has concatenated ambitions for research with other expectations of design studios. Graduate school design studios are commonly expected to be ‘research led’, but what that entails for students and their designing most often remains unclear. (My university is clear that this is a methodological issue rather than one of content.) My experience as a visiting critic is that too many students first “research” then ignore any requirement to connect their findings with their actual designs. Even outside the poor practices noted in McClure (2007), their studio leaders sometimes are frustrated by this and grade accordingly or often apparently don’t notice. Frustration with this quite usual pattern led to seeking another way to organize a design studio, although one not to be driven by my research interests but by ambitions for students’ learning.

The paper is concerned mainly with the detail of the studio’s results.

As is well known, Horst Rittel’s term for those problems that, unlike ‘benign’ problems, are hard to define, have no ready-made procedures for solving them and have no simple test for whether they are solved was ‘wicked’ (and, later, ‘tricky’) (Rittel and Weber, 1984). In general, if people are involved in a situation, problems are likely to be wicked.

Deliberative thinking in design is to consider heuristic approaches to the task, being reflexive in regard to your own design thinking and evaluating the outcomes of carefully considered options and/or conjectures investigated experimentally.

In the graduate architectural design Studio, Wicked Deliberations, offered in the first semesters of 2011, 2012 and 2014, students were expected to use their design skills to tackle a Wicked Problem of their choice, imagining themselves to have been commissioned by a committee to investigate the problem and, subsequently, to have to argue for their recommendations, including reasons for rejecting any options canvassed.

Common to students of the studio were these requirements:

Up to Week 7 (of 12) researching as a professional designer might, but ...

- Using their usual way of designing;
- Using another way, suggested by the problem, and;
- Using yet another way, “at right angles” to the first two;
- A final, argued proposal, deriving from research generated either through the preferred design approach ultimately pursued or from some hybrid of those employed, in report form, together with ...;
- a Reflective Journal containing deliberative reflections covering options canvassed, rejections, why and why various matters were included.

Given the framing of the studio, not surprisingly, there was a diversity of design propositions – from architectural to relatively abstract. The paper considers a number of these and other outcomes, including a rubric for interim review developed jointly with students, diversity of project problems and diversity of design research approaches. The paper makes observations based on students’ reflections on their work and canvasses a range of relations between research and design project that resulted.
2. Design research projects

In my experience of over fifty PhDs since 2000 (as supervisor, panel member, consultant, examiner), PhDs-by-project in design disciplines accord with colleague Alex Selenitsch’s categorization of three kinds (with my elaborations):

- Design projects that illustrate or test a theory (text comes first, focus is on the theory) – where to design is to conduct an experiment or to illustrate;
- Design projects that are later provided with an exegesis or explanation (text comes second, projects can be considered quite retrospectively) – a very common kind of PhD-by-project in design disciplines; and
- Projects where ideas and designing are feeding off each other continuously and the claim being established or discovery made is clarified both in text and through the multiple experiments that constitute the project. (Probably all PhDs-by-project actually are mixed in this way, with the first two kinds denoting ends of a “spectrum” of tendencies.)

The categorization applies quite well to final year independent design theses in pre-professional Masters degrees.

I prefer to offer a graduate design studio for students wishing to undertake “miscellaneous” projects, and concentrate on developing students’ individual design approaches and methods. Accordingly, it was the third category of design research endeavor that provided the model for the studio (with the experimenting tenor in sharp focus). A clear inspiration was the set of landscape and urban design research projects exhibited in Steenbergen (2008) with its summarizing of research and drawing techniques, wonderfully illustrated.

Koskinen et al (2011) provide the most comprehensive review of research methods used over forty years of design research – mostly from industrial, interface and graphic design work rather than from the larger scale design disciplines of architecture, landscape architecture and urban design, unfortunately. What all PhDs-by-project in design disciplines share is that both research methodology and even the (collection of) methods employed are likely to be relatively unique to the project. (Another Selenitsch observation.) This too proved a feature of the studio.

3. Wicked problems and design projects

A total of thirty-nine students completed the studio in 2011, 2012 and 2014 (fifteen, fifteen, nine, respectively). Fifteen had just entered the graduate school, twenty-one were next to do their Thesis, and only three were from the level between – a bifurcation consequent on the studio running in first Semester.

Projects were developed for Melbourne, the city and its suburbs, provincial Victoria, China, Jordan, Kuala Lumpur, London, Malaysia, New York, Rome, Sweden, Tonga and Turkey – ranging in scale from a series of installations around the city centre or an inner suburb, buildings or building groups, the whole of the city CBD or whole suburbs, to remotely located villages and village clusters.

3.1. Wicked problems

The range of Wicked Problems included:

- Increasing the density of heritage protected suburbs or the city, generally (a common topic);
• Accommodating the homeless;
• Multiple generations in contemporary housing (of particular interest to overseas students);
• Life in Australia for overseas students and/or migrants (at least two projects per year);
• Public fitness in hot tropical countries;
• Sustainable development;
• Food production in the city;
• Indigenous wildlife in the city;
• Revivifying regional towns, inner suburban streets or Pacific islands;
• Refugee camps and their uncertain longevity;
• Mixed-use and increased development of lower-scale, under-utilised and/or disused public and commercial buildings or areas of the city (quite popular), and ;
• Privacy in the contemporary city/Community and solitariness (another common cluster of topics).

And, apart from a handful of more or less conventional mass housing schemes, there were a range of projects that eventually proved not actually to have a Wicked Problem at base, but a hobbyhorse of the student: High-density housing for vintage car enthusiasts, Future cities, What to do with the former premises of increasingly disused sex bookshops, Care for the terminally ill and an Islamic Centre for Melbourne, for example. (Clearly, a number of projects entailed more than one Wicked Problem.) This range compares directly with the diversity noted by Salomon in his experience of final year, independent design theses topics in the United States (2011, 33).

### 3.2. Design outcomes

Design outcomes were just as varied as topics.

The Public Fitness in Kuala Lumpur project turned on providing complete changes of clothes at railway stations for commuters who exercised, running or cycling, on a rotating, overnight, dry-cleaned basis at mini shopping malls, together with a publicity campaign. A second project in Kuala Lumpur distributed a new museum system geared to attracting otherwise culturally disinterested youth through and around central railway stations, linking them with a modified railway carriage to be integrated in commuter trains. A third project in Kuala Lumpur developed a network of large-scale enclosures through part of the city associated with the original river to demonstrate how city dwellers might engage with indigenous fauna.

Doubling residential density in heritage-sensitive South Carlton (an inner suburb of Melbourne) turned out to be possible using narrow point blocks of unlimited height on under-utilized sites, even when they were not to be visible by pedestrians in heritage streets and could not overshadow residential properties for more than two hours (limiting practical heights to a maximum twenty stories).

Against the march to the seaboard cities, keeping villagers in Northwestern China might depend on villages, clustered in mutually complementary specialized craft and agricultural enterprises, paying close attention to their ancient ritual and literary roots.

Apparently it’s quite possible to run a multi-storey farm in a narrow city lane and to provide all the services a reasonable city restaurant would require. It simply requires ingenuity. And, central Melbourne’s rooftops could support numerous additional enterprises, besides residences, with systems of bridges, additional fire escapes, strategically placed, and a loop commuter dirigible service that could double as a crane lift service.
4. Design research approaches and methods

Three projects interested in revitalizing key streets took different research approaches, though two (Bridge Road, Richmond, and Sydney Road, Brunswick – both in inner Melbourne) shared the method of identifying and categorizing all functional programs on both sides of the street for the whole of the relevant lengths (2.25 km and 2.4 km, respectively). For the project in Richmond, however, a form of systematic analysis akin to three-dimensional linear programming (involving heritage overlays, property valuations and programs) helped determine location, extent and bulk of the subsequent design project (compare the generally two-dimensional projects arrived at analogously in McHarg {1969}). (This was certainly assisted through the student’s part-time employment in the urban design department of the local municipality.)

The City Scavengers project concerned indigenous fauna (particularly birds, platypuses and possums) and the inner suburbs. To better understand the lives of possums, the student constructed a possum suit and lived in it for a week.

The student who designed a holiday house designed to test the fitness of all ages at a remote beach on the principle that our dwellings could be designed less to be comfortable than to keep us fit, spent days at a time blind, hobbled or with her thumbs tied.

For the Secret Activities project supposedly investigating dubious commercial attitudes to women in comparison to attitudes to publically acceptable professions (nurses, nuns, teachers), without telling me, the student visited sex bookshops having constructed a jacket with a hidden camera under the armpit supposedly to capture interiors to enable plans to be better constructed. He wanted to convert the shops to local libraries. Neither I nor any other student was convinced when footage of strip clubs (with which he seemed particularly familiar), peep shows and other kinds of sex shops also appeared at an early stage.

Trying to make an architecture that could kinetically represent real-time web activity, one student abandoned her redesign of the surface of Melbourne’s Federation Square as a tessellation of pistons because of its likely behaviour as a people mincing machine. A second approach entailed construction of an avatar, dwelling in New York, exploiting the plethora of accessible real-time cameras all over New York. For several weeks, the avatar reported her (entirely fictitious) activities at parties, work and in everyday life on blog and social media, reporting on and reviewing stores, parties, entertainment, street scenes and so on, garnering a huge following. Besides the evidence from the camera vision, her approach to finding a site for the final project (a kind of distributed centre for community and multifaith gatherings in Union Square) depended on accessing publically available, three-dimensional, real-time (?) modeling of mobile ‘phone/SMS traffic in central Manhattan.

Apparently, there is a lingering Ottoman law that permits construction of dwellings between dusk and dawn on public land in Turkey. The student focused on the resultant informal housing, built on earthquake- and landslip-prone land without utilities, public or private (initially). This is eighty percent of housing in Ankara. He first showed that better housing, both typologically and in urban design terms, could be designed quite readily. This was not the actual problem. He next investigated game engines for automatically generating better urban layouts and, finally, role-playing game trials with fellows (as developers, architects, local government, bankers and material suppliers) to understand motivations, potentials for altruism and negotiation. His final product was an enormous, complicated precedent network of associated decisions that resulted in the housing and urban forms that were present in Ankara, showing just where pressure might best be applied judiciously to improve things.
5. Other outcomes and discussion

From week to week, the Studio was conducted on fairly common local lines with six hours of contact, twice a week, rather than at adjacent dedicated workspaces (on the École Polytechnique model – see Pfammatter (2000)) or in an assigned project room (a design lab of the Texas Ranger kind – see Caragonne (1995) or Gu (2003)) (a function of the level of public funding of Australian design schools). Studio, here, means a kind of design seminar, where students have to prepare work beforehand and bring it to the Studio session, prepared to put it in front of the group, to work in small groups or one-to-one with the Studio Leader for between two and six hours at a time.

I run studios as mutual help forums. So it is expected that fourteen or so other students will provide helpful suggestions for any single student’s work each Studio session – precedents, examples, data sources, methods. Likewise, each student should endeavor to learn from and closely examine the variety of other topics and approaches taken to them that arise in the Studio.

The University’s marking scheme implies an average of 73. Averages for the Studio were below this in 2011 and above it later (70.47, 75.00, 75.22), but the numbers have no statistical significance.

5.1. Rubric

In the spirit of constructive alignment (Biggs and Tang, 2007), and insisting that, at graduate level, students should take responsibility for their education, a long discussion with the 2011 cohort resolved the grounds for interim feedback in the form of a Rubric, the final (elaborated) form of which is shown in Fig. 1, below. (The Rubric shares many of the key features identified in Zehner et al, 2009, Part V, 82-92.)

The Rubric has elements concerning both the student’s learning and the project (allowing indirect measures of that learning). Given that the Rubric was developed jointly with the students and they were familiar with its structure, at interim project reviews students could provide useful feedback to peers or, as Studio Leader, quietly taking my time perhaps later, I could. However, as with the Faculty’s official design Rubric, this too is far too wordy for ready or engaged use by visiting reviewers on the spot.

The main categories are clear, and frequent issues arose with them:

5.1.1. Complexity of Wicked Problem as set out

(and program/philosophy, size of challenge, degree of resolution).

Productive Studio discussions arose in the first weeks of Semester with trying to be clear about the nature of the wicked problem being addressed (which is in the very nature of such problems) or what, exactly, was wicked about the issue in question and how others could assist the student with the puzzle.

There may be Problems that particular students should avoid and this will be difficult to detect perhaps until it is too late (at graduate level, students can usually design reasonable projects very quickly). I will be very reluctant to agree to another project on depression in youth, however.

Given the open-ended trajectory common to design investigations, it was surprising that only one student’s Semester trajectory ended so far away from where he started. His housing project for a consumer choice driven future where all building components (facades, floors and ceilings included), equipment and furnishings could be rented on an as-needed basis started off as an investigation of contemporary national border conditions and their violations in a world subject to increasing levels of
international air travel. The intermediate stage was a project for a Las Vegas-like commercial and hotel development strip at the intersection of the ring road with the road from the international airport to Rome’s city centre. The student took a while to realize for himself that designing was itself a research activity, that a design could be a research tool. This revelation allowed the subsequent freedom to attempt to deal with what really fascinated him.

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<td>Complexity of Wicked</td>
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<td>Able to outline ‘problem’</td>
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<td>Size of challenge</td>
<td>Unclear about the ‘size’ of the WP or what its</td>
<td>Sufficient scoping of wicked problem</td>
<td>Attempts to deal with a very large WP in rich ways</td>
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<td>Degree of resolution</td>
<td>Muddled, irresolute beginnings only</td>
<td>Digging into the unknown</td>
<td>Design outcome(s) demonstrated to grapple usefully with WP</td>
<td></td>
</tr>
<tr>
<td>Management of three</td>
<td>Approaches with insufficient exploration or</td>
<td>Communicated the strengths and weaknesses of</td>
<td>More than one approach picked up for design that results</td>
<td></td>
</tr>
<tr>
<td>design approaches</td>
<td>differentiation</td>
<td>all three approaches Sufficient difference</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>All three pursued to a reasonable point (1?)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Approach</td>
<td>Unbalanced justification</td>
<td>A clear logic in the final selection</td>
<td>Final approaches demonstrated to grapple usefully with WP</td>
<td></td>
</tr>
<tr>
<td>Presentation + Clarity of</td>
<td>Unclear about what was achieved or investigated</td>
<td>Understands what outcome was</td>
<td>Designed something tangible toward stated goals</td>
<td></td>
</tr>
<tr>
<td>outcome</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clarity of exploration</td>
<td>Unclear what is being explored or how the work</td>
<td>Clear exploration of approaches and their</td>
<td>Very clear about what is being explored and/or how the work itself explores the WP</td>
<td></td>
</tr>
<tr>
<td></td>
<td>itself explores any particular thing</td>
<td>implications re WP, perhaps uneven</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clarity of explanation</td>
<td>Unclear explanation</td>
<td>Clear explanation, though perhaps not in all respects or approaches</td>
<td>Compelling or convincing exposition</td>
<td></td>
</tr>
<tr>
<td>Deliberative &amp; Critical self-</td>
<td>Couldn’t clearly state how problem related to</td>
<td>Demonstrated deliberative and critical awareness of own approach though perhaps not uniformly</td>
<td>Clearly outlined goals + convincing argument for outcome</td>
<td></td>
</tr>
<tr>
<td>awareness</td>
<td>stated goals</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Keenness with own ideas</td>
<td>Uncomfortable, disinterested and/or</td>
<td>Challenging their own curiosity</td>
<td>Very keen about their own ideas and able to store what they think is valuable, tentative and/or best in them</td>
<td></td>
</tr>
<tr>
<td></td>
<td>detached from their own ideas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Development &amp; learning</td>
<td>Little evidence of student’s own learning in</td>
<td>Evidence of student’s own learning in their</td>
<td>Clear marshalling of evidence of student’s own learning in their work and argument</td>
<td></td>
</tr>
<tr>
<td></td>
<td>their explorations</td>
<td>explorations, perhaps uneven</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Did you manage to achieve</td>
<td>Student unable to show that they achieved much of</td>
<td>Student can show that they achieved much of what they set out to do</td>
<td>Student can show that they achieved much of what they set out to do, how and can evaluate the results</td>
<td></td>
</tr>
<tr>
<td>what you set out to do?</td>
<td>what they set out to do</td>
<td></td>
<td></td>
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</tbody>
</table>

Figure 1: Assessment Rubric developed in the studio
5.1.2. Management of three design approaches (and final approach).

Each year, despite discussion and references (Koskinen et al. (2011) and Steenbergen (2008) and others specific to the students’ problems), many students confused trying different forms of data analysis with trying different design approaches. Some confused clarity of emphasis of design phases with trying different design approaches (confusing data gathering or master planning with different approaches, for example). These confusions possibly provide additional comment on practices and thinking in conventional architectural design studios.

A common practice was to tackle more or less related projects that required or invited dissimilar design approaches because of scale, climatic or other locational issues.

Very few students could neither choose a final approach nor contrive a hybrid approach to the project.

5.1.3. Presentation + clarity of scheme (and clarity of exploration, clarity of explanation).

Here, the issue of clear diagrams always arose and similar sources arose (Domus Academy, nd.; Halprin, 1969; Lengler and Epler, nd.; Steenbergen, 2008; and Tufte, 1997, for example).

I don’t think that designers actually solve problems. I think that they make proposals. Sometimes solving a problem is part of the task, a means, but it is never the whole. Making a persuasive presentation of a designed proposal became very important in these Studios and other students frequently were very helpful when their fellows appeared stuck.

5.1.4. Deliberative + Critical self-awareness (and keenness with own idea, development and learning, did you manage to do what you set out to do?).

Many students were much more modest in their assessments of their own thinking and growth than their fellows were of that thinking and growth. But, very few expressed this in reflective journals or their reports and could be drawn out only in close tutoring or under questioning at presentation: “If you had the Semester all over again, what would you do differently? What would you keep and what would you change?”.

5.2. Design research

I don’t think it requires a design studio to be set up in this way to have students employ novel research or design methods or to produce surprising outcomes. (Zehner et al, 2009, vol. 1, refer to ‘Magic’ of Product, Person or Process.) Design studios by their very nature often result in surprising outcomes. But I do think that the studio demonstrated that the nexus between designing and researching can be very close if not identical rather than sequential (and mutually indifferent).

The commonest projects that eventually more or less tested theory were multiple housing schemes or projects to do with sustainability and/or densification of city and suburban areas or design for particular ethnicities (youth, students, immigrants or the aged). I cannot identify any projects that required explanations for design outcomes pursued. The three-approach phase of the studio virtually
precluded this. But, there were very definitely several superior projects that oscillated between being driven through the Semester by theory/text and project.

David Salomon’s review of the rise of the (educator-driven) research studio in American architecture schools focuses on their replacing of final year independent design theses (2011). He concludes that, while the research in such studios is likely to be imperfect as research, the real value of research studios is in the fostering of a future-orientated architecture of intelligent speculation. This is my chief claim for this studio.

5.3. An irony

One final note should be added. The project that received the highest grade over the three years was conducted exactly as I’d objected to with work in those other Studios: research first, design next.

In a country where a vanishingly small percentage of people attend church regularly yet politicians would lose their seat should they threaten the huge national fund ensuring the maintenance and restoration of desacralized churches of Sweden, it should be asked what to do about them should the situation change. Astonishingly comprehensive research for 400 churches (locations, plans, sections, elevations, materials, dates, photos, congregation sizes, histories of repair and reconstruction and stylistic analyses) was conducted. The subsequent design outcomes included master planning of an island-based village for incrementally relocating the 100 churches most at risk, the design of the five production line, enormous repair building, a visitors’ centre and overview facilities. Always so exquisitely presented, no-one noticed the irony, least of all me.

(her independent design thesis project, this year, was very definitely a design research project.)

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Environmental and Landscape Architecture
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Bringing schools to life through a co-design learning approach with children

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Abstract: This paper proposes that incorporating professional expertise (e.g. landscape architects and architects) in school ground greening projects, with a commitment towards engaging in a democratic participatory process with children (known as co-design), could lead to equitable and enriching outcomes for all stakeholders. These have been documented as: learning opportunities for participating children plus their greater ownership in the process and the result, fulfilment of environmental sustainability education and stewardship responsibilities within the community for landscape architects and architects, reciprocal benefits for these professionals through achieving better outcomes due to the creative input and knowledge of place that children bring to the process, and the establishment of community-integrated green spaces and wildlife corridors within the urban fabric. The paper draws on participatory learning theory, New Zealand case study projects and international literature sources to suggest a paradigm shift to architects and landscape architects towards engaging more with schools on school ground greening and building projects as a community service. This could see them contributing to creating pedagogically and ecologically richer school grounds that are creatively designed to encourage indoor-outdoor connections, sensibly planned for maintenance and sensitively planned to increase biodiversity and provide ecosystem services within communities.

Keywords: School ground greening; co-design; landscape architecture; children.

1. Introduction

School ground greening projects are on the rise. The transformation of concrete and grass-dominated school grounds into varied, ecologically-rich and sustainability-focused places of learning for children can benefit from the input of both architects and landscape architects. A recent contribution posted on the In Field blog site of the American Society of Landscape Architects claims the following:

A movement to green school grounds and connect students to nature is gaining momentum in the United States and around the globe, weaving the ideas of urban sustainability and ecological design together with academic achievement, public health, children’s wellbeing, sense of place, and community engagement. (Danks, 2014: para. 1)
Danks, herself a landscape architect, is a passionate champion for school ground greening, and author of the how-to guide *Asphalt to Ecosystems* (Danks, 2010). School ground greening is a term widely used for establishing gardens and mixed plantings within schools (Dyment and Bell, 2007), and as Danks suggests, the rationales and benefits are myriad and confirmed by others (e.g. Williams and Brown, 2012). However, the issue being proposed in this paper is that professionals such as landscape architects are not often actively involved in helping school management develop masterplans and implement discrete projects to develop school grounds into places of biodiversity and experiential learning. Instead this is largely undertaken by schools themselves, and very often by individual teachers – with potential problems of disillusionment due to over-burdening and/or lack of knowledge (e.g. Passy, 2014), or the departure of the staff member possessing the knowledge, so the process collapses. Schools are usually short of money, especially for ‘non-essential’ items such as gardens and creation of natural environments. Despite this, practice, supported by research, is confirming that greening school grounds can lead to positive learning outcomes, especially in maths, science and environmental learning, albeit there is consistent recommendation among reviewers for a more systematic approach to research (Ozer, 2007; Blair, 2009; Williams and Dixon, 2013). Research into participatory practices such as co-design, where school children and professionals work together on design and build projects (Parnell et al., 2009), is also indicating that children are natural designers and experts in their own environments. Including them in the masterplanning process and subsequent design briefs can unleash their creativity, develop valuable skills (including soft skills like communication), and lead to increased ownership of the space plus empowerment resulting from having greater control over their learning (Sorrell and Sorrell, 2005; Wake, 2010). The environmental advantages are untold and generally not well researched. For example: greater shading and cooling from planting trees and shrubs; food and shelter for birds; creation of insect, lizard and mammal habitats; restoration of stream courses and wetlands – all forming a more continuous green corridor throughout cities.

Where do landscape architects and architects fit into this? Rationales for contemporary school gardens are tied up with concerns adults have about modern childhoods including children being disconnected from nature, unaware where food comes from and poorly equipped to take on future Earth Stewardship roles (Williams and Brown, 2012). These are issues of relevance for Landscape Architecture as a discipline and landscape architects as professionals representing that discipline. For example, the New Zealand Institute of Landscape Architects has a stated role as advocates for the environment as well as working for and within communities (www.nzila.co.nz). This suggests that landscape architects could be a resource for creating better solutions through proactive involvement in planning processes for school ground greening initiatives. Architects could be similarly involved, for example in projects that include buildings, and are perhaps further advanced as a discipline than landscape architecture in working with schools and students, for reasons that are discussed in this paper.

2. Children’s learning and participation

In the 25 years since drafting and ratification of the UN Convention on Rights of the Child (CRC) (UNHCHR, 1989), children’s rights have been increasingly emphasized, including children participating in decision-making. Participation can be defined as active involvement in a process of decision-making where the fundamental requirement is for power sharing to occur, leading to opportunities for transformational learning (Reid and Nikel, 2008). Sterling (2010, p. 524) defines this as an “intrinsic and life-changing inner process.” It is now known that such participation builds soft-skills and other benefits such as increased self-confidence, leadership abilities and a strengthened sense of community (Sorrell
and Sorrell, 2005; Wake and Eames, 2013), as well as other specialised outcomes when concentrated within specific disciplines such as design (Wake and Eames, 2013).

Hart’s (1997) ‘ladder of participation’ is a well-known model describing children’s participation. The model proposed that the bottom three rungs of the ladder (1. Manipulation, 2. Decoration, 3. Tokenism) were ‘non-participation’ while the top five rungs are all degrees of ‘genuine participation’ (4. Assigned but informed, 5. Consulted and informed, 6. Adult-initiated, shared decisions with children, 7. Child-initiated and directed, 8. Child-initiated, shared decisions with adults). Hart has stressed that it was not implied that the eight levels should be sequentially reached or that the top rung (child-initiated, shared decision-making with adults) was best or most appropriate in every situation. Despite this, the ladder model has frequently been interpreted as a hierarchical measure of children’s participation and Malone and Hartung (2010) point out that an on-going problem is the reliance on such models as tools, rather than seeing them as theoretical frameworks.

Within children’s participation and power sharing with adults the direction of learning is set by children and builds their capacity for deep and transformational learning. If participation is centred around a project that is real (i.e. authentic) and personally relevant (i.e. local), such as transforming their school grounds, children are taking a role as active citizens, something Chawla and Cushing (2007) plus Malone and Hartung (2010) identify as essential for development of pro-environmental attitudes and behaviour.

Unfortunately, in many school garden situations, children are not given this agency, and are expected instead to follow adult directions, e.g. maintaining a garden created by others. Malone and Hartung (2010) suggest that one barrier is adult resistance to the required change in power relationships between children and adults. However, in order to develop into what Sterling (2010) terms ‘resilient learners’ who can adapt as required by circumstances, children must engage politically (Chawla and Cushing, 2007); yet there is a perception that if children take political roles they are being robbed of their childhoods (Malone and Hartung, 2010).

3. A case for co-design within school ground greening

As identified previously, environmental learning that is authentic and relevant encourages pro-environmental behaviour and this should include students engaging politically and in an advocacy role, not being passive participants (Chawla & Cushing, 2007), e.g. gardening under direction. Wake and Eames’ (2013) findings determined there were significant learning gains when students worked alongside architectural and building industry practitioners in grappling with design issues within regulatory frameworks. In this example, and with strong project support by school management, students learnt about building consents, risk assessment reports, waste management, performance of materials and design techniques as well as developing soft skills such as collaboration, confidence in public presentations and problem-solving. There is a growing body of research and examples of democratic involvement of students with architects (e.g. www.designingwithchildren.dao.theusefularts.org). This is, in part, due to the United Kingdom’s Government-led Building Schools for the Future Programme (BSF) of 2005–2010, which helped to mainstream school-based co-design projects between practitioners and stakeholders (Burke, 2007). Parnell, Patsarika, Proctor and Cave (2009, p.9) define co-design in this situation as
“... users tak[ing] an active, hands-on role in the design of the school building/grounds, working directly and collaboratively with the design team to develop designs through models, for example”.

I suggest that the lower cost and complexity of school ground greening projects make them more commonplace than building projects but also leads laypeople (e.g. teachers and school management) to think that landscape and plant specialists are not required or allowed for in the budget. Simply, state school grounds have typically not been valued as an asset by government departments and school managers in the way buildings are. Evidencing this, Downs (2006) comments that during the recent BSF period in the UK, funding shortfalls led to a lack of landscape architect involvement in school renewal projects, with volunteer assistance of teachers and parents used instead. Downs predicts this will lead to long-term problems with design and management. In contrast architects were an integral part of BSF and this has led to identification of a number of reciprocal benefits. For example, learning how to work with children and youth (Parnell et al., 2008), creating potentially better designs due to the input and creativity of the people who will use the space (University of Sheffield, 2014), and potentially securing future paid work through positive profiling (Wake, 2010). This latter may be regarded as a trade-off for working on projects with children that are rewarding in intangible ways, but not fully billable, as expressed by the co-design architect for an eco-classroom project (Wake, 2010, p. 175):

I absolutely love it. ... I come back from the classroom and think this is the best thing I do. ... The enthusiasm and liveliness of the kids is just wonderful. ... The disadvantages from our point of view is that it is not an economic proposition ... more than half of the time we are putting into the project is volunteer. ... We are doing it because ... educating people ... and the green environment is really important to us. ... And we have all gained a lot on a personal level. And I think that other clients can see what we are doing... What this is about isn’t the project in itself so much, it’s actually about what’s happening to those students.

With regards to landscape architects’ co-design input into school ground greening projects, I propose there would be similar benefits. This could perhaps result from landscape architects being proactive in offering their services to schools, for example, as community outreach projects that may not generate much initial income, but are rich in reciprocal benefits. In addition to the benefits already outlined this could include contributing to better planned school grounds that function as learning environments and provide ecosystem services within communities (e.g. shading, cleansing of stormwater, bird habitat corridors). In turn this would contribute to fulfilling professional responsibilities of landscape architects and could be used to promote the benefits in terms of maintenance through getting specialists to design school grounds rather than ad hoc planting by teachers and parents. With regards the benefits for school students, there is evidence to suggest that the experience of participating in the design process is pedagogically transformational and deepens their connection to place (Green, 2014).

If the current school garden movement is to be enduring, I propose that the methodology around the development and use of school gardens needs to encompass a range of partnerships and embrace democratic participation of children, in order to realise the potential of school ground greening projects through learning transformations. In their Australian-based research using Uzzell’s framework for school-community partnerships, Flowers and Chodkiewicz (2009) concur with this. They point out there are four levels at which partnership can occur. These range from learning being isolated within the school, to community members coming into the school, to schools going out into the community and, ultimately, schools working with communities as social agents for environmental change. These authors
argue that the last is the most effective for transformative environmental learning. Which implies the importance of building strong relationships outside the school and engaging students very actively with the process of school ground greening. This adds up to a vision of co-design partnerships between schools and landscape practitioners where students work alongside specialists to research, design, construct and use their outdoor school environments in a way that integrates curriculum learning, engages with local communities and builds empowerment.

However, it has been emphasised that children alone cannot execute complex design processes. The final decisions may need to rest with practitioners who have specialist knowledge (Iltus and Hart, 1995; Mannion, 2007). In this regard, the choice of design practitioners to work with children is crucial to the success of the project (Wake and Eames, 2013) as is open communication with children about the limitations to their participation (Hill, 2006).

There is research emerging that supports children as co-designers with adults in school ground greening projects. For example, in an Australian school garden project, Green (2014) found that children became proficient in design skills and knowledge when they were included in the designing and planning of the environments where they lived. This transformed the teaching and learning in the school due to the ownership children felt and the creativity and imagination required during the design process. Green acknowledges, however, that there are, to date, few examples reported of children as designers within school garden discourses. This example therefore illustrates a shift in approach whereby children’s learning was enhanced through empowerment and a departure from measuring being a mathematical or scientific endeavour (as school garden-based learning often is), to a design one where drawing, mapping, modelling, planting and building for aesthetic and practical solutions were foregrounded. I propose that this approach would be further enhanced through the inclusion of landscape practitioners to work with students in providing authentic and relevant environmental experiences both within schools and reaching out into the wider community.

4. Case studies

There are studies emerging which have investigated school ground greening projects that have a strong co-design focus with practitioners. One USA example is a school-ground greening project to establish an ecological habitat for children’s play and exploration in an area adjacent to the school (Derr and Rigolon, In press). A group of retired adults living in the wider community were also involved, having used this space for free play in their youth. The project utilised participatory processes including co-design with city planners and collaboration with the, sceptical, retired adults, who were eventually won over by the project’s process.

Similarly, in the USA, Smith (2011) portrays a high school for students who are considered challenging. The school has transformed itself and students through a process of both school- and community-based ecological and other sustainability-driven projects. Using projects that focus on five domains of sustainability: architecture, energy, water, forests and agriculture, students are empowered to bring about positive environmental, social and economic change within their communities through establishment of gardens, restoration of habitats and building of affordable, sustainable housing for students’ families. This holistic approach recognises that children’s lives at school cannot be significantly improved unless their home and family lives are secure.

In a New Zealand school-ground greening project I recently visited at Rhode St School in Hamilton, students aged 9-12 years old had the idea of developing an ecological island (a predator-free sanctuary
for endangered species) on the school playing fields (an adjacent park will be used for sports games). Students worked with a landscape architect and ecologist to develop a Masterplan for the site and the project is drawing on local expertise and involvement. For example, soil and tyres to create the island were donated by local businesses & the shipping containers were purchased through grants (see Figure 1a). With the help of an architect, students have researched sustainable ways of converting the top container into a bird hide (see Figure 1b) and the lower ones into a science centre, with local artists working with students to create murals (see Figure 2). A native tree canopy is being established and the island now needs a predator-proof fence in order to safely introduce threatened native fauna. The island will perform valuable ecosystem services as an area of native flora within the city, providing habitats for birds, insects, reptiles and freshwater creatures (once the moat separating the island from the rest of the school is operational). Students and their families are learning about sustainable practices of land use & building (e.g. recycling the container and insulating it for use as a science centre, as well as improving their neighbourhood and sense of belonging, through empowerment.

Figure 1: (a) The island composed of donated tyres and soil from community businesses (b) Opening windows in the bird hide show the developing native tree canopy & moat.

Figure 2: Science Centre in construction, with mural.
At a further case study school, Meadowbank Primary School in Auckland, a parent who is a landscape architect worked democratically with students to develop an environmentally, historically and pedagogically rich school ground that has been implemented over time (see Figure 3). For example, an amphitheatre was created on the site of a rubbish pile and it now provides a nature-enriched place for outdoor learning and an occasional romantic weekend wedding venue for community members (see Figure 4).

Figure 3: Landscape architect’s plan following students’ input.

Another collaborative project between school children and the landscape architect was the design of a ‘Lorax’ garden, with its cautionary tale about greed and unsustainability (see Figure 5). This example illustrates how the involvement of a landscape architect in a participatory school ground greening project can enrich both the landscape result and the learning for students through ownership and empowerment.

Figure 4: Interpretive sign about the amphitheatre constructed as part of the school ground greening project with input of a landscape architect working with students.
5. Conclusion

Landscape and building projects that are planned with children to be authentic (real) and relevant (local) have the potential to empower children and in turn their communities to take charge of their environment, through the ownership children feel and the messages they subsequently take home. With regard to school ground greening, it is suggested this could help to realise the largely unacknowledged and under-utilised learning potential of school grounds through creating enduring green spaces, which will become ever more important as cities expand and infill, and communities become more diverse and incoherent.

This paper has argued for a paradigm shift that could see landscape architects and architects having a role in formal learning through collaborative projects that create ecologically richer school grounds, which are sensibly planned for maintenance and sensitively planned to add ecosystem services and other facilities within communities. Engagement in participatory processes with children that encompass learning and environmentally sustainable outcomes is perhaps both a key challenge and an opportunity for design practitioners in the future. Further research to investigate such possibilities and suitable methods is recommended since investing in children’s design education is truly living and learning towards a better built environment.

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Bringing schools to life through a co-design learning approach with children

References


Designing the twenty-first century urban park: design strategies for a warming climate

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Abstract: With 2014 considered the hottest year on record, the implication of climate change on the liveability of cities is becoming ever more apparent. Accordingly, the role of open space is emerging as a pressing issue, with clients increasingly demanding evidence of design performance. In 2011 for example the New York City Department of Parks & Recreation in collaboration with the Design Trust for Public Space released High Performance Landscape Guidelines: 21st Century Parks for NYC. As Deborah Marton the former Director of the Design Trust comments, this type of document reflects a major shift in the conception of open space, ‘from park as end-product to park as work in progress’ (Carlisle and Pevzner 2012). This paper explores how two contemporary designs for open space in Asian cities have engaged with environmental simulation to increase the performative attributes of open space. Through the comparison of Singapore’s Gardens by the Bay and Taiwan’s Phase Shifts Park we highlight the different philosophies and technical challenges presented in these ambitious designs and conclude with a wider reflection on the technological manipulation of natural phenomena.

Keywords: Performance; open space; climate change.

1. Introduction

Environmental and civil engineering have a long tradition of testing design performance through physical modelling (such as wind tunnels or hydrological models) or digital simulations. Increasingly accessible software capable of modelling the fluid dynamics of wind, water, tides, heat, humidity and pollution present new opportunities for embedding temporality and change into design processes. Simulations and real time data offers techniques for introducing an evidence-based metric into design processes, heightening the performative ambitions of spaces and providing quantitative and qualitative arguments for the value of parks, gardens and green infrastructure.

Cities Alive: Rethinking Green Infrastructure published by Arup in 2014 uses social, environmental and economic benefits to argue for green infrastructure. Tom Armour (2014), Global Landscape
Architecture Leader at Arup, highlights the significance of metrics in the current economic context, stating ‘we need to get the value out of landscape’ by demonstrating its potential in lowering pollution and air temperature levels, reducing carbon and contributing to healthier cities. Similarly, Stephanie Carlisle (2014) environmental researcher and designer at Kieran Timberlake Architects, comments that ‘if we want to have projects built we have to be able to argue about what they are and what they do.’

Climatic challenges and environmental health risk such as the Urban Heat Island (UHI) phenomenon affect millions of people around the world as cities become warmer due to human activities. Conditions in many Asian megacities prove particularly challenging due to the combined factors of high temperature, humidity and poor air quality, which prevent citizens from engaging in outdoor activities, calling for actions to increase the resilience of cities. Awareness of UHI as significant health risk has emerged for instance in Japan since early 2000, leading to increased planting of street trees in addition to promoting low-tech means of cooling the streetscape with the support of local residents. These activities include planting fast growing annual climbers as shading devises (e.g. in front of windows or entire façades) or manually watering hot street surfaces utilising the cooling effect of evapotranspiration. Recently, this strategy has been adopted in building technologies, for example, in the so called Bio Skin design for the Sony City Osaki building in Tokyo designed by Nikken Sekkei, where a water-filled exterior façade system constructed of porous ceramic pipes extents across the entire height of the building. Utilising rainwater the Bio Skin responds to the hot southern winds prevailing in the summer months and has the capacity to cool adjacent outdoor spaces by two degrees Celsius.

Low latitude countries, such as Singapore and Taiwan, are exposed to even more challenging conditions with constant high temperatures elevated by high humidity levels and low average wind speed. (Yang et al, 2013; Chang and Roth, 2006; Lin, T-P, 2009). This is paired with a cloudy environment of subdued light and decreased efficiency of solar energy, supporting further dependency on fossil fuels and high air pollution levels (National Climate Change Secretariat. 2012). Within this context a significant and explicit shift towards improving the performance of buildings, parks and cities is evident. This paper discusses two projects that actively engage with these challenging conditions to provide comfortable and healthy outdoor environments, beginning with Singapore’s Gardens by the Bay followed by the Phase Shifts Park (known post competition as Jade Eco Park) in Taichung, Taiwan. This comparative analysis draws on interviews with designers and reviews of competition and design documentation. Embedding environmental simulations in the design process has provided a crucial strategy to test, control and predict conditions such as solar radiation, temperature, humidity, and air pollution in order to develop innovative schemes for the twenty-first century urban park.

2. Gardens by the Bay, Singapore

Singapore’s Gardens by the Bay emerged from an international design competition for a 54-hectare public garden. In 2006 the Bay south competition was won by the multi-disciplinary collaboration of Grant Associates (landscape architects), Wilkinson Eyre Architects and the engineering firms of Atelier One (structural) and Atelier Ten (environmental). The project’s success relied on the establishment of a successful growing environment for a range of plants within Singapore’s cloudy environment of subdued light and high humidity levels. Significantly this ambition was to be achieved within a carbon neutral energy system.

The design of the two feature biomes conservatories was particularly challenging. At close to 20,000 square metres, and up to 58 metres in height, the conservatories are some of the largest in the world. The challenge within the Singapore context was to adequately ventilate, cool and dehumidify the
equatorial environment, while meeting horticultural lighting requirements and limiting the carbon footprint. For 95 percent of the year, Singapore’s equatorial tropical climate maintains temperatures between 24 and 32 Celsius with humidity measuring between 17-21 g/kg (Davey et al, 2010, p.141). *The Cool Moist (cloud mountain) Dome*, designed for species from the mountainous tropical regions, requires mild air temperature night and day combined with an almost saturation level of humidity, while *The Cool Dry (flower) dome* replicates the Mediterranean springtime of mild dry days and cool nights.

A combination of physical and digital prototyping was used to develop this complex growing environment. In an important precursor to the competition, National Parks Board of Singapore (NParks) staged a multi-year research project with CPG consultants (Singapore) and German climate engineers Transsolar (Stuttgart) to identify the required growing conditions for the conservatories. Six prototype glass houses informed the initial briefing documents for the winning team. During the design process these prototypes continued to be used to test glass and equipment specifications, and understand their effect on plant growth. For the designers it was critical to identify annual and peak light levels to support plant growth, combined with specific temperature and humidity levels which would vary over the course of the day and year to simulate the dynamic change of plants within their natural environment (Bellew & Davey, 2012, p.38). A combination of proprietary software such as Ecotect and Radiance and bespoke software generated by Atelier Ten, facilitated the evaluation and comparison of various proposals Daylight simulation techniques assessed the availability and quantity of daylight for the inhabited volume for each hour of a typical year (Bellew & Davey 2012, p.49).

![Diagram](source: Grant Associates)
A dynamic shading structure, responsive to the changing solar environment, emerged as an important solution for achieving the desired growing environment. Internal light levels with and without shades were modelled for a complete reference year. The final scheme comprises 419 individually controlled external shades, featuring ‘an intelligent self-learning algorithm’ that adjusts shades in response to the sun paths, the geometry of the internal spaces and the external cladding (Bellew & Davey, 2012, p.56). Initially solar was assumed as the energy source for the environmental systems however the cloudy nature of Singapore reduces its efficiency. Discussions with NParks revealed that the city regularly prunes several million trees, generating extensive green waste largely incinerated or sent to landfill (Ferguson, 2014, p.27). Plans altered to include a bio-mass boiler fuelled by the city and garden’s horticultural waste. Steam from the boiler feeds a turbine to generate electricity. Remaining ash is used as fertiliser, while surplus energy is fed back into the grid.

Figure 2: Planting panels on the Supertrees and the suspended walkway of the Supertree Grove (source: Walliss)

The iconic Supertrees shown in Figure 2 perform an essential role in this complex energy system, which was conceived as a larger symbiotic relationship that included the conservatories and gardens, through an exchange of energy, air, water, nutrients and water cycles. This cycle is depicted in Figure 1. These spectacular tree like structures are multi-functional ‘environmental engines’ designed to disperse hot gases generated by the biomass boiler and the desiccant process, generate energy through photovoltaic solar panels and provide shade for the public areas below as well as extensive valuable habitat for birds and insects. The Gold Cluster of Supertrees, which is located near the entrance, conceals the major chimney from the energy centre’s boiler, discharging non-toxic flue gases high above any occupied areas. The steam turbine powers the electric chillers, producing chilled water to cool the domes. Adopting principles of thermal stratification, chilled water runs through pipes within the floor slabs, while the rising warm air is vented out at higher levels or is captured to harvest heat. CFD modelling allowed the engineers to analyse and optimise this airflow and accurately predict outcomes (Ferguson, 2014, p.30).

Any waste heat is used to regenerate the liquid desiccant, necessary to de-humidify the air for the Flower Dome (the cool-dry biome). Conventional cooling of humid air requires an energy intensive
process; chilled water removes water vapour through condensation, followed by reheating to the desired temperature (Ferguson, 2014, p.28). In contrast this system uses liquid desiccants to remove water vapour from the air through a chemical process; leaving the air temperature similar but drier. Used in conjunction with conventional cooling systems, this technology requires less energy, while the desiccant is recycled through treatment from waste heat from the biomass boiler. The Silver Cluster of Supertrees, masks the hot moist air discharge from the regeneration unit of the liquid desiccant dehumidification system.

This complex environmental system encompassing the entire garden facilitates a number of ‘virtuous cycles’ involving either the reuse of resources or the maximization of their use (Davey et al, 2010, p.142). The Supertrees however were designed as far more than environmental infrastructure. Their inspiration, states landscape architect Andrew Grant (2014), are the monumental karri forests of Western Australia (which feature a sky walkway) and the 1997 anime film Princess Mononoke depicting a young warrior’s encounter with forest gods and those wishing to destroy the forest resources and beauty. Rising 50 metres to match the monumental scale of the conservatories, the structures were conceived as a magical ‘other worldliness of space,’ including a unique night time experience. The largest configuration forming the Supertree Grove are particularly immense, supporting a 135m long aerial walkway suspended over twenty metres above the gardens, shown in Figure 2, with the tallest structure featuring a bar and viewing gallery.

The landscape architects worked closely with structural engineers Atelier One, led by Neil Thomas to develop the Supertrees. First versions, state Grant (2014) were very ‘clunky’ which ‘looked like bits of the Eiffel tower.’ Slowly the form evolved through a process of testing structural form and exploring environmental efficiency through physical and sectional analysis and three-dimensional studies. The geometries of the structures were established parametrically, and emerged as two repetitious modules that reinforce each other as ‘doubly curved anticlastic surfaces’ with the form developing structural stiffness (Bellew & Davey, 2012, p.99). Planting panels were designed to attach either directly to the concrete core, or to the steel skin covering the core. This novel typology challenged Singapore’s existing building codes, raising questions for authorities and engineers on how to classify them. Should they be considered buildings or bridges?

In contrast, to the Gardens by the Bays focus on developing optimum growing environments for plants, Taiwan’s Phase Shifts Park designed by landscape architect Catherine Mosbach and architect Philippe Rahm aimed to produce a more inhabitable environment for people. The park is currently under construction, expected to be completed in 2016. The scheme aims to give back the outdoors to the public by developing exterior spaces that diminish the experience of Taichung’s subtropical warm and humid climate. The park proposes a healthier and more comfortable outdoor environment, which emerges through the superimposition of two overlapping strata; lithosphere developed by Mosbach comprising soils, topography and rain-water, and atmosphere explored by Rahm which focuses on the effects of heat, humidity and pollution. CFD modelling was used to understand the existing atmospheric conditions and inform a spatial and experiential structure for the park based on extending the atmospheric range.

3. Phase Shifts Park, Taiwan

Philippe Rahm’s interest in atmosphere lies in its performative potentials. He aims to embrace climate within the domain of design, as distinct from controlling climate from a functionalist perspective to achieve optimum efficiencies. The design competition for Taichung Gateway Park provided Rahm the
opportunity to expand his explorations of atmosphere from the scale of the exhibition and architecture into an urban scale, whilst maintaining his focus on the human experience. This intent is signaled in the diagrams featured so prominently in the competition entry that depicts human physiological reactions to heat, humidity and pollution.

Mapping the climatic variations of the site through CFD modelling formed the starting point for the conceptualisation of the atmospheric strata. This modelling develops an understanding of the fluctuating conditions of heat, humidity and pollution, including the impact of the future architecture on the park’s edges. The models were developed by German firm Transsolar who used ANSYS Fluent software combined with weather data from the Taiwanese central weather bureau’s measuring device located close to the site (Frenzel 2014). From their models, the designers developed three graduation climatic maps that documented the intensity and variation of heat, air humidity and atmospheric pollution. These maps were overlaid and intersected to create a diversity of conditions, conceived as a series of Coolia, Dryia and Clearia ‘climatic lands.’ Rahm (2014) stresses that this approach is not a Modernist or functional response.

The aim is not to modulate conditions, for instance making the hotter areas cooler. Instead the scheme maintains and even extends the graduation of conditions, increasing qualities where areas are naturally cooler, less polluted and less humid. Consequently, this tactic is more than a pragmatic response, instead reflective of Rahm’s interest in designing space through voids, particles and atmospheres rather than lines and forms. A polarity of conditions is established, with hot spaces necessary to establish cool ones thereby ‘creating spaces by acting on difference’ (Rahm 2014). Space emerges through the transformative boundaries of atmospheres and conditions, not as hard spatial delineations. This concept extends into the graphic representation of the park as points and dots, where space is communicated through a graduation of light and colour rather than sharp demarcation of form. The Coolia, Dryia and Clearia establish an atmospheric structure for the park as shown in Figure 3, with circulation systems conceived to link similar climatic lands. These distinctive climatic conditions offer the rational for siting major program and activities. Sport, for example, is sited within areas of low pollution and humidity, water games placed in high humidity areas and indoor programs.

The insertion of climatic devices at strategic points is arguably one of the more controversial elements of the park. The devices offer ‘a contemporary extension of traditional furniture of parks,’ operating like the pavilions, grottos, trellises and niches found in older parks, and providing a texture of sensory experiences of refuge, delight and interest (Taichung Gateway Park International Competition Overview, 2013). These devices are designed to augment the existing conditions and offers a ‘tool box’ of approaches including ultrasonic speakers to keep mosquitos away, artificial water devices such as rain fountains for evaporative cooling, dry clouds for removing humidity from the air, depollution techniques and passive cooling techniques.

These technological interventions are supported by detailed planting regimes, featuring plants with particular performative attribute. For heat reduction, Acer serrulatum Hayata were selected for their large and dense canopy which provides maximum shading, for pollution the conifers Calocedrus formosana were nominated for their ability to absorb particulates from air, while for humidity Ficus microcarpa were chosen for their capacity to capture water by arial roots. Together these design strategies merge technological and biological performance to propose a twenty-first century response to climate change.
Designing the twenty-first century urban park: design strategies for a warming climate

Figure 3: The 'Climatic Lands Structure' for the Park emerged through the intersection of the thematic masterplans developed from the simulations (Source: Taichung Jade Eco Park, Taiwan, 2011-2016/Philippe Rahm architectes, Mosbach Paysagistes, Ricky Liu & Associates)
4. Technology and nature

Such an explicit manipulation of climatic phenomena, as demonstrated in Phase Shifts Park is rare in the design of open space. For Rahm, working with external conditions presented a very different design challenge to engaging with architectural spaces. In his previous work, states Rahm (2014) ‘the decision about temperature was not mine,’ instead determined by regulations, ambitions for energy consumption or comfort indexes. In the case of the park, the design team proposed a ‘graduation of place’ with wind speed the only parameter that could be definitively controlled by the climatic devices. Standing under the Anticyclone device shown in Figure 4 for instance it was possible to experience a reduction of temperature by up to six degrees in June, producing a temperature of 29 Celsius compared to 35 Celsius in surrounding space. This reduction however is not a baseline standard, instead always relative to the fluctuating external conditions.

Figure 4: Cooling Climatic Device (Source: Taichung Jade Eco Park, Taiwan, 2011-2016/ Philippe Rahm architectes, Mosbach Paysagistes, Ricky Liu & Associates)
Here we begin to see clearly the different design tactics regarding atmospheric performance that underlie the Gardens by the Bays and Phase Shifts Park. In the case of the park, the external conditions are constantly evolving, with any design manipulation understood as a factor of graduation rather than absolutes. While design interventions can offer a relative improvement of conditions, it is impossible to definitively achieve performance criteria. Further the added value of combining biological performance with technological intervention will only become apparent over time as the living system becomes more established. In contrast, the smart environmental infrastructure driving the design of the biome conservatories and the Supertrees presents a more prescriptive outcome, with the processes of digital simulation offering more accurate predictions of performance.

Of further interest are the different responses to the use of technologies within the schemes. Whereas the design of the biome conservatories is championed for its design and engineering excellence, including winning the 2012 World Building of the Year, Rahm’s climatic devices attract mixed reactions, despite their reliance of renewable energies (solar) and passive cooling principles. The insertion of what are perceived as ‘non-natural elements’ into a landscape is viewed with hesitancy, whereas conversely the application of sustainable technologies within a more explicit architectural program is championed. Yet are these not the same thing? Both are delivered in an energy efficient sustainable manner, one to improve the comfort of external space for people, the other to develop a more contained space appropriate for plants.

We argue that these contrasting responses reflect larger anxieties concerning the application of technology as a dystopian replacement to nature. Why replicate nature when you can simply plant a tree, and further isn’t technology the primary cause of environmental issues in the first place? This argument is not without merit. For example Dutch artist Daan Rosegarrde’s The Smog Free Project (2014) uses patented ion technology to make the ‘largest air purifier in the world’ to create the cleanest park in Beijing. The project is accompanied by the marketing idea of creating souvenir Smog rings from the particles captured from the air, with each ring representing the cleansing of 1000m3 of polluted air. Much emphasis is placed on the development of a ‘smog free movement’ promoted through exhibitions and public events. Nowhere in the extensive promotional material however is there mention of the energy requirements and energy source necessary for the purification process. This raises questions over whether the energy source remains brown coal, which creates the irony of the purifier both cleaning and contributing to air pollution. But beyond this question of energy, the Smog Free Project also presents a very limited response to the broader question of pollution and the performative role of open space in the Chinese City.

5. Conclusion

As we have highlighted in this paper, Gardens by the Bay and Phase Shifts Park demonstrate a comprehensive engagement with environmental conditions and phenomena, using technology to enhance design processes and the performance of constructed spaces and systems. Importantly these design approaches introduce a new aesthetic into the design of open space, merging the artificial with the natural as reflected in Rahm’s climatic devices and the iconic Supertrees. Rahm (2014) sees no difference between trees and machines, and is comfortable with the interaction between the natural and artificial, such as the potentially surreal experience of the park visitor uncovering a strange machine within a wild forest. In a similar response Andrew Grant (2014) states that the Supertrees should not be considered as a replacement to nature, nor design ‘elements’ to be reproduced in other locations. Instead, he highlights their origins in a very specific design context, emphasising their value in re-
conceiving infrastructure to operate intelligently to address environmental issues and limited energy resources. While some critics might react to the insertion of technology into what they perceive as a ‘natural landscape,’ we argue that the future of the twenty-first century urban park in the mega-urbanism of the Asian city lies at the very intersection of biological and technological performance.

References


Landscape (design) futures: setting a context for continuing dialogue?

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Abstract: How do we define an evolving role for the discipline of landscape architecture in the context of changes in tertiary education and professional practice? Where could its future lie? Acknowledging the multi-disciplinary nature of landscape architecture practice that requires an expanded oversight of contemporary practice and scholarship, this paper explores debates in contemporary issues faced by the discipline in the shifting, often conflicting practices in both higher education and the delivery of landscape architecture amongst other built environment professions. Framed around discussions at the Faculty of Architecture Building and Planning (ABP) at the University of Melbourne and based on dialogues with various stakeholders from the landscape and allied disciplines – academics, practitioners, students – the paper synthesizes future possibilities in repositioning the profession as well as strategic and tactical synergies between academia and practice.

Keywords: Landscape architecture; professional practice; education; research.

1. Introduction: Perspectives on an emerging discipline

Landscape Architecture is a relatively young profession still finding its way as a multidimensional practice in a design environment that has, in the past, privileged specialist disciplinary expertise. Over literally more than a century and half perennial debate has ensued on the merits or otherwise of the professional title, ‘landscape architecture’ and at times, the discipline itself. One aspect of such debate has involved professional competition. Abbott has suggested that professions operate within a system and that their interrelationship with other professions all vying for control over work is a crucial indicator of relative strength perhaps far more so than the self-serving processes of institutionalisation as professions emerge and attempt to develop firmer footings (Abbott, 1988). The profession in Australia began to emerge in the post-World War II years culminating in institutionalisation under the Australian Institute of Landscape Architects (AILA) in 1966 and the gradual increase in stature from the mid-1970s onwards. It was a profession far-outweighed in size relative to its peers of architecture and planning disciplines which had precipitated decades earlier (Saniga, 2005). The peculiarity of the Australian profession, which to varying extents is shared in other places and contexts, is that its
founders came from vastly different academic and professional backgrounds, including architecture, planning, forestry, and even the self-made practitioner who quite literally worked with their hands (Saniga, 2012, pp. 62-122). This had the potential to shape an identity in new and interesting ways as much as it had the power to undermine any collective identity that may have been struck.

The aim in this paper is to consider one aspect of the profession’s emergence, that of its own deliberations about its future, and to contextualise such discussions in the context of contemporary discussion and debate within tertiary education. For apart from the small size and relative newness, Australia’s landscape architecture profession has many peculiarities and complexities. Landscape architects often work within broad parameters of public space and contested bureaucratic domains characterised by multiple stakeholders and they, appear to consistently find the need to justify their discipline and defend potentially fragile professional territory into the future. This paper is an introduction to these issues and attempts to document a local case study based on the debates surrounding the University of Melbourne Landscape Architecture program as an academic discipline defined through its diverse practices as well as by its relatively small scale cohort in the context of a large architecture presence and University preferences for the economies of scale in relation to viability. Presented here are some threads of discussions that should be of value as a starting point for comparison and debate in other contexts, national and international.

2. Landscape Futures: Disciplinary tangles, strategies, think tanks and new collaborations

The quest to define a profession of landscape architecture, as introduced above, can be identified through time and across vastly different cultural contexts. The experiences of landscape architecture at the University of Melbourne are arguably ones that will find traction elsewhere. The degree of Master of Landscape Architecture was inaugurated in 1978 at the Centre for Environmental Studies within the Faculty of Architecture, Building and Town & Regional Planning, which was responsible for its administration (CES and ABT&RP, 1981, p. 1). From the outset, the multidisciplinary claim for the profession was a key part of the context of the program, the necessary knowledge deemed significant to the discipline included: natural sciences, humanities and social sciences, as well as links to ‘Agriculture, Forestry, Architecture, Planning, Civil Engineering and Surveying’ (CES and ABT&RP, 1981, p. 7). But of equal importance was the mission to advance the profession in Australia, from an academic and a practice (non-academic) point of view, and of establishing links with public agencies and with industry (CES and ABT&RP, 1981, p. 7). The optimism inherent in this quest was coupled with the launching of a new academic program for a relatively nascent profession, and suggested that at least the educators of the time thought that the future for the discipline ‘appear[ed] bright’ (Pike, 1979, p. 87).

The objectives of the program of landscape architecture at the University of Melbourne at this time included, in summary, the ‘primary’ objectives of training landscape architects for suitability in private and public practice, as educators, and, as being eligible for membership with the AILA (CES and ABT&RP, 1981, p. 8). The ‘immediate’ objectives were more heady, involving such things as the establishment of a ‘flexible program’ (CES and ABT&RP, 1981, p. 8), able to cater for a diversity of student background; instilling in students a ‘consciousness of the economic, social and political issues and not just the aesthetic considerations’ (CES and ABT&RP, 1981, p. 8) in professional practice; of developing in students ‘an understanding of and feeling for the Australian landscape’ (CES and ABT&RP, 1981, p. 8); and, to ‘develop problem-solving skills’ (CES and ABT&RP, 1981, p. 8) for working at all scales of landscape work. All of this was intended to be conducted within an educational environment
emphasising disciplinary relationships with ‘arts, humanities, the environmental sciences and with planning and related social sciences’ (CES and ABT&RP, 1981, p. 8). The disciplinary complexity and the inferred seamlessness of traversing broad specialist fields from arts to science to social sciences that was recorded here in 1981 clearly reflected an optimism that in fact the future of the new profession was that it should be in an overarching and a controlling position. Such a claim had been regarded more cautiously by some like Professor John Turner who ten years earlier had forewarned in 1971 regarding the future training of landscape architects that:

Landscape architects are faced with the problem of marrying two disciplines – town and country planning and applied biology, and at the same time inculcating a feeling for landscape and an aptitude for design ... only a few today would qualify (Turner, 1971, p. 24).

Whether or not the University of Melbourne’s new Master of Landscape Architecture program could indeed successfully ‘marry’ multiple disciplines is questionable. In 1983 Michael Martin McCarthy, who held a doctorate from the University of Wisconsin (1973) became the inaugural Elisabeth Murdoch Chair of Landscape Architecture. One of his prime concerns, communicated at length at his professorial lecture, was the impact of what he termed the ‘Information-Communication Age’ (McCarthy, 1983, p. 181) and the need to explore new directions by which to facilitate the valuing of landscape. By the mid-1980s, McCarthy and Ian Oelrichs initiated ‘Landscape Futures’, which from personal recollections was a ‘strategic program aimed at addressing the longer-term development of landscape architecture’ (Bull et al, 2000, p. 2). Also at around this time, which was approximately within 20 years of the institutionalisation of the AILA (1966), the AILA’s official journal, Landscape Australia, had been reporting annually on institute membership and numbers had grown from a few dozen founding members in 1966 to 276 members in 1986. Although there is not sufficient space within this paper to document at length the waxing and waning of the profession in Australia in its early decades, it seems important to record that within a decade of McCarthy and Oelrichs’ ‘Landscape Futures’ there were signs that the profession had started to become entangled in professional competition with the disciplines of architecture and planning and through the emergence of a new occupational pursuit, ‘urban design’. The Australian Prime Minister’s ‘Urban Design Taskforce’ of 1992 and 1993 was an initiative to report on the growth of urban design as a profession and to promote activity, a move that would have implications for landscape architecture. The future of landscape architecture by the start of the 1990s was defined by an ‘ever-expanding field’ (Saniga, 2012, p. 287) and landscape architecture’s disciplinary base was ‘becoming subsumed in larger, and perhaps more powerful, operational spheres’ (Saniga, 2012, p. 287).

Advancing forward a decade to the year 1999, Professor Catherin Bull, the Chair of the Landscape Architecture program at the University of Melbourne at the time, along with Ian Oelrichs, Leonard Lynch and Jacinta McCann (all landscape architects) initiated the ‘Landscape Futures Think Tank’. Their aim was ‘devised in response to changes in the sphere of landscape architecture and the world generally since the mid-1980’s, as a means of re-evaluating the future direction of landscape architecture in Australia’ (Bull et al, 2000, p. 2). The initiative came as a result of a ‘Green Paper’ put forth by the Landscape Foundation and The Australian Centre for Landscape Architectural Studies, which were an offshoot of the AILA. The intention was to run workshops on the topic of the profession’s future, the first being held in April 1999 in north-eastern New South Wales with Ian Oelrichs as host (Bull et al, 2000, p. 2). A second workshop held in November 1999 at the University of Melbourne titled ‘Framing the Discipline for the Next Decade: Positioning, Communication, Education and Research’ was compiled in an unpublished report authored by Professor Bull, Steve Calhoun (landscape architect), Alan Saunders
A. Saniga, G. Lee and S. Sintusingha (ABC Radio host for ‘By Design’) and Libby Ward under the title ‘LandScape Futures Think Tank’. The interest in this document is in the views, opinions and aspirations of the participants and how this might frame the discussion of the contemporary situation.

Much of the discussion centred on the delineation of overarching aims and objectives including defining core skills, key areas of activity, commonly held values, stakeholders, issues, operational framework and action. But the definition of a discipline of landscape architecture and its place in the broader context of practice in multiple spheres inclusive of architecture, planning, engineering and other disciplines came through strongly. Bull was paraphrased as being of the view that ‘we need to stop defining ourselves against other professions …[and to] … think about what we as participants in the discipline of landscape architecture want to be saying in the next decade, and how we develop the intellectual capital to inform these strategic decisions’ (Bull et al, 2000, p. 3). Saunders proposed that ‘practice often precedes theory…[and that] …”practice” was indeed the father, “profession” the son, and “discipline” the Holy Ghost (Bull et al, 2000, p. 3). Although Saunders (1954-2012) was not a landscape architect his knowledge of the built environment professions via hosting the radio program ‘By Design’ for many years no doubt exposed him to numerous projects, ideas and belief systems of architects, designers and landscape architects. In relation to the Landscape Futures Think Tank he went on to record that ‘awareness of landscape architecture would be greater if it were seen as a matter of dynamic activity rather than of artistic reflection or academic discipline’ (Bull et al, 2000, p. 1). Perhaps the value in these musings lays in the notion that there is a potential for disciplinary ‘silos’ to ultimately preclude innovation and creative research. Although the breaking down of these divisions, entrenched as they have been in the worlds of practice and symbolically upheld in professional institutionalisation, is seen by many as the great challenge, the question remains: what form would this new dynamism take and where is landscape architecture in such a context?

Over the past decade, the University of Melbourne’s conceptualization and implementation of the Melbourne Model provided a pedagogical context and opportunity in which to breach disciplinary silos and, for landscape architecture, to assess and reposition itself in a more dynamic academic context. In 2008 the built environment undergraduate degrees from across the university were amalgamated into a Bachelor of Environments (BEnvs) to advance more integrated teaching and learning, to promote speculation towards different practices that more effectively mirror the real world of multidisciplinary practice. The ABP offers architecture, landscape architecture, urban design and planning, property, and construction majors with other majors in the areas of science, engineering, geography, etc.

Over the years of implementation, the entrenchment of disciplines and disciplinary interests, amongst other factors, has remained a major obstacle to such objectives in the undergraduate regime. This has led to initiatives for a top-down restructuring ongoing since 2014 with the original multidisciplinary objectives giving way towards a teaching and learning model of disciplinary alliances and complementarities in double-degrees and major-minor offerings. However, students and the professions still focus on the disciplinary name as proof of educational outcome even while they often acknowledge interests in many disciplines. To this end, the design focused architecture specialisation continues as the major focus for BEnvs students in 2015, with the consequence that a career in landscape architecture might be regarded as a mere sub-consultancy to architecture and to a lesser degree urban planning. While the operational reality of the BEnvs manifested the same difficult forced multidisciplinary marriages and relationships – with the result that smaller disciplines were in some ways disadvantaged in relationship to a bias towards larger disciplines - the structure of the degree that promoted breadth over depth to varying degrees, helped provide clearer knowledge of and contextualise the landscape architecture discipline in the context of the built environment.
The increasing prominence of research as a core academic activity in the university emerged as a principle aim over the past two decades. This posed a challenge to professionally orientated disciplines such as Landscape Architecture in locating the “research and teaching nexus” (Baldwin, 2005), particularly through the notion of research-led teaching aiming to identify and establish synergies between what had been broadly separated academic activities of research and teaching/training. Here, for the first time, it arguably expanded the debate into the identity of and what constitutes landscape architecture research.

Professionally accredited, discipline-focused studies are provided at the graduate level in the Masters of Landscape Architecture degree. The AILA Education Policy and Standards documents are the basis for program accreditation, yet they provide somewhat muted guidance on diversity and innovation in balance with what is described as the provision of a standard of education. The AILA documents encourage links and partnerships across the spectrum of education and research activities that relate to the landscape architecture profession (AILA, 2012). AILA’s Charter espouses a range of principles that are broadly concerned with values, the aim to protect-enhance-regenerate design with respect for culture and nature, and for the future, and to promote and embrace responsive design. With regard to the future of the profession, the primary focus is design-led action with regard to future change under the condition of triple bottom line resilience (AILA, 2013).

Interestingly, the original early 1980s Master of Landscape Architecture (MLArch) by coursework and the corresponding MLArch of today are not so different structurally, in that they both encourage non-cognate mature age students from a wide variety of disciplines into the first year of the expanded 3-year program. The primary outcome of that first year involves preparation for an intensive two year landscape architecture focused masters course of study. The primary distinction between ‘then’ and ‘now’ rests in the current focus on design theses as a primary indicator of critical direction and application to real world projects, whereas the program 30 years ago was to some degree more concerned with landscape planning and applied research achieved primarily through written theses. Today, an increasing emphasis on design research across the MLArch reflects growing interest from the profession and from within the academy in the essential connections between academic/student research and everyday design practice; in particular that research led design is necessary to confront issues and projects that increasingly demand input from many scientific and humanity based disciplines working together.

3. Research driven LA academic agenda: Landscape Futures Reimagined

These recent changes in higher education and academic research have acted as a catalyst for continued discussions revolving around the search for synergies between research and teaching, the main activities in academia. The question of the future of landscape architecture has returned time and again as a focus for discussion and debate that has ranged from who are we, where are we going, to nowadays embracing a primary concern for applied action within an expanded area of multidisciplinary practices that broadly cover design, ecology and engineering with a measure of economy and governance also in play. In early 2013, the Australasian Educators of Landscape Architecture (Australia and New Zealand, the AELA) met at the University of Melbourne for a workshop chaired by Professor Gini Lee, the current Chair of Landscape Architecture at the University, on the topic of ‘Landscape Futures’. Issues raised at the meeting included the resurrection of the AELA group charged as both a forum for advocacy and for research and pedagogical collaboration, a desire for agenda setting opportunities and dissemination and as a body that promotes international exchange of ideas and practices defined through landscape
architecture. This meeting acknowledged that futures had now become more dependent on strategic positioning of the discipline within the expanded field of academic institutions as well as in partnership with other public bodies.

One initiative that emerged from this meeting was a successful grant application from the Office of Teaching and Learning Grant Scheme led by the then RMIT University Landscape Architecture Professor SueAnne Ware. This involved collaboration between five programs across Australia and New Zealand: RMIT University, the University of Melbourne, Adelaide University, the University of Western Australia and Lincoln University in Christchurch New Zealand. The group, nominated as AMiLA – the Australasian Masters of Landscape Architecture group – was modelled on the successful European EMiLA program established to provoke student exchange and research collaboration across programs. This pilot program enabled comparative modelling across similar MLArch programs that resulted in a matrix that clearly identified the great diversity in pedagogical approach across Australia. A summer workshop/studio intensive was also delivered in January/February 2015 as a partnership between RMIT University, the Melbourne School of Design (MSD) at the University of Melbourne and the City of Melbourne Urban Design Groups. Under the readily accessible themes of Urban Resilience design students from five universities worked together to provide novel and potentially innovative design solutions based on research for three sites of critical importance for the City of Melbourne; the Carlton Squares, Southbank Boulevard and West Park at Docklands. In the short term this program achieved threefold outcomes; firstly, student exchange through design research provided an intensive and thought provoking range of possibilities for students, academics and Council officers; secondly, ongoing publication of the studio workshop outcomes are in the process of becoming embedded in City of Melbourne publications and hopefully informing policy; and thirdly, innovative collaboration has been demonstrated through a national and international pedagogical and research agenda.

A second initiative stemmed from a scheme internal to the MSD at the University of Melbourne under the banner of ‘iGroups’. This was an initiative intended to promote discourse and collaboration towards ‘blue sky’ thinking. One such iGroup was proposed around Landscape Futures commencing with a nascent consultation with groups of likely allies across the University and including local external bodies. Among the potential allies identified for inclusion were the Victorian Eco-Innovation Laboratory, the Melbourne Sustainable Society Institute (MSSI), the City of Melbourne, Parks Victoria, and Local Councils. Participation was proposed through a network of graduates, the AILA, the broader University of Melbourne community including health, engineering, urban planning and so on. The aim of these “collaborations” was to seek to establish “…affiliations and inter/discipline/s through the landscape futures lens” to “ensure a local national international agenda with practice, academic partners, institutions, government, NGO’s, foundations”. Through a pilot project/s, these connections were to be investigated and, being authored by landscape architecture academic stakeholders, the “collaboration – research – teaching nexus” demonstrated (iGroup proposal 2014). This thinking was also informed through input into selected international research agendas. The Landscape Futures project intended to provide continuity and updating across the previous futures agendas including for the group to link to the Urban Futures initiative established by MSSI.

During the development of the proposed iGroup, a key December 2014 meeting, facilitated by the Dean and MSD director, sought to catalyse focussed and in-depth discussions, through posing three landscape research themes of; landscape ecology – urban focus, health agendas for cities, and performative landscapes, to potentially define ABP’s Landscape Architecture program. This initiative and proposed themes informed the finalised February 2014 proposal for the Landscape Futures ‘iGroup’ authored by Gini Lee and Sidh Sintusingha. The question “Why (form such a group)?” was posed with
the document offering some answers including; facilitating landscape research and teaching directions across inter- and trans-disciplinary practices; providing mechanisms for collaboration across allied and non-allied practices; and, enabling outreach and engagement locally and in the region and as a means for consolidation of existing expertise and research foci in the landscape architecture group and with their current collaborators.

Key barriers and challenges were identified in landscape and urban practices in that a strategy for engagement is required that could be sustained, aligned to the critical question of how to establish these alliances in the context of knotty and multidimensional environmental and social problems; areas in which landscape architecture knowledge was not necessarily recognised as having value. Yet, it is argued that while the demonstrated existence of active, broad-based real and potential allies across practice and funded academic research, such as Australian Research Council Linkage programs, is evidence of the centrality of the landscape in broad discussions and actions on global and local environmental challenges, this does not necessarily result in recognition of a clear role for the landscape architecture discipline. Again, the onus is placed on the discipline (both its academic and professional practitioners) to engage and remedy this situation. In the final ABP Landscape Architecture Advisory Panel meeting for 2014, the assembled practitioners and students engaged in a lively debate about the very issue of Landscape Futures, although this was not the formal topic of conversation. It is clear that the complexity of issues, values and conditions that face landscape architecture and urban design practitioners and academics are in flux as all grapple with concepts of indeterminate change, and how groups and individuals might approach novel agendas and/or solutions through diverse practices, both inside and outside the academy. What was not in question, as had been in the past, was what Landscape Architecture practice was. Rather, the issue rested with the ‘how’ to evolve as responsive and innovative academic practitioners, through gaining better understanding of the complexity and breadth of present and future landscape conditions, in order to act through a combination of practices that includes, but is not limited to, design; in a sense, for landscape architects to embrace concepts of practical activism towards affecting novel and workable solutions to the aforementioned ‘knotty problems’.

International perspectives also align with this thinking on Futures. The Melbourne School of Design project towards adopting a landscape (design) futures agenda has sought to present an examination of the current history and state of play in landscape architecture education through our perspectives gained through teaching. The recent historical overview of the idea that both the profession and academia seek to imagine new horizons through the term Landscape Futures is ongoing. By comparison, the new program at Peking University which is closely allied to the well regarded landscape architecture and planning firm Turenscape, and its high profile landscape architect leader Kongjian Yu, publishes a yearly Landscape Architecture Frontiers call for research papers which both inform their similarly named professional/education journal. Through publication agendas for research with such topics as The Power of the Market, Energy Efficiency Landscapes, Disaster Landscapes, Archaeological and Heritage Site Conservation and Landscape Architecture in Arid Environments are proposed, reinforced through examination of realised projects. Each title is accompanied by an agenda setting paragraph, which states the context of the issue and a suggestion for action. These ideas are both prescriptive and provocative but they do not necessarily suggest the need to confirm their interests within a broader institutional or professional framework
4. Landscape research foci as response to the University of Melbourne’s three ‘Grand Challenges’

Building upon previous discussions including the review of the ABP’s landscape architecture degrees of both the BEnvs and MLArch, February 2015, and reading and synthesizing landscape architecture research in terms of the framework of the broader University’s Grand Challenges (University of Melbourne, 2013) for research, Andrew Saniga synthesized a draft discussion paper on the landscape architecture program’s “research foci” (April 2015). Strategically, it was a ‘blue sky’ vision, yet offered a practical agenda that identifies and speculates upon real and potential intellectual spaces for landscape architecture in the university’s strategic research agenda for multidisciplinary collaboration. The draft is concurrently an important justification of the discipline and a potential plan of action – a practical necessity in an era of the University’s research-led priorities that guide and challenge academic roles in teaching and training. Yet, the foci can serve as the means to mitigate the gap between research and teaching that is often left to individual programs and staff to redress, depending upon the methods that participants choose to position themselves within such agendas. A critical issue in seeking collaboration in an institution where academic progress is still largely calibrated through individual endeavour is to enable and mentor buy-in of such overarching agendas.

The review called for all staff to engage in a process of reaffirming the importance of establishing foci for landscape architecture in order to strengthen and clarify research-led teaching and to aid in communicating to students and the broader community (including the AILA and their accreditation requirements) the research endeavours and strengths of landscape architecture staff both as individuals and in their collective efforts. The proposed outcome is a clear articulation of these foci in a concise document for online publication, providing agenda setting projects and appropriate materials for engagement events and to be used in relevant communications.

Taking the first of the University’s three Grand Challenge’s as both framework and potential provocation, *Understanding our Place and Purpose*, the review focuses on improving the human condition through an understanding of Australian identity, in the broadest sense but with particular reference to Australia in the context of the Asia-Pacific region. It includes investigations of ‘multiculturalism, economic innovation and development, social equity, communal wellbeing, political systems and enfranchisement, global efforts to improve the lives of people in developing countries, fostering creativity to enrich lives, and building our knowledge of the present, recent and distant past’ (University of Melbourne, 2013, p. 10). This Grand Challenge embraces creative arts, humanities, and social sciences research and calls for collaboration beyond traditional boundaries. Opportunities for landscape research acknowledge current research and teaching content through investigation into ‘Rural, Remote and Indigenous Landscapes and Communities’. Building upon ABP research and landscape architecture subjects, this focus covers areas from landscape heritage, conservation, management and interpretation in rural and remote cultures, including Indigenous cultures and settlements in transition. It is also inclusive of research into landscape assessment and planning.

The second Grand Challenge, *Fostering Health and Wellbeing*, while ostensibly concerned with biomedical research, this Grand Challenge also calls for a holistic outlook in embracing other aspects of public health including cultural attitudes to healthy living, the design of physical space in response to human health, and the history and philosophy of health and wellbeing. Although this area is the least developed in the landscape architecture group there is a recognised opportunity for synergies to be developed with other academic fields, which is in part the purpose of the review. The predominant focus of the ABP resides in approaches to urban landscapes and environments especially in regard to
their responsiveness to human health. The distinct and changing nature of urban spaces and living environments calls upon research and teaching that embraces both a historical and a contemporary approach including perceptions, performance, place making and the concept of healthy cities from ecological, social and economic perspectives.

The final of the University’s Grand Challenge’s is the area most obviously connected to the environmental concerns and practices that concern landscape architecture values and practices. Supporting Sustainability and Resilience intersects with the previous two challenges and is inextricably linked. However, engagement in the field of sustainability and in managing environmental change (including degraded landscapes, rehabilitation, landscapes post-natural disasters, etc.) with ecology as the primary field of research is potentially a distinguishable research foci as it embraces links with the sciences and engineering, horticultural and natural systems and the values people hold and aspire to for resilient futures. In this overarching field, landscape architecture can most readily bring a design language to projects for urban and ecological systems, infrastructural projects, post-industrial and peri-urban development and scalar and temporal overview of large scale landscape dynamics. In particular, landscape design thinking is particularly suited to projects undergoing substantial change, wrought by climatic, economic, social, economic, political and cultural influences.

In developing these foci, a narrative for contemporary practice in landscape in ABP can be articulated, which is of benefit to students, staff, the broader academic community and other collaborators. How to articulate such practices requires application beyond single one-line headings. These summaries are useful but they can provide a potential for a too-confined perspective on the meaning and values behind such terms, leading to intellectual silos and project dead ends. On the other hand, the foci can contribute to a solid specialisation and expertise of benefit to others. This is a critical aspect of landscape architecture knowledge and practice – it has to achieve the local and the universal, the specific and the abstract, simultaneously. The intent of the document is as a working model for landscape architecture research in the program and by extension the University and external stakeholders. In the sense that the general themes are elaborated upon more specifically in relation to research programs past, present and future, such documents are by necessity open-ended. For example, the theme of ‘performative design’ includes a number of meanings and interpretations depending upon the research focus, and most landscape architecture academics at the ABP would see identification under this concept. What is required is discourse around the recognisably diverse practices in landscape architecture to uncover the multidimensional meaning of this term and associated approaches, whether it is data, modeling and digital driven, a physical expression of engagement in landscape or something else perhaps allied to a collaborative arts focus.

5. Conclusion: What of practice (academic and the profession)? The power-relations factor

This paper poses questions from the point of view of landscape architecture academic stakeholders, and suggests the occurrence of an ongoing review of the profession and the discipline. Educators are responsible in part for the link between research endeavours and the profession, and the education of future practitioners. What have been implicit in this discussion are the underlying intellectual power relationships across the contexts of both academic and professional practices. These are more concentrated when there are hierarchical relations and contestations on the overlaps in the many disputed areas of design research and professional practice. Even in the area of ‘design’, the landscape architecture discipline is pushed to a critical reflection of normative practice and often to return to self-
justifyatory tropes such as: What sets of skills do landscape architects bring? When and where do other disciplines value the input of landscape architects? How does landscape architecture engage in the creative roles of digital design and construction processes?

From the issues raised above, a more disciplinary neutral question might rather be posed as: Which design and planning processes and/or mechanisms draw out and fully utilize disciplinary strengths, across allied and other less obvious collaborators? Landscape architects can benefit from acknowledging that their skill base has the potential to continually expand in the context of the dynamic context of landscape. Landscape Futures discourse needs not primarily to be concerned with a ‘call to arms’ to discuss what landscape architecture ‘is’. Rather, the value of landscape architecture in the context of environmental, social and economic problems seems more widely accepted than three decades ago, at least in the Australian context. Perhaps the debate lies in the extent to which strategies for successful conceptual thinking leading to effective implementation and robust management regimes are already being enacted. It is up to landscape architecture academics and practitioners in partnership to firstly recognise and communicate the effectiveness of responsive and resilient projects for changing systems and situations looming in our collective futures. Once this is broadly achieved only then can successes (and also shortcomings learnt leading to improved practices) be measured and appreciated by our collaborators and ultimately by the public at large.

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Looking for new futures for the springs in the Japanese city of Mito

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Abstract: This study demonstrates a transition in the environment and human behaviour surrounding spring water over a 100-year period. First, 38 remaining springs in the city of Mito were investigated by local residents and the local authority, analysing how waterfront spaces and survey locations were used. According to the results, spring water was used as drinking water, washing water, and firefighting water. Spring water close to farmland was used for agriculture. However, in recent years, water quality has degraded and it can no longer be used as drinking water. Therefore, a park with hydrophilic water was recently constructed. Some springs near shrines were seen as sacred places for water spirits to cleanse themselves. In addition, some spring water was used for environmental education and disaster prevention training. Based on these findings, it is important for us to consider the active use of spring water and waterfronts in order to promote the use springs for multiple purposes.

Keywords: Human behaviour; hydrophilic water; spring water; waterfront.

1. Introduction

Mito of terrain have a complex relief, which is compounded by the plateau and the basin there. Between the plateau and the basin, spring water is overflowing. Springs have provided resting places for people from the 1800s and have been used in people's daily lives. In specially, Kairakuen is well-known as a city park in a central area of the City of Mito in Japan. The Kairakuen was founded by Tokugawa Nariaki, the ninth feudal lord in Edo-era. The Kairakuen was a landscape gardening project started by Nariaki Tokugaw. The park opened in July 1842. The name "Kairakuen" comes from a saying within the Book of Mencius which states, "The ancients would share the pleasures with people, so their pleasures would be hearty and deep." Togyokusen (a natural spring) which is analyzed in this paper, is located at Kairakuen. Many people have been known to have been healed by Togyokusen. Togyokusen is a treasure, it has been used as a healing source. Thus, spring water is treasured by residents in a centre area of Mito-city. At the spring location in a central area of the Japanese city of Mito, a healing culture around springs has been nurtured in close relationship with daily life.
However, the amount of spring water has been reduced due to the influence of recent urbanization. The relationship between daily life and springs has been diminished by the spread of water supply facilities. After hearing from local residents, it became clear that awareness of the presence of springs has diminished. Springs are a valuable cultural resource in the region, and were an important water source for firefighting at the time of the disaster. Under these circumstances, the Japanese Ministry of the Environment issued guidelines for spring water conservation and renewal in March 2010. In recent years, there has been a growing movement for conservation and renewal of spring water. In a review of previous papers, there were few that discussed spring water and human behaviour.

This study focused on springs which has familiar to people as a healing source from the 1800s, and investigated the remaining spring water locations in Mito city centres. Besides, the transformation process behind the exploitation, topography, and utilization of spring water has been investigated. In addition, it proposes methods for renewing spring water in the future.

2. Methods

Firstly, 38 remaining spring water locations were found in Mito city centers while walking systematic and hearing from local residents. As a result, this study investigated the distribution of all 38 locations of spring water, their current present condition, type of topography, installations, and positional relationship between neighbouring temples and shrines. A field survey of springs was carried out from December 2\textsuperscript{nd} to 30th, 2014. This study assumes the springs to be natural.

Next, 16 spring locations with installations were interviewed by local residents and the local authority, analyzing how waterfront space and survey locations were used. Information derived from hearing research was based on current utilizations of spring water, changes in the surrounding environment, current development conditions, and factors for these transformations. Interviewees were residents and people involved with neighbouring temples and shrines. In addition, we asked the local authority how to have involvement in spring water. The survey took a total of 10 days in December 2014.

3. Results of investigation into locations, conditions, topographies, and circumstances of springs

Figure 1 shows spring water locations in a central area of the Japanese city of Mito. There are 5 areas in which spring water is concentrated. After comparing locations and topography, spring water appears to be more distributed along cliff lines, such as mountain slopes, cliff bottoms, and valleys. Table 1, shows the condition, topography, and circumstance of the spring water. Figure 2 shows types of topography. Type a) is a cliff-line type gushing from the cliff face of a plateau-terrace; type b) is a valley-head type gushing from valley terrain, such as a horseshoe, type c) is wetland or pond type groundwater seeping into the lowland. The examination results of all 38 locations show that 75% of the spring locations are of a cliff-line type, a), and that 25% are a valley-head type, b). Many springs are fragmentarily spread along the cliff line, and from a small valley distant from the cliff. The next survey checked whether or not there are installations at the springs. In this study, an installation is considered to be a space directing human behaviour into a certain setting according to space planning. The results confirmed installations at 34% of the springs. Furthermore, these installations are currently accessible. There is a difference in height of installations. We also confirmed that 26% of springs neighbour temples and shrines. If springs are located close to temples and shrines, they are presumed to have some relationship.
Thus, springs are concentrated in five areas. Additionally, there is a tendency at some locations for spring water to flow into the ground. Table 1 shows different tendencies in present condition, types of topography, and installations. Specially, it was predicted that there would be a close relationship between installations and neighbouring shrines, and that daily use at shrines would contribute to the active use of spring water. Based on this analysis, it was predicted that 18 springs are connected to installations or shrines. The next sections analyze these 18 locations in detail.

Figure 1: Spring water locations in a central area of Mito

Figure 2: Types of topography
Table 1: Condition, topography, and circumstance of springs in a central area of Mito

<table>
<thead>
<tr>
<th>No.</th>
<th>Area</th>
<th>Name</th>
<th>Present Condition</th>
<th>Type of Topography</th>
<th>Installation</th>
<th>Neighboring Shrine and Temple</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>North Horse Tableland</td>
<td>Surround Ibaraki University</td>
<td>Small Park</td>
<td>b)</td>
<td>present</td>
<td>present</td>
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<tr>
<td>2</td>
<td>North Horse Tableland</td>
<td>Bakui</td>
<td>Park</td>
<td>b)</td>
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<td>-</td>
</tr>
<tr>
<td>3</td>
<td>North Horse Tableland</td>
<td>Yougyougo</td>
<td>Pond</td>
<td>b)</td>
<td>present</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>North Horse Tableland</td>
<td>Musho</td>
<td>Park</td>
<td>b)</td>
<td>present</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>造成的高中</td>
<td>Ibaraki high school</td>
<td>Unusable</td>
<td>a)</td>
<td>-</td>
<td>-</td>
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<td>6</td>
<td>North Horse Tableland</td>
<td>Mesui</td>
<td>Large Park</td>
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<td>present</td>
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<td>Kyudou</td>
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<td>Ochanominu</td>
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<td>Small Park</td>
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<td>a)</td>
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<td>present</td>
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<td>Taro</td>
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<td>13</td>
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<td>a)</td>
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<td>Sawawatari</td>
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<td>a)</td>
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<td>Togosanzen</td>
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<td>-</td>
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<tr>
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</table>
4. Results of Investigation into Transformation of Spring Exploitation

This section investigates 18 springs particularly through the results of hearing from local residents, as well as the local authority, and analyzes how waterfront spaces and survey locations are used. Table 2 shows a transition in spring water fishing beginning 100 years ago. Although springs had familiar to people as a healing source from the 1800s, springs have changed the role after 1900 or later. Since the recent 100 years changed very large role, this study analyzed paying attention to the last 100 years. As a result of considering the changed role, seven roles have emerged. This study analyzed whether these seven roles had penetrated to what extent, to analyze the state of transformation of springs. In table 3 and 4, it was applied as same. Table 3 shows a transition in daily spring water use beginning 100 years ago. Further, table 4 shows a transition in spring water use at shrines and temples beginning 100 years ago. Spring water use in daily life is divided into 7 categories: drinking water, agriculture, hydrophilic parks, various means of subsistence (such as fishing), faith, environmental education for children and local residents, and disaster prevention use such as firefighting. In the hydrophilic park, users in park can commune with spring water, plants, soils and living things. Local residents around the 18 springs mentioned the seven methods during the interview.

Based on the results of interview, human actions at springs are as follows:

1. Daily life uses, such as drinking, washing vegetables, and washing clothes.
2. Agricultural use in the irrigation of rice paddies and upland fields.
3. Subsistence use in breeding fish and producing sake.
5. Faith use in mental relaxation at temples and shrines, and for guardian spirits.
6. Educational use for biological and environmental education.
7. Disaster prevention and relief, such as drinking water and firefighting water during a disaster or disaster prevention training.

The reasons springs were no longer used were considered to be reduction of water availability, changes in the aquifer, and water quality deterioration.

Firstly, those interviewed described a transformation in the exploitation of water at spring installations. The results revealed a reduction in the amount of water available due to urbanization, deterioration of water quality, water spread, daily use, and the agricultural use of the Edo era. However, in recent years, as installations have been built by the local authority and community, many people have engaged in hydrophilic use.

A transformation in human behaviour at springs and neighboring shrines and temples was also described. This section investigates temple precincts and the spaces neighboring springs. At temples and shrines neighboring springs with installations, the installations were used by the temples and shrines. In celebration and worship rituals carried out regularly over long periods of time, these spaces have become bases for the local community. This has led to the implementation of a variety of spring water uses.
Table 2: Transition in fishing at springs starting 100 years ago

<table>
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<tr>
<th>3. Yoyogiyo</th>
<th>100years ago</th>
<th>50years ago</th>
<th>Now</th>
<th>19. Koda</th>
<th>100years ago</th>
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Table 3: Transition in daily spring use starting 100 years ago

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<th>50years ago</th>
<th>Now</th>
<th>4. Musho</th>
<th>100years ago</th>
<th>50years ago</th>
<th>Now</th>
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<td>8. Nanagari</td>
<td>100years ago</td>
<td>50years ago</td>
<td>Now</td>
<td>9. Ochanomizu</td>
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<td>50years ago</td>
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Table 4: Transition in spring use at or near shrines and temples starting 100 years ago

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<th>1. Small Park</th>
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<th>50years ago</th>
<th>Now</th>
<th>6. Meisei</th>
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<td>Disaster prevention use</td>
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<tr>
<td>11. Sinnyou</td>
<td>100years ago</td>
<td>50years ago</td>
<td>Now</td>
<td>17. Togyokusen</td>
<td>100years ago</td>
<td>50years ago</td>
<td>Now</td>
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<tr>
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<td>50years ago</td>
<td>Now</td>
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<td>100years ago</td>
<td>50years ago</td>
<td>Now</td>
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Looking for new futures for the springs in the Japanese city of Mito

Finally, transformations in the uses of spring water installations were also described. Table 5 shows human behaviour in open spaces at spring installations. Daily life use and agricultural use has declined at many spring locations, while hydrophilic use has been amplified by certain installations. In some cases, the local authority built installations at developing parks, or the local community built the installations themselves. In the latter case, the spring water location was recognized as a common property of the community. Installations were made at various levels, such as the development of local communities, city park development, or the development of temple precincts. Springs located within temple precincts, as neighborhood installations, have multilateral uses for faith, environmental education, and disaster prevention. Based on my survey, the fact that these are much biotope in hydrophilic parks was suggested. Since biotope with a natural spring water is to tell the truth to people, it is very effective for environmental education. Otherwise, when residents carry out disaster prevention activities in the

<table>
<thead>
<tr>
<th>Installation</th>
<th>Neighbor Shrine and Temple</th>
<th>Daily life use</th>
<th>Agricultural use</th>
<th>Hydrophilic use</th>
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Table 5: Human behaviour in open spaces at spring installations
region, residents can confirm an importance and location of springs by using the actual spring. Thus, in the central city, springs without installations are not beautiful natural landscapes due to pollution and poor water quality, and so management of the environment is needed, such as by cleaning up unwanted dust and other unsanitary conditions. In additional, a project to regenerate springs as a healing source should be carried out, which has become less in recent years. Reconstruction of springs along with healing is required in useful during daily life and emergency

5. Conclusion

Where residents share the spring water as common property, field installations have been constructed. Specifically, local communities have been centralized around everyday involvement at spring locations. There were differences in the transformation and location of exploitative spring functions and history. Where spring water locations are integrated into temple functions, special installations have been constructed. Through regular ritualistic festivals and worship, they became a base for local communities. Spring water has a wide variety of available uses for daily life, agriculture, hydrophilic use, faith, disaster prevention, education, and more.

In the past, spring water was used for drinking, washing, and fighting fire. Spring water close to farmlands was used for agriculture. However, in recent years, water quality has degraded, and it can no longer be used as drinking water. Therefore, parks with hydrophilic water have recently been constructed. Springs near shrines are sacred places for gods of water to cleanse themselves. In addition, some spring water has been used for environmental education and disaster prevention training.

Based on the above findings, the local community and the local authority should collaborate to develop installations at spring locations. At the same time, they should encourage diversified spring water uses, and cross-promote in order to use this diversity, specifically to develop foot-traffic networks and event programming at springs. They should work towards hydrophilic uses that include developing a promenade, furthering faith and local culture, and promoting complex uses for experience and environmental learning. In addition, disaster drills using spring water should be implemented. Processing methods necessary for using spring water in daily life should also be developed. It is important to assemble diversified uses. Specifically, it should be important for us to consider the active use of spring water and waterfronts in order to promote the use of springs for multiple purposes.

Acknowledgements

Thank you to the local residents and the local authority for their cooperation in this study.

References

Roy Mann (1973) Rivers in the City. New York: Praeger Publisher.
Management of business activities along streets; an often neglected aspect of urban design

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lesanmary@gmail.com, morten.gjerde@vuw.ac.nz

Abstract: Amongst researchers, urban designers and city managers there is increasing interest in how streets can support social activities. Throughout history, streets have been much more than channels for moving about the city, they have also been places for social intercourse. Street-based social activities are stimulated by relationships that exist between a street’s physical characteristics, the land use activities that take place there and how these two factors are managed over time. Streets are different from other forms of public open space (such as parks) in that they support commercial and retail activities. The paper discusses the importance of business management, arguing that retail activities make important contributions to the perceptual qualities of the street which in turn can make them more successful. The extent to which footpaths become the public domain of different ethnic and cultural groups in multicultural societies also depends greatly on the characteristics of the privately owned businesses along the street. But which business activities encourage cultural diversity in multicultural settings? To answer this question, the paper examines one street in each of three socially and ethnically diverse New Zealand communities. The findings are then considered in relation to the way shopping centres are managed. The case is made for stronger management strategies for the land use activities that line public streets in order for them to remain vital to a range of ethnic cultures. Shopping centres, on the other hand, appear to be stuck in formulaic tenancy mix practices and could benefit by adopting practices that are responsive to local social and cultural characteristics.

Keywords: Streets; cultural diversity; tenant management.

1. Introduction

Public spaces provide opportunities for a wide range of functional, social and leisure activities and the most important type of public space, arguably, is the street. Throughout the world the majority of public life is acted out on streets (Mehta, 2013). Social interpreters and scholars suggest that people’s lasting images of a city are of its streets.

Think of a city and what comes to mind? Its streets, if a city’s streets look interesting, the city looks interesting, if they look dull, the city looks dull (J. Jacobs, 1961, p. 29).
Little wonder then that streets are the domain of interest for urban planners and designers. However, some scholars lament the tendency for streets to be primarily conceived of as movement channels at the expense of how they can function as social spaces (A. Jacobs, 1993; J. Jacobs, 1961). Streets have traditionally catered to a broad array of activities including walking, cycling and standing. Streets in multicultural societies are also where people from different ethnic backgrounds find opportunities to interact in space and time. As cities become more multicultural, the challenge is to design spaces that appeal to the breadth of cultures that are represented in the population. A challenge for planners and urban designers then is to manage public spaces that will appeal to people of different social and cultural backgrounds. But what are the qualities of streets that will help ensure that it will appeal to people having different backgrounds? Urban planners and designers have recognized that;

“... It remains difficult to isolate physical features from social and economic activities that bring value to our experiences...” (A. Jacobs, 1993, p. 270).

Social activities in streets spring from the interrelationship between land use activities, businesses, the physical elements of the streets, and planning and design strategies that manage all of these in the street space (Mehta, 2013). Some studies of streetscape quality have looked at the physical characteristics of the setting, but in isolation of the uses and management of the businesses that line the streets. See for example Hass-Klau et al. (1999). Even when studies have looked at both, they have tended to focus on the design and management of the public space, owned by councils and public organizations. Other studies have examined retail and commercial development according to land use and zoning policies, but the relative potential for the business activities to stimulate and sustain social activity along streets in a multicultural society has not yet been studied (Lesan, 2015). The present research aims to understand how business activities could help streets to become more or less multicultural.

2. Open-endedness

The term open-endedness, a spatial characteristic that provides for adaptability and flexibility, was first coined by Amos Rapoport (1990) in relation to residential environments. Adaptability relates to the possibility of a space to accommodate different uses without significant changes to the physical characteristics of an environment. Flexibility refers to a space that accommodates different uses and activities by being open to changes (Fernando, 2006).

In her examination of streets in different cultural contexts, Fernando (2006) found open-endedness to be a key characteristic that could encourage a diversity of land uses to flourish. Her research demonstrated that urban streets in different cultural environments could enrich public life by their open-endedness. Open-endedness can allow ethnic based commercial activities to shape the appearance of ethnic shopping strips, with New York’s Chinatown offered as an example of this. Open-ended streets are those that enable footpaths to adapt and change to a wide range of activities and uses without affecting the general appearance of streets and their architectural characteristics. Open-endedness allows for the associated physical features of the footpaths to be easily arranged or rearranged.

In this manner, ethnic based business activities can shape the appearance of commercial strips such that they reflect their dominant ethnic clients. These ethnic enclaves play an important role for immigrants and become places where they could participate in a rich and diverse social life (Mazumdar, Mazumdar, Docuyanan, & McLaughlin, 2000). Furthermore, open-endedness allows street’s land-use
activities to be tenanted by different types of businesses and tenants and therefore offers numerous possible business agglomerations along streets. The latter definition of open-endedness is used in the current study.

While Fernando described open-endedness in terms of ethnic enclaves and streets in their original geographical locations, she did not discuss its specific usefulness for analysing streets in multicultural environments. There are many culturally mixed urban centres around the world as cities are getting more diverse and multicultural and this certainly confirms the relevance of understanding how the public space network of these places can each be made to function more democratically. While there is evidence to suggest that many New Zealanders of similar cultural backgrounds choose to live in the same urban areas (Poulsen, Johnston, & Forrest, 2000) there is nothing to suggest that these areas develop into cultural ghettos or enclaves. One key factor that helps ensure this does not happen is that these neighbourhoods almost always include significant numbers of people of at least one other ethnic background. The present study was conducted in order to understand the effect of open-endedness in New Zealand’s multi-cultural society (Lesan, 2015).

3. Methodology

Three streets in socially and ethnically diverse communities around New Zealand were examined using a multiple issue-based case study method (Francis, 2001; Francis & Griffith, 2011). The case study selection process employed census data on the demographic characteristics of a wide range of districts and neighbourhoods around two main cities in New Zealand (Auckland and Wellington). The first case was that of Newtown; a neighbourhood where Europeans are the dominant cultural group. The second case was chosen in Papatoetoe; a neighbourhood with a balance of all ethnic groups. The third case was selected in Otahuhu; a district where is dominated by non-Europeans (Pacific Islanders).

Each street has a different business agglomeration. The number of businesses, their type (services, eating, fashion), and the variety of each type were used to measure the diversity of business activities in each case study. Riddiford Street is a traditional main street located in the Newtown neighbourhood of Wellington. The commercial heart of Riddiford Street is comprised of independent, small, unique stores. The street contains a variety of shops, cafes, eating places, services, second-hand and affordable shops, and an international chain restaurant. St George Street is one of the two main business areas in the Papatoetoe area of South Auckland. The street consists of two fruit shops, a number of takeaways, bakeries, barbers, a pharmacy, second-hand and flat-rate (dollar) shops, liquor shops, dairies, real estates and a chocolate shop. With the predominance of Asian flat-rate shops, takeaways and liquor shops, St George Street lacks the diversity of retail activities seen in Riddiford Street. Great South Road is a popular shopping destination in the Otahuhu neighbourhood of South Auckland. Business agglomeration of the street targets ethnic populations such as Pacific Islanders and Asians (Indians).

A mixed-methods qualitative approach consisting of behavioural mapping and on-street user semi-structured interviews formed the basis of the research. Data were collected on both weekdays and weekends between March and April 2013 and a sample of 30 or less users of each street were interviewed. The mixed-methods approach of the study helped to explore different behaviours and activities on the street, perceptions of users, their motivations for using the street for leisure and social activities, and their expectations and specific cultural needs in the street.

The extent that a neighbourhood commercial street is inclusive could be measured and understood by the type and range of activities and the actors that it supports (Mehta, 2014). The percentages of
each ethnic group participating in stationary, static and social activities and compared with the percentages of each ethnic group residing in a neighbourhood and the range of activities (necessary, optional, and social) of each ethnic group will be used in order to measure how each street served different ethnic groups (Figure 1).

4. The importance of land use activities in streets as public spaces

The findings reveal that retail activities are the main concern of people in multi-cultural streets. In each of the streets, participants’ responded to questions about business activities with more certainty and clarity than they did to other attributes. The case studies revealed that the retail tenant mix and the diversity of shops offering goods and services on the street are the main reason people are attracted to use the footpaths (Teller, 2008). Keeping the current diversity and even adding more diversity to the business activities of each street were among the recommendations made by people from different cultural backgrounds to the question of how streets could become better. The lack of diversity among business activities in St George Street generated concern amongst the participants and subsequent analysis comparing the business activities to the other two cases confirmed this perception. Multiple two-dollar shops and similar takeaway businesses began to create a monotonous image; the similarity between the shops and eating places along St George Street had led to complaints about the quality and attractiveness of the area to some shoppers and reduced the levels of window shopping (Lesan & Gjerde, 2014).

Again, when participants were asked about the important spaces for their ethnic social and leisure activities most of them referred to businesses. The responses confirm the important role of businesses in stimulating static and social activities and a majority of those responses were linked to the provision of ethnic cultural shops and restaurants. Asians and Pacific Islanders stressed the importance of ethnic restaurants for their social activities. A part of the Asian cultural group is Muslim and the provision of Halal eating places played an important role for their leisure activities. Maori and Pacific Islanders were greatly observed in relation to takeaways and fast-food restaurants. Cafes could be understood as a cultural eating place related to the European culture as many European we observed in front of cafes. Furthermore, participants mentioned the importance of cafes for their ethnic group social activities.

Thus, having a range of food shops catering to different tastes would be an important factor that increases diversity in the area and could attract people from different ethnicities. The case studies suggest that while each business along the streets could attract specific or a mixture of ethnic backgrounds, the business agglomeration has the major effect of making streets multicultural.

Different types of business and tenant management along streets and the ways in which they relate to one another attracted different responses from each of the ethnic populations studied. This ethnographic study demonstrated clearly that streets, depending on what they have on offer, could have a significant role as a social space among different ethnic cultures. In each case study the types of businesses and tenant assortment were only able to create interest among a specific range of cultures and socio-economic groups. The ways in which each street was used by different ethnic cultures were mainly dependent on the mix of its business activities and retailers.

Different types of businesses and tenant management might create familiar environments and provide settings for people of specific ethnic backgrounds to frequent streets for static and social activities or exclude them from using the space. The fewer shops and premises comprising daily services, fashion shops and food establishments convey meanings for specific cultures, the fewer the people of that culture frequent the street for static, leisure and social activities. On the other hand, if
the range of different businesses relating to specific ethnic cultures on the street widens, the chances of leisure and social activities increase among the members of that culture. None of the streets studied completely related to a specific culture. The mix and percentages of ethnic groups in each case study were different.

Riddiford Street attracted diverse cultures by the number of services such as supermarkets, banks, fruit shops and ethnic stores. The diverse range of food establishments from affordable takeaways to more pricy and upscale ethnic restaurant generated interest among all different cultures. The type of fashion and household items, also attracted great numbers of Europeans and Asians compared to Māori/Pacific Islanders. The overall composition of businesses that encourage lingering was perceived less affordable among these groups. St George Street and Great South Road on the other hand, attracted greater numbers of Māori/Pacific Islanders and Asians. The tenant assortment comprising services, Asian flat-rate fashion/household shops and takeaways attracted great numbers of these groups to the street.
Europeans were observed in smaller percentages in these case studies. Europeans mostly came to St George Street by themselves and their activities mainly occurred in relation to different daily services. The flat-rate type of fashion shops and Asian takeaways did not generate interest among Europeans. Nor were they observed sitting nor did they make positive reference to the atmosphere of the street. Together this suggests that St George Street is not perceived as a place for social/leisure activities by Europeans. Great South Road comprises a number of Asian fashion/household item shops that overwhelm the narrow range of services and food establishments. The types of business assortment did not attract many Europeans to the footpaths and they were mostly only observed at the bar. While the bar became a place for social encounter among Europeans, it did not encourage them to stroll up and down the street to contribute to a multi-cultural character. Different aspects ranging from the type and quality of businesses, the social structure of businesspeople, and the management of the shop frontages among other possible reasons might have created an unfamiliar setting for Europeans and thus decreased their desire to use the space in Great South Road. It is important to note that the same type of premises might also function, act or communicate differently in various settings. Mazumdar et al (2000) describe how a similar coffee shop might function differently in a traditional environment to an American mall. Having a limited number of businesses offering familiar goods and services might not make enough interest in attracting specific cultures to streets. Instead, the tenant mixture is an important factor to attract different cultures to a place. Thus, the variety of businesses and tenancy mixture of retail activities, such as cafés, fruit and grocery stores, takeaways and bakeries, ethnic premises, and their associated characteristics, could provide the means for the static and social activities of different ethnic groups.
Unlike ethnic enclaves, in which the familiar is created in an unfamiliar setting through a range of familiar retail and business activities (Mazumdar et al., 2000), in multicultural streets the familiar and unfamiliar together shape the environment. The businesses, elements and characteristics that are familiar for one culture might be unfamiliar for the others. If business activities along the street create an exotic and non-familiar image for ethnic cultures, it is less likely to be used as a place for recreation. The findings of this study suggest that retail and tenant management could create environments where visitors and shoppers of various backgrounds feel a sense of belonging and identification and reinforce their social bonds.

Retailing is recognised as an important factor in the cultural, economic and public life of the city (Goodman & Coiacetto, 2012). Business activities and commerce such as various services, culinary, fashion and delicatessens greatly influence street life and could be understood as the very basic condition of the foundation of streets. Cultural diversity on streets would be most effectively achieved through strong management strategies of the business, retail activities and services and their associated characteristics rather than the aesthetic characteristics of the design elements. The most common suggestion for all case studies is to retain the existing variety of uses and services and simply add more. This confirms the importance of a pluralistic approach towards land-use planning and inclusionary retail activity controls on commercial streets in multi-cultural contexts. Planning could guarantee a mix of businesses that target a diverse range of cultures and others that serve to specific ethnic groups. As Preston and Lo argue:

“Planning at the neighbourhood level should ensure a mix of retail activities, some serving a diverse clientele and others that cater to specific ethno-cultural groups” (2009, p. 73).

Scholars define public space as a space that is not organised by private individuals or organisations, and is therefore open to the public (Madanipour, 1996). Findings of this comparison suggest that streets are public spaces of a city in which the socio-cultural backgrounds of the users are mainly influenced by the businesses, retail activities and services (private property). In other words, the extent that footpaths become public or a common property of different ethnic and cultural groups greatly depends on the context of the privately owned businesses along the street. Shopping can be an important stimulus to cultural diversity of streets in the city. Having a right mixture of land-use activities on the street that supports a wide range of necessary, optional and social activities for different cultural groups is critical for streets to become more public. Thus, it is important to note that promoting cultural diversity on streets could happen in the collective action of both public and private sectors.

Land-use activities and businesses have the potential to draw people from different ethno-cultural backgrounds to streets and therefore create opportunities for social interactions. However, open-endedness itself cannot be depended upon to create streets that are more public and multicultural. This condition could lead to mono-cultural spaces that exclude members of other cultures. While it is important that retail activities along the street allow a wide range of choice, including on social and cultural grounds, it can be difficult to achieve this in reality. Streets usually lack a defined and determined management concept in terms of their tenant retail activities and store assortment and tenant mix in streets is usually not controlled (Teller, 2008). While higher level planning of retail and other activities on the streets could provide for social and cultural diversity as well as reinforce the image of the city, the free marketplace does not allow for this. Individual owners make their own decisions and business plans based mainly on economic factors. While the concept of siting new businesses along the street might be carefully considered, they do not necessarily help create more
ethnic diversity. For example; the economic viability of the retail units on shopping strips as multi-owned properties, is related to individual owners and operators who must ensure that they choose the type of business to safeguard their financial return and minimise the risk of their investment. In many cases the provision of retail activities is linked to the economic profile of the district. An emphasis on affordability to attract customers in areas with low income levels could put off members of other socioeconomic groups.

5. Learning from shopping centres

Shopping centres are at the other end of the spectrum from public streets when it comes to how their retailing activities are managed. Shopping centres have a strong organisational discipline (managed by a specialised organisation) and vigilant tenant management where many retail units are managed as a single property in order to succeed in today’s competitive market (Laniado, 2005; Pitt & Musa, 2009). What are the implications for streets in multi-cultural settings? Is the strong tenant management of shopping malls able to help streets become more multi-cultural and diverse?

The quality of management of shopping centres including tenant mixture is considered as one of the crucial factors that affects their success (Morgan & Walker, 1988). Tenant mix in shopping centres refers to the arrangement and combination of different retailers that occupy a space in the shopping centre in order to function successfully as individual units and optimise the centre’s performance. In this vein, the managers develop an operative business model for tenant location, tenant selection and the structure of lease contracts. Retailers in shopping centres usually include a fairly standard range of tenants such as department stores, supermarkets, apparel stores, and leisure amenities (Pitt & Musa, 2009). However, tenant mix in shopping centres is investor-oriented; in other words, the assemblage is shaped around the ultimate goal of creating value and maximising the centre’s profitability through the optimum services they provide to the community (Latham, 2003; Pitt & Musa, 2009). Thus, they often accommodate those with sufficient funds and lead to the exclusion of non-consumption public (Lloyd & Auld, 2003; Shaftoe, 2009). Furthermore, the existing regulations and management priorities in privately owned public spaces sort and filter users according to predetermined appropriateness of behaviours and use (Davis, 1992; Ne’meth, 2012). Thus, the development of such privatised spaces such does not coincide with the concepts of inclusion and democracy (Kohn, 2004; Németh, 2009; Nemeth & Schmidt, 2011).

Internationally, some shopping centres and malls have shown signs of weakness and have failed or are in the process of failing (Laniado, 2005; Southworth, 2005). “People are facing a mall saturation or mall fatigue” (Southworth, 2005, p. 152). There are different reasons that have made patrons become less attracted to shopping malls. In this vein, many of the malls are losing their demand and attractiveness among customers due to the same formula they are using; similar department stores, same national chains, similar layout and brands, and parallel architectural themes (Laniado, 2005). On the other hand, traditional main streets are finding more popularity compared to malls. People want to spend time in places that have street life, sense of place and community. Therefore, there is now a new movement that tries to move away from large isolated regional malls towards inspiring from downtown centres and street life. In this regard, many mall owners are transferring their malls into place-making projects and naming their projects lifestyle centres, and townscape malls (Laniado, 2005; Southworth, 2005). Similarly, streets have been also influenced by shopping malls by using strategies such as removing or reducing vehicular traffic, integrating parking, adding pedestrian amenities, and creating themes, such as Fremont Street; the old main shopping strip in Las Vegas (Southworth, 2005).
Management of business activities along streets; an often neglected aspect of urban design

Figure 3: Botany Centre in Auckland. Unlike streets, shopping centres use strong and vigilant tenant management techniques

While streets and shopping centres are learning from each other to become more successful, streets should also learn much from these centres to become more public and multicultural. It is time to look at streets with a new lenses that combines quality aspects of streets and malls. In this regard, streets should take business agglomeration as a challenge in order to improve cultural inclusion and street life as well as ensuring profit and economic viability for individual businesses.

6. Conclusion

Neither of the approaches (open-endedness vs. non-flexible business management strategies) are able to support a mixed-life and successful street alone. While there are merits in each of these approaches, mixed life, diverse streets could benefit of amalgamation of management of business agglomeration and open-endedness at the same time. This would include an “anti-formula” business agglomeration that supports cultural differences and assists different small individual ethnic shops to develop. In other words, while general rules and regulations manage business activities and their agglomeration that along streets, they should stay away from certain strict formulas and also encourage levels of adaptability and flexibility. For example; while having higher levels of rules and regulations, it is important to encourage retailers to customize their shop fronts and allow for differences. This would allow businesses to change over time and let tenants put their own stamp on these environments. Therefore, each of these streets would create a distinguishing identity and recognizable image.

Cultural diversity along streets will be achieved more effectively through strong management strategies for the business and retail activities. The management of business activities along street is a neglected aspect of urban design and has been under-addressed by municipality planners and policy makers. Urban planners, designers and landscape architects can learn from the new generation of malls (lifestyle centres) in order to create the right mixture of retailers on streets where Street management encourages and motivates possible tenants which would enrich the retail portfolio of the street in order to make streets become more public and multicultural. Further research could investigate whether the right tenant mix along streets in multi-cultural societies helps create a familiar setting and shapes a sense of place for people of various backgrounds. In other words, how could retail activity controls on commercial streets lead towards cultural inclusion? remains an open question.
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Urban growth and pedestrian thermal comfort

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Abstract: Melbourne is the second largest city in Australia, and its population is anticipated to reach 6.5 million by 2050. In October 2013, Plan Melbourne was released by Victorian government, aiming to intensify several districts to protect the suburbs from urban sprawl. The City of Melbourne’s draft municipal strategic statement identified City North as a great urban renewal area which can accommodate a significant part of the growth. Given the previous heat-related incidence in Melbourne in 2009, the potential threat to human health and pedestrian comfort will be exacerbated, if planning professionals exclude climatic conscious urban design in their practices. Therefore, this study aims to investigate the effect of the future structural plans on the microclimate and pedestrian thermal comfort in City North through numerical simulations. A three dimensional numerical modelling system, ENVI-met was used for the simulation. Field measurements were conducted across the study area to validate the simulated outputs. A clear reduction was reported in the average daytime mean radiant temperature, surface temperature and PMV values after implementing “Plan Melbourne” strategies. The outcomes of this study will assist urban planners in developing the policies which can effectively decrease the vulnerability to the heat stress at pedestrian level.

Keywords: Urban growth; urban design; pedestrian thermal comfort.

1. Introduction

There has been a drastic increase in the world population in recent years. New megacities are born, and current megacities become more populated (United Nations, 2014). The task of urban designers in accommodating increasing number of world population in urban areas, which cover only 3% of the world’s land surface is very challenging, especially if the aim is to consider sustainability in the design process. Furthermore, urban climatic considerations are usually reported being neglected in the process of urban design, due to the lack of interdisciplinary works and constraints in transferring this knowledge into urban planning practices (Arnfield, 1990; Kleerekoper et al., 2012). This exclusion has resulted in the rise of the most thoroughly documented human modification of climate in the atmospheric science, known as urban heat island (Oke, 1982).

Increased air and surface temperatures trigger heat-related diseases in cities, increase cooling energy demand and worsen pedestrian thermal comfort (Moonen et al., 2012; Tapper, 2012). A study
conducted by IPCC (2011), indicate that the average temperature rise caused by urbanization will be greater than the temperature rise due to global climate change over the next 100 years. According to Victorian department of sustainability and environment, four days heat wave in Melbourne in January resulted in 374 excess deaths, mainly among vulnerable groups of people such as elders and children. This, highlights the significant role of urban design and urban planning in decreasing the pedestrian thermal discomfort, particularly during the heat waves.

Rapid urbanization modify the outdoor thermal environment. Human thermal comfort is defined as the condition of the mind in which satisfaction is expressed as thermal comfort. Study of Hoppe (2002), shows that the satisfaction is achievable when there is a balance between the heat flow from and to the body (Höppe, 2002). The factors influencing the individual’s outdoor thermal comfort are known to be the interaction of the air temperature, mean radiant temperature, relative humidity, and wind speed. Additionally, personal parameters such as metabolism rate and thermal insulation value of the clothing affect the thermal comfort.

The air temperature is the temperature of the air surrounding the human body. Some of the scholars found that the effect of air temperature alone on pedestrian thermal comfort is insignificant (Matzarakis and Endler, 2010). Mean radiant temperature indicates the level of radiant temperature received by human body. The radiation includes all the radiative fluxes (direct, diffuse, reflected solar radiation and longwave emissions from the surfaces. Radiation is very important in comfort studies, particularly in outdoor environments. The reason is that there is a substantial level of radiation in outdoor environment which affect the thermoregulatory system of human body (Kenny et al., 2009). Relative humidity defines the ability of an individual to lose heat via evaporation (sweat). Wind speed and direction are important factor in dissipating the heat via convection. Metabolic heat influences the comfort level, as each individual gains different level of heat via different activities. The thermal insulation of clothing defines the thermal resistance between the human body and environment.

The relationship between urban design parameters and pedestrian thermal comfort has been the subject of many studies (Golany, 1996; Sanaieian et al., 2014). Some of these studies examined the influence of city design on wind flow and reported the effective role of ventilation in mitigating the high urban air temperatures and improving thermal comfort (Oke, 1982; Kim and Baik, 2005). The other studies focused on the effect of urban design strategies on the magnitude of received solar radiation and its outcome on pedestrian thermal comfort (Santamouris, 2013).

Australia is one of the highly urbanized nations in the world, as 75 to 82 % of its population live in urban areas (Australian Bureau of Statistics, 2011). Melbourne is the second largest city in Australia. The population of Melbourne is projected to grow by at least 25% in the next ten years to reach to 6.5 million by 2050. Melbourne has undergone a tremendous transformation during the last two decades, both through city-centre regeneration and outer-suburban developments. Nowadays, the city is experiencing a rapid development mainly in its central area. To outline the vision for Melbourne’s growth to the year 2050, “Plan Melbourne”, was released in October 2013, by Victorian government. This study aims to examine the impacts of future structural plans on microclimate and pedestrian thermal comfort.

**1.1. Plan Melbourn aims and objectives**

One of the principles of “Plan Melbourne” is the idea of “An Expanded Central City”. Melbourne’s central city will become Australia’s largest business and residential centre by 2050. The existing central city comprising the CBD and Docklands will be expanded to include City North.
The existing built form in City North is predominantly a low-mid scale. This, includes dwellings, institutional buildings, offices and other uses. Structure plans provide guidance to the community, planners, business, government and developers about the appropriate directions and opportunities for future changes. According to the structure plans, this area will be developed to provide a diverse mix of uses associated with more dense urban environments. Proposing various street typologies, expanding urban forest by increasing the canopy coverage and transition from low-rise to medium rise urban area are some of the strategies presented in “Plan Melbourne”. Figure 1 shows a potential future built form in City North according to the structural plans. Future development of this area without considering its microclimatic consequences may result in adverse impacts on the climate of the city and pedestrian thermal comfort. Additionally heat island effect is exacerbated by urban consolidation and rapid urban developments. But, promoting holistic urban design and planning policies would significantly mitigate the adverse impacts of urbanization on climate of the cities and public health. Therefore it is highly important to investigate the possible future consequences of “Expanded Central City” on microclimate and outdoor human thermal comfort. Because, thoughtful design of future structural plans would significantly change the thermal environment, manipulate microclimate through alterations in the surface energy balance and avoid extreme events such as heat waves.

![Figure 1: Potential future built form in City North (Source: www.melbourne.vic.gov.au).](image)

2. Methodology

This study aims to investigate the effect of future structure plans at a neighbourhood scale. Therefore, field measurement alone was not enough to answer the research questions at this size. On the other hand, assessment of the outdoor pedestrian thermal comfort is a very challenging task, due to the complex interactions between the built environment, vegetation, and atmosphere. ENVI-met (V3.1, Beta 4) is selected as an appropriate tool to investigate the effect of various urban design strategies on microclimate and pedestrian thermal comfort. ENVI-met is a three-dimensional microclimate model that simulates the interaction between surfaces, plants and air in an urban environment with a typical resolution of 0.5 -10 meter in space and 10 seconds in time. Simulations are at least for 24 hours, but to achieve more accurate results, it is recommended to run the simulations for 48 hours (Bruse, 2010). The original model is summarized in (Ali-Toudert, 2005).
ENVI-met is chosen in this study, because it is the most comprehensive model in regards to the calculation of outdoor thermal comfort. Furthermore, the outputs of ENVI-met include four main parameters that affect the human thermal comfort; air temperature, mean radiant temperature ($T_{\text{mrt}}$), wind speed and relative humidity.

The underlying equations for the physical model has roots in a) temperature and humidity, b) mean air flow, c) turbulence and exchange process and d) radiative fluxes. The calculations of temperature, humidity, turbulence and exchange processes are explained by Bruse and Fleer (Bruse and Fleer, 1998). ENVI-met has all the algorithms of a CFD, such as Navier-Stokes equations for the air movement, E-e for atmospheric flow turbulence equations, energy and momentum equations and boundary condition parameters. The advantage of ENVI-met over CFD, is that ENVI-met dedicates a special numerical model for the soil, plant, surface and the air and calculates the interactions among these parameters. Additionally, ENVI-met is capable of predicting the outdoor thermal comfort, via meteorological inputs as well as human biometeorology factors. Calculation of short-wave radiation in ENVI-met is conducted via the sky view factors in the urban canyons, the albedo of urban surfaces and the leaf area index of the vegetation in the area input file. Long-wave radiation is calculated by taking the wall’s horizontal long-wave emissions into account. These emissions can be either coming from the ground or from the sky. Calculation of surface temperature is conducted via the balance of all net-wave radiation and heat fluxes from both hemispheres. Further details about the equations and architecture of ENVI-met model are presented in (Ali-Toudert, 2005).

Figure 2 illustrates a schematic layout of ENVI-met model. The model consists of several sub-models. The main 3D model that which consist of grid cells is developed to create buildings and vegetation. The size of the grid cell depends on the size of the area input file and required resolution for the output parameters. The main model starts from the ground level to a height of at least twice the maximum building height in the domain. The air movement around the building is also calculated in this model.

Second is a 1D model that is located above the main module and it creates a boundary condition, which extends to a height of 2500 meter (Wania et al., 2012). Third is a 2D soil model which is located below the main module, and it goes 2 meter below the ground level. The main task of this model is to calculate the heat and moisture transfer in the soil. In order to achieve a numerical stability, there are some lateral borders around the main model which are known as “nesting grids”.

In ENVI-met, the soil is modelled in detail. The thickness of the soil layer increases by moving from the ground to the deeper parts of the ground. Each grid cell has a soil profile which is characterized by its thermal and moisture properties.

In ENVI-met vegetation are characterized by their leaf area density (LAD), i.e. the total one-sided leaf area ($m^2$) per unit layer volume ($m^3$) in each horizontal layer of the tree crown. The (LAD) for a specific plant is a total of the ten LAD in different horizontal layers. In contrast with the soil and vegetation models, building model is greatly simplified in ENVI-met. Because buildings are characterized only by the albedo and thermal transmittance (U value). Furthermore, same values are applied to all the walls and roofs.

The vegetation model is formed on a 1D column with a height of $z_p$. The distribution and the amount of the leaves in a tree is presented in its leaf area density (LAD) profile (Bruse, 2014). The plants are also defined by their root area density (RAD). RAD, begins from the surface and it goes below the root depth. The soil model, is a one D model with three layers, with three different layers (0- 20 cm, 20-45 cm, and 45-175 cm). The type of the soil can be different at each level. ENVI-met package has some default plant and soil database. However, the unique characteristics of Melbourne’s vegetation are not
listed in the package. Measuring and calculating the leaf area index, foliage feature of the plants and soil characteristics are not included in this study. Therefore the default trees are customized according to the characteristics of the trees in the study area (the alteration was made on the height of the trees).

\[\text{Figure 2: Basic layout of ENVI-met (Source: www.model.envi-met.com).}\]

2.1. Simulation and verification with field measurements

In majority of studies using ENVI-met, some minor or major modifications were made to the inputs or boundary conditions of the model, to increase the accuracy of the model. In this study, seven points are selected to conduct a validation assessment for the air temperature and relative humidity.

\[\text{Figure 3: Locations of the selected points for the field measurement (source: www.au.nearmap.com).}\]

The measurement points are located in seven urban canyons that differ from each other, in terms of the orientation, aspect ratio, surface material and proximity to the vegetation. Figure 3 shows the boundary of the selected area in City North and indicates the location of the measurement points. The characteristic of each measurement point is listed in Table 1.
Table 4: Descriptions of different measurement points.

<table>
<thead>
<tr>
<th>Point</th>
<th>Description</th>
<th>SVF</th>
<th>Pavement</th>
<th>H/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Open space</td>
<td>0.9</td>
<td>Asphalt</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Under the tree canopy in an urban park</td>
<td>0.26</td>
<td>Grass</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Est-west canyon</td>
<td>0.5</td>
<td>Asphalt</td>
<td>0.4</td>
</tr>
<tr>
<td>4</td>
<td>NW-SE canyon</td>
<td>0.4</td>
<td>Grass</td>
<td>0.8</td>
</tr>
<tr>
<td>5</td>
<td>NW-SE canyon</td>
<td>0.4</td>
<td>Asphalt</td>
<td>2.7</td>
</tr>
<tr>
<td>6</td>
<td>N-S canyon</td>
<td>0.7</td>
<td>Asphalt</td>
<td>0.5</td>
</tr>
<tr>
<td>7</td>
<td>Under the tree canopy in a street</td>
<td>0.3</td>
<td>Grass</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Nikon Coolpix 5400 with Fish eye Converter FC-E9 0.2x (to capture the sky view factor image at each point), a portable weather station (located at point 1 to monitor the climatic data in an open area), HOBO data loggers (installed at points 3,4,5,6) and comfort carts (installed at points 2,7) were used to conduct field measurements in 6th and 7th January 2015 (typical hot summer days in Melbourne). The air temperature, relative humidity, wind speed and mean radiant temperature were recorded. The simulation was run with the recorded climatic data for 6th January for the validation purpose. Figure 4 illustrates the area input file with the existing buildings, vegetation pattern, pavements and shows the location of the receptors.

Figure 4: Area input file in ENVI-met and locations of the receptors.

The area input file is configured with the climatic data recorded by portable weather station at point 1. The initial air temperature, relative humidity, wind speed and direction obtained from point 1 were inserted in the configuration file. Point1 is located in an open space which is the best location to monitor the meteorological parameters of the study area. One of the limitation of the software is that the model does not allow a variation for the building envelope properties, U-values or internal temperatures for individual buildings. All the calculations in this version of ENVI-met are based on the initial inputs of the air temperature, humidity and wind speed which are kept constant during the simulation. A logarithmic law is used in calculating the wind profile, based on the wind speed at 10 meter above the ground level as well as the roughness length. Calculations of the air temperature and humidity is also based on the initial temperature, specific humidity at 2500 meter and relative humidity at 2 meter above the ground level. Therefore, hourly forcing of the data was not possible.

As discussed, plants in ENVI-met are characterized by the type of the plant according to the CO2 fixation, plant type (whether it is deciduous, conifers or grass), short wave albedo of the plant, the
height of the plant, total depth of the root zone, leaf area density and root area density for 10 different horizontal layers. According to Melbourne's urban forest visual, vegetation in the study area are categorized into Eucalyptus, Platanus (plane trees), Ulmus (Elms), Corymbia (Gums) and Quercus (Oaks). Eucalyptus and Gums are native Australian plants which are categorized as evergreen. Whereas the rest are exotic vegetation. A major constraint of the specified values for vegetation functional types and their form (shape, structure and size) is that they are broad and generalised and not specific to individual species. We modified some of the plant properties in the Plant database to make them as close as possible to the real plants. However the vegetative species within the study site were diverse and we had a limited number of plants in the plant database. Table 2 and 3 list the name of the vegetation which are employed in the area input file. The information in the configuration file is listed in Table 4.

<table>
<thead>
<tr>
<th>Street name</th>
<th>T1,ds,h,g,ds,l1,Mo,Sk,TH,</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grattan Street</td>
<td>T1,ds,h,g,ds,l1,Mo,Sk,TH,</td>
</tr>
<tr>
<td>Swanston Street</td>
<td>T1,ds,l1</td>
</tr>
<tr>
<td>University Square</td>
<td>dm,TH,A1,h</td>
</tr>
<tr>
<td>Leicester Street</td>
<td>B1,bs,T1,g,TH,h,c1,ds,T2,Mo,D1</td>
</tr>
<tr>
<td>Barry Street</td>
<td>B1, D1, h,c1, L2, TH,l1, Sk</td>
</tr>
<tr>
<td>Berekeley Street</td>
<td>L1,TH,D1,ds</td>
</tr>
<tr>
<td>Elizabeth Street</td>
<td>T2,L1,g,TH,ds</td>
</tr>
<tr>
<td>Victoria Street</td>
<td>dm, Mo, A1, TH</td>
</tr>
<tr>
<td>Queensberry Street</td>
<td>TH, dm, D1,T2, B1, C1, Sk, T1,g</td>
</tr>
<tr>
<td>O'connel Street</td>
<td>ds,D1,Mo</td>
</tr>
<tr>
<td>Peel street</td>
<td>TH, L1,D1</td>
</tr>
<tr>
<td>Pelham Street</td>
<td>B1, ds</td>
</tr>
</tbody>
</table>

Table 3: List of the plants used in the simulation.

<table>
<thead>
<tr>
<th>Plant’s name in ENVI-met</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>Tree 10 m very dense, leafless base</td>
</tr>
<tr>
<td>ds</td>
<td>10 m dense, distinct crown layer</td>
</tr>
<tr>
<td>DM</td>
<td>20 m dense., distinct crown layer</td>
</tr>
<tr>
<td>dm</td>
<td>Tree 20 m dense., distinct crown layer</td>
</tr>
<tr>
<td>A1</td>
<td>Tree, light 10 m</td>
</tr>
<tr>
<td>B1</td>
<td>Tree 3m dense, distinct crown layer</td>
</tr>
<tr>
<td>C1</td>
<td>Tree 3 m very dense, leafless base</td>
</tr>
<tr>
<td>D1</td>
<td>Tree, light 3 m</td>
</tr>
<tr>
<td>TH</td>
<td>Tree 15m dense, distinct crown layer</td>
</tr>
<tr>
<td>L2</td>
<td>Tree, light 20 m</td>
</tr>
<tr>
<td>L1</td>
<td>Tree, light 15 m</td>
</tr>
<tr>
<td>Mo</td>
<td>Tree 20m aver. dense., no distinct crown layer</td>
</tr>
<tr>
<td>T2</td>
<td>Tree 15 m very dense, leafless base</td>
</tr>
<tr>
<td>SK</td>
<td>Tree 15 m very dense, distinct crown layer</td>
</tr>
<tr>
<td>bs</td>
<td>Tree 20 m dense, distinct crown layer</td>
</tr>
<tr>
<td>g</td>
<td>Grass 50 cm aver. dense</td>
</tr>
<tr>
<td>h</td>
<td>Hedge dense, 2m</td>
</tr>
</tbody>
</table>
Table 4: Initial set up for the configuration file.

<table>
<thead>
<tr>
<th>Input</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start simulation</td>
<td>12 am (6.1.15)- 12 am (8.1.2015)</td>
</tr>
<tr>
<td>Total simulation time</td>
<td>48 hours</td>
</tr>
<tr>
<td>Save mmode state</td>
<td>60 min</td>
</tr>
<tr>
<td>Wind speed in 10 m a.b ground</td>
<td>1.7 m/s</td>
</tr>
<tr>
<td>Wind direction</td>
<td>171</td>
</tr>
<tr>
<td>Roughtness lenght</td>
<td>0.1</td>
</tr>
<tr>
<td>Initial temperature atmosphere</td>
<td>297K (24 C)</td>
</tr>
<tr>
<td>Specific humidity in 2500 meter above ground level</td>
<td>9.5</td>
</tr>
<tr>
<td>Relative humidity in 2 m</td>
<td>57%</td>
</tr>
<tr>
<td>Building’s inside temperature</td>
<td>19.85 C</td>
</tr>
<tr>
<td>Heat transmission of the walls</td>
<td>1.94</td>
</tr>
<tr>
<td>Heat transmission of the roofs</td>
<td>6</td>
</tr>
<tr>
<td>Albedo walls</td>
<td>0.2</td>
</tr>
<tr>
<td>Albedo roofs</td>
<td>0.3</td>
</tr>
<tr>
<td>Factor of shortwave radiation</td>
<td>1</td>
</tr>
</tbody>
</table>

The air temperature and relative humidity are compared between the simulated outputs and measured values for the January 2015, at the selected points. Regression analysis is carried out to examine whether there is a significant discrepancy between the simulated outputs and measured values. Table 5 presents the R square values for points 1 to point 7. According to Table 5, there is an acceptable agreement between the measured and simulated values for the air temperature in the majority of the locations ($R^2 > 0.5$). The lowest level of $R^2$ is achieved at point 6, by 0.32. A plausible explanation is due to the proximity to the construction site, which is resulted in higher measured air temperature. However, there is a perceptible difference between the measured and simulated relative humidity. Therefore, series of sensitivity analysis were conducted, to improve the accuracy of the model by decreasing the difference between the simulated and recorded outputs.

Table 5: Comparison between the simulated and measured air temperature and relative humidity at different selected points in the study area.

<table>
<thead>
<tr>
<th>Point</th>
<th>$R$ Square ($R^2$) Air temperature</th>
<th>$R$ Square ($R^2$), Relative humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.97</td>
<td>0.64</td>
</tr>
<tr>
<td>2</td>
<td>0.96</td>
<td>0.57</td>
</tr>
<tr>
<td>3</td>
<td>0.66</td>
<td>0.14</td>
</tr>
<tr>
<td>4</td>
<td>0.51</td>
<td>0.10</td>
</tr>
<tr>
<td>5</td>
<td>0.69</td>
<td>0.44</td>
</tr>
<tr>
<td>6</td>
<td>0.32</td>
<td>0.56</td>
</tr>
<tr>
<td>7</td>
<td>0.92</td>
<td>0.74</td>
</tr>
</tbody>
</table>

3. Results and discussions

In this study, we quantified the effect of “Plan Melbourne” strategies on the air temperature, mean radiant temperature, surface temperature and PMV, as a thermal indices. We used PMV as a thermal index to show the thermal condition across the study area after the modifications caused by “Plan
Melbourne”. PMV is described as “the index that represents the mean thermal sensation vote on a standard scale for a large group of persons for any given combination of the thermal environmental variables, activity and clothing levels” (Van Hoof, 2008). We calculated thermal comfort for a 1.7 m height male, with light summer clothing value (0.5), 0.3 m/s walking speed, and 116 Wm$^{-2}$ metabolic heat. The output results of the heat balance equation derive a seven-point scale of an individual’s comfort level according to the ASHRAE comfort scale. Table 6 lists PMV’s different scales of comfort level.

<table>
<thead>
<tr>
<th>Thermal comfort level</th>
<th>Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot</td>
<td>+3</td>
</tr>
<tr>
<td>Warm</td>
<td>+2</td>
</tr>
<tr>
<td>Slightly warm</td>
<td>+1</td>
</tr>
<tr>
<td>Thermally neutral</td>
<td>0</td>
</tr>
<tr>
<td>Slightly cool</td>
<td>-1</td>
</tr>
<tr>
<td>Cool</td>
<td>-2</td>
</tr>
<tr>
<td>Cold</td>
<td>-3</td>
</tr>
</tbody>
</table>

The simulated output variables selected to compare microclimatic conditions and human thermal comfort across the study area are the average daytime surface temperature, mean radiant temperature and predicted mean vote (PMV). These output parameters were assessed as an average across the model domain for 48 hours. The distribution of the surface temperature, mean radiant temperature and PMV values across the study site was calculated by obtaining an hourly area average of each grid point within the model domain by the EXTRACT tool.

The average PMV distribution across the study area is shown in Figure 5. It demonstrates that future scenario display lower values of predicted mean vote than the existing condition. At the existing condition, the highest level of PMV is depicted at mid-afternoon by 4pm. Increased building height and tree canopy coverage caused by implementing the “Plan Melbourne” strategies will be resulted in deeper geometric form of urban canyons. The maximum reduction in average daytime PMV, was recorded at mid-afternoon by 0.6. Figure 5, 6 and 7 show that shallow urban canyons exhibit higher level of the surface and mean radiant temperature than the future scenario. The surface temperature at the existing condition is slightly greater than the future scenario, whereas the difference on the mean radiant temperature (which is the most important parameter in calculating pedestrian thermal comfort) between the existing and future scenario, reaches to 5.2 C ° in the late afternoon. A plausible explanation for this reduction is that trees reduce the SVF, providing shade during the day and substantially reduced street canyon $T_{\text{mrt}}$ and improved comfort condition at pedestrian level.
Figure 5: Daytime (9 am- 18 pm) distribution of PMV values at current and future scenario.

Figure 6: Surface temperature distribution in the existing and future scenario.

Figure 7: Mean radiant temperature distribution in the existing and future scenario.
4. Conclusion

This study aims to investigate the effect of future structural plans on the microclimate and human thermal comfort in one of the rapidly growing urban area in northern part of Melbourne. Structural plans provided a perspective for potential future built form and landscape features across the study area. Increasing the building height and tree canopy coverage by 26%, are listed as strategies in the future structure plans. We selected ENVI-met as an appropriate numerical model to predict the microclimate change that will be imposed through “Plan Melbourne”, as it is capable of predicting the outdoor thermal comfort, via meteorological inputs as well as human biometeorology factors. Network of monitoring stations in the study area provided a representative picture of different urban canyons and allowed the opportunity to verify the accuracy of the model at different locations and at different times of the day. This study is conducted via numerical simulations and the simulated outcomes were verified against the field measurements. A typical summer day is selected to monitor the air temperature, relative humidity, wind speed and direction in seven different urban canyons in the study area. The accuracy of the model is improved by conducting series of sensitivity analysis.

The findings of this research emphasis on the important role of urban planning strategies in improving the summertime discomfort at pedestrian level. Average daytime thermal comfort (PMV), mean radiant temperature (\(T_{nrt}\)) and surface temperature (\(T_s\)) are calculated across the study area for the existing condition and future scenario under the summertime condition. The results show an improvement in the thermal condition at pedestrian level in the future scenario, as lower level of PMV, \(T_{nrt}\) and \(T_s\) are depicted.

Future works will examine the impact of the pavement material, urban parks and green roofs to further improve the summertime thermal condition at pedestrian level. Additionally, the impact of these strategies will be investigated across various street hierarchies (as defined by “Plan Melbourne”), to understand the role of urban geometry on the microclimate of the cities.

In conclusion, there are innumerable possibilities for the future urban form, geometry, landscape design and pavement materials and this will dictate the prevailing microclimatic condition and pedestrian thermal comfort. Therefore, it is essential to examine the potential influence of planning strategies on the microclimate of the cities, particularly in high density developments.

References

Australian Bureau of Statistics (2011) 'Regional population growth Australia '.
Bruse, M. (2014) ENVI-met Version 3.1 BETA V.


Using real-time data for understanding temperature behaviour in outdoor environments

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Abstract: The use of sensor based real-time data offers valuable insights into the management of temperature conditions in outdoor environments. Where city temperatures have been traditionally measured at static locations, emerging sensing and data logging technology now allows for localised data collection that can provide information on site specific temperature behaviours. Viewed in this way, real-time temperature information has the potential to allow design decision making to be responsive to specific place conditions and adaptable to changing future situations.

Keywords: Data; design; temperature; thermal comfort.

1. Introduction

1.1. Usability of outdoor spaces

The use of outdoor environments can contribute to urban liveability through improving the health, environmental and social conditions. However this is dependent on the quality and the experience of the outdoor space. The usability of outdoor space is determined by how habitable it is for both human and non-human users, specifically, the experience of temperature is an important contributor to the comfortable use of a site (Chen and Ng, 2012; Brown et al., 2015; Niu et al., 2015). Under current climate change predictions, cities in Southern Australia such as Melbourne are expected to experience more extreme temperature conditions, including heat waves. These predictions have serious implications for the use of outdoor environments, particularly in cities where temperatures are often exacerbated by Urban Heat Island (UHI) factors such as hard surface massing, minimal vegetation, and limited water (Hunter Block et al., 2012; DE, 2014; Bureau of Meteorology, 2015a).

Writing in 2002, Spagnolo and de Dear stated; “The outdoor microclimate is generally assumed to be beyond architectural and mechanical control” (Spagnolo and De Dear, 2002). Since then, technological developments have begun to propose ways for design to influence and control outdoor microclimates through manipulation of airflow, shade, radiant heat from materials and green infrastructures. This is a developing area of knowledge which suggests that urban microclimates are no longer beyond design
control for improving certain conditions such as thermal comfort performance (Hunter Block et al., 2012; Norton et al., 2013; Trundle et al., 2013).

It is well established that thermal sensation is influenced by climatic variables including air temperature, wind, humidity and radiant temperatures (Höppe, 2002; Jendritzky et al., 2012). In outdoor spaces the behaviour of temperature is dictated by these changeable atmospheric conditions as well as local physical site conditions. An important challenge for designers of these spaces is to understand the complex variables and how they work within a specific location. The many variables and complexities of working in external space is one of the reasons that microclimate conditions are difficult to influence. However, real-time data can provide some insight into the behaviour of dynamic outdoor site qualities and how they might be managed (Fraguada et al., 2012; Fraguada and Melsom, 2014).

In this paper three Melbourne based studies of real-time data capture for investigating temperature behaviours in localised urban conditions will be discussed. Using accessible and low-cost technologies for logging temperature data in the field, these studies aim to utilise data to create site specific knowledge of microclimate behaviour which could inform design decision making.

2. Methodology

2.1. Sensor hardware for data collection

The sensor hardware used for these investigations was the iButton Hydrochron (temperature and humidity) and Thermochron (temperature only) data loggers. iButtons are stand-alone sensing and logging devices embedded with a 1-Wire transmitter/receiver, a globally unique address, a thermometer, a clock/calendar, a thermal history log, and 512 bytes of memory (Maxim, 2014). The iButton is 17mm in diameter and contains its own battery. The recorded temperature range is between -40 to +85°C with an accuracy to +/- 0.5°C which is within an acceptable range of accuracy under the international standard ISO 7726:1998 for measuring the thermal environment (ISO, 1998). iButtons can be programmed to log data at any interval and will last up to ten years depending on the frequency of use (Maxim, 2014). The iButton sensors are encased in a stainless steel protective unit. Whilst this contributes to their durability in external environments, this casing also heats up when exposed to direct solar radiation and will record over-estimated air temperature readings by several degrees Celsius (Johansson et al., 2014). Methods for dealing with this limitation include appropriate shielding of sensors to avoid direct sunlight exposure and positioning of the sensors under or behind physical elements to avoid direct solar exposure.

2.2. Locations and timings

The objective of the studies was to reveal the behaviours of temperature across very small microclimates within the Melbourne region through collection of continuous on-site data. In the following studies, the iButtons at all locations were programmed to capture and log data at half hourly intervals starting on the hour so as to correspond with the published Bureau of Meteorology weather station data. For comparison, daily weather observations were collected from the Bureau of Meteorology (available online for the previous 14 months and in half hour intervals for the previous 72 hours). This data included temperature, apparent temperature, humidity, wind direction, wind speed and wind gusts as well as rainfall (Bureau of Meteorology, 2015b).
2.2.1. Pilot Study Site: Shopping Centre Car Park, Moorabbin

The pilot study site was a car park and surrounding streets in Moorabbin, a suburb 16km to the south of Melbourne City. Current use of the site is largely as a car park for the Moorabbin Woolworths, one of the busiest in Melbourne. Surrounding the area is a small business district within local residential housing.

Six sensors were installed over a variety of surfaces and locations to test varying climate conditions (Table 1). Sensors locations were chosen at sites that were thought to best demonstrate thermal difference rather than seek similarities (Figure 1). Observations were collected between August and September 2014.

Table 1: Sensor locations at Moorabbin test site showing sensor proximity to different materials.

<table>
<thead>
<tr>
<th>Sensor Location</th>
<th>Trees</th>
<th>Turf</th>
<th>Bitumen</th>
<th>Concrete</th>
<th>Shade*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jasper Rd</td>
<td>Yes**</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Carpark Surface</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Taylor St Telegraph Pole</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Carpark Middle South</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Carpark Underground</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

* Shade indicates areas that are in continuous shade
** Yes Indicates proximity of Surface material is within 1m of the sensor

Figure 1: Location of iButton data loggers at the Moorabbin Street14 competition site.

2.2.2. Test Site One: Urban Materials Lab (UML) at the Carlton Connect Building, Carlton

To investigate the thermal behaviours of commonly used surface materials in the outdoor conditions of Melbourne a series of test boxes were developed and sited on the roof of the Carlton Connect building in Carlton. The UML consists of three 1m² test boxes at 0.3m depth that are constructed from 45mm thick Australian F17 hardwood and finished with outdoor timber furniture oil (Figure 2). Materials tested were bitumen, brick paving and concrete aggregate paving. To simulate street surface
construction, these materials were laid on compacted soil and bedding material. iButton sensors were installed at the surface level of the material to record surface temperature and at 0.5m above the surface to record radiated heat temperature. Observations were collected between December 2014 and June 2015.

Figure 2: Test boxes on the roof of the Carlton Connect Building in Carlton.

2.2.3. Test Site Two: Redmond Barry North Court at the University of Melbourne

A complimentary and concurrent study was conducted at the Redmond Barry North Court, University of Melbourne, to investigate the thermal behaviour of a designed, enclosed space. The Redmond Barry North Court is enclosed by a building to the south and west and a 1.5m high brick wall to the north and east. The site includes multiple variations of hard surface, including concrete and brick, and soft surface materials, and measures 750m². The more diverse spatial arrangement also includes vegetation and water (Figure 3). In this study, data loggers were installed on the underside of north facing wooden seats. Each of the monitored seats is adjacent to a different surface material; vegetation, turf and concrete paving. A fourth sensor was installed in the rock sculpture located in the small pond (Table 2). Observations were collected between December 2014 and June 2015.

Figure 3: The Redmond Barry North Court, photo taken from the south east. Sensors were located under the boulders in the centre and along the row of seats to the left of the image.
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Using real-time data for understanding temperature behaviour in outdoor environments

Table 2: Redmond Barry Court sensor proximity to different surface materials.

<table>
<thead>
<tr>
<th>Sensor Location</th>
<th>Vegetation</th>
<th>Turf</th>
<th>Concrete Paving</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>West Seat</td>
<td>No</td>
<td>No</td>
<td>Yes*</td>
<td>No</td>
</tr>
<tr>
<td>Middle Seat</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>East Seat</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Rock Sculpture</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

* Yes Indicates proximity of Surface material is within 1m of the sensor

3. Results and discussion

3.1. Pilot study site: shopping centre car park, Moorabbin

The pilot study was developed as a result of participation in the Australian Institute of Landscape Architecture (AILA) and City of Kingston Street14 ideas competition, which asked for a design response to a shopping centre car park (AILA and Kingston, 2014). Our entry ‘HeatStreet’ won the prize for Best Urban Tactic. The response from the jury described the competition entry as ‘robust’, ‘sophisticated’ and ‘clever design’ (Kingston City Council, 2014). Participation in the competition provided a valuable opportunity as a pilot study for the collection of localised temperature data. Whilst the dates of the competition were not ideal for investigating extreme heat conditions, they were still useful for testing the thermal behaviour of the site microclimate as distinct from the closest weather station, 5km away at Moorabbin Airport.

This site represented a valuable test of localised and unique conditions, demonstrating typical suburban Melbourne car park conditions such as extreme solar radiation, wind and limited shade. Most urban thermal comfort and Urban Heat Island (UHI) research is conducted in the central areas of cities, not in these kinds of suburban conditions and certain phenomena and physical characteristics that are well evidenced in high density city conditions, such as urban canyon effect between buildings, were not observed at Moorabbin (Norton et al., 2013; Trundle et al., 2013; Doick et al., 2014; Shickman and Alliance, 2014). Within the site, the variations of temperatures across the small scale were as much as 10 degrees Celsius on some days. This difference was most evident during the day between the locations most and least exposed to solar radiation. The bulk of the Moorabbin site is hard surface bitumen or concrete with minimal vegetation. The most exposed locations of the site, such as the central car park were also the areas of densest bitumen and concrete coverage. As anticipated, exposed bitumen surfaces were by far the warmest during the day (Figure 4). However, these areas were also the coolest during the night.

Further analysis of the data through 24 hour behaviours revealed additional nuances and complexity of temperatures within the site microclimate. As a counter to the temperature readings on the most exposed areas was the Jasper Rd location within a small stand of mature eucalypt trees. The sensor positioned here recorded temperatures cooler that the exposed space of the car park during the day, however it frequently retained the most heat throughout the night (Figure 5). If thermal performance is to be understood through complete 24hr cycles of heating and cooling then it was the open space of the car park that was best able to disperse heat, and the shaded stand of trees least able to disperse the heat.

These findings correlate with the phenomena of sky view factor in dense urban environments, where tall buildings or trees planted in enclosed spaces trap hot air and limit how much heat can be released into the atmosphere, particularly overnight (Norton et al., 2013). The importance of heat dispersal
became an interesting question further developed through concurrent research into the health impact of heat. It has been found that it is the cumulative effect of heat build-up over prolonged time (periods without cooling such as hot over nights) that causes the most severe health impacts including heat stress and mortality (Steffen et al., 2014). The data from Moorabbin suggested that limited peak day time temperature conditions was important but other factors also needed to be considered to disperse heat to achieve the effect of respite.

Figure 4: Temperature readings from Moorabbin over four days illustrating heat variance over full days. The bitumen surfaces (Carpark Surface and Carpark Middle South) heated the most, but were able to cool off.

This study revealed the difficulty of balancing the reduction in heat build-up in the day and dispersing heat at other times. We can identify specific areas of the site that provide shade during the day, but these would benefit from increased airflow to aid heat dispersal at night (for example Jasper Rd, East Tree), as well as areas of the site that would benefit from temperature reduction during the day, without detracting from the ability of these locations to disperse heat (Carpark Surface, Carpark Middle South, Taylor St Telegraph Pole). These findings illustrate how specific areas within a microclimate can be identified for different approaches to thermal comfort influence. Further, the impact of these will work in cohesion with one another depending on proximity of site features.

The research from Moorabbin showed that working with the iButton data loggers can aid understanding of specific site conditions as compared to generic data from the closest weather station. This pilot study also led to further questions about temperature behaviour in outdoor space in Melbourne. These questions included:

- How do the common hard surface materials found within Melbourne compare to one another?
- How quickly does heat disperse from these materials?
• How do other microclimates within the Melbourne climate behave under complex spatial conditions?

Two further studies were developed to investigate these questions and expand on the findings from the pilot study.

Figure 5: Temperature readings from Moorabbin over four nights between 12:00am and 5am. The Jasper Rd location under a stand of trees was cooler in the day, but did not cool as well overnight.

3.2. Test site one: Urban Materials Lab at the Carlton Connect building

The outdoor area of much of Melbourne is dominated by hard surface materials. This is especially evident in the spaces of high pedestrian activity such as streets, plazas, tram stops and car parks which are largely treated with bitumen, concrete, bluestone or brick.

Whilst the UML Test Boxes are sited outdoors, there is no way to completely control the influential conditions of temperature variance for the purposes of the study. Positioning the boxes on a rooftop has limited the number of physical variables and ensures the boxes are treated to the same climatic factors. This is a more controlled testing situation than is possible to achieve in most urban open space. The siting on the roof is also the primary limitation to the UML where the mass of the materials in most urban outdoor space is far greater than can be tested in a simulation space. However, the study is not intended to quantify material performance but seeks to understand relative thermal performance between these materials within the context of the Melbourne climate.

Initial comparisons of the surface level temperatures of bitumen, brick paving and concrete aggregate show that bitumen and concrete aggregate are comparable for temperature fluctuations of both heating and cooling. Bitumen surface heats the most and brick is often the coolest, though there is insufficient evidence to suggest this would be a better surface option for thermal performance under different conditions. More interesting is the dispersal rate of temperature from the surface measurements to 0.50cm above the surface (Figure 6). Consistently the data shows that despite the
relative differences of surface level temperatures, the temperatures at 0.50cm above are just a few degrees above air temperature suggesting that, in the open and very well ventilated site, it takes minimal distance to disperse the heat accumulated in the material.

![Graph showing temperature readings from UML Test Boxes over 5 days illustrating heat variance over full days. Although the surface temperatures were much higher than 50cm above during the day, all surfaces were able to disperse the heat effectively overnight.](image)

Figure 6: Temperature readings from UML Test Boxes over 5 days illustrating heat variance over full days. Although the surface temperatures were much higher than 50cm above during the day, all surfaces were able to disperse the heat effectively overnight.

The UML is conceived as a long term study of the behaviour of temperatures in Melbourne across these materials and in comparison to one another. It is hoped that a full year of climatic variation will provide insight into how these materials might be best worked with in Melbourne over time. The data collected from the UML between December 2014 and June 2015 was discussed here, but it is anticipated that the complete cycle of twelve months of data will provide further insight into temperature behaviour through both seasonally warm and cool periods.

### 3.3. Test site two: Redmond Barry North Court at the University of Melbourne

Using the same equipment and collection methods as already described, this site was used to expand on the data being collected from the UML in a more complex arrangement. The data from this study compared the temperature behaviour across four locations, with three sensors located on the underside of wooden seats and a fourth sensor placed under a rock sculpture. Whilst the seats heat and cool together in very regular cycles, the western most seat, which is adjacent to the concrete paving heats more than the others. The location to the east end of the Court benefited from being near to vegetation and from reduced solar exposure.

This study demonstrated significant temperature variation within a very small space. Analysis of the daily cycles of temperature variation show evidence of solar exposure being the biggest influence on thermal behaviour at this site. The effect of shadowing from the mature trees to the north, which impacts on the East Seat and Rock is apparent in the graphs (Figure 7).
Following from the pilot study and additional research, we had assumed that the heat wouldn’t disperse effectively at this site overnight due to restricted sky view factor, influence of hard surfaces, north facing aspect and barriers to air flow including the buildings, trees and walls. Despite these physical characteristics the behaviour of peak temperature followed by rapid cooling at all sensor locations suggests the variables influencing thermal behaviour in this site are sufficient to moderate heat build-up.

![Figure 7: Temperature readings from Redmond Barry North Court over three weeks illustrating heat variance over full days. Although the West Seat and Middle Seat were hotter than East Seat, all seat locations were able to disperse the heat more effectively than the rock.](image)

The Redmond Barry North Court as a microclimate has its own distinctive pattern of heating and cooling. Peak temperatures were observed between 12 and 2pm, and tended to peak for short periods of time. Of note in this site, as part of the University Campus, is that the peak times of use are quite specific. The majority of student classes occur over two twelve week periods from early March to late May and early August to late September. In terms of peak use, this site may actually provide highly preferable thermal sensation conditions throughout the majority of the day during semester time. Interestingly, the pattern of peak temperatures recorded at this site can be compared with the greater Melbourne climate pattern which often records peak temperature in late afternoon (Bureau of Meteorology, 2015b). The data in this instance has revealed performance characteristics within this microclimate that are valuable for understanding this site as unique to other parts of Melbourne.

4. Discussion: Data as behaviour informing design

4.1. Melbourne based studies

In urban environments, spatial and material arrangements work in combination with variable climatic forces to produce different thermal sensations. Whilst the collection of meteorological data has been occurring for over a century, the use of this information in design is a developing issue. The studies
shown here suggest that logging behaviour of temperatures over periods of time in unique microclimates can reveal indicators that have a bearing on design decision making for those localised conditions. For design and planning, the use of localised data is often assumed to be too specific for application in large scale decisions or the development of guidelines (Spagnolo and De Dear, 2002; Givoni et al., 2003; Fraguada and Melsom, 2014; Brown et al., 2015). We argue that it is this specificity that makes real time data the most useful for design as evidence based approach to site conditions. Specifically, the Melbourne climate displays certain characteristics of air flow and air temperature difference that is subject to much variability. Rather than attempting to generalise results, the use of on-site monitoring of real-time data is useful for considering how to work with this variability.

The studies discussed here attempt to uncover a particular approach to data collection and application which is focused on the dynamic quality of temperature at specific microclimates, rather than relying on data from nearby weather stations or sporadic on site readings. We propose this is a useful tactic for informing the design of outdoor spaces for improved thermal sensation performance, which requires knowledge of changing and often complex variance in local phenomena as well as larger scale environmental measurements. These studies hope to serve as proof of concept for the use of real-time data logging technologies for design professionals.

4.2. iButton sensor hardware

There are acknowledged limitations to the use of sensors as described here. First, data capture from public sites is a potentially problematic issue though it is worth noting that the kind of data being collected is meteorological and not personal. Second, the fidelity of data sets can be compromised through sensor positioning, un-calibrated loggers or constrained time frames for data capture (Fraguada et al., 2012; Fraguada and Melsom, 2014; Johansson et al., 2014). Knowing that the iButtons were likely to give inaccurate temperature readings in direct sunlight exposure necessitated positioning the sensors under surfaces and behind physical elements. This strategy for positioning of the sensors had the benefit of making our data loggers unobtrusive, which also serves to minimise interactions between users of space and the hardware.

For design professionals, the time limits of projects is rarely suited to long term site studies and must rely on previously produced data. Our studies have shown that the information provided by long term data capture is extremely valuable. Logging of temperature information meant that we needed to collect data every 4-6 weeks. There are options that allow collection of data wirelessly or through a web interface that may be more convenient, however for basic data collection purposes where the number of sensors is small and the sites within a limited area, manual data collection is achievable. The ability to pick up real-time data over relatively short periods of time, such as days and weeks still offers significant insight into on site behaviours.

The accessibility of data loggers such as the iButtons is a relatively new occurrence as reliable sensor devices have only become mainstream in recent years. The standard iButton Thermochron cost US$23 per unit and the Hydrochron cost US$83 per unit in 2015, which is considered an accessible pricing range. The availability of this technology provides a particular temporal and spatial knowledge through real-time data that previously hasn’t been as accessible. This technology offers an alternative to the traditional site analysis by incorporating a much more complex set of dynamic environmental forces such as thermal behaviours. Therefore the application of local real-time data needs to be reviewed and understood as an analytic tool but also as a design tool (Fraguada et al., 2012).
4.3. Future directions

The preliminary studies and supporting in progress research work have been useful for expanding an area of design thinking (but needs further and more detailed investigation for definitive findings). So far the research has been successful in expanding site specific information beyond the visual characteristics and purely subjective recordings of personal observations. This has also been successful in challenging common assumptions about thermal behaviour and influences within the Melbourne climate such as mass tree planting.

Key areas to be expanded include the increase of data capture to include volumetric recordings of spatial conditions. This will allow for the qualities of heat dispersal to be better understood in the study sites. Further investigation collecting other kinds of localised real-time data related to thermal sensation such as wind and humidity, will assist in developing knowledge of site microclimate behaviours. There is also the potential for further analysis that is directed around peak times of area usage, such as the times of peak use noted in the Redmond Barry North Court. Being able to balance the thermal performance of a space over 24 hours whilst also working to affect temperature behaviours during peak times, provides an interesting challenge. For example, at the Moorabbin site the peak times for visiting the shopping centre are between 2:30 and 5:30pm (AUSPOLL, 2006; ARUP, 2009). This provides a critical temporal period for which to consider heat behaviour with site use.

The next steps for expanding the studies discussed here include completing a years’ worth of data capture at the UML and Redmond Barry North Court sites, and both of these tasks are underway. The second half of 2015 will reveal different thermal behaviour results to the ones already logged as the Melbourne climate shifts into seasonal warming. The Redmond Barry North Court site is also scheduled to undergo design changes; the mature trees to the north of the site will be removed and the outer brick wall will be adjusted. We predict that both of these changes will influence the microclimate behaviour within the space and hope to continue monitoring the conditions until after the redevelopment to record the comparable differences. We also plan to return to the Moorabbin Junction site to expand on the initial pilot study. This work would include application of real-time data as a design tool for informing site design, an important step in working with data beyond the analysis stage.

5. Conclusion

Real time data capture through sensor and data logging is becoming an accessible tool for design professionals to make informed decisions about localised sites. These tools reveal site specific knowledge of complex behaviours which can inform design decision making. This expands the understanding of site to include the dynamic and complex conditions of microclimates such as thermal sensation. In the context of climate change and the predicted challenges facing outdoor environments, the use of real-time data is an important tool for design to mitigate these conditions.

References


Wayfinding in traditional Chinese private gardens: a spatial analysis of the Yuyuan garden

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Abstract: This paper presents a study of wayfinding in a Traditional Chinese Private Gardens (TCPGs). One of the most well known features of the TCPG is its network of indirect pathways. These pathways shape the experience of the space and contribute to its perceptual and aesthetic properties. When walking through a TCPG, the pathway chosen is one of the dominant factors affecting a visitors’ spatial experience of the garden. But such is the complexity of the TCPG that understanding how people navigate through these spaces is relatively difficult. Therefore, this research explores the choice of walking paths in a TCPG using a mathematically derived analysis of the plan. One historic TCPG, the Yuyuan Garden, has been selected as a case study. The method used for the analysis is based on convex mapping, a Space Syntax technique. Three measurements derived from this analysis are extracted to capture essential topological patterns in the TCPG. The results identify the main paths and sub-paths people are likely to take when walking in this garden. Through this process the paper demonstrates a method for capturing the social and spatial properties of the TCPG and provides possible new insights into the properties of these important heritage sites.

Keywords: Traditional Chinese private gardens; wayfinding; space syntax.

1. Introduction

The Traditional Chinese Private Gardens (TCPGs) is recognized as a special type of landscaped space with a particular set of characteristic properties. Developed primarily in the sixteenth and seventeenth centuries, and distinguished in part by its rich spatial arrangement and its associated aesthetic properties, today the TCPG is accepted as having unique aesthetic and experiential properties (Peng, 1986; Tong, 1997). Past researchers have typically analyzed the TCPG from various qualitative perspectives (Chang, 2006; Li, 2011; Lu, 2009, 2010) although a small number of studies have also considered their spatial properties using quantitative methodologies. Despite this past research, the spatial properties that make TCPGs unique have rarely been measured and generalized mathematically. Without such a set of measures, the characteristics of TCPGs cannot be replicated in contemporary landscape design practice or maintained as part of the restoration process for these heritage structures.
One of the most important features of the TCPG is its complex network of arborescent paths, allowing visitors to choreograph their own experience of the TCPG to suit their particular needs. It is this property of the TCPG, pedestrian wayfinding, that is the focus of the present paper.

The particular choice of path is an important factor that affects visitors’ spatial experiences when walking in a TCPG. However, where most models of wayfinding in architecture and design are concerned with optimal or functional pathways, the TCPG poses a different problem, that of excessive choice. This paper uses a Space Syntax technique to develop a deeper understanding of the mathematical complexity of wayfinding in the TCPG. Using one well known TCPG – the Yuyuan Garden – as a case, the paper explores the properties of pathways in TCPGs. In particular, this paper is focused on measurements of access topology relative to spatial types, within the TCPG.

This paper commences with a background to both TCPGs and to Space Syntax, before the method used for developing the results is described. The majority of the paper consists of the presentation of the results for the Yuyuan Garden along with a discussion of how these might be interpreted.

The results of this research are necessarily limited by three factors. First, as only a single case is examined, the results cannot be generalized to comment on other TCPGs. A larger sample, possibly divided by region or dynasty, could be used to develop a more nuanced set of results as part of a future study. Second, this is a study of planar properties, without taking into account the three-dimensional geography of the gardens. However, as wayfinding in visually dense environments is generally undertaken topologically, rather than geographically, this is a reasonable starting point for a study. Finally, only one measure, access topology, is examined in this paper. Future research will include additional factors, and multi-factor approaches to understanding wayfinding in the TCPG.

2. Background

2.1. Traditional Chinese private gardens

The typical TCPG features a dense network of paths and spaces, punctuated with artificial landscape features, ponds and small streams, paved squares and covered corridors or bridges. All of these features are organised in a relatively constrained and clearly defined area (Figure 1). Researchers have analysed the specific properties of the TCPG from various qualitative (Hunt, 2012; Tong, 1997) and quantitative perspectives (Chang, 2006; Li, 2011; Lu, 2009, 2010; Wang & Wang, 2013) and have identified the importance of understanding their dense spatial configurations and the changing vistas experienced during wayfinding (Li, 2011; Peng, 1986). For example the qualitative studies of Keswick (1978) and Zhou (1999) explore the spatial character of TCPGs from a historical and social perspective. Conversely, in a quantitative approach, Chang (2006) studied the Lin-family garden using Space Syntax techniques to examine 310 spatial units using convex map analysis. Chang’s study effectively provided a new way of understanding the spatial characteristics of this garden-type in terms of their spatio-functional qualities. Lu (2009, 2010) undertook research into the spatial properties of the Yuyuan Garden using a combined method drawn from Space Syntax and Shape Grammar. Lu’s study developed a formal language for examining Chinese private gardens as well as demonstrating an effective approach to linking the physical system to cognitive processes. In a related manner, Li (2011) studied the visual-perceptual character of the Lingering Garden also using Space Syntax techniques. Li’s study was focused on visual analysis using convex mapping and measures for integration. However, that study did not conduct a
quantitative analysis addressing the type of large-scale planning and connectivity issues, that are often described as the most critical spatial features of the TCPG.

Figure 1: Yuyuan Gardens in Shanghai (http://www.nipic.com/show/1/62/3909654k374f806b.html).

2.2. Space syntax

As the previous section demonstrated, of the small number of quantitative studies that have been undertaken into the mathematical properties of the TCPG, by far the most common approach is to use Space Syntax techniques for extracting information. Space Syntax is a collective name for a number of techniques used for analysing the topological properties of space, such as permeability and intelligibility, for which the space is abstracted into a graph (Hillier & Hanson, 1984). Extensively developed over the last few decades, Space Syntax methods have been widely applied in research in urban planning, architectural design and landscape design, amongst other areas. One of the strengths of the Space Syntax approach is that it provides a way of understanding architectural and urban spatial configurations by translating their properties into topological graphs, which can then be mathematically analyzed (Ostwald, 2011; Ostwald and Dawes, 2013). Space Syntax techniques combine unique mapping approaches with Graph theory mathematics in order to capture different spatial properties (Ostwald, 2011). Generally, Space Syntax has three approaches to abstracting space (architectural, urban or landscape) into a graph: convex mapping, axial mapping and isovist mapping (Klarqvist, 1992).

The first of these three, convex mapping, is the primary approach used in the present paper. In its original variant it partitions space into a set of convex shaped (visually-defined geometry) boundaries which are then represented by the nodes of the corresponding graph (Ostwald, 2011). The connections between the spaces then become the vertices in the graph. While this process is purely geometrical, a variation of convex mapping uses social boundaries (that is, based on hosted or functional activities) instead of geometrical boundaries to define the “convex” spaces and, thence, to produce the nodes and vertices of the graph (Peponis and Wineman, 2002). Convex graphs are particularly useful for understanding the organization of space in terms of permeability and accessibility (Ostwald, 2011). For this reason, past attempts to understand the TCPG have tended to use the functionally or socially defined variation of convex mapping to extract mathematical information from the TCPG. This is also the approach taken in the present paper. However, it must be acknowledged that such permeability graphs are not often used for studying wayfinding, with axial mapping techniques being preferred. However, the axial maps are, by definition, concerned with finding the ‘fewest’ and ‘longest’ paths or vistas through space, being an optimal network of connections (Hillier 1995). However, passage through the TCPG is not completely governed by such considerations and thus, as the starting point for a new analysis, the functional or social variant of convex space mapping offers a reasonable method for
considering wayfinding and intelligibility. Furthermore, as the next section reveals, a variation of the method is used to focus the method on aspects of spatial choice.

3. Analysis method

This paper uses the social or functional variation of the convex mapping technique, where the spaces are defined by their associated activities rather than their geometric features (Peponis and Wineman, 2002). Given that wayfinding is the focus of this paper, the defining activity for determining the graph is the role of a space in terms of movement and navigation. For this reason, the space of the TCPG is divided into two distinct sets of elements: narrow pathways which are mainly perceived as a connection between two points, and any other elements in which a person might stop for a social for functional reason. The latter spaces include the intersections between pathways in the garden as well as “fat” spaces (that is, those with higher ratio of area to perimeter) such as squares and buildings. The end of pathways (either a dead-end or exit from the system at an entry) is also considered to have the quality of a pause or stopping point and thus it too is identified as a space. The resultant spatial graph can then be made in two ways. Firstly, the pathways can be treated as nodes in the graph and the stops (intersections and buildings) as the edges which connect the paths. The inverse is also possible by considering the intersections as the nodes of the graph and pathways as the edges. The focus of this paper is on the latter approach, where stop points or places where decisions can be made about movement are the nodes, while the (segments of) pathways between any adjacent two of them are represented by the edges of the graph. In this variation, the shape of a pathway (straight, curved or broken) does not affect its connecting function as long as there is no possible detour from the pathway except from its ends.

Three properties of the ‘stop-point, pathway graph’ are measured: integration ($i$), choice ($C$) and intelligibility ($I$). Integration is a global value of each vertex (intersection) revealing the degree by which it is included into or isolated from, the whole system (Hillier & Hanson, 1984). In other terms, it relates to how much one space is accessible from other spaces, on average (Peponis and Wineman, 2002). Choice is the number of times a vertex is located on the (shortest) path between all other vertices in the system (Bafna, 2003). The choice value suggests the likeliness of the vertex (intersection) being passed through as well as its importance in decision making about movement. It is also possible to measure a local choice where for each vertex, the system is defined locally based on the vertices close to that vertex (that is, applying a maximum syntactic radius $r$) (Hillier, et al., 2007). The local choice identifies the focal points of the system. Finally, the intelligibility value suggests the overall clarity of the system (the garden in this case) as perceived by a user inside it (Klarqvist, 1992; Peponis and Wineman, 2002). Intelligibility is defined as a Pearson correlation between integration and the connectivity values of all vertices (the connectivity value of a vertex is the number of directly connected or adjacent vertices to that vertex) (Hillier et al., 1987).

Whereas most Space Syntax analysis is undertaken using DepthmapX (Varoudis, 2014) software, for the present research software produced by the authors has been used. This new software, Giraphe uses Dijkstra algorithm (Dijkstra, 1959) for finding the depths in the graph and applies the common calculations methods of integration and choice in Syntax algorithms (Hillier and Hanson, 1984) as displayed in Equations 1 and 2 respectively. In these equations, $k$ is the total number of the vertices; $MD$ is the mean depth of a vertex; $V$ is a vertex and $P_{ij}$ is the shortest path between $V_i$ and $V_j$.

$$i = \frac{k-2}{2MD-1} \tag{1}$$
$C_a = \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} (V_a \in P_{i,j} \rightarrow 1)$

The main difference between Depthmap and Giraphe is the more user-friendly interface and the more intelligible visualization of the latter in regard to the circumstances of this research. Another difference is that Giraphe does not apply a normalization coefficient for integration values, because such normalization is useful only for comparing different systems (i.e. gardens or buildings) (Hillier and Hanson, 1984) that is not a matter in this research.

4. A case study: Yuyuan garden

The Yuyuan Garden is located in the city centre of Shanghai, in southern China. It was built in the 16th century and has an area of around 20,000 m$^2$. Parts of the garden were destroyed during the Second World War, although most sections have since been repaired or rebuilt. The Yuyuan garden is well known for its delicate and subtle planning and for its artificial mountain with water in its centre (Figure 2).

![Figure 2: Yuyuan Garden plan.](image)

Three values for the Yuyuan Garden are calculated for pathways and intersections: average integration ($i$), average choice ($C$), and intelligibility ($I$) (Table 1). The relatively low intelligibility ($I$) result suggests that in the Yuyuan Garden, visitors find it difficult to understand the space as a whole. This supports the widely observed spatial property of TCPGs, where their features that are regarded as being “hidden” from view, or are a “surprise” to visitors (Li, 2011). These results may also be interpreted as indicating that the organisation of the entire garden is more likely to be understood in terms of intersections ($I = 0.28$) than pathways ($I = 0.09$). This also confirms the standard view in wayfinding
theory (Ellard 2009) and the results developed by Ostwald and Dawes (2013) for the architectural analysis of interiors.

Table 1: Convex map analysis results of pathway and intersections in Yuyuan Garden (Mean value).

<table>
<thead>
<tr>
<th>Item</th>
<th>Count</th>
<th>Mean integration (i)</th>
<th>Mean choice (C)</th>
<th>Intelligibility (I)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pathway</td>
<td>215</td>
<td>12.91</td>
<td>1291.98</td>
<td>0.09</td>
</tr>
<tr>
<td>Intersection</td>
<td>141</td>
<td>8.25</td>
<td>714.12</td>
<td>0.28</td>
</tr>
</tbody>
</table>

In addition to the three global mean measures (Table 1), the integration (i) and choice (C) values for individual intersections of the pathways were also determined. Choice value indicates the likelihood of a point being passed through by a person while navigating in the garden (or a local portion of the garden). The choice value was measured over three scales in the system. Firstly, the global choice was measured by considering the garden as a whole, then considering the choice value for each intersection in a locality limited to three (r = 3) or six (r = 6) intersections from it. Given the low intelligibility of the entire organisational structure of the garden, it might be assumed that practical wayfinding within the garden would occur at a local scale rather than relative to the whole system. Figure 3 shows the results for the integration (left) and global choice (right) measures for Yuyuan Garden. Figure 4 shows the local choice values, where r = 3 and r = 6. In each of the figures, the circles show the position of the intersection while their size and darkness represents the value of the measures. The squares indicate the position of the original entries to the garden. Two of the entries have now been closed; these are shown in grey.

Figure 3: Yuyuan Garden plan. Circles show the position of each intersection while their size and darkness represents the global value of either integration (left) or choice (right). Squares represent entry points.

The integration results (Figure 3) suggest that the middle of the garden is the most integrated area, which means that the middle part is more topologically accessible in the garden, in comparison to other
parts. It is, based on this data, more likely to feature important places for gathering, because it is easier to access from other parts of the garden. Around the middle part of the garden, there are various water ponds, with bridges, covered corridors and pavilions on top of the water. It would appear that in the original planning, the middle part of the Garden may well have been intended to be an important place, most probably for family gatherings.

The Global choice analysis (Figure 3) indicates that there is one clear main path identified by connecting the high-choice intersections. The path extends from the north-west to the south-east corners in Yuyuan Garden. The result suggests that this is the main path visitors are likely to move through. Interestingly, the main attractions in the Yuyuan Garden are in fact located along this path. While not definitive, this does suggest that this analytical approach is valid for extracting spatial characteristics from the plan graph. Furthermore, at the end of the main path there is an artificial hill with a pavilion on it, which may have been intended as an important view point to draw visitors along the path.

The local choice values, for a syntactic radii of 3 (Figure 4), also identify other significant intersections in the structure of the TCPG (marked by numbers 1 and 2). Furthermore, the significance order of the intersections along the main path has changed (marked by numbers 3 - 6). By connecting these important local nodes, two other paths are identified which detour from the main one. Interestingly, these two paths meet each other again and flow towards the north entry. It is also noteworthy that the closed entries are not directly engaged in these paths. From the results for a higher syntactic radius of 6, the main path can still be identified, however, the significance of the two minor paths is reduced.

Figure 4: Yuyuan Garden plan. Circles show the position of each intersection while their size and darkness represents the local value of choice, with a syntactical radii of 3 (left) or 6 (right). Squares represent entry points.
Just as it is possible to correlate the data developed from this analysis with several actual properties of the Yuyuan Garden, so too, some of the results can be understood in terms of patterns present in the garden. For example, a close review of the important choice points along the main path suggests that most (5 out of 6) points are located at least one intersection away from the entry to a building (Figure 5). In a completely functional plan, the buildings would be expected to be closer to the main path, but this result confirms that the organizational structure of the Yuyuan Garden relies in indirect connections, or perhaps a strategy wherein buffering occurs between active functions (walking and navigation) and passive functions (resting, indoor socialization and private activities).

![Figure 5: Yuyuan Garden plan detail. Example of relationship between major intersections and buildings through minor intersections.](image)

**5. Conclusion**

This paper presents a spatial analysis of the Yuyuan Garden in terms of wayfinding and focussing on choice-points or intersections considered as part of both a global and a local spatial structure. These points are critical to the navigation of the space in a topological sense. Through this research some principles of spatial planning and design in the Yuyuan Garden are revealed, along with a potential new insight into the visual and geometric character of TCPGs.

Three main observations can be made using the method adopted here. First, a main path is identified in the Yuyuan Garden which, based on the syntactical model, people are more likely to use when navigating through space. The main attractions are actually located along this path offering a direct correlation between the mathematical model and the actual garden. Second, some important intersections along this pathway, where people are likely to pass through or visit, are located one intersection from a building. This pattern occurs in 83% of the cases considered (relative to the main path). Third, the measured intelligibility values for the Yuyuan Garden are relatively low, which means that when people are walking in the garden, it is difficult for them to understand the space of the garden as a whole. However, at a more local level, the network of high-choice positions, suggests that the garden is more intelligible as a collection of small-scale connected subsystems.
These three findings further suggest some principles (either intuitive or conscious) which may have been followed when the garden was originally planned. It is possible that the designer started by defining a main pathway, and then allocated important attractions and structures along it, but not immediately adjacent to it, drawing people away from the primary path, by way of secondary paths, to specific locations. However, while these observations are supported by the mathematical analysis, they cannot be extrapolated to cover other TCPGs. This is a pilot study of just one case analysis, nevertheless, a future study comparing using this method, and a larger sample size, may be able to reveal or generalise these important, but elusive properties of the TCPG.

References


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Generative, Parametric and Evolutionary Architecture
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Coding randomness: accepting unpredictability in modular systems through the use of computation

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Abstract: Through exploration of the dynamics of biological systems Kauffman (1992) found a ‘magic region’ of phase space where spontaneous organizations in nature reach a peak of complexity somewhat between periodic and chaotic arrangements, expressing a kind of random code. While the networks with which Kauffman was primarily concerned are biological, his analysis can be extended to architectural design. Positioned between too much and too little order, the moment of randomness is the medium in which new strategies for architecture could emerge. With these insights this paper introduces a series of possible housing structures that illustrate some of the key working methods available in digital systems such as ‘generating’ and ‘compositing’ taking as starting point computational strategies oriented to geometry and where the random factor plays a decisive role. Design can be inspired by this random nature, as nature is not designed with strict parameters, but it may evolve from a core of generative expressions of code. Architecture in fact could be conceived in a similar way the generative randomness develops into complex organisms, from the very bottom processes. This particular organizing principle - from code to shape - in Nature systems, acts along this paper only as an inspiration to the design process.

Keywords: Code; generative design; randomness; modular dwellings.

1. Introduction

The aim of this study is to develop a method for automated generation of residential building layouts using computation for graphics applications. This system intends to be adaptable to the constraints of low-cost modular construction industry. The project develops a computational tool to generate a network of three-dimensional dwelling structures derived from real-world functional requirements. The presented approach is an architectural tool that makes use of the idea of randomness to achieve an endless variety of computer-generated buildings produced under specific functional requirements.
It is an intention to show that randomness along the project is in some extent controllable even if the obtained results (dwelling aggregates) are in fact every time differentiated. Randomness in this project-exercise is not dissociated of intentionality; it is not associated with lack of control, arbitrariness or incoherence. This exercise contributes to a certain discussion about designing with architectural parameters and conditions, but also with degrees of freedom and resulting from the random arrangements – the generative through the random. Along the paper, the medium of programming using Python programming language will allow to model and control complex decisions and to refine a stochastic search process driving and disciplining that way the random experiments. As Littlejohn (2001), in order to survive within a dynamic environment, natural systems must be able to change, to be somewhat unpredictable: in other words, this could be referred to as morphogenesis. The same way, design methodologies constructed according to a certain degree of unpredictability are changing the way we think architecture, operating a fundamental revision in our mental processes. According to Vacas (2004) we are in front of a new kind of intelligence immerse in the new generations of digital technologies. The use of these processes represents a new way of thinking architecture in terms of computational process. According to these premises, the concept of randomness will be scrutinized, from his broader meaning up to more practical application in architectural design, interconnecting concepts of computation, generation of form and functionality. This paper will try to explore the concept of uncertainty, the role of the random factor applied to genesis of form in modular growth architectural structures. This study proposes an approach to computer-generated buildings using randomness as a motivation to achieve diversity on the architectural outcome, but departing from functional requirements common to the architectural practice. For that reason the initial modules Xx and Xy for developing the project include a concise list of functional requirements: number of bedrooms, social areas, amenities areas and approximate square footage (Figure 2).

2. References on modular structures

Few of the initial attempts of modular structures in architecture can be traced back to Durand (1813) and his modular elements grammar system that anticipated contemporary modularity in architecture and building industry. More recently, especially the past decades have witnessed the spread of modular construction into numerous applications in architecture, through the work of architects like Kisho Kurokawa or Moshe Safdie. By aggregating concrete modules in multiple geometrical configurations, Habitat 67 by Safdie (1971) was able to break the traditional form of orthogonal residential blocks, locating each box overlapping its immediate neighbour within specific rules of connection. Habitat 67 pioneered the emergence of unpredictable spatial organizations for residential buildings.

Habitat’s prefabrication technique was applied in Kisho Kurokawa’s Nakagin Capsule Tower, where a total of 144 residential modules are connected and rotated around a structural core of vertical communications. For Kikutake (1960), Kisho’s experiment on residential high-rise structures is a prime example of the Metabolism modular architecture, known for it’s focus on adaptable and growing systems building design. Many other examples can be found in the avant-garde movements in the 1950s and 1960s, such as the Archigram group, Yona Friedman and the Groupe d’Etudes d’Architecture Mobile, or through the work of Superstudio. These architects-urbanists pioneered the design of a three-dimensional urban structure as the framework of the new urban expansion of the postwar era reconstruction, many time
Coding randomness: accepting unpredictability in modular systems through the use of computation (Sadler, 2002; Friedman, 1999; Lang, 2003).

These historical examples presented as pioneering experiments into the compositional power of modular structures present substantial limitations due to a certain drafting culture and the available tools for architectural design. According to Schlager (2000), the precise and accurate character of the referenced projects is reflected through practical response in a form of a building. Nowadays the fast achievement of a high level of compositional complexity is available with the introduction of new computational technologies, opening the possibility to simulate not just a single building solution but a vast number of building variations. The complexity of the assembly process, complex growth morphologies and modular variation and differentiation is possible with the use of advanced digital tool and computation oriented to graphic software.

The research presented in this paper addresses the limitations of design conception in the modular structures, analyzing several case studies in history, and proposing a new computational methodology for designing modular collective dwelling systems. At the same time borrows from such historical examples from the 1960s and 1970s the ever-present idea of functionality and adaptability to real scenarios. Especially the work of Ricardo Bofill in the built project Kafka Castle in 1968 is inspiring for this research study. The complex is an assemblage of prefabricated cubes, a three-dimensional composition generated by two mathematical equations resulting on an aperiodic design. This strategy based on a generative process that created volumetric overlapping and juxtaposition is in fact very similar in concept to the research project proposed along this paper. Along with the concern about the functionality, place and sensibility to local materials in the work of Bofill (Frampton, 1983) plays an important role in this paper, as explored in more detail under the section 6, serving as a real case study of acceptation of the unpredictability of code and mathematical abstract thinking applied to design compositions.

There is an emerging generation of designers and researchers making use of digital design tools and computation along with a new wave of software to support architectural design. The study of the interface designer/computing-machine led to the expanded application of digital tools in architecture projects. Looking closer on the recent developments in computational models applied to the generation of architectural spaces and specifically residential buildings, many researchers have explored algorithms for automated spatial allocation. As it is the case of the Boyd (2004) automated processes, that operate on combination of rectangular shapes in the plane or the Shaviv (1974) methodology for subdividing a regular grid creating residential units. To date, the application of spatial allocation algorithms has been limited to regular - based on orthogonality - architectural projects (Kalay, 2004). Harada (1995) introduced shape grammars to three-dimensional graphic applications and developed a system for interactive manipulation of architectural layouts. But seems compositional methods based on shape grammars have so far not produced complete building layouts even if implemented with optimization functions (Stiny, 2006). Other kind of advanced algorithms were developed for generating architectural freeform geometries and exploring form-finding strategies (Pottmann, 2007). However, none of these automated techniques is producing residential building layouts from specific functional requirements.

Recently many studies about modularity and self-regulating systems have been produced by architects like Michael Weinstock and the multidisciplinary office Ocean (Weinstock, 1998), Benjamin Aranda and Cris Lasch (Aranda, 2005), or the incursions into programming and modular structure by Meredith (2012). Most of the experimental work in digital architecture of the 1990s sought to create space through computational generative processes. But the wide spread of computational tools easily
accessible to designers also led to generalizations about the configuration of modular architecture systems as solely an information system or a graphic composition, presenting in the majority of the cases, abstract scenarios far away from real implementation as residential buildings. This paper proposes a system versatile enough to adapt and configure to specific demands of the modular construction industry, producing low-cost-effective solutions (Figure 2). Under this main purpose the paper explores then a computational methodology for replication of residential modular typologies based on the power of Text Programming Languages for Visual Graphics Applications. As a future proposal, the section 7 discusses the development of a collaborative real-time platform between architectural design, final user and fabrication process.

3. Spatial vocabulary, maximum diversity dwelling system

The project featured in this paper, rather than presenting predictive housing structures, it questions the disciplinary boundaries by standing for the conviction that computation power can generate architecture outcomes embedded with functionality and aesthetic meaning. It revealed specially important for this research paper the pioneering work done by Johnson (2001), that comes from experimentation in pure computation applied to modular growth in biological systems. The role played by the unpredictable geometries driven by code and complex algorithm present in Nature system was an inspiration to explore compositing and generating techniques to develop collective housing structures. Examples of the evolved geometries or housing aggregates will be presented, which utilize the Xx and Xy dwelling modules as in the Figure 1 and in more detail in Figure 2.

The digital simulation of this architectural structures started by sampling randomly with the ‘Packing Script’. A script in Python programming language was developed to simulate the rules of connection between pre-established dwelling modules xX and xY, performing random alterations each time two modules are connected face to face. This allows explorations in incremental arbitrary directions and with random values at each iteration of the algorithm, without requiring the designer’s intervention or even knowledge of specific effects of the connection rules set. The geometries are reproduced with mutations of the connections for each new generation or iteration of the script (Figure 4). The idea is to change randomly the position between xX and xY's each time a new element is connected.

The next step in the process was the modification of the script in order to permit selective growing by the user, picking preferred results from the evolving geometries. Artificial evolution of the housing structures is performed by first generating and displaying a population of simple random modules and then ask the user for interactive selection (algorithm with directional growth). This way more perceptually successful geometries, or more driven ones, can evolve.

![Image of contact possibilities between xX and xY elements: juxtaposition face-to-face using the rectangular connector surface. Due to the individual shape of the elements and the positioning between them, the assembly system achieves three-dimensionality.](image-url)
Figure 2: Examples of typologies T1 and T2, based on the combination Xx and Xy modules. The element xX was developed to represent in scale a small services module and xY was meant to have the minimum proportions of a living and/or sleeping compartment. Both modules are inscribed in a bounding box of 2,43(x) by 6,05(y) by 2,59(z) meters. The proposed modules pretend to be cost-effective, totally pre-fabricated, minimizing production costs and specialized labor on site.

4. Rules for packing

The characteristics of packing in this exercise, repetition of self-similar modular elements, provided the inspiration to tectonic assembly. This process simulates the connection of new units on each available face (empty). The ‘0’ and ‘True’ values enable the user to decide for an automatic and random growing or a more driven decision. ‘Init’ and ‘Add’ routines permit the user to introduce an ordered set of values to the modular connections. The experiments with systems of rules are:

4.1. Randomness

Phyton script implemented allows infinite possibilities of xX and xY modules packing. All the solutions obtained seem to be noisy. The algorithm creates random associations of modules, connecting face to face each generation of new elements (Figure 6). The result is a number of housing aggregates connecting the modules xX and xY at different orientations, where ‘spatial compositions’ are generated randomly, without concern with structural stability, functionality or use of the interior spaces.

At the same time, this process and its formal result investigate a new aesthetic outcome in design in which random compositions and automatically generated three-dimensional patterns can be accepted as valid criteria. It also challenges traditional notions of functional occupancy, technology and tectonics and raises questions on how, for whom and where such architectural structures can be implemented.
Figure 3: Grammar of connections between modules \( xX \) and \( xY \). Few growth possibilities according to the face-to-face packing rule. Only self-similar faces may be used to perform connections.

4.2. Periodicity

Changing the script to be possible to drive the growing in specific direction, it means asking the user to select the faces where the next connections will be, we obtain quite different results. In this case the packing of modules will follow a specific pathway, bounded by the face-to-face only possible association. The modular association of elements forms more stable configurations. By stable it is meant regular structure not dissociated of intentionality (Figure 5).

Figure 4: ‘Packing Script’, Python programming language script to generate random packing of modules \( xX \) and \( xY \), using the graphical interface PyTopmod 2.223. Image of the script developed by the authors.
Figure 5: Diagram of evolved examples with periodic patterns. The images show different possibilities of growth by applying the packing script. The models are obtained by an active intervention of the user, driving the way xX and xY elements are packed together.

Figure 6: Diagram of evolved examples using aperiodic rules. The images show different possibilities of growth by applying random connection rules between xX and xY elements. The models are obtained with no intervention of the user.

The functionality of the script with periodic growth is shown in the following pseudocode (1):

```
# Define Main Subroutine
# Get User Input:
# Get the Module (array, the identifier of the starting geometry to replicate)
# Get an array of 3-D reference points (with more than two points specified, then the function will align three-dimensionally the object between each other, similar to align or orient command in 3D graphic software)
# Get an array of 3-D target points (this will be used to start the recursive function)
# Get the amount of iteration (double, value for the number of iterations of the Aggregate function)
# Start the recursive process:
```
# Call the Aggregate function (custom function, inputs: the 3D module, the reference points, the
target point and the amount of iterations)
# End Main Subroutine
# Define Function Aggregate (inputs: the Module as object, 9 points coordinates, and the amount of
iterations)
# Define 9 points for 3D alignment
# Take 3D object as input and create 2 copies
# Aggregate Function Calls itself:
# Call the Aggregate function (inputs: the newly created objects, point coordinates and Threshold)
# End Function

5. Random mutable rules

New rules may be explored in order to change de connectivity conditions between \( x_X \) and \( x_Y \), obtaining that way new sets of formal results and continue playing the role of unpredictability along the conceptual process.

5.1. Edge connections

Any node of physical connection between elements can mutate into a new connection expression. For example, changing from face to face connection between modules to edge connection. This allows for large changes, and usually results in a significant alteration of the final structure.

5.2. Vertex directional connection

Finally, if the new rule of contact is a vertex and a vector, the direction of growth can be adjusted by adding random coordinates each time the algorithm iterates, packing new elements \( x_X \) and \( x_Y \).

Other types of mutations could certainly be implemented, but these are sufficient for a reasonable balance of slight modifications and potential for changes in complexity. It is preferable to adjust the mutation frequencies to prevent the experiments from drifting towards large and “slow” forms without necessarily improving the compositional results of the aggregates as possible dwelling structures. Edge and vertex connections have immediate impact in the ability of the final aggregates to be structurally stable compositions and make the experimentation not viable as a functional architecture. As explored in more depth in the next section, a real implementation of these systems is desirable to test the ability of both the methodology and software to generate modular growth collective housing compositions.

6. Possible future, 1:1 scaled implementation

This research began with a real proposal to develop modular pre-fabricated houses. This way the paper also focuses on the rethinking of the standard housing typologies that designers, contractors and buyers can find in catalogues of modular pre-fabricated houses. We proposed other architectural prototypes and new ways to combine them, creatively, using the power embedded on the computational systems applied to design. The majority of the examples found in literature and transposed into architecture projects do not make a link with real implementation by the construction industry. The examples found, tend to be more exercises of design for the sake of building a computational process. Believing in a constructive premise, this system can be easily implemented in the construction industry, departing from simple modules - \( x_X \) and \( x_Y \) - to produce creative, unpredictable housing aggregates or collective
dwellings. Figure 7 shows a possible implementation in a real scenario, departing from the previous results based on periodic growth. This modular technology enables construction time to be reduced by up to half those of traditional building techniques while minimizing on site disruption and remaining significantly more environmentally friendly.

This project introduces an approach to a real liveable and significant environment. Its goal is not only to achieve a highly photogenic form of scenography, as observed in the majority of the recent experiments into computational modularity applied to architecture, but merge together functionality and the compositional power of computation.

Figure 7: Possible future, implementation of a modular housing settlement in hypothetical real scenario.

7. Future directions and conclusion

As future work, there is a possibility to continue developing the algorithmic process under this research, by creating a real-time collaborative platform between designer, clients, engineering systems and fabrication. By using graphic software applications with COM technology that allows the implementation of code in Python for Applications (creating an software application opened in real-time to the inputs of all intervenent in conception process) it is possible to bring multidisciplinary performance feedback to the project. This work could lead to a data-driven approach to automated generation of modular residential structures, based on the inputs and functional requirements given directly by end users, clients, developers and technicians.

It is also possible to develop fitness functions that could restrict the growth system of the aggregates to specific conditions of the geographic site. Imposing site-specific conditions, physical limits, scale and density, we should evolve towards more controlled aggregations, due to selection of improvements instead of simply random mutations.

A large part of architectural research is presently measured not so much with forms and objects as with the conditions in which these forms can emerge. Thus stable structures no longer exist within the design process, or in other words stability is not an absolute given but rather, it derives from dynamic
balance characterized by multiple and interdependent fluctuations. One of these fluctuations is in fact data. In this case data is related with shapes and is affecting directly the formation of architectural structures. The paper explored computing technologies that allow discovering, describing and unlocking unpredictable geometries, it also contributes to a radical change at the level of the conception strategies for design and architecture. Being part of the process is a key rule played by the designer.

Playing with code, based on digital design processes and random growth conditions, focuses on the procedures of architectural becoming. This method attempts to release the designer from predetermined formal or functional typological definitions. Departing from random decisions, the explored method bases the production of the architectural geometry as an expression of code or computation, allowing the emergence of architectural entities as part of undetermined experiments. It is hard anyway, to evaluate the formal consistency of the built architectures from the scripting techniques. A human decision, as well as an approach based on the functionality and real implementation of the modular structures as a residential space acts as a strategy to reduce a vast range of potential results.

References

Parametric design approach to space syntax methodology for designing a master layout

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Abstract: This paper investigates the potential of using parametric software to analyse the attributes of spaces using Space Syntax methodology and implementing the outcomes in an urban design project. This research aims to reveal the attributes of spaces in a proposed site for a new town centre and an aquatic centre development in the town of Rosebud, Victoria utilising Space Syntax methodology. The study specifically focuses on finding the most walkable and visible areas in the existing project site or in the initial design sketches. To locate these areas, this exploration uses the Isovist-field test for visibility and the axial-map test for permeability. Whilst the application of Space Syntax to the case study site provides a vehicle for the research, a key aim of this project is to test the performance of the available software and identify its strengths and weaknesses. The final aim of this study are: revealing the areas with maximum views and vistas and identifying obstacles for views and The axial analysis for permeability can reveal the underutilised spaces in the early stages of design an urban master layout.

Keywords: Space syntax; parametric design; isovist; master layout.

1. Introduction

According to Winston Churchill ‘We shape our buildings; thereafter they shape us’ (speech, 1944). This is an indicator of the interaction between cities and citizens. City spaces and its inhabitants are interconnected and interrelated in various ways. For instance Tim Stonor’s recent studies on the integrity of urban spaces show that almost 80% of all retail shops in London (a significant contribution to revenue generation for the city) are located on 20% of the most spatially accessible (integrated) space. Spaces with less permeability and integrity showing the highest crime rate is also other examples of the interconnection and links between spatial configuration and inhabitant (Stonor, 2013). These type of socio-spatial connections and relations are some of the main drivers for urban planners. Urban planners aim to capture and manage these links not only between spaces and functions but also between social and behavioural connections.

Space Syntax is one of the methods and techniques that help planners to analyse spatial configurations. Over thirty years ago Space Syntax Theory as developed by Professor Bill Hillier and
Professor Julia Hanson in the book The social logic of space (Hillier & Hanson 1984), gained prominence in the field of urban planning. Space Syntax Theory argues about the importance of spatial configuration in human behaviour and efficiency of cities from the inhabitant’s point of view.

On the other hand shift to a computer aided design (CAD) was a major pivot for designers who utilised it in their designs, however, CAD technology is not able to simulate the situation but only can represent it. As Groat and Wang (2002) explain the term Simulation is often confused with the term representation, though they are in actual fact two different concepts. Simulation is more about prediction whilst representation is about demonstrating a scene at one point in time. Parametric design was another shift in the design environment which made a type of simulation possible using computers and software. Combining the CAD parametric tools and Space Syntax theory progresses the capabilities of designers in analysing the spatial configuration in their project and also enhances their ability to analyse existing and future urban spaces. Researchers at the University of TU Delft (Nourian; Rezvani; Sariylidiz, 2013) and TU Wien (Schaffranek 2014) are developing add-ons for Grasshopper that implement Space Syntax methodologies for designing as well. The significance of this combination is to provide designers a tool to assess the existing space and revitalise it through their design. This research study employed Space Syntax methodologies and parametric software tools to create more space analysis diagrams and layout options to provide planners an opportunity to compare alternative initial urban layouts. It provides an opportunity for them to combine the strengths of different options and eliminate weak points in the layouts to achieve the best feasible master plan.

The aim of this research project is to examine a parametric design approach to planning a vibrant town centre based on Space Syntax methodology. The research demonstrates a computational prototyping project which analyses an urban situation and explain a planning process to improve permeability, walkability and liveability in Rosebud a town in Victoria. The study employs Space Syntax methodologies and parametric software tools to generate different layouts to create a better connected town. The process of analysing urban space and generating initial layouts with Space Syntax theory can be implemented manually using several tracing pages, however, the risk of errors occurring increase due to the laborious processes involved. Recent advancements in higher performance computers and softwares involved in the urban analysis and Space Syntax methodology have been able to counter these manual processes. This research investigates the feasibility of using selected software and plugins to generate diagrams and layouts during the early stages of planning based on Space Syntax theory in a case study in Rosebud, Victoria. Parametric design software has become popular in architecture and other design fields. However in the urban planning field this method is relatively new. This research examines increasing efficiency of urban planners by creating more space analysis diagrams and layout options to provide them an opportunity to compare alternatives in a shorter period of time, combine the strengths of different options and eliminate weak points in the layouts to achieve the best feasible final master plan. For instance by analysing the Isovist field on site (the visible area from any nominated spot in a space), designers are able to identify the most visible areas of the site and allocate these areas to commercial and retail to maximise opportunities for businesses. It is recommended to read this study against the files and animations that generated in different software you can find on the ASA or author’s website.
2. Methodology

2.1. Space Syntax methodology

Space Syntax is a method of investigating how inhabitants of a space relate to the space itself and also each other. Space Syntax Theory examines how spaces relate to people, and influences social behaviour. Space Syntax introduces a set of techniques for the analysis of spatial configuration especially where it is a significant aspect of human affairs. Space Syntax methodology provides designers with a tool to simulate the likely effects of their design both in buildings and on a broader urban scale.

Space Syntax as a method for analysing space and its interconnection to a user of the space aims to quantify the quality of space. Quality of space in this context means the attributes of space. Some of attributes from Space Syntax point of view are: a space could be convex or concave, has a larger visible area or less visible area and be more integrated or less integrated with other spaces around. Space Syntax Theory argues that people behave differently in response to spaces with different attributes and this is the reason some spaces become more popular than others or why people have different feelings within different types of spaces. This response to different spaces is possibly a result of people's implicit recognition of different attributes (characteristics) of space. It is not an intentional reaction to space, it means people do not analyse the space while they walk down a street, however, it is a kind of psychological human response to certain characteristics in a space.

Development of Space Syntax methodology is an attempt to explain people’s behaviour as a result of attributes of space. It is a possibility, if Space Syntax is able to define the attributes of the space then create a technique to predict how people will behave in a space. Space Syntax aims to interrogate what constitutes character and attribute of space and as a result suggests how people will respond. For these reasons, this research paper will focus on using Space Syntax methodology as an analytical method for urban planning. Space Syntax Theory takes into consideration the following three main issues, the sense of movement through space, interaction between people in space and seeing ambient space from a point. Space Syntax implements mathematics to produce a methodology which is logically and mathematically provable and repeatable. The purpose of Space Syntax methodology is to create an outcome based on which designers are able to assess their design before construction.

2.2 Methodologies for simulation

For this chapter of experiments a series of software, plug-ins and add-ons are employed to simulate the process of configurational analyses based on Space Syntax Theory for the town centre of Rosebud. Some researchers are studying Space Syntax analysis using Grasshopper within their research (Nourian; Rezvani; Sariylidiz, 2013) however as far as this research paper is aware there is no existing unique software that is able to perform and visualise all aspects of Space Syntax methodology. The main aim of this study is to establish a general rule of procedural steps for using various software and add-ons (based on a given case study) for urban designers to analyse urban spaces. The approach in this research is the use of Grasshopper and its add-ons for the ability to instantly produce more layouts and provide planners an opportunity to quickly make comparisons between these alternate layouts. Although this study will require programming the main aim is to create a convenient process to analyse Space Syntax in urban design.

The process and simulation focuses on the following points:
• Generate the site under the investigation as accurately as possible for analysis.
• Simulate the axial map and analysis of the axial line of the site.
• Simulate and analyse the Isovist phenomena in the site.
• Prepare the initial layouts based on the outcomes of the above simulation.
• Adjust and redefine the initial layouts and simulate them to achieve more layouts.
• Compare alternative layouts to reveal the most effective one or combine the best parts of different layouts to achieve the most appropriate one.
• Design the final master layout.

This is an interactive process; it means after producing each set of analysis planners and architects can debate about the outcome and redefine or adjust all or some parts of the previous design until they believe the outcome has met their criteria. The final stage is to develop the best sketch layout to produce the detailed master plan.

3. Analysis

3.1. Pre-analysis

The first step of the Pre-analysis phase of this investigation is collecting data, information and drawing. Three main sources of information are applied in this study; Mornington council, OpenStreetMap (www.openstreetmap.org) and site visiting. The first drawing investigated for this study was a large CAD file from Mornington’s city council covering all of Victoria’s Southern peninsulas. A careful process of filtering and extracting the essential information from this CAD file is crucial to prepare proper drawings for the area under this investigation. The second source for obtaining data is the OpenStreetMap website. This website encompasses information of many cities and metropolitan areas around the world. Information from this website can be exported into a file which is visually interpretable with Grasshopper’s add-on ‘Elk’.

The next step is cross-referencing the previously mentioned obtained documents to identify any inconsistencies for any further modification. The ultimate goal for this stage is to produce a DXF file including the networks and the town of Rosebud. To achieve this goal the information extracted from these sources (Mornington Bay Council and OpenStreetMap website) need to be manually (through CAD programs) redrawn and simplified. The reason for this is plug-ins and add-ons of Rhinoceros are not directly cross compatible with interpreting the exported data from sources which contain a large number of curves and lines. Moreover, another complication is the disconnection between two lines or curves, resulting in an unsuccessful outcome. The best solution for this issue is to redraw (trace over) this obtained data in ArchiCAD or AutoCAD and export the result as a DXF file. In future, the ideal solution is to upgrade the plug-ins and add-ons to be able to tackle this issue and be able to use the files directly from other sources without the need to manually redraw.

3.2. Analysis

The analysis in this study has two main parts: axial-map analysis and Isovist field analysis. The first step in the process examines the existing network situation of the town of Rosebud. For the proposed examination, the DXF file that was generated through the Pre-analysis phase is then imported into the Depthmap software. The outcome of the axial line test on the proposed site revealed a poor integration of pedestrian accessibility between both sides of Point Nepean road which runs at an angle along the
grid. Currently, the over 50 metre wide Point Nepean road creates a physical barrier for pedestrian accessibility from both sides, which and acting as an obstruction to permeability. Several proposed alternative road configurations have been examined to determine the most successful one which shown on Figure . All proposed axes tested use Space Syntax methodology and the outcomes are compared against each other. It provides a guideline for designing the next axes leading to the next stage.

![Image of Point Nepean Road and proposed site](image)

**Figure 1:** Point Nepean Road with over 50 metres width and proposed site on the isolated side of Town

During the site analysis and site visit three main hotspots were identified for the town of Rosebud. The first hotspot is the food precinct on the south side of Point Nepean road; the second one is the Sound Shell (a shell like stage for music performances) on the North side of the Point Nepean road and lastly is the Rosebud Jetty located farthest from the site. These three hotspots formed a straight axis. Hotspots in the context of this analysis are attraction points for people. The site visit demonstrated that the food precinct is the most crowded place in the town and the sound shell is the place for various kinds of performances especially during summer. By preparing a connection between these three points hypothetically, a vibrant and active axis will form. The axis will maintain the flow of people and create a pedestrian movement path between nodes and the aquatic centre can enhance this phenomena. All these factors can theoretically create an active town centre for Rosebud.

Further examination of this axis reveals the potential for pedestrians’ activity. The test also showed that the proposed site for aquatic and town centre can be enhanced by making multiple connections from the existing road on the south side of Point Nepean road to the site. Figure 2.
The second examination of the proposed site is the Isovist-field. Isovist is the visible area from a single observation point and it continuously changes while an observer moves through space. For the site project the best integrated axial lines, mentioned above, have been used as the main guideline for initial sketching for the town centre master plan. These initial sketches for the master layout have interpreted this guideline into pedestrian movement. See Figure 3. This newly created pedestrian movement on the town centre acts as the ‘lifeblood of its urban spaces’ (Stonor, 2013).
At this stage, three main pedestrian movement paths which extract from initial sketch were tested for the Isovist-field which were utilised by Rhinoceros and Grasshopper. The Isovist-field investigation can be used for redefining or changing the master layout or the building on site to achieve the best visual integration. The first movement path is the axis from the food precinct to the sound shell as the pedestrians’ main access for the project. The second one is the north point access which indicates the direction towards the capital of Victoria, Melbourne. This axis has another importance on the site; it demonstrates the sea channel which all ships use to sail from the Ocean to Port Phillip and Melbourne. See Figure 4.

![Figure 4: Isovist-field for the intersection point of two axis that forms centre of civic plaza](image)

The Isovist-field can parametrically change, these parameters in this study research are the observer’s point of view and the radius of the observer’s depth of field. This study fixes the depth of field to a 500 metre radius and automatically changes an observer’s point of view. The axial map and Isovist-field test generates an initial layout for the master plan of Rosebud centre. This initial sketch which is supported by several tests developed to design a final master plan for the town centre of Rosebud and its aquatic centre. See Figure 5.
4. Application of analysis

This section investigates the application of axial and Isovist-field analysis in the field of urban design. This study discusses the above mentioned analysis to assist urban designers to gain a better understanding of their design before proceeding with large budget projects. This analysis is also applicable towards the process of revitalisation or remodelling of an existing urban area which uncover the elements that are under performing. These analyses provide evidence for designers and decision makers to support or reject a design or urban design strategy.

For example, the study on Isovist-field for the Rosebud town centre project proposal discovered that area A, (See Figure 6) was most visually accessible within the site and also from the commercial strip on the southern side of Point Nepean Road. Thus, appointing area A of the site for retail and commercial activities can further promote the growth for business. Additionally, this will vastly improve the project as whole to activate the civic centre. These analyses result in redefining land use and enhance the brief of the project to increase the chances of prosperity of the project from a financial point of view.
Another example of how these analyses form the urban design in this project is the axial map analysis for walkability. Although the Isovist-field analyses indicates visual access to area A, the axial map shows that area A is not easily accessible for pedestrians in regards to walkability. For instance, area A is easily visible from the southern side of Point Nepean Road, however, because of current poor permeability of Point Nepean Road physical access is affected. The reason for this repercussion is the large width of Point Nepean Road and the fast vehicular traffic that travel along it. The axial map analysis, See Figure 2, simulates a more walkable area from the southern side to the northern side of the road if road conditions were to change. The above investigations result in a new design for the master layout of Point Nepean Road.

These new conditions of the road are:

- To provide two alternative routes for the vehicles which need to travel faster.
- To reduce the width of Point Nepean Road to ten metres.
- Shared zones for Point Nepean Road with a maximum speed limit of 10kph for vehicles.
- Using cobblestone flooring and speed limit signs to indicate to motorists that Point Nepean Road is a shared zone for vehicles and pedestrians.
- Plant trees to produce shading for pedestrians using the road.
- Increase the footpath width on the commercial side to 8 metres to make the area more accessibly convenient for customers and retail owners.

These types of analyses provide the city authorities a tool to evaluate the planner’s design against Space Syntax methodology. Most times designers are pre-occupied with many other aspects of the project and are not fully engaged or understanding the bigger picture of the design in relationship to the

Figure 6: Master layout has designed based on Isovist and axial analysis. Area A shown in light red colour.
surrounding context or the impacts that their design makes on the site. In some cases, some designs that Architects propose for the project are flawed as Isovist and axial-map analyses are able to reveal inconsistencies and contradictions in their design stages. As an example, a cantilever in a project which is independently and aesthetically appealing blocks the view of a landmark for pedestrians, or a well-designed shopping centre without strong integration to the surrounding environment will have problems in leasing shops.

5. Future direction

This study examined the usage of parametric software and Space Syntax theory in design of a master layout from a real project. This experiment reveals the advantages of employing Space Syntax methodology for analyses of space configuration with parametric software and using the outcomes to design more vibrant and active urban spaces in accordance to the guidelines of the project. Despite being in the early stages, there are some individuals who are currently working on finding more convenient methods of conducting Space Syntax analyses utilising parametric software.

The type of issues raised in this research study that demands further investigation include, among others;

- Designing plug-ins for Grasshopper to demonstrate Isovist-field in 3D and analyse the volume of a project instead of its 2D floor plan.
- Designing plug-ins for Grasshopper to graphically visualise the outcomes of analysis rather than numerical values.
- Collaborating with designers of existing plug-ins to upgrade them in terms of being more effective and user friendly. For example some features of particular plug-ins are incompatible when files with many lines or layers are applied to them.
- Designing a single plug-in that incorporates the essential analyses from different plug-ins merged into one. Preparing an easy step by step manual or road map to use all of the above mentioned software and plug-ins in master layout designs to aid designers in implementing all the analyses more effectively.

6. Conclusion

A solid understanding of space attributes is the key factor for designers to create space configurations that meet the purposes of a project. Interpreting the intangible attributes of space to the tangible with an analytical method of decoding the quality of space configuration is the primary aim of Space Syntax theory. As Hillier says, ‘Configuration seems in fact to be what human mind is good at intuitively, but bad at analytically’ (Hillier, 1996). This research study conducted analyses under Space Syntax methodology and utilises the outcome to design a better living environment for residence for the town of Rosebud.

This experiment showed the feasibility of the combination of Space Syntax methodology for the analysis of the space configuration and parametric software. This provides planners and designers with a powerful tool to analyse their existing project for revitalisation or new design. These outcomes are used to evaluate their final urban design which in turn helps the designer produce a more accurate result in line with the purpose of the project. This research study shows the feasibility of this process through a case study and clarifies the existing opportunities and weaknesses as well. The next step is to make the
opportunities more accessible and clearer for designers to tackle the weaknesses and obstacles in the process as outlined in previous chapters.

The potential benefits are numerous. First this approach can maximise views and vistas and identify obstacles which might restrict these. Second the use of axial analysis can avoid the creation of “dead space” which is rarely visited by pedestrians and can become a location for crime or vandalism. Third the identification of hot spots where pedestrians’ activities is high can signal the best location for facilities and shops where maximum economic value can be exploited.

The future development of Space Syntax, building on the analyses outlined here, has the potential to assist designers to improve amenity, commercial value and public satisfaction at various scales of projects.

References

Interactive Environments and Collaboration
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Flipped teaching: finding room for interdisciplinary content and peer learning

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Abstract: Three years ago we introduced flipped teaching strategies to large cohorts of first-year university students learning about construction. Paradoxically, our aim in providing online content was to improve and expand the on-campus experience. By transferring lecture content online we were able to extend our two-hour face-to-face tutorials to three hours and also increase the interdisciplinary content in keeping with the spirit of our new undergraduate degree. The transition has not been without hurdles. Each semester we have refined content and adopted strategies aimed at consolidating and accelerating learning but we continue to be surprised by what students excel at and what they struggle with. As we begin our sixth experience of the flipped classroom, we are exploring the potential of learning analytics to promote a deeper understanding of core issues while concurrently struggling with the issue of students who come unprepared to classes. At the heart of this teaching and learning approach is the ambition for students to work collaboratively, bringing together knowledge across discipline domains and across learning styles and strengths. We see benefit in Eric Mazur’s iterative approaches to peer instruction to encourage deeper understanding of how structures, construction and materials interconnect into a knowledge system.

Keywords: Flipped teaching; learning analytics; peer learning; just-in-time teaching.

1. Background to flipped teaching

We adopted flipped teaching in 2013 for our classes of between 230 and 360 first-year students who were learning about construction. It was an opportunistic decision made possible by a $50,000 teaching and learning grant. We had just three months to transform the way we taught. We anticipated difficulties but, surprisingly, our anticipated problems were easily solved. We found unexpected hurdles and each semester we continue to make changes as we gradually learn what works.

Flipped teaching is not a new idea. The physicist and educator, Eric Mazur, back in the early nineties saw benefit in moving the lower-order teaching activities involved in content delivery out of the classroom in order to free contact time for higher-order tasks such as the application and integration of learning (Mazur, 2012).
The change from conventional lecture and tutorial structure to a flipped approach is summarised in Figure 1: In-class and out-of-class delivery. (source: Author based on Steed) Flipped teaching, which is also referred to as flipped instruction, the backwards classroom and the reverse classroom, turns teaching on its head. Content that is normally delivered face-to-face is delivered online. Online delivery has advantages; students can learn at their own pace and time replaying segments that are complex or confusing as required. This can be useful for students whose first language is not English, particularly because the content includes the introduction of construction terminology, which may be unfamiliar. Flipped teaching is more than introducing a blended learning environment for students where online resources complement physical and face-to-face resources (Garrison and Kanuka, 2004). Flipped teaching is a strategy that enables students to be more active in class.

The idea of students as sponges or blank slates ready to receive the necessary knowledge of their discipline is outmoded and yet the lecture format has remained intact for the past 600 years. Mazur (2012) suggests we are in the twilight of the lecture. The University of Adelaide is the first Australian university to propose the entire university transition to flip teaching beginning with first year students; their plan is to shift away from lectures to online learning integrated with small group work. The Vice-Chancellor, Warren Bebbington describes the lecture format as obsolete, ‘my view is they’re gone; they’re never coming back’ (Dodd, 2015). His view is supported by a recent study which tested the hypothesis that lecturing maximised learning and student performance (Freeman et al., 2014). Based on a meta-analysis of over 200 studies it was found that active learning in undergraduate science, technology, engineering and mathematics (STEM) courses improved student performance when compared with traditional lecturing. Results of the meta-analysis suggested that traditional lecturing correlated with students being 1.5 times more likely to fail than were students in classes with active learning.

Active learning requires students to undertake higher-order learning activities. Taxonomies of higher-order and lower-order learning tasks have been compiled with the most famous known as Bloom’s taxonomy (Krathwohl et al., 1964). Rote learning through memory of content alone is considered as lower-order learning whereas integration, application and creation of new knowledge is recognised as higher-order learning.

2. An interdisciplinary approach to construction teaching

Our construction subject introduces structural principles, material properties and construction strategies. Previously these three strands had been taught largely in parallel, with engineers taking a predominantly mathematical approach to teaching structures, while architects focussed on construction
Flipped teaching: finding room for interdisciplinary content and peer learning

learning using detailing strategies. We found students did not translate the learning across the different domains once they went into later subjects. Flipped teaching has enabled a more interdisciplinary approach. Using flipped teaching we have developed a hands-on experimental and case-study approach within the longer studio times.

As well, all students come together as a group for six-weekly sessions in the theatre. These sessions lie at the heart of our interdisciplinary approach. Because we are no longer focussed on delivering content within the lectures, we are able to run panel discussions with designers, project managers, construction managers and engineers taking students through the process of transforming a design idea into a built reality. Students begin to understand how professionals collaborate across disciplines.

This interdisciplinary approach is challenging for students as it requires them to apply many disparate learning skills and strategies but it also opens opportunities for students to excel in a range of ways. Howard Gardner challenged the idea of intelligence being a single entity by identifying seven types of intelligences. Arguably our subject now includes learning across all of Howard Gardner’s (1999) multiple intelligences with the exception of musical intelligence. Structural understanding involves bodily-kinesthetic, logical-mathematical and learning from nature. Construction and material learning involves visual-spatial understanding and learning through verbal linguistic strategies. Inter and intrapersonal learning underpin the studio learning using group work and peer learning (including group quizzes) and the out-of-studio self-directed learning.

Learning occurs through reading, research, analysis, experimentation, testing and review. Increasingly we are getting students back onto construction sites as a rich learning environment even though there are increased logistical hurdles with large student numbers and increased health and safety constraints within the construction industry. Through exercises, site visits, model-making and research, students learn about forces and support systems, the key material groupings of metals, masonry, ceramics, polymers and timber and basic construction strategies.

The learning outcomes for students are an introductory understanding of how structural principles, material properties and construction systems underpin the form and fabric of the built environment. Students are expected to develop an appreciation of construction processes and detailing and begin to understand how these are communicated within working drawings. More broadly, students begin to appreciate the environmental implications of construction decisions and how construction links to the local circumstances of available materials and labour.

We understand that even though many of our students may not have attended a construction site or laid a brick, they still bring a deep knowledge of structural and material principles developed through their day-to-day living. Likewise it is no longer possible or necessary for students to grasp the complete knowledge set needed to be effective within the construction-related professions. Techniques and terms learnt within the first-year of a university course might be out-dated by the time they graduate as the industry shifts towards more off-site construction and new materials and processes. Online resources means that information is readily accessible and so rote learning seems to be no longer useful. Instead, students need to have the skills to search, analyse, understand and critique construction; this requires first-principle knowledge about structures and materials. Our aim in the course is effectively to develop their intuitive understanding of construction based on the principles of structures, material groups and qualities, as well as building performance in terms of heat, light, moisture, air flow, longevity, ease of construction, ease of use, safety etc. Students tell us that they particularly value the hands-on learning of model building and testing as well as the learning from visiting live construction sites.
3. We made mistakes and encountered unexpected hurdles

Previously we had been giving two hours of lectures per week and these were always recorded and made available for students online. We found that many students were choosing not to attend the lecture classes, and preferred to listen online. By around the fifth week of the semester, the lecture theatre would only be one third full. For us this was a clear message that students could cope with flipped teaching approaches that would enable us to provide a richer on-campus experience using small-group strategies alongside a new kind of theatre experience. Instead of lecturing on content we were choosing to run six theatre sessions with demonstrations and panel discussions.

Things we thought would be hard were often easy but we sometimes found ourselves stumbling across unexpected hurdles. In the process of trying to resolve these difficulties we were forced to reflect on our own learning about teaching and the need to keep adjusting strategies particularly for those students who do not yet have the independent learning skills expected of university students.

The fundamental mistake we made in the first iteration of flipping the classroom was to simply record and upload the lectures that had previously been provided face-to-face. We were missing the opportunity to refine and focus content into themes and shorter blocks of delivery. By the second iteration we completely transformed the content and delivery into multiple short blocks, usually between seven to fifteen minutes each. We compressed content to the essential elements we believed students would need for the later studio class and we built stronger links between the online learning and the studio activities. This strategy of shorter videos not only helped us to better structure the content but also enabled students to more easily fit the videos into their lives.

The second problem, to do with WiFi connections in the theatre, was harder to anticipate as even the university information technology experts took some weeks to determine the cause. To encourage students to complete the weekly online learning we decided to do weekly quizzes when we came together as a group in the theatre. These quizzes contributed to a small component of the final mark. We researched audience-response devices and decided on phone-based licences rather than physical clickers, as students carry their phones whereas clickers would need to be handed out each week or remembered by students. We were in a new theatre and were told that the theatre was equipped with WiFi. We paid for licences and students logged on but when questions were asked only ten to fifteen per cent of the students were able to successfully upload their answers. It turned out that our new theatre was not sufficiently equipped for every student to be online concurrently. Our solution in the second iteration of the flipped classroom was to swap the quizzes to the studio time slot and to make them paper based. This solution has had benefits as tutors get immediate feedback on how their group of students is performing and they can quickly respond to gaps in knowledge.

There has been an unanticipated sense of loss for us as lecturers as we flip the classroom. Even though we present within the online content we had not anticipated the loss of the weekly lecture ‘performances’ in front of students. Lectures have always been a core teaching role for academics so it can be confronting to no longer experience that the same level of face-to-face contact time. Instead the tutors take on a larger role and the time we spend as a group in the theatre is used primarily for panel discussions with some Q+A and almost no traditional lecture content. One challenge from this is the requirement for greater instruction and coordination of the tutors than normal in order to ensure the content and activities are delivered in tune with the weekly learning objectives.
4. But some things went better than expected

One of our main concerns going into the flipped teaching mode of delivery was how to provide a professional online presence without access to affordable green-screen technologies and editing support. This has turned out not to be a significant problem. We did use some of our grant funding to do some introductory videos using green-screen strategies so students could see the lecturer in the first weeks. We then we did the bulk of the presentations using simple screen-capture software. The benefit of this basic and accessible technology is that we can easily redo and refine online learning each semester once we see what works. This means that the presentations are not as sophisticated or as entertaining as the online TED (Technology, Entertainment and Design) talks which have set a high benchmark in podcasts but they are kept succinct and focussed on content if not entertainment. Another successful decision was to translate podcasts into ‘You Tube’ formatting which has enabled students to access the content on a range of devices.

A decision bringing benefits beyond our expectations has been the shift from a two-hour tutorial to a three-hour studio format where students are doing hands-on exercises or site visits each week. The flexibility provided by shifting from two hours to three hours has been substantial. We try to largely complete exercises and feedback within the tutorial time, which frees up the students’ external time commitments to focus on the online learning and research for the main assignment. One of the great benefits of the three-hour studio has been that we can use the city and the campus as learning laboratories, taking students out to look at construction sites helping them to ‘see’ the construction, structural and materials decisions being made. The three-hour studio has meant that students can work their way through a complex set of working drawings, interpreting parts of the orthographic scaled drawings into full-scale diagrams as well as three-dimensional models.

5. Our evolving understanding of the potential of weekly quizzes

Students who attend to weekly online learning prior to the studio session will benefit more from the in-class small-group teaching and yet we are aware that not all students manage to keep up. Our initial strategy for the weekly quizzes was for every weekly quiz to contribute a small percentage to the final mark. While this made sense it caused more stress for students than we anticipated. In later iterations we therefore changed the quiz assessment so only three quizzes contributed to the final assessment mark. The non-assessed quizzes gave formative feedback to students who could see how they were doing in relation to others. In this sense, students perceived them as part of their learning rather than part of our ‘policing’ of learning. The performance metrics of the students undertaking the quizzes was invaluable for tutors to give on-the-spot instruction whenever it became apparent that students were confused.

In the most recent iteration we continue this structure but have inserted a group quiz based on peer learning strategies (Boud et al., 1999). After attempting the questions individually, students are randomly allocated to groups of three to negotiate an agreed response. In the process of negotiating an agreed response students need to either convince others or be convinced through explanation and clarification. Generally the wisdom of the group prevails and a higher percentage of answers are correct.

6. Learning analytics and the bell curve

The shift to quizzes has highlighted our access to what students know and how we can fill knowledge gaps. We record responses to every quiz and exam questions and get overall figures for the class. The
quizzes were an indirect component of the flipped teaching environment but we are finding them a powerful feedback loop for us to provide ‘just-in-time’ teaching and feedback (Novak et al., 1998). It has only been in the most recent semester that we have started to understand the potential of learning analytics not just to track students’ use of the eLearning environment and their marks for the subject but to provide studio content or extra eLearning in response to gaps in student knowledge. Learning analytics is defined as ‘the measurement, collection, analysis and reporting of data about learning and their context, for the purposes of understanding and optimizing learning and the environments in which it occurs’ (Ferguson, 2012, p. 304).

Tracking activity of students accessing the eLearning was not originally possible within our earlier LMS environment. For the most recent semester we developed a two-part linking into the You Tube based content which has enabled us to see who is viewing what and when. Figure 2 shows how students access eLearning immediately prior to an assessed quiz and prior to the exam. Further work can now be undertaken to see whether there is the expected correlation between accessing eLearning and assessment marks.

Along with the eLearning tracking we are now tracking more carefully individual components of assessment with the aim of developing stronger mastery of learning strategies. Even the summative assessment within the exam is in an accessible format that will help refine the teaching of learning for future cohorts. For example in this most recent iteration ‘load path’ understanding was a focus in studios and quizzes and we found students generally did well on these questions in the final exam but struggled with the simpler concept of a ‘beam span’. This detailed feedback will guide future teaching.

Our construction subject was a case study for a small research project exploring how students might also make use of learning analytics to gain insight into their learning using the subject assessment dashboard within the LMS environment. This work indicated that students were well equipped to reflect on and respond to the assessment although they tended to be primarily focused on whether they were achieving higher than the average score rather than whether they were on track to achieve their preferred assessment outcome. ‘For many students, the comparison of their data to that of their peers was obscuring their view of progress towards their overall goal in the subject. For example, although several students indicated that they were aiming for the highest grade possible, they were satisfied when they saw that they were performing slightly above class average’ (Corrin and de Barba, 2014, p. 631).
Since implementing flipped teaching strategies we are not yet able to confidently state that we are seeing an improvement in learning outcomes overall but we do see a wider division of students as results shift towards a double bell curve rather than single bell curve with a cluster of students excelling and another cluster of students struggling. This is not entirely unexpected, as flipped teaching strategies require students to be more self-organised in order to benefit from the studio format.

We see potential to develop the area of learning analytics particularly to provide us with just-in-time feedback to adjust teaching to improve learning but also to provide students with immediate feedback on how they are progressing relative to our expectations and relative to other students.

7. The textbook controversy

Our first-year students mainly come from secondary schools where subjects normally have a textbook comprehensively covering the content required for passing and excelling in the subject assessment. Prior to flipping the classroom, we provided students with a workbook which covered the core content and prepared students for the exam. Students appreciated this approach and have stated in feedback that they found the workbook approach reassuring, giving them a clear program of knowledge content. Given the student preference for a textbook or workbook approach, it is worth explaining why we have chosen to no longer provide the comprehensive handbook or workbook for the subject.

The role of university educators has shifted substantially over the last two decades as information becomes readily available to students. Academics no longer attempt to focus on content delivery and can instead start to help students develop a framework for knowledge and critical thinking and research skills. In teaching first-year students, we see advantage in providing a bigger framework of knowledge that maps out a pathway into professional practice rather than simply the foundation blocks needed for first-year students. We use a well-known text, which continues to be useful for graduates entering practice. We help students to manoeuvre through the text, highlighting differences in language and approaches across cultural and national boundaries.

This controversy around the role of the textbook highlights a particular difficulty we face as educators of first-year students who arrive at the university with expectations regarding the learning experience. Part of what we do as coordinators and tutors is to manage student expectations and introduce them to university learning. We have changed to flipped teaching but this is just one of the eight subjects they take in their first year which means that students are likely to be somewhat confounded by the multiple expectations of university teaching and learning.

8. What the students told us

In addition to the university’s regular feedback loops (subject evaluation surveys), we have implemented further feedback mechanisms. The most recent was a focus group over lunch on the final day of semester attended by 23 students (of the 230 strong student cohort). We offered lunch and brought together both international and local students of mixed abilities (based on assessment results at that time). These particular students attended because they were either invited or volunteered to take part in the session. We achieved representation across the studios but recognise that we were unable to guarantee balanced representation in terms of gender, SEO standing, local and overseas students, age, construction experience, learning styles etc. and that the composition of the group may distort the results obtained. The focus group was led by our faculty’s teaching and learning expert and no staff from the subject attended.
The focus group was structured into three parts. Students initially responded to a one-page SWOT Analysis (Strength, Weakness, Opportunity, Threat) with a request for one sentence on each. In addition, we prepared the list of adjectives shown in Figure 3: Survey instrument within focus group discussion and asked students to circle any they felt relevant and add more if they wished. We attempted to include oppositional adjectives but did not use the standard ‘likert’ style of questionnaire, which asks students to scale responses according to their degree of agreement. Our simplified method has advantages in being quick to answer and meant that students highlighted only those that were most important. The main part of the focus group was a ‘conversation with a purpose’ (Burgess, 1988) led by the faculty’s teaching and learning academic. The feedback from the three survey instruments of the SWOT, the descriptors and the focus group discussion is summarised below.

In the open-ended SWOT analysis, ten of the 23 students highlighted the eLearning as a strength and five suggested that uploading the lecture slides would improve the subject. Given the SWOT analysis was open-ended, we were not expecting this amount of repetition from students. However we were surprised that no students highlighted the site visits as a strength; indeed four felt the ‘site visits were not sufficiently organised’ and another two felt they ‘took a long time’. Given our large student numbers (up to 360 per semester) we consider it to be a logistical achievement to manage to negotiate access to 30-50 sites needed each semester. As we write, we are still pondering what adjustments we should make for future student cohorts and are somewhat reassured by the recently released Student Evaluation Surveys (SES) where one-third of the 90 students who responded with comments highlighted the site visits as a strength with none commenting negatively. Perhaps a structural difficulty of the SWOT method was limiting students to one positive comment only and almost fifty per cent choosing to highlight the eLearning. In the SWOT, five students felt there was too much information and not sufficient time for learning to ‘sink in’ and another felt the ‘eLearning took too long’. Five students found the three-hour studios to be long if there was not an activity, which is also a curious comment as we perceive each studio to contain an activity. Perhaps some activities with smaller bodily movements such as drawing were not perceived as activities. Interestingly, five students highlighted the difficulty of the new terminology being introduced as a threat particularly for students with language difficulties.
The adjectives most commonly selected and least commonly selected are noted above. Given the limited number of participants, we were unable to link the subject descriptors to the student descriptors but we aim to run the survey in future semesters to complement the standardised Subject Experience Survey undertaken by the university.

It was perhaps in the final conversation with students that some of the more subtle strengths and weaknesses were described. No student had been a part of a flipped classroom previously and they were interested in the experience and intrigued by the concept. There was consensus on the value of the new model, although different students appreciated the different strategies differently. For example, the video recordings were particularly welcomed by the international students present. In the focus group discussion there seemed to be agreement on the value the industry panel discussions and the more ‘hands on’ elements of the subject. A concerning consensus amongst the students that the weekly content delivered through the online platform was not related to the activities undertaken in the studio session. This feedback is both bewildering and alarming for us as we had focused on tailoring the weekly activities to apply and test the concepts and contents delivered online. It seems we need to further refine the communication and the weekly activities to ensure students are able to link the weekly iterative learning taking place rather than perceiving the online work to be unrelated to the studio content. A more thorough briefing with the tutors will also be needed to ensure they help students conceptualise the content in more holistic ways rather than seeing a disconnection between the hands-on learning and the online learning.

Students were asked to give feedback on the quiz format particularly as we had refined the quiz format in the most recent semester to include a group as well as individual response. In the focus discussion, students said the quizzes seemed to work well as accents and boosters in the subject’s progression even though four students highlighted the quizzes as a weakness in the SWOT analysis. Students said that they tended to catch up with online delivery when the quizzes have marks associated to them if they had dropped behind. The online statistics described in the section on learning analytics supports this statement. In terms of the group quizzing, the impressions were mixed. While some thought the group quiz was a good idea, others thought the outcome was too dependent on the particular group.

Students told us that the Discussion Board within the Learning Management System (LMS) was not a helpful tool for organization because it had no notifications, as opposed to Facebook which is what most of them ended up using instead. This may be an area for future improvement although we also see advantage in student initiated Facebook environments complementing the Learning Management System. Students did appreciate the Announcements we made within LMS because they did help with managing time and tasks.

9. Bringing it all together

The recently released university-wide Subject Experience Survey for the most recent semester included room for students to make multiple comments on the subjects. As well as the positive comments on the site visits there were many comments related to the restructuring of the subject.

Getting so much time with the tutor was good, as we were always able to ask questions. I liked that we did a lot of hands on activities in class, such as the model building, sketching, and walking around campus to observe the elements we were discussing. (Anon student)
Online learning is excellent and provides each individual student time to complete the study as they see fit—easily allows for revision through the week or at the end of semester and breaks down information into accessible sections. More subjects could take a leaf from the online information provided through this subject. (Anon student)

The entire structure of the course was brilliant. There was a clear educational progression over the course of the semester and the assignments and each weekly quiz complemented the learning process without being too much of a burden. The site visits were also great, but it would have been easier if they were coordinated and integrated into the schedule of the subject. (Anon student)

We are still refining our flipped teaching approach and learning (as teachers) with each iteration of the subject. Our next step will be to focus more on just-in-time feedback for students as they complete each set of eLearning and implementing Mastery Learning strategies into the quizzes. We would not consider returning to the traditional lecture format. We argue it is time for even the most engaging university lecturers to consider whether part of their content might be more efficiently and effectively delivered online. This online delivery can paradoxically enhance the on-campus experience for students and open up possibilities for more higher-order, hands-on, integrative and interdisciplinary learning.

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References

How do we sketch with someone 1000 miles away?: distance collaboration for designers

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Abstract: This paper frames preliminary explorations in the process of connecting new designers in an online, distance learning environment, developing strategies for distance education and collaboration. The research seeks to better understand the multifaceted issues developed by the loss of in-class face time in relation to growing global communities and education systems. The involved authors have begun to explore the complexities of not only communicating technical knowhow as it relates to design (both in terms of building systems and software instruction) but also at engaging the loss of the physical studio interactions. There has been substantial study regarding the efficacy of online instruction as it pertains to general subject matter, however, study into specific relationships and interactions in the design process remain fertile ground for research (Harrison, 2015). The authors are exploring remote technological solutions to support the behavioural dimension that in-class interactions provide (desk critique with trace paper, group critique, peer teaching, etc.). This paper discusses the implementation of an online instruction methodology while additionally exploring its efficacy in getting students to explore tools, ideas and concepts beyond simply following instruction. This seeks to engage the question – How do we sketch with someone 1000 miles away?

Keywords: Design; education; pedagogy; technology.

1. Introduction

This paper describes the initial steps that the authors have taken to develop a strategy that overcomes the challenges that conducting “real time” and interactive design crits with geographically separated participants presents.

This paper emerges from a project that began as a conversation between two people who were physically present in the same space at the same time. The participants, Ben Slee, an Architect, and Mark Olweny, Dean of Architecture at Uganda Martyrs University outside Kampala, identified the challenge of finding appropriately qualified teaching staff to deliver an Architecture degree of
international stature in Uganda. Through discussion, it was determined that it would be possible to connect collaborators from around the world to teach students in Uganda through a virtual communication array.

Subsequently, a series of corporeal and virtual conversations identifying challenges specific to teaching design and architecture took place and expanded the conversation beyond the preliminary team. There is no doubt that it has been tried, notably however, it is difficult to find a description of a framework that has been shown to be successful. There is also no doubt that many tools for enabling virtual conversations and sharing information in real time across the globe have been developed and are often available at no financial cost. However it is also clear that these are tools that we must learn to use, in the same way we learn to draw and share ideas, and that these tools do not facilitate the multiple and simultaneous communication methods that are present in the traditional design discussion or studio crit. Hence the question: How do we sketch with someone 1000 miles away?

2. Methodology and structure

The structure and methodology of this initial study follows the following format: The first part of this paper reviews existing practice and theory that explores interactions between people in the same physical space and in cyberspace. The second section describes a case study that used an online asynchronous instruction system to teach design. The third part of the paper reviews the technological hardware available to enable sketching in cyberspace. The fourth part of the paper describes and tests a two tablet system developed by the authors to enable synchronous sketching in cyberspace between people who are separated geographically. The fifth part of the paper sets out how this system can be used to deliver a unit of study to architecture students in Uganda and how the authors propose to evaluate the efficacy of the system.

3. Existing practice and theory

Mitchell (Mitchell, 1995) explores the implications of the emergence of cyberspace on how people interact with one another and therefore our conception of and creation of space (architecture). One of the themes that emerges is the significance of corporeal presence in our interactions and the opportunities and challenges that “dissolving the proscenium between the real world and the virtual” presents. The design crit is an excellent example of the challenges presented in mediating traditionally physical synchronous interactions into the virtual world.

The traditional studio based design crit involves a group discussion where each member and the tutor are physically present in the same space at the same time. Verbal communication is only one dimension of interaction and, as in all conversations, body language and eye contact are important for coordinating discussion. However, significantly, the design crit involves shared sketching in real time on paper where members of the group contribute to the same drawing, the manipulation and observation of physical models and physical gestures. It is this shared, multimodal experience that differentiates the design studio from other types of conversation. The act of sketching or drawing often elaborates on a reality and happens intuitively (Phillips, 2013). Sketching is to capture an animate thought, and is thus beyond perception (Fisher and Santacatterina, 2011). This action is completely transparent from brain to pencil (Lawson, 2014). Schon calls this "tacit knowledge" (Schön, 1983). The educational process simultaneously embeds several types of quale (a quality or property as perceived or experienced individually by a person).
Existing online teaching methods, which celebrate the monologue, are ineffective instruments in developing discussion beyond fact uploading and technical instruction. Within the literature review, online teaching is often engaged in lecture format; students review an online lecture, and are subsequently tested on that lecture material. These formats are monologues and discussion is limited to what can be articulated on online forums, an action that arguably eliminates the animate thought; the technology presents a sense of isolation within the digital environment (Carroll, 2013). The act of compression revokes the gestural thinking and the dialogue never evolves within a humanistic framework. These developing models are asynchronous and lose emotive engagement between participants. The design studio is a complex space where learning relationships and processes are constantly shifting between participants (Mewburn, 2012).

There has been substantial study regarding the efficacy of online instruction as it pertains to general subject matter, however, study into specific relationships and interactions in the design process remain fertile ground for research (Harrison, 2015). The authors are exploring remote technological solutions to support the behavioral dimension that in-class interactions provide (desk critique with trace paper, group critique, peer teaching, etc.).

3.1. Research framework – emotional response theory

This research operates from an Emotional Response Theory (ERT) framework. ERT as described by Mottet, Frymier and Beebe (2006) acknowledges the importance of implicit communication systems that are articulated through a system of various biologically shared signals (use of personal space, facial expressions, body posture, as well as paralinguistic features of communication such as tone, rate, pitch and volume (Mottet et al, 2006)). Under ERT, we see a constructed relationship in which the professor’s interactions with the student directly inform their emotional responses to content. While these messages are often unintentional expressions of underlying emotions (Mead, 1934), their impact plays a profound role in the design studio setting. ERT posits that the emotional state of the subject predicts whether they will approach or avoid places, ideas, etc, including how subjects approach or avoid learning (Mottet et al, 2006; Mehrabian, 1981; Russell and Barrett, 1999; Vinson and Biggers, 1993) and is supported by Biggers and Rankis (1983) who reported that emotions account for a large percentage of variation in research studies predicting behavior. Stated simply, ERT “predicts people will pursue what they like, people like what they feel positive emotions for, and people’s emotions are influenced by the implicit messages they received from others (Mottet et al, 2006).”

Within online learning environments, students may have issues establishing positive emotional experiences due, in part, to the lack of implicit messages being received from professor to student (Brooks and Young, 2015). Titsworth et al (2010) examined classroom emotion as influenced by three communication behaviors: non-verbal immediacy, clarity and communication competence. Brooks and Young (2015) observe that while clarity and communication competence might be transferable to online environments, non-verbal communication and immediacy, which play a foundational role in design studio crits, remain difficult to translate.

3.2. Historic and present technical limits of technology

Architects use sketching and diagramming in their design process to perform functional reasoning, formal arrangements, analogy transfer, structure mapping, and knowledge acquisition (Do, 2002). In recent years, the architectural design practice has witnessed a change in the use of technology, from the
important yet tedious Computer Aided Design (CAD) drafting of construction documents, to using digital tools to explore new design possibilities. Some of the changes in technology usage include: parametric interfaces to create and control 3D models, rapid prototyping, and virtual communication and collaboration. With regard to sketching, Lawson (1994) depicts the relevance of the ‘unique’ hand-brain connection and how it affects the design process. A technology has not yet been developed to remotely streamline the cognitive processes involved in sketching and diagramming.

In their research Broll et al. (2004) introduced ARTHUR as their solution to the limitations of paper-based sketches in collaborative architectural design. The ARTHUR system is an Augmented Reality (AR) enhanced round table that supports complex design and planning decisions for architects. As an approach to capture a designer’s thought process in sketches, Do (2002) proposes a framework for reasoning that is represented with drawing marks, acts, and reacts. This study illustrates the possibility of developing design support tools based on these concepts.

Van Dam (1997) wrote,

“Raster graphics-based networked workstations and ‘point and click’ GUI WIMP (Graphical User Interfaces based on Windows, Icons, Menus, and Pointing devices) are the legacy of Xerox PARC that we’re still using today”.

However, the dawning of ubiquitous computing is transforming and moving beyond Xerox PARC’s legacy. In 2010 George and Blake (2010) introduced Objects, Containers, Gestures, and Manipulations (OCGM) as the “universal foundational metaphors of Natural User Interfaces (NUI) paradigm”. If the next generation of design-related software and digital tools is going to fully integrate with the designers’ sketching and multimodal interactions, then these new human-computer interaction paradigms and NUIs will need to be developed around these intentions.

4. Online asynchronous Q&A instruction: case study 1

As a case study for online tutorial instruction, Professors Dustin Headley and Allan Hastings of Kansas State University engaged in the incorporation of online video instruction to resolve a lack of capacity in facilities. The studio environment included 27 second year undergraduate students that were subsequently spatially divided between two spaces, the design studio and the computer lab, to accomplish the design of prosthetic skins for 3D printing. All students had no prior knowledge in the computer and during the three week project were transient between the two spaces. Given the sheer number of students involved, it was impossible for each studio professor to effectively communicate with all students at both a technical and conceptual level within the scheduled timeframe (Monday, Wednesday and Friday from 130P-530P). As such, alternative methods of communication were engaged in an attempt to offset these issues. Students were charged with developing questions, both design and technically related, to communicate with the studio professors. The questions were then answered and shared through video conversation and demonstration through open discourse on Facebook.

As observed by the authors, the lack of one-on-one interaction had dramatic effects on how the students used the video feedback. Students consistently skimmed the conceptual discussion embedded in the video content to extract the more tangible instructional (how-to) content. The lack of implicit communication and immediacy cues projected to the students made the process of evaluating the value of different components of the content next to impossible. The students simply could not ascertain what was important for professional discourse and development beyond accomplishing the task at hand.
5. Review of the hardware: on the ground with the technology

Before thinking about developing an innovative system, the authors tested existing technology, specifically tablets. To achieve this, the authors developed an experiment to test three different tablets, comparing each for the participant’s functional preference.

The experiment methodology was simple: two video cameras were used to film the participants, each of which was given a simple sketching task to be completed using one tablet at a time (see figure 1). Later on, the participants filled out an Attrakdiff questionnaire (Hassenzahl et al., 2003) rating the tablet they had just used. There were small differences in the tasks with every iteration; this counterbalanced the order of the tablets and the task variation to help avoid bias. The three tablets used were: iPad air, Microsoft Surface, and Wacom CINTIQ. The task was to draw a simple floor plan for an apartment or small house.

![Figure 1: Participants creating their sketches.](image)

<table>
<thead>
<tr>
<th>Device</th>
<th>PQ</th>
<th>HQ-S</th>
<th>HQ-I</th>
<th>ATT</th>
</tr>
</thead>
<tbody>
<tr>
<td>iPad</td>
<td>5.142857</td>
<td>4.52381</td>
<td>4.352381</td>
<td>4.695238</td>
</tr>
<tr>
<td>CINTIQ</td>
<td>4.961905</td>
<td>4.447619</td>
<td>4.180952</td>
<td>4.704762</td>
</tr>
<tr>
<td>Surface</td>
<td>5.219048</td>
<td>4.695238</td>
<td>4.4</td>
<td>4.980952</td>
</tr>
</tbody>
</table>

Table 1: Answers to Attrakdiff questionnaire evaluating tablets.

\[\text{PQ} = \text{Pragmatic Quality} \]
\[\text{HQ-S} = \text{Hedonic quality - Stimulation} \]
\[\text{HQ-I} = \text{Hedonic quality - Identity} \]
\[\text{ATT} = \text{Attractiveness} \]
Initially, the authors hypothesized that the majority of participants would be familiar with iPads, which would be a major influencing factor. It was also thought that the high-end capabilities of the Wacom CINTIQ would be another major influence. Despite being right about participants’ previous tablet experience (12 out of 15 had previously used iPads) the Microsoft Surface was the tablet with the highest score across the four different products dimensions measured by the Attrakdiff questionnaire (see Table 1). The more expensive and arguably more capable Wacom CINTIQ was previously used by only one of our participants, who picked the Wacom as their preferred tablet. The main issue for the participants with the Wacom CINTIQ was the pen hovering feature (there is no contact with the surface of the tablet required to direct the pointer on the screen).

All the sketches created by the participants (See figure 3) where created using an HTML 5 online interface called A Web Whiteboard (https://awwapp.com/). During the first dry run for the experiment the authors realized that using a desktop based application, such as Autodesk Sketchbook, had one particular problem: The interface, while similar in icons, was different across the different tablets. This meant that in some of our first tests the participants ended up evaluating the graphical user interface (GUI) instead of the actual tablet. To avoid this, we moved to use the online software, which remained the same across all 3 devices.
6. Proposition: working synchronously while remote

There is no silver bullet. Based on our previous research into preferred interfaces, the Microsoft Surface Pro was selected as an ideal base technology to utilize in the development of an ERT driven critique rig that simultaneously embedded effective drawing tools and options in the coordination of the communication technology. The technology also lends the advantage of a full operating system.

A two tablet system was developed to enable remote communication within the student-teacher relationship. One tablet was designated for video conferencing while the other was oriented towards drawing and review. The tablets operate independently of each other. This enables the user the freedom to assume whatever body posture is comfortable with the drawing tablet without adjusting the video interaction (Figure 4).

To engage the multimodal dimensions involved in ERT, Zoom, a video conferencing and recording software was engaged. This engaged dimensions of facial expressions, body posture (environment dependent), as well as paralinguistic features of communication such as tone, rate, pitch and volume.

Figure 4: Shows the collaborative drawing on the tablet with the student at home on the other side of the work space.

Notably, while similar to tools like Skype, this software afforded more consistent audio and video quality. This software enables the consistent logging in and out of participants for a single user (the instructor sets up a nine to eleven digit conference code and the students join for their appropriate time, or multiple students join for discussion). Participants can record their crits, enabling the revisiting of content from the discussion, and thus expanding the potential value of the interaction, extending into theological dialogues that can be revisited. Further, recording enables the analysis of the interaction itself.

For drawing tablet, a combination of the online resource “A Web White Board” (http://awwapp.com) was embedded in Windows Surface App “Screenshot” by Wild Lion Software while also connected to Microsoft OneDrive. The resulting combination enables students and instructors to take pictures of their trace paper drawings for collaborative review sessions or google search images and load them in the drawing space, subsequently this enables the saving of images at any moment during process from either side of the conversation. With added features of OneDrive, previously
scanned trace drawings or computer renderings can also be at the fingertips of both the reviewer and the reviewed (Figure 5).

The resulting process embeds the advantages afforded by the technology (remote collaboration, synchronous engagement, extravagant documentation, etc.) with emotional response and interaction through drawing and the pen.

![Figure 5: LEFT, Shows first year design student receiving crit from remote reviewer. RIGHT, The resulting drawing for the collaborative discussion.](image)

### 7. Implementation: Uganda and beyond

This project was initiated by a desire to find a way of teaching Architecture students at the Uganda Martyrs University, Kampala. This final part of the paper addresses how this proposal can be implemented in that context and how we might assess its efficacy.

#### 7.1. The course

It is proposed that we develop and teach an undergraduate unit called “Design and Construction Technologies”. This course is intended to convey technical knowledge primarily through lectures and an understanding of “design”, or the ability to assimilate and synthesize that knowledge in the context of a site and a brief through a practical exercise taught through tutorials. The technical knowledge covers structures (beams, bending moments etc.), material properties and construction systems. The practical exercise covers the synthesis of that knowledge through the designing a simple structure with a particular brief on a particular site to create delight; the Vitruvian ideals of strength, utility and beauty.

#### 7.2. Practical arrangements

It is proposed that this will be achieved by developing a course where the lectures are delivered through video link. The opportunity for a question and answer session will be desirable but not necessarily required. The tutorials can be delivered using the tablet sketching system combined with the video conferencing system. This platform may be augmented by social network chat forums (e.g. Facebook) (Schnabel and Ham, 2014). The tutors will be drawn from leading practitioners around the world who are also experienced teachers. They will take charge of small tutorial groups, which is 3 – 5 students. It is anticipated that these students will, as a group, receive between 1 and 2 hours tutorial time each week. Coordinating international time zones may be a challenge however the platform allows student groups and tutors considerable flexibility in arranging and attending tutorials. There is, for instance, no need for
the tutor to be in any particular place for the tutorial they must simply have set aside the time and have an adequate internet connection.

7.3. Assessing the efficacy

The quality of the course and the delivery of the course will need to be assessed. It is anticipated that this will be done through quantitative and qualitative feedback systems:

- Qualitative student and tutor feedback

  A questionnaire will be developed asking students and tutors to score the following four aspects of the course on a 5 point scale (1 – poor, 3 – neutral, 5 – excellent) augmented by more detailed written feedback.
  
  - Ease of use
  - Ability to interact with the students
  - Ability to interact with the tutor (or other tutors)
  - Simplicity of timetabling tutorials

  Marks from the final assessments of student projects will also be used as an assessment tool. It is proposed that these marks are validated using an external moderation process with a group of tutors from a leading school of architecture outside of Uganda.

8. Discussion and conclusion

In this paper the authors have tackled the problem of delivering a studio based design course to architecture students in Uganda using tutors who are dispersed around the world. In particular the challenge of creating a "virtual" studio environment has been identified. A virtual environment that facilitates the exchange of ideas through shared sketching, physical gestures and emotional cues. A system using existing and readily available technology has been proposed. Finally a framework for implementing and evaluating the system has been proposed.

The system combines the advantages of web based video communication with a web based sketching tool to allow students and teachers to sketch with, speak to and see each other simultaneously. Combined with cloud based file storage it allows participants access to a record of previous ideas that are often lost in the real studio. Compared to existing on-line teaching systems the proposition prioritizes the synchronous engagement of the participants.

The project is at an early stage and it is clear that while the proposition offers enormous opportunities there are limitations. The complexity of the studio environment and the process of sketching has been identified by Mewham (2009) and Phillips (2013) where multiple methods of communication and thinking are applied simultaneously and the roles of teachers and students are often exchanged. The authors do not pretend that this proposition can replace or replicate that experience. Bandwidth, screen size and camera angle are obvious technological limitations. The emotional experience of video conferencing is very different from a conversation between people in the same physical space. Skills with the technologies, particularly the social/emotional skills for virtual communication along with the sketching and rendering skills appropriate for the tablet interface need to be developed by participants. This does represent a real hump for those participating, however, the benefits greatly outweigh the costs.
The final part of the paper set out a framework for implementing this system and the technology to deliver a course in Uganda and evaluate its efficacy. The next stage of this project is to develop and test that framework. This system creates vast opportunities for global collaboration between students, teachers, schools and professionals. Significantly it can allow those with significant expertise in designing and creating sustainable built environments to teach in cities and countries that are developing rapidly and who need to rapidly expand their indigenous professional knowledge base without being physically present. As this system develops it will allow all of us the opportunity to sketch with people thousands of miles away.

References


Harrison, D.J. (2015) Assessing Experiences with Online Educational Videos: Converting Multiple Constructed Responses to Quantifiable Data. International Review of Research in Open and Distributed Learning. Vol. 16 (1)


Onsite and online: a 4-dimensional multi-disciplinary learning environment for construction industry professionals

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Abstract: Work-integrated learning has been suggested as a means to apply theoretical knowledge in a real-world context. Yet tensions exist between the opportunities afforded by the workplace, and the demands of placing large student cohorts in that workplace while ensuring pedagogical rigour. For students in construction-related disciplines, access to building sites to contextualise learning is a further problematic issue. This suggests opportunities exist for alternative approaches to providing the benefits of work-integrated learning through simulated real-life contexts. This paper reports on an Office for Learning and Teaching funded project that investigates this issue. The project involves the development of an interactive digital learning environment based on time-lapse 3-dimensional (4D) visualisation and other resources associated with the design and construction of the University of Queensland's Advanced Engineering Building. The 4D environment provides a realistic context for simulated problems that activate student learning using a collaborative problem-based approach to enhance critical thinking skills. A pilot version of the 4D environment has been trialled and interim results indicate that the 4D environment is flexible in terms of its use across different learning activities and disciplines, and that it enhances the learning experience in terms of developing observation, reflection and collaboration skills.

Keywords: Digital learning environments; immersive learning scenarios; construction industry.

1. Introduction

Addressing the imbalance between theory and practice to produce graduates who can engage effectively in their chosen professional settings is a recently recurring theme in higher education (Kek and Huijser, 2011, Litchfield et al., 2010). Work-integrated learning, where students apply disciplinary knowledge and skills in a real-world context, is one approach that seeks to address this issue (Billett, 2009; Orrell, 2011). However, in construction related industries such as architecture, the ability to
contextualise learning as a realistic experience is hampered by the dangerous, fragmented and litigious nature of the industry (RCBCI, 2002; Safe Work Australia, 2012). There is also limited involvement of the tertiary sector in construction-related research. Innovations in the industry, therefore, have a tendency to be retained as proprietary knowledge for competitive advantage. Conversely, the generic body of professional knowledge has a tendency to remain static, standardised and largely theoretical (Johnson, 1972; Macdonald, 1995) with academics reporting that they have difficulty in maintaining an industry-relevant contemporary knowledge base (Ostwald and Williams, 2008).

Much has been made in the higher education literature of the advantages of work-integrated learning, both as a means to address the practical application in a real-world context of the disciplinary knowledge and skills gained in a classroom (Billett, 2009; Smith, 2012), and as a means to engage students in what it means to participate in a real work environment (Orrell, 2011). However, tensions also exist between the opportunities afforded by the workplace, and the demands of placing large student cohorts in that workplace whilst ensuring educational validity and pedagogical rigour (Lester and Costley, 2010). This suggests that opportunities exist for alternative approaches to the provision of work-integrated learning through an alternative technology-enhanced medium (Keppell et al., 2011). While computer simulated virtual reality environments linked to gaming technology have been developed as educational platforms, there are limitations to the contextual realism and practical detail offered by such environments. An alternative approach is to create a virtual environment based on digital photographic images captured across the course of a ‘live’ construction project.

This paper reports on interim findings of an Australian Office for Learning and Teaching funded project titled ‘Developing a 4-dimensional interdisciplinary learning environment for construction industry professionals’. The two-year project consists of four stages with the digital learning environment prototype currently being trialled across three Universities, five programs and seven courses. The following paper is structured to initially provide background to the challenges facing the construction industry and education. With this context in place, the paper then describes the 4-dimensional (4D) learning environment, including the various approaches to the use of that environment in the three courses that have trialled the prototype so far. The paper concludes with a summary of the results of a questionnaire survey administered to students involved in the initial trials.

2. Contextualising the learning environment

2.1. The challenges facing the construction industry

The construction industry is a significant sector of the Australian economy. In 2008-09, construction accounted for 6.8% of Australia’s gross domestic product (GDP) making it the fourth largest contributor to GDP. In the same period, 984,800 people or 9.1% of the workforce were employed in construction related activities making it the fourth largest employing industry in the country (ABS, 2010). A further small but growing contribution is made by the sector to national export earnings, primarily in the area of specialist architectural and engineering consultancy services (DFAT, 2011). At a broader socio-environmental level, the construction industry has a further considerable impact on quality of life and the sustainability of that way of life, principally through the design of safe, liveable and energy efficient buildings and urban environments. Having a strong and innovative construction industry is, therefore, an important foundation for Australia’s future.

Recent studies, however, suggest there are several fundamental flaws in the structure of the industry. In 2002, the Royal Commission into the Building and Construction Industry (RCBCI) described
the industry as having a highly complex and competitive structure that limited innovation and contributed to poor productivity. Furthermore, the Commission noted that new construction projects were designed and managed on an individual basis and drew on a disparate range of skills that varied throughout the life of the project. The Commission concluded that the transient and multi-disciplinary character of construction projects, together with the fragmented nature of the industry and adversarial procurement methods, impacted on the capacity for innovation and continuous improvement across the construction supply chain (RCBCI, 2002). Recent industry figures and academic studies indicate little has changed. There continues to be a high number of small firms operating in the industry and a high degree of specialisation (IBISWorld 2012). There also continues to be concern about the capacity for innovation, particularly in relation to collaborative practices (Dossick and Neft, 2010), knowledge management (Sheriff et al., 2012) and the integration of new technology (Love et al., 2011a and 2011b).

2.2. Challenges facing education for the construction industry

In an extensive survey, Ostwald and Williams (2008) explored changes in the structure and content of architectural programs across Australasia, and the future challenges facing architectural education. The study concluded that curriculum ‘overcrowding’ (too much material), curriculum ‘drift’ (course isolation from foundational knowledge) and curriculum ‘fragmentation’ (non-design courses perceived to lack relevance) have undermined the teaching of core professional skills in architecture programs. While construction technology, one of four main curriculum areas, had maintained a relatively consistent weighting at 19-20% of coursework offered in an architecture program, the demands on technical content had changed significantly. There was also a perception amongst academic staff that maintaining industry-relevant knowledge was a problem. In a study of the advantages of immersive learning environments for engineering students, Cameron, et al. (2009) found that the loss of industry placements was having a further impact on the level of insight and appreciation of design and operational issues amongst undergraduate students.

An additional issue for the education of construction industry professionals is an expectation that graduates will be able to operate effectively as members of multi-disciplinary teams. The Oswald and Williams (2008) study reported that the design and assessment of group work was a growing educational challenge. This finding was reinforced by Tucker et al. (2014) who established that there was limited emphasis on the teaching of teamwork skills in architecture and related design programs. There was also limited understanding amongst academics of what leads to effective teamwork, and how to design curriculum that would enhance the learning of teamwork skills.

Finally, several studies have explored game-based computer simulated virtual reality learning environments. de Freitas and Neumann (2009), for example, reported that the self-directed nature of computer simulations had the capacity to empower learners. There is, however, still a need for structured activities and academic interaction to support the acquisition of primary knowledge before more open-ended exploration can be effective. Marcelino et al. (2010) found the level of user interaction to be a major strength of computer simulated environments. While an avatar navigating through a virtual world is interactive, navigating in learner teams through a live construction site provides a level of real complexity that further enhances a sense of collaborative immersion and experience relevance. More recently, Nadolski et al. (2012) argued that computer simulations support the acquisition of higher order skills more efficiently and effectively than traditional learning methods, despite acknowledging high initial costs and the need for research on the effectiveness of knowledge and skills transfer in different practical settings. To date, no studies have been found that focus on the
development of a 3-dimensional learning environment using digital photographic images of a ‘live’ construction process over time (4-dimensions), and none have been found that compare computer simulated with photographic digital learning environments.

3. Developing the learning environment

In December 2013, a project team representing architecture and civil engineering at the University of Queensland, construction management at the University of Newcastle, and architecture at the University of South Australia were awarded a 2-year $220,000 Australian Government Office for Learning and Teaching (OLT) Innovation and Development grant. The primary goal of the project was to address problems associated with the provision of a realistic, practical and multi-disciplinary experience for students in construction related professional disciplines. The project was designed to build on an existing OLT funded 3-dimensional learning environment for process engineers developed by Professor Ian Cameron and others (Cameron et al., 2009). The project utilised 75 high resolution, 3-dimensional digital photographic surveys undertaken at 1-2 weekly intervals (4-dimensions) throughout the construction of the University of Queensland’s (UQ) Advanced Engineering Building (AEB).

The photographic surveys, and processing the surveys into an initial 4-dimensional digital learning environment prototype, were undertaken through a University of Queensland Teaching and Learning Strategic Grant. The photographic surveys utilised a Nikon D200 digital SLR camera with an AF DX 10.5 mm fisheye lens, and AF-S DX VR Zoom-Nikkor 18-200 mm and 55-200 mm digital lenses for general photographic work. The digital images were uploaded onto a computer at the conclusion of each survey. AutoPano Giga V2.6 software was used to stitch and render photographs taken at each survey node into large panoramic photos. PanoTour Pro V1.7 software was used for internode and equipment hot spotting, and the export of KrPano panorama XML files. KrPano software provided the 3D panorama functionality. Finally, Microsoft OneNote software was used to digitally mark-up the location of survey nodes on floor plans and a unique python script program was used to calculate node coordinates.

While documenting every aspect of the construction process as frequently as possible was a temptation, it was determined that this would ultimately reduce the effectiveness of the final 4-dimensional environment as a learning tool. Incremental changes to the overall construction site and progress on important building elements would become imperceptible. Navigating through the site once the data had been built into the software would also be difficult. To achieve a consistent and concise survey over the course of the construction period, the following rules were devised:

- Avoid capturing redundant and repetitive construction processes that deliver minimal educational impact and increase the processing workload and file storage requirements.
- Conduct a test survey to become familiar with the site and determine the ideal survey locations.
- Avoid survey nodes on temporary structures that become unavailable at a later point in time.
- Where a temporary obstruction does occur at a survey node, find the next best or closest location to continue the survey. Identify the original node to be revisited at a later point in time.

Comparison screenshots of the 4-dimensional learning environment are shown in Figure 1 (Survey 3 dated 7 June 2011) and Figure 2 (Survey 34 dated 7 March 2012). Figure 1 is taken from Level 2 and Figure 2 is taken from Level 6 of the building. Both shots are facing in the same southwest direction with Figure 1 taken at the edge of the construction site and Figure 2 taken from within the building itself. The timeline across the bottom right of the screen allows students to move chronologically between surveys, the plan at the bottom left of the screen allows navigation horizontally between several nodes.
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on a particular level of the building, while the vertical bar between the plan and timeline allows navigation vertically between levels of the building. Within the learning environment, students can use a mouse to rotate each image 360 degrees horizontally and vertically, zoom in on particular areas to better assess detail, and enlarge the floor plan to move around the building.

Figure 1: 4D construction learning environment, Level 2 Node 6 dated 7 June 2011.

Figure 2: 4D construction learning environment, Level 5 Node 2 dated 7 March 2012.

In addition to self-directed access to photographic surveys that visually capture the construction process over time, the prototype has been expanded to incorporate other resources associated with the design and construction of the UQ’s AEB (drawings, contract documents and interviews), as well as simulated problems to activate student learning (Francis and Shannon, 2013) using an immersive learning scenario approach to enhance critical thinking skills (Kek and Huijser, 2011). Additional resources are available using a drop-down menu. This particular project is unique in that it integrates ‘factional’ contract and project management resources, as well as interviews with key members of the
design and construction project team, to enhance the real-life context. In so doing, the environment expands the existing 3-dimensional images into a multi-user 4-dimensional learning environment.

4. Methodology

The 4-dimensional learning environment adopted an ‘exploratory learning’ pedagogical model (de Freitas and Neumann, 2009) derived from Kolb’s (1984) ‘experiential learning’ model. Kolb’s original four-stage model defined a cycle of learning from concrete experience, to observation and reflection on that experience, to forming abstract concepts, before testing in new situations that in turn become concrete experiences. In Kolb’s model, experience relates exclusively to ‘lived’ experiences. Technology-enhanced learning approaches, however, may relate to virtual experiences and ‘transactional’ learning, or set tasks designed as a choreographed, team-based learning pathway. The resultant five-stage model separates Kolb’s second stage into exploration and reflection stages, emphasising the expanded role of social interaction in the immersive learning experience. Within this framework, the 4-dimensional learning environment has been utilised in a variety of ways across four disciplines and seven courses, from a self-directed learning resource to an immersive learning environment (Table 1).

Table 1: 4-dimensional learning environment pilot study participating courses and learning activities.

<table>
<thead>
<tr>
<th>Program and Year</th>
<th>Course Title</th>
<th>Learning activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1, Bachelor of Construction Management (Building)</td>
<td>Building Codes and Compliance (250 students, mixed-mode)</td>
<td>Evaluation of fire safety issues in an immersive learning context. Direct assessment of student comprehension using codes, construction drawings and 4D environment.</td>
</tr>
<tr>
<td>Year 1, Bachelor of Construction Management (Building)</td>
<td>Construction Technology 1 (350 students, mixed-mode)</td>
<td>Demonstration of site safety issues and construction processes in a lecture context. Indirect assessment of student comprehension using construction drawings and activity sequencing in the 4D environment.</td>
</tr>
<tr>
<td>Year 2, Bachelor of Engineering</td>
<td>Reinforced Concrete Structures and Concrete Technology (250 students)</td>
<td>Demonstration of concrete design and construction processes in a lecture context. Indirect assessment of student comprehension using construction drawings and activity sequencing in the 4D environment.</td>
</tr>
<tr>
<td>Year 3, Bachelor of Architectural Studies</td>
<td>Architecture and Technology (99 students)</td>
<td>Demonstration of services and sustainable design integration in an immersive learning context. Direct assessment of team-based comprehension using construction drawings and the 4D environment.</td>
</tr>
<tr>
<td>Year 3, Bachelor of Construction Management (Building)</td>
<td>Construction Business Management (150 students, mixed-mode)</td>
<td>Evaluation of management actions in an immersive learning context. Indirect assessment of student comprehension using role-play, reflection, factional contract documents and the 4D environment.</td>
</tr>
<tr>
<td>Year 2, Master of Architecture</td>
<td>Architectural Practice 2</td>
<td>Evaluation of contract administration issues in an immersive learning context. Direct assessment of team-based comprehension using factional scenarios and the 4D environment.</td>
</tr>
</tbody>
</table>
The 4-dimensional learning environment project adopted an action research methodology (Easterby-Smith et al., 2008) to ensure feedback was incrementally collected and fed back into the developing learning environment. The project was divided into four stages of approximately six-months each:

- Development – investigated alternative learning strategies and technology options, access to construction documentation and key personnel, and existing course curriculum.
- Usability trial – established how best to integrate other resources into the learning environment, devised new curriculum and assessment strategies, and trialled Version 1 of the 4D environment.
- Pilot study – embedded of other resources into the learning environment and conducted pilot trials of Version 2 of the learning environment.
- Evaluation – will see the incorporation of pilot study results into Version 3 of the learning environment and further trials before and finalisation of project.

5. Results – Prototype trial and pilot study

In Semester 2 2014, an initial usability trial of the 4-dimensional learning environment Version 1 was conducted with Year 3 Bachelor of Architectural Design students at the University of Queensland (UQ). The trial employed an in-class scenario-based activity each week for four weeks. Scenarios required students to access the 4-dimensional learning environment and observe specific structural, environmental and construction issues. The aim was to engage students in team-based problem solving and reflection on how particular construction activities are carried out, and specific building elements are fabricated. The scenarios also aimed to link those activities and elements to the 2-dimensional information communicated in construction drawings. This was followed in Semester 1 2015 by a pilot study with Year 3 Bachelor of Architectural Studies students at the University of South Australia (UniSA). The pilot study used Version 3 of the learning environment as an in-class demonstration tool and resource for additional self-directed student learning. Results from a five-item Likert-type scale and open-ended evaluation questionnaire administered to students are summarised below. Fifty-nine of 98 or 60% of students enrolled in the UQ course completed the usability trial survey, while 57 of 99 or 58% of students enrolled in the UniSA course completed the pilot study survey.

5.1. Appearance

In response to Question 1, ‘Did you like the appearance of the learning environment?’ 19% of UQ students and 33% of UniSA students strongly agreed, while a further 57% of UQ students and 63% of UniSA students agreed with the question. Question 5 was an open-ended question that prompted students to offer suggestions for future improvement. Positive responses were made about the realistic appearance of the site, rather than the appearance of the learning environment itself. Suggestions for improvement in the usability trial included increasing the size of the floor plan in the viewing pane and enabling different floor plans to be overlaid to show the relationships between them. This has been addressed in Version 3 of the learning environment. Further comments from both cohorts related to image sequencing with suggestions that images showing particular views should be taken from the same nodal position in each survey, and on each building level. This would enhance user orientation from survey to survey but cannot be undertaken retrospectively. The variable vertical and horizontal progress of construction activity also make it a difficult undertaking for any future case study projects.
5.2. Navigation

In response to Question 2, ‘Did you find the learning environment easy to use?’ 12% of UQ students and 28% of UniSA students strongly agreed, while a further 54% of UQ students and 63% of UniSA students agreed with the question. Navigation, or ease of use, generated significant written comment in the usability trial. Although intuitive, many described the environment as ‘slow to load’, and that it ‘froze’, ‘stuttered’ or ‘crashed’ during use. The node selection function on floor plans was similarly problematic and there were difficulties with the chronological survey selection function. Specifically, adjustments to the timeline slider caused the view to zoom out and the node to relocate on the floor plan causing confusion and frustration. These basic functionality issues were addressed in Version 3 and there were fewer comments about ease of use in the UniSA pilot study but several references were made to the consistency of node locations from survey to survey.

5.3. Content

In response to Question 3, ‘Did you find the learning environment assisted your understanding of architectural technology?’ 25% of UQ students and 23% of UniSA students strongly agreed with the question, while a further 56% of UQ students and 70% of UniSA students agreed with the question. Despite appearance and navigational issues, the positive impact of the learning environment on student understanding of the construction process was almost universally supported in both the Version 1 usability trial and Version 3 pilot study. Open-ended responses indicated that the environment provided more information than 2-dimensional photographs or ad hoc site visits, and was a useful tool for understanding the day-to-day operation of a construction site. Positive feedback was given in relation to enhancing understanding of construction sequencing, as well as the requirements of particular construction activities and specific building elements. Additional comments related to the way the learning environment revealed the building structure and architectural detailing, while the zoom feature enabled valuable close examination of particular details. The learning environment was also considered to aid comprehension through comparison of 2-dimensional construction drawings and 3-dimensional images. Suggestions for improvement included the incorporation of time-lapse videos of key construction processes to help bridge the 1-2 week gap between digital surveys.

5.4. Learning experience

Question 4, ‘Did you find the learning environment enhanced the architectural technology learning experience and, if so, why?’ resulted in 12% of UQ students and 23% of UniSA students strongly agreeing with the question, while a further 67% of UQ students and 66% of UniSA students agreed. Comments about the extent to which the environment enhanced the learning experience referred to the creation of a positive link between theory and practice, bringing the construction process to life, and helping to consolidate theoretical material presented in lectures. Some suggested concepts explained in lectures became easier to visualise 3-dimensionally after using the learning environment, while some in the usability trial commented that the learning environment facilitated group collaboration and discussion, which in turn enhanced their understanding of coursework material. The instant access from classroom to construction site was considered a positive, as was the capacity to re-visit the site and follow aspects of the construction process independently. Suggestions for improvement in the usability trial included more defined learning tasks with clearer aims and links to assessment. A guided tour was suggested as well as more detailed whole-of-class explanations of construction processes and building elements as students using the environment discover them. Respondents in the pilot study found the
site to be a useful interactive visual aid that enhanced their comprehension, while the capacity to view 2-dimensional and 3-dimensional information together enhanced their understanding.

5.5. Improvements

Other suggestions from both the usability trial and the pilot studies included developing the learning environment for use on a tablet and providing additional building case studies of various scale and complexity. Having consistent node positions on each floor and across each survey was a common request as was including call-out labels to explain key construction processes and building elements.

6. Discussion

The 4-dimensional learning environment prototype has, thus far, been well received by students and academics in two different programs. The possibilities offered by the learning environment range from use as a simple demonstration tool for an academic delivering a conventional on-campus lecture through to an immersive learning scenario and assessment system requiring engagement with the full array of resources offered within the environment (contract documents, construction drawings, 4-dimensional images, and interviews with key project team members). It is apparent, however, that the learning environment used as a simple visual aid represents a shallow engagement with the pedagogical possibilities that it offers. While there are issues, such as dependence in pre-determined nodes and the consistency of node locations from survey to survey, the learning environment can provide genuine and cost-effective improvement over traditional lecture-tutorial activities but only when it is fully utilised and holistically integrated into the curriculum. ‘Virtual’ work integrated learning has the potential to satisfy, at least in part, student and employer demand for a balance between theory and practice, and provide work-ready graduates who have the capacity to engage immediately in their chosen professional settings. The benefits are, however, contingent upon the skilful integration of immersive scenario learning into those parts of the curriculum where their full benefit can be realised.

7. Conclusion

Work-integrated learning as a means to achieve a balance between theory and practice is a topical feature of higher education (Orrell, 2011; Smith, 2012). While work experience has had a long tradition, particularly in professional education, the pressure of student numbers and the need for pedagogical rigour have impacted on the opportunities available for students to spend time in workplace settings of relevance to their degrees. In construction-related professions, workplace health and safety concerns have an additional impact on student access to ‘live’ building sites. Within this context, opportunities exist to explore alternative ways of providing the benefits of work-integrated learning through simulations of real-life contexts. Although studies have explored computer simulated virtual reality environments, none have focussed on the development of a 4-dimensional learning environment based on a ‘live’ construction project. The OLT funded project outlined in this paper is an attempt to provide such an environment for the education of construction industry professionals.

Acknowledgements

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Modes of Production and Mass Customisation
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Digitally fabricated housing: tracking the evolution through two decades

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Abstract: The author is investigating the ability of digital fabrication tools to provide an alternative method for creating affordable flexible single family residential units as a part of an ongoing PhD research. This paper presents a review of previous attempts within the time frame of twenty years with a thorough analysis and breakdown of the prototypes. It provides a time line tracking with milestones of the usage of digital fabrication tools in housing construction. The analysis will include but not limited to: Design/construction time – overall cost – materials for primary/secondary structure – tools for virtual design/actual fabrication – special design methods/considerations (when applicable). The case studies are organized in a comprehensive chronological table. The paper suggests there are three main trends for digital fabrication in housing.

Keywords: Digital fabrication; housing; low-cost; low-impact.

1. Introduction

There is an incremental increase in the demand for housing units with the growth of the population especially in poor and developing countries (UN, 2005). Many countries face very high risks with the spread of informal housing settlements around large cities. Moreover, according to United Nations Higher Commission for Refugees global trend report (UNHCR, 2015) an estimated 13.9 million individuals were newly displaced due to conflict or persecution in 2014. This includes 11.0 million persons newly displaced within the borders of their own country, the highest figure on record. The other 2.9 million individuals were new refugees.

It’s undoubtedly a global crisis that is formulating with almost 60 million persons living in camps or currently homeless. Putting these factors into account, a novel rapid low cost housing methodology needs to be created as the practice of construction industry in these countries lacks efficiency and is one of the economic sectors with the lowest productivity and industrialization rates (Alvarado and Turkienicz, 2010).

Meanwhile, with the rise of personalization and individualism, mass customization is becoming an important business strategy for several types of industries. The unstable and unpredictable demand
levels; heterogeneous desires; price, quality and style consciousness; high levels of buyer power; competitive intensity; product differentiation; and market saturation are among the forces shifting the focus of manufacturing from mass production to the new paradigm of mass customization (Pine, 1993). In order to implement mass customization, it is necessary to integrate various manufacturing technologies into a structured framework capable of combining human and technological factors in addition to old and advanced technologies.

Various modernist architects have been fascinated with the concepts of pre-fabrication and industrialization of the building industry specifically in the field of housing. Numerous attempts were made during the last decades to design and construct houses with a notion of “one size fits all”; a strategy that had its motivations and justifications after WWI and II. More recently, with the integration of parametric design tools with robust digital fabrication technologies, a new paradigm has started in which these technologies promise to address the design and construction of housing units with more flexibility and variation, hence a more customizable approach.

2. Aim and Objectives

The aim of this paper is to analyze the previous trials and built prototypes of digitally fabricated housing in order to understand whether they would qualify as long-term solutions to the shortfalls of housing units in developing countries. The paper also discusses the degree of success of the precedents in providing adequate solutions for their intended purposes. The discussion is made on the basic characteristics relating to cost, flexibility, convenience and environmental responsibility.

The selection of the case studies in this paper aims at displaying a representative sample that covers the spectrum of digitally manufactured housing not only from a time-progression point of view but also highlighting the trends and milestones in the development of this specific housing construction methodology. Table 1 provides a timeline of the selected projects and their analyzed aspects. It is challenging to draw a precise line between “prefabricated” and “digitally fabricated” housing, as prefabrication occasionally includes parts or assemblies that were constructed using digital fabrication tools. The case studies in this paper represent prototypes that used digital manufacturing technologies for the major part of the construction, e.g. primary/secondary structure.

Due to the novelty of some of the case studies and the difficulty of finding reliable published information, the author established direct communication - when possible - with parties involved in design and construction in order to guarantee the accuracy of the information provided. The data gathering techniques included but were not limited to emails and inquiries through official websites.

3. Trend 1: Social orientation, democratization of manufacturing

A common trend that is community enabling and socially oriented can be deducted from the following case studies. We can also note that these prototypes were defined as post disaster interventions and basically reliant on the end-user as an active contributor not in the design process but more in the construction phase. Since the community is at the heart of the process; open source digital information, Hackerspaces (Hackerspaces, 2015) and Fablabs (http://www.fabfoundation.org/fab-labs/what-is-a-fab-lab/, 2015) become the core of this trend for housing development. The highlighted examples used a puzzle like, do-it-yourself approach as a means to reach an efficient, rapid and affordable construction. The degree of success in reaching these goals is yet to be evaluated.
3.1. Case study 1: The instant House, Massachusetts, USA

This prototype was a research initiative by Professor Larry Sass in the department of Architecture at MIT in 2006. The aim was developing a novel design and fabrication process for mass customized emergency, transitional and developing contexts (Botha and Sass, 2006). The Instant house process produces a customized, habitable mono-material plywood structure, assembled manually with rubber mallets and crowbars. The materials are connected with a limited number of joint types that sustain their assembly through friction, such that nails, screws or glue are not needed during assembly.

The process proposes the development of an automated generative system, first for shape design and secondly for fabrication through a generative subdivision based on the Wood Frame Grammar (Sass, 2005). Sass (2006) proposed a framework for the design and fabrication process associated with the instant house which is basically divided into 5 different stages: shape design, design development, evaluation, fabrication and construction.

According to Sass (2006) the parameters for the initial shape design are defined based on regional criteria with a set number of variations assigned to each parameter. Parameters include climate, location, spatial constraints, vernacular influence and stylistic variations. Afterwards, the selected iteration goes through a preliminary evaluation process. The design development phase involves the subdivision of the initial surface model in CAD using Wood Frame Grammar (Sass, 2005). After the design development process produces parts for fabrication, a scaled laser cut model is produced using the same geometry for full-scale house. This scaled model is used for the confirmation of construction sequence and subjective design evaluation in real space. The fourth stage “Fabrication” is the stage in which machine G-Code generation, nesting, cutting, post processing and packing are performed. The fifth and final stage is “Construction” in which two people construct the one-room cabin in three days eliminating the need for cranes and scaffolding due to small component sizes that can be easily handled.

3.2. Case study 2: The Shotgun House, New Orleans, USA

As a progression based on the previous work done by professor Larry Sass in MIT on the instant house, the digital design and fabrication unit lead by Sass developed another prototype for the New York MoMA exhibition: “Home delivery, fabricating the modern dwelling” in 2008. The design was based on a classical style New Orleans house known as the “shotgun house”. The intent was to show diverse potentials for using digital fabrication technologies for building a fully ornamental legacy house in a post disaster area like New Orleans that was hit by Hurricane Katrina in 2005. The house was assembled of 5000 plywood components all held together by friction, with no nails or glue. This structure used the same system of wood joining used to construct the instant house out of plywood (Sass, 2005). Secondary components (ornamentation, doors and windows) were also sustained by friction/snap-fit.

3.3. Case study 3: ECOnnect, Delft, Netherlands

Pieter Stoutjesdijk and Hugo Nagtzlaam, two Dutch architects based in Delft, initiated a small company called “ECOnnect” with the main aim of developing an open source platform for exchanging design and fabrication information related to building digitally fabricated houses. They partnered with ECOboard, a company that produces bio-based panels from agricultural residues such as straw and reeds (Stoutjesdijk, 2014). Their motivation was to provide an adequate housing solution for the exponentially increasing population through democratization of the manufacturing process. Stoutjesdijk (2013) argues that the direct connection between atoms and bits offered by digital fabrication enables
the creation of buildings in the same way software is created. Digital, customizable blueprints of physical building parts could be shared and developed globally like pieces of source code for a script, before directly being constructed locally with digital fabrication devices.

One of the first applications was a post-disaster mid to long term shelter designed for Villa Rosa; an informal settlement in Haiti. In February 2014, ECOnnect started producing the first full scale house in the Netherlands. The estimated budget for the construction of the house is 10,000 US dollars in developing countries and twice as much in the United States and Europe. They claim to have reached a concept that perfectly fits its climatic, cultural, technological and historical context. The final results of these efforts are yet to be seen and evaluated with the final constructed house.

3.4. Observations

Since these prototypes were basically designed for post-disaster situations, they do not offer large spaces with flexible layouts. The surface area is a demanding requirement when it comes to long term living (excluding New Orleans shot gun house which offered a reasonable living surface area of 55 m²). When it comes to cost, the three case studies did not include wet and technical spaces which significantly reduces the complexity of the design and construction and thus the cost. However, it can be easily understood that in a refugee or post disaster camp using private amenities attached to or integrated in each unit is considered a luxury. The use of a monolithic material such as Plywood or ECOboards in addition to end user involvement for assembly on-site also contributes to cost savings.

When it comes to environmental performance, there were no environmental analyses performed through the design of the above mentioned prototypes, at least in published work. Claims made by their authors for reducing carbon print and being environmentally driven was not substantiated by early design analyses or ecological foot print calculations. However, their main focus was more oriented towards speed, cost and ease of construction in hazardous situations.

This work opens up an interesting line of research but it remains unclear how it can be applied to larger housing types. It might be difficult to maintain a straight correspondence between design and building components beyond a certain scale.

4. Trend 2: Seeking technological efficiency

In the middle of the spectrum lies another group of case studies that combine an economy and efficiency stand point with technological automated tendency in search for efficient, allegedly affordable long term housing. The core value here is not “affordability for all”; in contrast, it is more related to the exploration of potential savings in materials, resources and construction time.

4.1. Case study 4: System 3, New York, USA

Two Austrian architects: Oskar Leo Kaufmann and Albert Ruf designed a prototype for the Museum of Modern Art exhibition in New York held in 2008. The exhibition “Home Delivery: Fabricating the modern dwelling” aimed at showcasing diverse procedural, formal and technological innovations in prefabricated architecture. Kaufmann had designed System 1 and System 2 with a kit-of-parts approach instead of modules or blocks in 1997 and 2001 respectively. System 3 used a different approach to the design and construction by dividing the house into two basic zones: Serving space and naked space. The serving space comprises wet spaces, vertical circulation element and technical spaces for electricity and heating and was completely manufactured and assembled off-site while maintaining its size within a
standard container. The naked space is the rest of free space that can be configured based on personal needs and preferences of end-user. It is also digitally fabricated off-site and flat-packed into a container.

The prototype presented in MoMA exhibition (2008) was considered by Kaufmann and associates to be the nucleus of the system and the simplest form of what could be achieved through its use. The aim was developing a system that is expandable, movable, affordable and for lifelong use. The elementary material used for the whole building was timber which gives the building a monolithic feel extending from inside to outside.

4.2. Case study 5: Micro Compact Home, Munich, Germany

A team of researchers and designers based in London and technical university of Munich (2001 to 2005) developed the concept of the Micro compact home in response to growing need for short term living accommodations for students, business people, leisure use andweekenders. The inspiration for the design of this micro house was basically taken from Japanese teahouses combined with efficient space planning usually deployed in aircraft, yachts and cars manufacturing (2015). The main structure is timber framing with Polyurethane foam for insulation covered by Anodized or Polyester powder coated Aluminum external cladding. The house is planned for basic human needs within a space of 2,4×2,4×2,4 m.

4.3. Observations

Despite the very small surface area of Micro-Compact Home (6.75 m²) which definitely translates into cost savings for running costs of maintenance and operation, the initial cost for construction is surprisingly high. According to the official website, the price provided for a single unit and frame (excluding delivery, installation, connection to services, consultants’ fees and taxes) is 43 000 USD. The inclusive guide price is from 56 000 to 100 000 USD subject to site conditions. The average price per unit meter in this case is almost 10 000 USD, which is definitely high compared to average construction prices in Europe. Space efficiency and compactness is a strong feature in this house design, which might be logically tied to affordability, but on the contrast, this house provides a striking example on the higher end of the economical scale of digitally fabricated houses.

On one side, building a customizable system using dual zoning approach adopted in System 3 has a great potential. The flexibility offered in the use of naked space opens different configuration possibilities including vertical stacking and future extensions and more flexibility for end users. On the other hand, using timber as a monolithic material for the façade and interior finishes with perforations in the exterior skin is highly questionable from an environmental performance point of view. Although exterior timber panels were covered with insulation paint, it would surely be a concern in more extreme weather conditions. The cost for this prototype was not available as it was financed by different sponsors for MoMa exhibition. However, compared to other prototypes it can be projected that the budget is not on the higher end of the spectrum.

5. Trend 3: Process-driven

With an obvious lean towards the process, these prototypes showcase explorations and conceptual investigations towards how buildings are to be constructed. The motivation for authors of the following prototypes was always the process and know-how and the expansion of possibilities and potentials of digital fabrication tools with small or no regard to economical drives.
5.1. Case study 6: Cellophane House, New York, USA

At the higher end sits this built prototype designed by Kieran and Timberlake, two American architects based in Pennsylvania, USA. They took part in the New York MoMA exhibition: “Home Delivery: Fabricating the modern dwelling” held in 2008. Despite the fact that this house is not entirely digitally fabricated, it is safe to conclude the involvement of digital fabrication devices in many aspects of construction. A strong link was established between design and construction activities through extensive use of Building Information Modeling tools. The building was entirely modelled to very high levels of detail, and the model was used to communicate the development of the project with different manufacturers(2015). Designers claim to have used a paperless process from conception to final assembly. Construction was broken down into “integrated assemblies” defined as “Chunks” and wholly manufactured and assembled off-site then delivered via trailers to the site.

5.2. Case study 7: Facit Homes, London, UK

Facit Homes is a London based Studio and workshop designing and manufacturing custom designed digitally fabricated housing. They claim to be the first company in the world to use a purely digital design and production process from conception to final fabrication(facit-homes.com/making-it-happen/budgets-prices-costs, 2015). They registered a trade mark for the process called “D process” in which a “Mobile manufacturing unit” is delivered for the construction of the house on-site. Their design and construction process starts with preparing a full detailed 3D model in a CAD environment. Designed parts are then nested and cut using a computer numerical control milling machine on-site. The milled parts are then assembled into bigger building blocks (cassettes) that can be handled by one or two unaided people. The cassettes are assembled like pieces of Lego with high precision tolerances. They argue that this process is more efficient and consumes less time compared to standard construction methods. Despite using digital fabrication technologies for the manufacturing of the majority of components of the building, Facit Homes team still relies on professional carpentry experts for manual work(facit-homes.com/making-it-happen/budgets-prices-costs, 2015).

5.3. Case study 8: Embryological House, California, USA

Within the time frame defined for the scope of this paper, “Embryological House” (1997-2002) by architect Greg Lynn signals a milestone in digital design and fabrication of housing units. Although it was highly theoretical and chronologically precedent compared to other case studies, it offered a novel notion of house typology beyond the modernist “kit of parts” model to an organic, flexible, genetic and generic prototype from which an infinite number of iterations can be generated(Lynn, 1998). The project was developed with geometrical modeling and character animation software (MicroStation and Maya), as well as digitally-generated physical mock-ups(Greg Lynn: Embryological House, 2007). One of the most prominent aims of Lynn’s creative process is pushing the capabilities of existing automated manufacturing technologies for the production of non-standardized architectural forms.

The Canadian Centre for Architecture (CCA) houses the physical mock-ups and digital files associated with the project. And while a number of its iterations have been sufficiently developed to allow their construction potential to be tested to a certain extent, a constructed architectural version has yet to be built. Embryological House remains a conceptual project as originally designed - existing entirely in digital format.
5.4. Case study 9: 3D Printed Canal House, Amsterdam, Netherlands

This is an ongoing three years research activity initiated in 2014 by DUS Architects, an Amsterdam based architecture office founded in 2004 by Hans Vermeulen, Hedwig Heinsman and Martine de Wit. The aim of their research is to explore potentials of 3D printing for building industry through building an actual full-scale house on one of the canals of Amsterdam. Canal houses have a big significance and symbolism to the history of Amsterdam. They try to investigate what this traditional archetype can be in a 21st century context showing how to combine traditional local values with new innovative ideas (http://3dprintcanalhouse.com/construction-technique, 2013). The DUS team is performing many trials and building prototypes using different materials for 3D printing with a main focus on bioplastics. They aim to print with a material that is sustainable, of biological origin, melts at a relatively low temperature, and has structural capacity. They are also researching the possibilities of printing with recycled materials like plastics, but moreover looking into using wood pallets and natural stone waste.

5.5. Observations

It can be seen from these case studies that cost savings were not the driving force for development of these prototype. For instance, the overall cost for Cellophane house was within one million US dollars for a house that is 168 m², resulting in an average of 6000 US dollars/m² which is definitely higher than the average construction costs of 1500-2000 USD (Dol and Haffner, 2010). However, very useful lessons can be learned from this specific prototype; just to name a few:

- The use of controlled factory environment for construction provides better control on overall quality of constructed assemblies.
- Robust planning using BIM tools resulted in an ease of assembly and disassembly of a relatively large multistory building.
- Almost all parts can be reused in different configurations as they were disassembled with no material loss.

On the negative side, using aluminum as primary structure raises concern about embodied energy due to high energy consumed for manufacturing of profiles. The thermal bridge effect caused by high conductance of aluminum is also questionable.

On the other hand, environmental aspects of Facit Homes built prototypes were considerably better than other case studies. They include better insulation means, air tightness and overall passive design ideas. They have been designed on a case by case basis which also accounts for better fitness to context.

Although not being the only or the first investigation into 3D printing applications in construction, the canal house represents an important milestone in housing applications, due to its scale, material selection and location and the fact that it is multi-storey. Advantages of 3D printing over traditional building techniques: the possibility of using a high level of detail and ornament; variation as the process goes straight from raw material to final product, thus eliminating waste. There are no transport costs, as designs can simply be transferred digitally and printed locally. In terms of disadvantages, it is evidently a huge challenge to create a building that complies with current building regulations as there is the question of insulation, fireproofing, wind loads, foundations, etc.
<table>
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<th>Country</th>
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**Table 1:** Timeline of Digitally fabricated housing from 1995 to 2015

<table>
<thead>
<tr>
<th>Micro Compact Home</th>
<th>The instant house</th>
<th>Lobolly House</th>
<th>System 3</th>
<th>Cellophane House</th>
<th>New Orleans House</th>
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**Table 1:** Timeline of Digitally fabricated housing from 1995 to 2015

<table>
<thead>
<tr>
<th>Materials</th>
<th>Primary Structure</th>
<th>Secondary Structure</th>
<th>Claddings</th>
<th>Interior finishes</th>
<th>Process</th>
<th>Tools</th>
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<td>Plywood</td>
<td>Plywood</td>
<td>Western red cedar timber - glazing</td>
<td>Plywood - Sanitary fixtures in stainless steel</td>
<td>Full CAD modeling - Partial fabrication - Off-site full assembly - One module delivery</td>
<td>Various CNC Milling</td>
</tr>
<tr>
<td>Plywood</td>
<td>Anodized Aluminum profiles</td>
<td>Plywood</td>
<td>Plywood</td>
<td>Plywood</td>
<td>Shape generation - Scripted part and joint generation - Puzzle Approach</td>
<td>Rhinoceros - ETCam</td>
</tr>
<tr>
<td>Plywood</td>
<td>Bosch Aluminum Framing + Steel Connectors</td>
<td>NA</td>
<td>Skins: Transparent PET recyclable Material with PV cells</td>
<td>PVC</td>
<td>Full BIM from conception to coordination - integrated assemblies</td>
<td>Revit Architecture - Rhino - ETCam</td>
</tr>
<tr>
<td>Plywood</td>
<td>Plywood</td>
<td>NA</td>
<td>Plywood</td>
<td>Plywood</td>
<td>Shape generation - Scripted part and joint generation - Puzzle Approach</td>
<td>CNC Milling</td>
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<td>Plywood</td>
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<td>Plywood</td>
<td>Plywood</td>
<td>Shape generation - Scripted part and joint generation - Puzzle Approach</td>
<td>Manual Carpenter</td>
</tr>
</tbody>
</table>

**Table 1:** Timeline of Digitally fabricated housing from 1995 to 2015

<table>
<thead>
<tr>
<th>Facit Homes</th>
<th>ECOHouse</th>
<th>3D Printed Canal House</th>
</tr>
</thead>
<tbody>
<tr>
<td>2012-present</td>
<td>2013</td>
<td>2014</td>
</tr>
<tr>
<td>London-based firm - K. Bell</td>
<td>London-based firm - K. Bell</td>
<td>3DUS Architects</td>
</tr>
<tr>
<td>Pieter Stoutjesdijk &amp; Hugo Nagtegaal</td>
<td>Pieter Stoutjesdijk &amp; Hugo Nagtegaal</td>
<td>Amsterdam, Netherlands</td>
</tr>
<tr>
<td>Off-going</td>
<td>Off-going</td>
<td>In-coming</td>
</tr>
<tr>
<td>Variable</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

**Table 1:** Timeline of Digitally fabricated housing from 1995 to 2015
6. Discussion

The paper tracked a number of prototypes and built projects (Table ) that highlight different approaches and stand points towards the relationship between manufacturing technologies and construction industry. Some research initiatives and published work approach digital fabrication from a completely industrial, mechanical point of view, attempting to completely alter how buildings are conceived by applying mass production/mass customization technologies which are widely used in vehicles, aviation and other well-established manufacturing industries. Two of the strongest advocates of this approach are Stephan Kieran and James Timberlake. They skillfully demonstrate that contemporary building construction is a hierarchal process, in both design and construction, where segregation of intelligence and information is the norm(Kieran and Timberlake, 2004). Parties involved in the construction industry (architect, contractor, consultant, client, etc.) are motivated and derived by different goals which represent a process that is not as efficient as it should be.

On the other side of the spectrum lies a different approach which considers fabrication as a tool to empower people to think, build, experiment and be able to realize their own ideas away from corporate gurus, hence it takes more of a social decentralized standpoint. Supporters of this approach are trying to disseminate technology transfer and education through Fablabs and Hackerspaces which have at heart the issue of public enabling and democratization of the means of design and production.

Between these two approaches exists a great pool of opportunities and spaces to explore potential synergies between local craftsman knowledge and expertise and sophisticated new technological solutions in search for economic and efficient construction. It can be seen from selected projects that some powerful conceptual ideas are yet to be developed into more robust solutions. Potentials for future work and development in the field of digitally manufactured housing is far from conclusive.

7. Conclusions

The author will build on understandings obtained from analysis and evaluation of precedents to develop a system that is self-sustaining specifically in developing countries from an economic, social and environmental point of view. A theoretical framework will be formulated for the next stage of the research investigation in which the proposed system attempts to offer new ranges of flexibility through the following procedures:

- Merging concepts of “Kit of parts” with pre-assembled modules “Chunks” in search for more freedom in formal and spatial expression.
- Space planning with social factors in consideration; for example: open kitchens are not widely embraced due to the nature of food and cooking activities that have strong odors. It is also well-known that families in developing countries are mainly extended families with relatively high number of children which in turn necessitates gender separation for sleep space planning.
- Maintaining a maximum affordable budget with respect to construction costs in developing countries which are quite different from European and American bench marks for affordable housing.
- Exploring the use of local recyclable sustainable materials.
- On-site fabrication creates user involvement and attachment which in turn translates to a more successful housing intervention.
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From research to practice: exploring 3D printing in production of architectural Mashrabiya

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Abstract: Digital fabrication has suggested the supplanting of labour via robotics since it affords substantial increases in speed and accuracy in the development of architectural components. This potentiality might offer solutions for architectures on the verge of extinction due to vanishing skilled labour. This research investigates the possibilities of using new manufacturing techniques to replace the historic artisans with digital master craftsmen, specifically re-developing the Mashrabiya. The work looks at several case studies in architecture and 3D printing; bridging the gap between historically relevant climactic design strategies and digital or parametric design and fabrication. This paper concludes with a summary of a parametrically developed Mashrabiya screen system developed by the authors that is programmable based on core criteria found in the archetype and is currently being explored for product development. The work contributes to the developing body of knowledge surrounding the applications and implications of technologies that enable mass customization.

Keywords: Mashrabiya; architecture; 3D printing; façade; parametric design.

1. Introduction

“Architecture needs mechanisms that allow it to become connected to culture. It achieves this by continually capturing the forces that shape society as material to work with it. Architecture’s materiality is therefore a composite one, made up of visible as well as invisible forces.” Moussavi (2008).

Contemporary 3D printing is currently disputing the boundaries of construction and manufacturing which were previously confined within traditional making techniques. As a result, this is generating a gap between digital intentions and physical media (Choma, 2010). Choma (2010) appropriately asked the question: “How do we qualify the necessities of fabrication processes in the current discourse?” Market demands and the changes in social lifestyle have demanded innovation of traditional products to suit today’s needs. In the Middle East, since the early ages of the Islamic religion, the harsh environment...
and the social variables have shaped design, architecture and product manufacturing (Fathy, 1986). The complexity of such culture is seen in the production of Mashrabiya, an element that operates within social, architectural, cultural and environmental infrastructures. This traditionally hand crafted architecture is an “endangered species” as a result of the loss of the required craftsmen in its construction.

Formally, the Mashrabiya is a wood lattice screen, that is then manufactured by crafting and assembling an array of small wooden parts that are then fitted together to form the overall assembly. Historically, this system has maintained five architectural functions through parametric variation of its members: passage of light, control of airflow, temperature of air current and humidity, and the privacy of the woman’s quarter (Harim) in courtyard houses in the Middle East (Fathy, 1986). The small wooden parts are made in a variety of ways, however, more commonly, they are turned on a lathe by hand or machine.

Within digital fabrication, technology has begun to suggest the supplanting of labor via robotics since it potentially affords substantial increases in speed and accuracy in the development of architectural components and assemblies while also maintaining specifically programmed dimensions of craft (Dritsas and Yeo, 2013). If form does in fact follow parameters through specifically articulated protocols (Anderson and Tang, 2011) then perhaps the appropriate answer to Choma’s question is in the translating and subsequent reprogramming of culturally relevant architecture constructs through proper design and manufacturing.

This work is an investigation into the possibilities of using new manufacturing techniques that replace the historic masters with digital craftsmen and a 3D printer of large scale objects such as Mashrabiya screens is discussed and tested here. The work looks at several case studies in Architecture and 3D printing; bridging the gap between the digital intentions and physical media while simultaneously engaging demand, function and manufacturing. This research contributes to the understanding and implications of technologies that enable mass customization. The designed screen product hints to its economic model, as well as an inventory of prices and materials of large scale printers. This will be significant in predicting the future benefits and obstacles of 3D printed large scale architecture products in the coming 5 - 10 years. This research represents the second phase of a three year research project, looking into these manufacturing processes and parametric programming of the cultural and functional conditions. The role of the new protocols in current practice is the core of this research.

2. Manufacturing architecture in the age of the 3rd industrial revolution

2.1. 3D printed architecture products

Rapid Prototyping or 3D Printing is an additive CAM process through which various materials are layered through various machining processes. The materials utilized typically are intended for a short life expectancy and are non-performing structurally; they are meant for immediate analysis and evaluation of form, scale, fit, etc. (Rael and Fratello, 2011). Exceptions to this are emerging as the parametric modeling and digital optimization become more integrated into the design process. Crolla and Williams (2014) Smart Nodes, is a strong example of how the technologies are enabling new modes of production and assembly in Architecture. As noted by Crolla and Williams, this technology is not necessarily “new” but as its patents have begun to expire the machines and the materials have become prolific and omnipresent. It can be hypothesized that the cost of this technology could potentially be reduced to the
extent that additive manufacturing could be competitive with traditional manufacturing (Crolla and Williams, 2014).

Winsun Decoration Design Engineering Co. already advertises the 3D printing of homes as a ‘Product’ (yhbm.com, 2015) (Figure 1) and Brian Peters (2013) has developed 3D printers capable of 3D printing customized bricks that are parametrically optimized around structural and ornamental performance.

![Figure 1: Winsun Decoration Design Engineering Co. Concrete 3D printing homes technology (http://www.yhbm.com/index.php?m=content&c=index&a=lists&catid=67).](image)

While questions arise in light of this revolution as notions of authorship become relevant and the cultural implications of potentially supplanting construction labor loom in the future, this technology has great potential to save historic architectural paradigms and construction types (Dritsas and Yeo, 2013). Given that, according to WinSun, the Egyptian government recently put in a 20,000 unit order with Winsun, the revolution is upon us. The potential for the exploration of 3D printing being informed by parametric systems guided by culture and environmental issues exists, but simultaneously the risk of generating an expansive Pruitt-Igoe that might not able to be killed with dynamite also looms on the horizon.

### 2.2. 3D printed architecture products deriving function from Mashrabiya

A conceptual pod based on the Mashrabiya passive ventilation characteristics, the Microclimates project, proposed by Postler and Ferguson in 2009, adopts a Grasshopper algorithm to deform an Islamic pattern into a several standing 1-2 meter pods that are claimed to passively cool the nearby environment if supplied with water from top. Depending on sand material supplied and printed by D-shape the concept targeted hot humid climates but was never built due to possible high cost. The second concept was recently promoted by Emerging Objects (Fratello 2014) in its cool brick product and wall assembly. Using ceramics and a porous form to act as a cooling screen in arid climate.

Both cases relied on the environmental quality of Mashrabiya screens but almost ignored the aesthetics and culture as well as the social domain Mashrabiya screens act within. A closer object to Mashrabiya social role can be seen in 3D printed textile as both serve a veiling role. However, structure
complexity, material durability and surface quality are still a concern. Research in both ceramics and wood as well as other sustainable resources, like salt 3D printing, is ongoing and promising.

3. Digital & physical development of 3D printed parametric Mashrabiya

Currently, the authors’ research is exploring the potential for 3D printing a culturally informed, environmentally reactive Mashrabiya screen system that leverages the manufacturing capacities of 3D printing. Notably, other means of fabrication were also explored, but none yield the flexibility of full customization in the way 3D printing can. In developing the reactive digital representation, Grasshopper 3D was utilized to redevelop the diagram that drives the geometries of the tradition Mashrabiya. Once the traditional zoning and functionality was understood, variation was embedded into the system to enable the programming to be reactive to the programmatic requirements of the interior architecture behind the screen (Figure 2). The system adjusts a set of apertures as well as adjusting the thickness of the members to set the desired transparency against the appropriate level of ventilation (Figure 3).

Figure 2: TOP, Diagram showing the traditional design and function of Mashrabiya. MIDDLE, Traditional mapping of components within system. BOTTOM, Programmable parametric variation.
In concert with the digital development of the parametric model, ABS and SLS 3D printing have been targeted due the proliferation of the both technologies to test both functional parameters as well as the feasibility of the manufacturing process. These technologies are ideal given that parts can already be easily remade at low cost. Notably, both technologies are not designed for long term wear and tear, especially in the harsh environment of the Middle East. Resultantly, current research is exploring the application of automotive paint as a finish (Figure 3). Given the scale of the parts, the maintenance required of automotive paint and its durability in various climates represents a potential solution that would be appropriate for Mashrabiya scale architectures that are nonperforming structurally.

4. Methods for reviewing the developed work

A mixed method approach is used to gather and analyse information and data in this research. Both primary and secondary data has been collected to determine a SAFE value of 3D printed architecture and Mashrabiya based on the authors previous work. Primary data generated from semi structured interviews and focus groups were done during 2014-2015. More secondary data was gathered from 3D printing market reports, manufacturer’s websites and literature case studies.

The semi-structured interviews included 25 Architects, designers, manufacturers and economic specialists. The focus group invited 6 members to discuss the topic and a proof of concept parametric model validity within a Middle Eastern country, Bahrain, as a research context. The SAFE value approach refers to Social and Aesthetic, Functional and Economic indicators, and is used in this research to get a framework that is then used to thematically analyse data gathered. A parametric model or a proof of a new Mashrabiya concept is also included as a result.
5. SAFE evaluation framework

In developing the framework for evaluating the value of the architectural product that will be resultant from the research the authors explored both architectural and product evaluation criteria. SAFE (social, aesthetic, functional and economic) was distilled and developed based on research within the literature review (Veryzer 1995, Biem & Jensen 2011) and engages targeted parameters to define success of a product in an architectural context. The four criteria evaluate these parameters:

- SOCIAL - Within the social and cultural setting, how does the design work respond appropriately to the urban context?
- AESTHETIC – How does the produced design fit into the fashion values and context of the given culture?
- FUNCTIONAL – What performative functions does the product achieve in the context of social/cultural, environmental/climatic, and emotional criteria?
- ECONOMIC – How feasible and sustainable is the production, transportation, assembly, and installation?

6. SAFE value of 3D printed Mashrabiya

Looking back at the case studies and the parametric Mashrabiya developed, the benefits of 3D printed Mashrabiya are analysed here according to the data gathered from various interviews and focus group within Bahrain as a case study of an Arabian Gulf country.

6.1. Social value

The social character of Mashrabiya has changed substantially as societies utilizing the architecture have evolved. With the loss of labour in their construction, Mashrabiya have become cartoons of their former designs. What was previously contextualised by climate, social obligation, and culture has fundamentally changes as the social character of Middle Eastern communities has changed after the oil boom. However, the Islamic religion’s appreciation to visual privacy is still a priority and a major concern in building and window shading solutions.

Analysis on data gathered from focus group indicated potential future social values of 3D printed Mashrabiya. The 3D printed Mashrabiya may functionally supplant the socially eroded versions that have resulted from the westernization of the Middle Eastern cultures. The applied patterning systems represent a technological solution (a value that is resultant from westernization) that can simultaneously re-address the social concerns of the architectural degradation of the Harim.

6.2. Aesthetic value

The richness of the Islamic patterns that once governed Mashrabiya screens has been considered a traditional aesthetic that modern construction has generally rejected, either through cartooning or through abandonment: Mashrabiya are being substituted with abstracted Islamic patterns that are subsequently “painted” onto contemporary facades or large reflective glass openings. New individualism and exhibitionism in building can allow mass customisation to be welcomed if designers acquire new digital skills and tools to enable them to design aesthetically appealing screens using new parametric software and 3D printing that simultaneously engages in architectural performance, which again addresses the westernization of Middle Eastern Cultures.
6.3. Functional value

Many new housing projects are designed with ignorance to sun direction. They foster large sized openings of fixed glass after relying mostly on AC systems and hardly relying on passive ventilation. This has created an extra amount of sun penetrating the interior. Shading devices are of extreme importance in hot countries. A 3DP Mashrabiya may provide complex geometry and aesthetics that best serve and aesthetically and functionally metamorphose to owners needs and design desires as well as respect the huge emotional and religious attachment of Mashrabiya privacy role in these communities. Strauss (2013) condition the development of the technologies from sophisticated prototypes to reliable one to have an impact on building envelopes and facades.

6.4. Economic value

The economic validity of a 3DP Mashrabiya is highly dependent on the material, scale and cost of production in comparison to mass production using CNC or GRC moulds. Lattice structures are analysed by Wohlers report (2014) to reduce cost as less material is used. However, with the cost difference from a CNC screen of $930 to a 3DP Mashrabiya of $3000 by SLS or $ 2400 by PMMA offered by Voxeljet. Specialists would say it is yet very early for architecture to be a valid substitute to mass production elements. However, when it comes to Mashrabiya and the intensive labour and craft it requires against the value of the digital craftsmen design freedom, 3DP was agreed to have a benefit as supported by the focus group members, and the interviews. Moreover, concrete 3DP and FDM by d-shape or PMMA by Voxeljet are already steady in this field. The prediction of a lower cost in the coming 5 years for 3DP Architecture with polymers is nearing this threshold perhaps but not in metals. An alternative option suggested to produce the window screen is to use the lost-wax method that may be economically feasible. The fact that 3DP can speed up the prototyping process but not the manufacturing process of a product can add a cost for time spent versus quality achieved. Strauss (2013) claims that by 2020 the technology will change existing building details

6.5. SAFE value of 3D printed architecture and 3DP Mashrabiya

By examining the values offered by SAFE, it is evident that 3D printing in architecture might not be yet applicable in enormous building projects as printers size might be enormous and difficult to control but smaller products like columns or screens are viable. 3D printed Mashrabiya screen is proven to offer social aesthetic and functional benefits that may be economically viable in the coming 5 years.

The holistic approach of looking at the social, aesthetical, functional and economic issues of 3D printing potentially enhances the suitability of the product to be 3D printed. This value is of high importance when looking at architecture products that are aesthetically appealing but not functional or simply out of the cultural concept of its potential end users.

7. Conclusion and discussion

In the post digital age, how we design and make has been called into question as new considerations in culture as well as performance have found themselves being codified. In developing the parametric models of both our culture and our construction we discover the fundamental rules at play, rules that govern the social and aesthetic constructs that we are a part of. Never before has there been such a global community and its impact is being felt across cultures. Design and making have become liquid
through ubiquitous computing and digital manufacturing. These malleable tools suggest the distillation of both construction detailing and cultural/social identity and awareness.

The constructions that have been developed (both digital and physical) explore the methods that are currently available in light of the emerging disruptive technologies. While there is evidence to suggest that these constructions can be made through other means, the adaptability of 3D printing enables the execution of mass customized constructions regardless of siting conditions. The research suggests that not only is the method for production a valid solution but that it also enables the crystallization of cultural moments: the construction is direct result of the programmed values in the design.

As the research develops, present and future resultant parametric models and constructions methods suggest the production and fabrication of socially and functionally intelligent architectural products and also the evolution of codified systems to embody evolving cultural values. Each model provides a snapshot of the culture, as it is understood by the research; interrogating the passage of light, control of airflow, temperature of air current and humidity, and the privacy of the woman’s quarter (Harim) in courtyard houses in the Middle East. Extending this logic into future architectures might not only save archetypes, but also more clearly reveal the socio-economic, cultural and performative criteria that informed their forms.

Lastly and perhaps most importantly, cultures do not exist in stasis. New questions regarding the codification and construction result from the inquiry into contemporary building. Building codes that were non-existent in the historic models require the reshaping of the parametric design to accommodate for foundational architectural issues such as egress and must be addressed in the new models. The design work and culture is fated to change and evolve. These new modes of design production represent an opportunity to not only codify the products themselves into mass customized products but also suggest that we might be able to reflect on cultural values of both past and present and program new trajectories in social development.

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Programming for prefab

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Abstract: Contemporary architectural programming, as a holistic process rather than static document, is utilised for effective communication, control and evaluation of design proposals across the whole construction project cycle. Designing for prefabrication benefits from planning and control of processes, with a strong client focus, and established relationships between project team members. This planning, control and communication for prefabrication can be improved by the understanding and integration of architectural programming concepts, resulting in a more effective, efficient and responsive design-phase, leading into the efficient construction phase that prefabrication is widely known for. Improving the design process for prefabrication stands to benefit the delivering business, project team, and most importantly, quality outcomes for the commissioning client.

Keywords: Prefabrication; architectural programming; design; process.

1. Introduction

“A doctor doesn’t necessarily give his clients what they want. In some cases he could be jailed for that. A doctor gives his clients what he thinks they need. So it should be with the practice of architecture. But the trick is to distinguish between wants and needs.” (Peña and Caudill, 1959, p. 178)

The architectural programme has traditionally been an important first stage of a project. Acting as a pre-design phase, the determination of a programme is typically in the form of a fixed document that is used for communication, evaluation and control of the subsequent design phase. Prefabrication’s fixed, and efficient construction phase, means that controlling and determining the design phase is even more important than traditional construction, yet there remains little research as to how to programme effectively for prefabricated projects.

This paper begins with a literature review to set out an understanding of the development of architectural programming, not only in academic research but also a task that has developed within practice. The literature review will first determine an historic understanding of programming, as well as how contemporary perspectives are shaping the way in which it is used today and being adapted and refined for future practice, before defining why programming specifically for prefabrication is important.
The second part of the paper will focus on a case study. As part of an ARC industry linkage project, the research is able to benefit from ‘live’ industry experience; to observe and analyse current practice, to implement research-based change and to gather feedback from this implementation that can measure its effectiveness and progress future research.

By considering programming as a holistic, project-long, process. It is likely that the principles of architectural programming can be brought to prefabricated housing design and delivery. Primarily, the aim is to streamline, and control the design phase, increasing not only efficiency, but also qualitative client outcomes. Design phase control has direct impact on construction, allowing high-quality design outcomes for clients and efficient design-delivery and construction for manufacturers of prefabricated housing. Prefabricated construction differs from that of tradition, as design choices must be finalised before construction proceeds due to the ‘manufacturing’ nature of the building process, without the possibility of on-site variations to the design and construction. Effective architectural programming allows a continuous feedback loop to develop for all stages of a project (especially through strategies such as post-occupancy evaluations). This allows not only product offerings to be improved, but also the delivery process to be refined. In this way, offerings are adaptable, and responsive to changes in the market, offering a continuous stream of improvement, in line with one of the core principles of industrialised house building, identified in Swedish research as Systematic Performance Measurement (Lessing, 2006, p. 94).

2. The power of programming

Depending on the geographical context of the research, the terms ‘design brief’ and ‘architectural program’, are used with much the same meaning, as will be shown in cited works. British-English invariably uses the term design brief, while researchers in the American-English tradition have chosen the term architectural program. For the purpose of this research paper, I have chosen to use the latter, for the following reasons. Within Australian architectural practice, there is an assumed understanding of design brief. This understanding, however, is one that is often closed to new thinking and innovation and therefore a less familiar term to British-English users may be appropriate. The term architectural programme, by its definition, also infers the sense of a time-based, on-going process, beyond the single document perspective of a brief. As will be shown, this is important when considering how prefabricated architecture is designed and delivered.

In order to understand how architectural programming for prefabrication can be refined, it is first important to understand the context in which a contemporary understanding of architectural programming developed. Architectural programming as an academic, and practice-based field of research arose from concentrated research during the 1960s and 70s. This research had its genesis in on-going changes in approaches to design stimulated by societal change after the Second World War. Developments in technology, increased demands on designers by population growth, and an increased awareness of public participation, led academics and practitioners to examine the role of pre-design planning (Cherry, 1999).

Peña and Caudill were among the first researchers to publish the base requirements for effective architectural programming. The key points of which remain pertinent today: making clients part of the design team, conduct research into the client and the project type, as well as to present and communicate architectural analysis as one would an initial scheme (Peña and Caudill, 1959). Over the following decade, Peña developed his definition of architectural programming, summarising it as, “a statement of an architectural problem and the requirements to be met in offering a solution” (Peña and


Focke, 1969, p. 3). During this time, Peña and his contemporaries viewed programming and designing as two distinct, but complementary activities. The initial, programming phase of a project would seek out and define the problem, while the following design phase would present the solution.

By the late 1970s, there were a number of guides for practitioners that described this static phase-bound document. Sanoff saw the programme as “a communicable statement of intent” (Sanoff, 1977, p. 4), to enhance client and architect communication, track the progress of a project, and as a tool to measure the quality of design. This understanding continued through the 1990s. Cherry (1999) still viewed programming and designing as distinct activities. Cherry subtly acknowledged that alternate forms of programming were beginning to emerge, but she believed these suited only certain circumstances and were not applicable to the majority of design projects.

Contemporary research into architectural programming has expanded its definition, beyond that of a single, static, phase constrained to the production of a one-off document, into a process that is dynamic, continuous and linked to procurement method, furthering the original intentions of expanded client input. This progression of understanding is summarised by Nina Ryd, who describes modern programming as being; “an integrated part of the entire construction and management process, and not just as a part of an early stage” (Ryd, 2004a, p. 233).

Much of the original intention of programming, to be a client-involved problem definition tool, remains unchanged, and Heintz and Overgaard (2009) identify three core functions of programming; to carry information, serve as inspiration, and function as an effective control of the design outcome. Their definition is expanded to include a sense of the intangible, for “…programs must convey not only the technical requirements of the spaces listed, but also the feel – both of individual spaces and the project as a whole.” (Heintz and Overgaard, 2009, p.1). This requirement to balance the ‘hard’, technical requirements with ‘soft’, intangible information is the key factor that Heintz and Overgaard identify as being important to contemporary programming and parallels Ryd’s (2003) requirement for programming to involve multiple perspectives, balancing ‘external’ and ‘internal’ constraints. This shift in programming complements an industry-wide move toward integrated project delivery, where consultant inputs are provided to a project as early in the process as is possible, which is especially important to prefabricated projects.

Communication during a construction project is vital to its success. However, communication protocols are often determined solely on the terms of the construction industry, diminishing the client’s ability to effectively take part, “...the client or provider of facilities is largely forced to steer this process on the terms of the construction sector with the aid of tools developed for building production” (Ryd, 2004b, p. 87). Appropriately tailored communication is important to ensure efficiency but greater effort must be taken during project programming to include the client. This can be as simple as ensuring the designer has understood the client’s wishes for the project rather than working on the assumption that once documented, client preferences are clear (Heintz and Overgaard, 2009). To this end, it is important that both parties are clear when communicating to avoid misinterpretation, communication must focus on both those expressing information as well as the recipient (Bogers et al., 2008).

The way that architects receive, interpret and use the process of programming and associated documents is critical, as this has a direct impact on the efficiency and effectiveness of the design phase. Historically, little research has been conducted into this relationship between client-expression, and design-interpretation, though some contemporary investigations have been conducted (Bogers et al., 2008; Heintz and Overgaard, 2009). Balancing approaches is an imperative of effective programming facilitation, so as to minimise the natural conflict between client and architect,
“The clients’ strive for a more systematic and objective approach might differ from the more chaotic, intuitive and artistic approach designers have.” (Prins et al., 2006, p. 115).

This combination of communication and interpretation is what gives inspiration to designers, who look to engage with and provide high-quality outcomes for their clients, architectural programming also forms a metric to assess design outcomes and ensure quality (Bogers et al., 2008), allowing the process and resulting designs to be critically examined, and controlled with ease. Architects often undertake their own programming activities to gain an understanding of the project and insight into the client. This aspect of programming must be acknowledged to occur, for inspiration comes to every designer differently, and in this paper there is no strict definition of how programming should seek to inspire, rather programming must acknowledge the designer’s requirements for a project’s success. The activities undertaken by a designer can take the form of client conversations, visits to the client’s home or workplace, and investigative research into similar building typologies (Heintz and Overgaard, 2009). These interactions can slow the design process, and while the stated aim should not be efficiency, rather effectiveness – it is important that designers be allowed opportunity to gain access to this soft information. Structuring in this opportunity will also mean later control and evaluation is simpler, however it can be a barrier to effective programming in the delivery of mass-produced housing solutions, so a period of client consultation becomes imperative. Contemporary understanding of programming to have the most value when implemented as a continuous process, rather than the traditionally produced document, further highlights the dichotomy between efficiency and effectiveness. The dynamic and on-going approach can be difficult for construction team members to accept in place of something which was previously static and constrained to the start of a project (Blyth and Worthington, 2010). Prins et. al's (2006) idea of introducing phase-bound dynamic stages of programming for sign-off may be valid to alleviate some of these concerns, and also stands to work well with the constraints that off-site construction brings with regards to late design changes.

Further barriers to effective programming are highlighted by Barrett et al. (1999) research. It was found that there are two main forms of failure in programming: “Rule-based” errors arising from team experience that is no longer relevant and causes poor performance, but which is continued with because they are ‘tried and tested’ methods, and “Knowledge-based” errors which come about through a lack of understanding as to how to effectively programme (Barrett et al., 1999, p.9).

3. The need to programme for prefab

There is clearly great scope to improve the content and structure of programming documents and processes in architectural projects in general (Bogers et al., 2008; Heintz and Overgaard, 2009), and when considering programming for prefabrication, there is little in the way of specific existing research. Involving architects and the project team in early project programming has benefits, shown in the literature review. A strong client-focus is also vital to programme communication, producing an inspiring, informative architectural programme that is process focused, rather than “a list of specific spaces required in the new building, together with their dimensions.” (Heintz and Overgaard, 2009, p.2). By achieving these improvements, it is more likely that the project will be both efficient and effective in both the terms of construction and design, and also engages with the move in prefabricated projects towards integrated project delivery teams working together from an early stage, and a shift in mind-set from that of product design to one which also focuses on the process of the design.
Prefabrication’s historical focus has often been that of technical gains associated with the end product, commonly “driven by expedient construction methods rather than design outcomes” (Newton, 2009, p. 283). An effective process for programming ensures high quality client-input to the construction project, and in a prefabricated project’s case more importantly, input to this often neglected design process. Clients are the providers of ideas and inspiration to the project, and are the metric that judges its success (Ryd, 2003), so to not include clients in a project’s process is to lose this critical input, regardless of whether the design is unique, or mass-produced.

“Industrialised house-building is a thoroughly developed building process with a well-suited organization for efficient management, preparation and control of the included activities, flows, resources and results for which highly developed components are used in order to create maximum customer value.” (Lessing, 2006, p. 93)

Lessing’s definition of industrialised house building reveals that construction, or technical efficiency on its own is not enough to optimise prefabricated housing construction. Lessing summarises, that effective prefabrication lies within a triune of “process, organizational and technological” efficiency (Lessing, 2006, p. 93). It is apparent that an effective process of architectural programming is well suited to the optimisation of prefabricated construction.

It is in this same thesis, that Lessing (2006) identifies the need for industrialised house builders to shift from thinking about ‘projects’, and towards ‘process’, as manufacturers do. He notes that prefabricated housing companies should appoint a ‘Process Owner’ to oversee “process structure, product and process development and improvements as well as the house-building process” (Lessing, 2006, p. 92). This role is not dissimilar to the ‘Brief Manager’, proposed by Blyth and Worthington (2010), who also make an effort to differentiate it from the role of ‘Project Manager’, which Lessing defines as being in charge of delivering individual projects. Importantly, the roles are intertwined, with the overall process relying on information gathered during the individual delivery of projects.

The hard gains of construction quality, that prefabrication excels at, is demonstrated in Japan where manufacturers, “establish their own quality standards in order to improve structural resistance, durability, and amenities” (Noguchi, 2005, p. 26). This ‘quality’ is then sold as added value, through a strategy identified by Noguchi as ‘cost-performance’. Yet despite this focus on innovation which concerns the build quality, there are clearly opportunities for increased design inputs and outcomes, demonstrated by these same manufacturers who are able to control and customise the design to suit varying clients and sites, yet seem unable to display the kind of design outcomes that we would expect from smart and innovative housing;

“...the overall appearance remains the same: an interpretation of a generic western suburban house, clad in ceramic tiling with a very predictable colour palette ranging from brown to beige.” (Aitchison, 2014)

There is clearly the opportunity to investigate a similar marketable value proposition in the softer quality of design in terms of a product that is responsive to individual clients’ needs, as well as the market more broadly. This has been demonstrated during a recent study trip undertaken by the author to Sweden, where innovative construction companies in Stockholm are leveraging ‘design-quality’ in the promotion of their built product; whether a construction-developer, undertaking prefabricated projects only in timber construction, and then promoting both the environmental and design outcomes to gain market differentiation, or a developer, who has been undertaking a number of multi-residential projects
with high-profile architects, then marketing a holistic project ‘story’, carrying the value from initial design through to the end-marketing, effectively thinking of each project as a whole process.

4. Case study

As an applied design research project, this study uses a ‘live’ business to analyse, synthesise and evaluate the research. This brings the opportunity to gather feedback on the implementation of the research within the lifecycle of the project. In doing so, this case study has been conducted in a manner familiar to a designer, using principles of ‘action research’ that is,

"...a term given to studies that examine a concrete situation, particularly the logic of how factors within the situation relate to each other as the process moves toward a specific empirical goal.” (Groat and Wang, 2013, pp. 43–44).

Three main methods of gathering data have been used, in line with the principles of action research:

- **First-hand experience** – involvement with Happy Haus has in the role of what the project team have called the ‘embedded architect’, allowed both observation and participation during client meetings in the pre-design and design-phase. This has allowed the researcher an opportunity to observe interactions, as well as to participate in conversations regarding client-inputs.

- **Interviews and Analysis** – clients and the management of Happy Haus have been informally interviewed, to understand how they structure and control each ‘delivery’ project, and ‘range’ commission; from pre-design through to the installation of houses on-site, these interviews were documented an a number of process diagrams formulated (Figure 1).

- **Market Analysis and Comparison of Existing Literature** – the literature review has developed an understanding of how programming can be applied to a contemporary construction process. Project files from Happy Haus were also reviewed to understand their delivery process across a number of projects. The publicised and marketed aspects of Happy Haus, and other prefabricated housing companies’ design processes have also been documented and analysed.

![Diagram](image)

Figure 1: Example of interruptions to flow of Happy Haus’ existing delivery process, brought about by the need for additional design input, construction advice, or costing changes. (source: Author)
The interviews, and analysis of Happy Haus’ existing process, demonstrated that greater structure was needed to effectively gather client inputs and to then communicate the resulting design solution. The core elements of architectural programming were being handled without a clearly defined structure. Poor communication was causing delays; there was an informal approach to gathering client inputs for the inspiration of the delivery architect. The opportunity was also being missed for programming to be utilised to control client-provider interactions in order to evaluate the design outcome and there was a lack of structured exchanges of information, meaning that the programme was not forming the initial stages of the project contract (Prins et al., 2006).

Research then compared Happy Haus’ stated process for delivering projects with the publicised and marketed processes of other prefabricated housing manufacturers in the Australian market (Figure 2). These process analyses were conducted using the publicly available information on their websites, and showed that most companies promote a clear set of structured meetings to address specific project stages. Companies also charged fees early and regularly, demonstrating that each task has a value associated with it, as well as promoting regular and early construction and costing advice to eliminate ‘surprises’ late in the process. In combination with the architectural programming literature review, this market analysis formed the basis of suggestions as to how an effectively programmed prefabrication process might be implemented. These diagrams revealed a clear meeting structure to be important to a shortened design-phase, as well as the importance of early construction/consultant advice to the process.

Figure 2: Summary of key process meetings of 3 Australian prefabricated housing companies, showing early payment and construction input, as well as regular construction advice. (source: Author)

Implementing these ‘delivery’ process changes also stand to benefit the ‘range’ procurement process and resulting designed product. Allowing Happy Haus’ engagement of architects in the future to be relevant and responsive as there will be a greater level of documentation and data regarding client preferences and their reception of previous designs. This evidence-based commissioning process will deliver relevant market information into the design process, and avoid the traditional route of...
architectural ideas being formulated ‘on the back of an envelope’. Not only is this information important for new ranges, but also allows the refinement of existing offerings. The refinement of process and product, common to industrial and product design, is identified as a vital aspect to architectural evaluation by van der Voordt and Van Wegen (2005) who demonstrate that both ex ante and ex post evaluations improve the quality of programming and design through to the construction process and habitable commission. Lessing (2006) identifies systematic performance measurement to be an important factor in understanding and optimising prefabrication’s repeated processes and products. The resulting structured process could be similar to that of the ‘Lean’ inspired, visual planning approach to programming, discussed by Lessing that creates an open and collaborative atmosphere early in the design stage. This can be beneficial to a prefabricated design project as there is a collaboratively agreed design phase with frequent meetings leading to a shorter design phase with fewer errors.

It is important that programming retains its original intent in line with Heintz and Overgaard’s (2009) understanding of programming, this involves greater opportunities for the client during consultation and design phases by introducing a series of design tasks and complementary sign-offs, so allowing greater client authority in a more effective process of decision-making (Figure 3), these exchanges also establish Prins et al’s (2006) contractual aspect of programming. By introducing greater control and structure to these phases, they are also made more efficient, resulting in an optimised balance with effectiveness.

![Consultation Exchanges Diagram]

**Figure 3:** Example programming exchanges; collaborative provider-client relationship and symbolic contractual responsibilities enabling greater control over process and increased client involvement in design decisions, eliminating need for changes at late stage of project. (source: Author)

Controlling design discussions in this manner, with a team member in the role of Process Owner and a design co-ordinating Project Manager it is possible to facilitate these open client discussions and design-team interactions, while also tracking their effectiveness for improvement. Consideration of design delivery, means that not only is it possible to have a streamlined delivery process that is efficient
and effective, but it is also possible to deliver high levels of customer choice and customisation in a simple and controlled manner, before considering a technologically driven mass-customised approach. This consideration places greater emphasis on the ‘softer’ aspects of industrialised house construction, that Lessing (2006) identifies the management of, and integration with the ‘harder’ aspects, as being important to overall success: greater planning and control, client focus, and long term relationships.

5. Conclusion

This paper has sought to demonstrate the importance and benefits that an effective process of architectural programming can have on prefabricated construction. Programming leads to efficient and effective control over the design process and consequently the constructed outcome. An improved quality of process has the potential to match the constructed quality that prefabrication is known for. These gains are delivered by greater, more structured, client involvement, ultimately providing an enhanced user experience of the project’s process, as well as satisfaction with the resulting product.

There are obvious benefits to be gained by extending this initial programming implementation beyond the consultation and design phases of projects, in order that the programming effort becomes continuous and holistic to deliver its full potential to all aspects of the prefabricated process, and to build a fully formed ‘feedback loop’ as is common in product design. The next phase of research will consider how programming can be optimised for these construction and occupancy phases to build this loop, and also report on the implemented changes to process that have been identified by this paper.

Happy Haus have taken steps to programme greater structure in their client interactions, with clear exchanges at each design phase, to give greater control in the delivery of projects and more clearly articulate client wishes into the design process. An employee who will own and control the programming phases has also been appointed, in order to implement the design phase programming recommendations, and future research will continue to observe and analyse the evolving case study.

Greater attention during this next period of research will also be given to analyse how integrated project teams can facilitate a holistic approach to programming. An integrated approach to programming is defined by van der Voordt and van Wegen who view it as being one that is cyclical, with a series of internal reviews and feedback loops. Their six phases are described as planning, programming, design, construction, occupancy and redevelopment (van der Voordt and van Wegen, 2005, p. 164), and corresponds to Lessing’s (2006) view of industrialised construction being a continuously improving process, benefiting from the re-use of experience, and led by a Process Owner. This next research stage will also consider the occupation of the delivered houses, and how user feedback can be organised and used from the design of delivery projects and impact on the ranges of designs available. This stage will consider how a prefabricated housing company might engage and interact with independent architectural firms who are disconnected from both site and client in their design efforts, as is the nature of mass produced housing. Evidence gathered from an improved delivery project process can be analysed and fed into this commissioning process, to allow more soft inputs from clients, and hard data gathered during delivery and siting of projects to inform these architect’s designs, alongside the structural and detailing pragmatics that designing for prefabrication naturally demands. In this way, programming can provide clear and structured inspiration, as demanded historically by Peña and Caudill (1959) and recently by Heintz & Overgaard (2009).

There is still great scope to programme for prefabrication more effectively, but by bringing a contemporary understanding of architectural programming to the process together with new research into modern methods of construction, there is increased opportunity to create a responsive and flexible
design process that can lead to improvements in communication, control and the evaluation of the resulting design outcome. These improvements mean higher quality design outcomes for clients, as well as more efficiency in the design-phase for the delivering architect, meaning that prefabrication can make gains not just in the construction phase as is commonly perceived of the building method, but also in the planning and design stages which occur before the project moves into the factory. This increased programming focus also means that prefabrication can deliver excellence in design, and open up new opportunities for architects, rather than being considered a sub-optimal form of architectural project delivery, adding design-value to projects for both the delivering business and clients.

References


Urban prototypes: plywood architecture

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Abstract: The widespread availability of automated fabrication tools is rising dramatically. The pairing of CAD/CAM software and automated tools presents a shift in how the designer can take part in the manufacture process. This paper investigates how computing technologies can be effectively utilized to democratise the production of building components through simple design to build workflow, standardised building materials and CNC fabrication. Two dimensional sheet products such as plywood can easily be manipulated to create a large number of three-dimensional forms. By examining and adopting existing novel plywood construction techniques similar to an 'Ikea' like kit-set building systems effective construction methods were developed and produced. Basic CNC technology enabled the researchers to design and fabricate conventionally complex structures and artefacts without too much formal fabrication training. The projects however required large amount of preparation, prototyping and innovative thinking to overcome budget and material challenges. The success of the projects heavily relied on digitally produced components and a digital workflow specifically tailored to produce components for unskilled assembly build process.

Keywords: Digital fabrication; plywood; CNC.

1. Introduction

Technology is undoubtedly changing the way we practice architecture. Although students may be lacking in technical ability required for regulatory authorities, their exposure to software at universities is allowing for a new discourse in how architecture can be fabricated. Computer aided design (CAD) and computer aided manufacture (CAM) in particular has become a popular medium for students to express themselves through making. Students have become accustomed to ‘design to fabrication’ workflow with the use of digital fabrication tools. The construction industry in general is regarded to be a slow to uptake new technology. Although CAD/CAM is relatively a young subject within architecture, it is common place in the automotive, aerospace and shipbuilding industries (Leach, 2002). This same design to fabrication process is now becoming prevalent by practicing architectural practitioners throughout New Zealand.
This paper is split into three sections. The first portion will review how digital innovation is enabling designers to play a larger role in the design to fabrication process. In the second portion, examples of existing applications of novel plywood construction systems will be presented. To finish, a review into the University of Auckland’s (UoA) School of Architecture and Planning (SoAP) Timber Technology Class will take place, before ultimately leading to the final discussion of the EDFAB project findings to date and its explorations with off-the-shelf construction products.

1.1. Innovation

When designers are presented with the task of designing products for the masses, a perception of mass production and commercialisation comes to mind. Producers add value to their standardised product lines by providing mass customised or made to order options. This normally comes at a higher cost, but consumers are willing to pay for individuality. The process of mass customization requires the consumer to directly engage with the manufacturer and is only possible through powerful design software that is simple and easy to use. The trend to personalise artefacts will continue to rise with further advances in automated machines (Sheil, 2012). Industries such as clothing, automotive, electronics, jewellery and publishing are already starting to take notice. Customisation of clothing and shoes has become a popular option for many consumers. Sporting brands like Nike, Adidas and Reebok provide basic designs that can be altered to match size, colour, type of material and labelling through their online web-stores.

More season designers can download open source 3D modelling software like Blender to design virtual objects, which in turn can be uploaded to online additive fabrication services - commonly named 3D printing - like Shapeways for rapid prototyping or final production. Turning our attention to 3D printing in the architecture field, many academics, engineers and architects around the globe are investigating how different types of large 3D printers can produce entire pieces of architecture. While many may be investigating very different materials and fabrication tool, the objectives remain the same. Engineer Erico Dini has created D-Shape, a large format 3D printer that uses sand and chemical binding agent to create a stone like material. His technology aims to target CAD/CAM architects like Universe Architecture to create full scale houses. Dus-Architects, in contrast has partnered up with Ultimaker to create an oversize desktop sized 3D printer called the KamerMaker. It has the ability to build large hollow components at 3.5 meters in height with bioplastic, with some sections to be filled with eco-concrete. Even though many are looking to develop a viable 3D printing solutions for architecture, the fact still remains that more research is needed before a commercially viable system can be produced (Fairs, 2013). The advantages 3D printing cannot be understated and holds the promise to push architectural aesthetic full of integrate detail and complexity.

Automated innovation in the New Zealand market-place is assisting with the development of 'modern methods of construction' in everyday building practise. Steel framing company FRAMECAD has developed a design, manufacture and build system dubbed the 'factory in a can' (Burgess, 2014). It is essentially an automated steel forming machine encased into a forty foot shipping container that produces steel framing components for building on-site. This portable mobile factory can be dropped off at any location to produce steel framing elements for commercial or housing projects on-demand. The flexibility of the system allows it to be useful for emergency relief housing and for projects in remote regions. The success of this product is recognised globally, where units have been utilized in a wide range of countries from Afghanistan to Brazil (Burgess, 2014).

Fletchers Aluminum, a window and door supplier has also been proactive with product innovation, with the development of the Smartfit system. It is a first of its kind in New Zealand and it is designed in
accordance to the New Zealand Building Code and practices. The product comes complete, ready for installation with no loose parts. Everything from the window flashings to the sill support bar are all integrated within the window, allowing for reduction in human error and time during installation. It must be noted, that without the use of an automated CNC machine this product could not be possible for mainstream production. The automated process also allows for made to order options, which will be discussed in the EDFAB section of this paper.

1.2. Designers as a maker

The term designer as a maker is a condition whereby the designer and fabricator are one and the same (Sheil, 2012). File-to-factory or CAD/CAM technology is enabling designers to directly communicate with fabricating machines such as CNC routers to produce goods. It has presented a shift to how the profession can approach and engage with design to production and as a result hold the promise of producing novel outcomes (Sheil, 2012). It can allow capability of manufacturing and construction to be a cohesive process, allowing for a creative dialogue between design and fabrication. If this type of working is pursued, one cannot work just as a designer or a fabricator, but as both; therefore, conventional thinking must be relinquished. The designer now must have the capacity to learn new skills, be adaptive and flexible to create design strategies. Another role digital fabrication technologies can play, is in the potential to bring back production from developing countries like China. The differences lie in the scale of production. Small groups or individuals can set up advanced design workshops armed with CNC routers, robotic arms, 3D printers, laser cutters and the more conventional hand-held tools (Bianchini and Maffei, 2012). In this way, crafted artefacts whether it is building components or furniture can be produced locally.

The advent of personal computing and other electronic gadgets has provided the younger and upcoming generations with a view of the world radically differently from the previous generations. This substantial shift in thinking is allowing them to usher in a technological and social change to challenge the way architecture is practiced (Kolarevic and Klinger, 2008). As a response, there is a growing trend for architectural graduates to take part in the building process through digital fabrication (Harper and Jackson, 2015). Many tertiary institutions such as the University of Westminster and London Metropolitan University provide design-build studios. Impressive results have allowed them to take part in Nevada’s Burning Man Festival and the Solar Decathlon Competition (Mamou-Mani and Burgess, 2015). Design to build Studio 19 hosted by Unitec Institute of Technology and Strachen group Architects is another great example of allowing students to take part in the construction of social housing.

Victoria University’s Makers of Architecture is a great example of how students can engage with design-build projects. Their built project ‘Warrrander Studio’ boast the title of first entirely digitally designed and fabricated cross laminated timber (CLT) house in the country. What is impressive is the way four postgraduate students were able to push the boundaries of residential construction in New Zealand. Digital technology was not only used to minimise the need for skilled labour onsite, but also to develop a CLT specific cladding system. The team utilized paramedic software and CNC machining to create a ‘bed-frame’ like structure which accommodated everything from building paper to sheet cladding as prefabricated panel. Dubbed the Cassette Cladding system, it allowed the building to be assembled onsite and made water-tight all within a week, as the panels could be lifted and slotted into pre-routed slots of pre-assembled CLT structure. These panels are also designed to be easily detached for future maintenance or alteration (MakersofArchitecture, 2014).
The rise of design-build architectural practices cannot just be attributed to digital technologies, but to a specific way of thinking. Many recent graduates and young architects are just as comfortable banging away with a hammer, as with designing on a drawing board or three-dimensional model. Fluff Bakery, a tiny coffee shop in New York was designed and built by Lewis.Tsurumaki.Lewis Architects. The visually sensual bespoke interior was created by understanding the physical and visual attributes of plywood and inventing a novel application of it to creating a visual and tactile interior (Kellogg, 2006).

2. Plywood architecture

Plywood as a building product has existed for some time. It is a standardized product that may be overlooked. It is a versatile material that can be repurposed to make a large variety architectural products. In the past two decades, the gradual uptake of digital technologies and the advances in plywood production has allowed for innovation to occur.

Early innovator Larry Sass from the Massachusetts Institute of Technology researched how digital technologies and plywood could be used to solve the housing problems through digital fabrication. In 2008, at the 'Home Delivery' exhibit at Museum of Modern Art (MoMA) he presented the Instant House (citation). The result of the project identifies how plywood is an extremely dynamic material with the ability to be an effective medium for production of easy to handle structural and ornamental two dimensional components. Larry Sass (Sass, 2007) notes that the only ingredients and tools that are required are plywood, a CNC router, a rubber mallet, a crowbar and a computer.

The English based Facit Homes made famous by architectural show 'Grand Designs' has been manufacturing plywood homes for some time. Like FRAMECAD, Facit has also adopted mobile factory production systems for the creation of plywood building components. The use of BIM and proprietary plugin software enables Facit to parametrically design a site responsive architecture to meet their clients' needs and tastes (Bell and Southcombe, 2012). The difference between the Instant House and Facit Homes systems is how their two dimensional CNC plywood components are fitted together to form a three-dimensional modular panels — or chassis as Facit describes it — that act like oversized Lego blocks. Once these panels are added together to form the structural core of the building, it is made watertight using conventional building methodology. Cellulose insulation is pumped into the hollow cavities within the panels and internal linings are fitted to form the interior space. The design of this construction system has been developed with non-skilled labourers in mind to allow for greater human participation (Koones, 2014).

2.1. Community oriented design and fabrication

Digital fabrication is increasingly becoming accessible not just through universities, but through makerspaces and commercially available desktop machines, such as Makerbot and Formlabs 3D printers. Online forums and open source software is allowing many to build their own desktop devices. Dr Dermott McMeel (McMeel and Walker, 2015) from the University of Auckland, questions how these digital tools can disrupt the protected positions of the design and construction professions. How can a designer operate in communities with increased access to information, diverse expertise and new technologies? To what extent can design and construction be democratized?

Although open source software and services may seem to be free, there is a hidden associated cost. To form a successful social enterprise, a large amount of built-up knowledge has to take place through online forums and other community networks. The price of research, tools and expertise in these
projects is hard to quantify, but could be said to work on the basis of a gift economy. Like Linux software, other similar creative commons have started to pop up, such as ‘Instructables.com’ and Flicker.com. By sharing resources, such as knowledge, digitally connected communities can develop new construction methodologies. The concept of sharing knowledge is not new: the Walter Segal Self-build system is testament to this, existing well before the online open source initiative (Parvin, 2013).

Within a New Zealand context large interest has been poured into plywood community oriented construction systems. Two major systems that have made headlines are Wikihouse and Click-Raft. In a global context the WikiHouse organisation looks at how end demographic populations and local communities can empower themselves to solve housing problems. It is based on an open source architectural construction set where anyone can download free software – like Sketch Up – to individualize a library of predesigned flat pack templates (Galilee, 2012). Much like the Larry Sass Instant house two dimension components ‘printed’ from plywood will make up the flat pack building components. Wooden mallets, made from plywood, are the primary tool used to force friction joints together. They are designed with unskilled labourer in mind. The WikiHouse NZ Chapter, is a well-funded community organisation that resides in Christchurch. In short time, it has made strides in educating the local public and has developed a New Zealand specific WikiHouse construction system that differs to from its United Kingdom counterpart. Recent funding grants worth $300,000 from the Canterbury Community Trust is testament to its success (Harvie, 2015). The downside to the Wikihouse system is its complexity. The design relies on a large array of component parts that requires skilled and informed individuals to make a large array decisions (Stralen and Cezarino, 2015). When looking at WikihouseNZ, professional 3D modelling software Rhinoceros 3D is being utilized to detail and design their proof of the concept of the ‘Backyarder’.

Click-Raft by Wellington architect Chriss Moller is a New Zealand specific home-grown systems developed in New Zealand. The ‘Click-Raft’ construction system prides itself of how it can be adaptable and “adjusts to its environment in the sense that a tree does”. It is only possible to do this through its CNC milled plywood click-leaves and click-beams to form a lattice structure. They are simply clicked together to form floor, wall and roof elements in different configurations (Bell and Southcombe, 2012). What is interesting with the Click-Raft System is how its origins are not from a digital design background, but is are based on physics, mathematics and material science. It is only recently been conformed and made more user specific by CNC technology.

3. Student work

The Arts and Crafts movement rejected mass production and mechanisation. However, University of Auckland’s Mike Davis argues that the meaning of craft can have varying definitions, depending on context (Davis, 2013). Today, a craft in the context of production should also be identified with digital technologies. Understanding of material, learning how to create effective well-defined milling tool paths and finishing products are all traits of the practice of craft.

Even though technology can allow for a larger scope of participation, understanding and knowledge are key for successful results. If we look at MIT media lab’s Mediated Matter Group’s and their G3DP glass 3D printer, it is hard not to notice the array of disciplines that were needed for its conception and development. Collaborations and expertise had to come from not only MIT’s mechanical engineering department, but also from its Glass Lab and the Wyss Institute (Rosenfield, 2015). McMeel draws parallels to Karl Marx and his theories in regards to the dangers of dehumanizing production through the replacement of workers with technology. Our recent history of prefabrication has ultimately created
mass produced housing which seeks out to dehumanize production and force regularity to the landscape. As a new wave of technology is introduced, a responsibility lies with the designers not only to explore seductive forms and efficient construction, but how individuals and communities can be involved in the design and construction process (McMeel and Walker, 2015).

Experiences into design and construction of structure, ornamentation and weather proofing are highlighted with two simple construction case studies completed by students, researchers and lecturers at SoAP. The first study evaluates the successful MArch(prof) construction projects, in which a series of deceptively simple, but complex plywood 10m² structures were built. The second case study looks into the EDFAB’s prototype, a sleep-out built to investigate novel plywood house production.

3.1. Timber Technology Class

Drawing influence from Wikihouse and Click Raft, student Melanie Pau and Senior lecturer John Chapman re-invented the second semester Timber Technology Class in 2012. The first project entailed designing a plywood structure to improve safety and visibility at a primary school in a deprived area. In the following two years, four other shelters utilizing similar design and build principles were built. With each year, students built on and developed on the previous year’s construction techniques and in the process made new discoveries. The success of these projects has led to an established course within the SoAP which has subsequently received a number of international and national awards including Bentley Systems’ Scott Lofgren Student Design Awards and Design Institute of New Zealand’s Spatial Gold Pins.

Like WikiHouse, the selection of Plywood was seen to be a versatile product that not only could perform structurally and aesthetically. However, the standard size plywood sheet, 2400 x 1200mm was a limitation that had to be overcome. Over the years, different techniques where developed. A play with laminated portal frames was the original solution. The following year, a fear that the harsh New Zealand weather would delaminate the plywood resulted in a reciprocal structural system (figure 1). similar to Alvaro Siza and Eduardo Souto de Moura 2005 Serpentine Gallery Pavilion to be utilized.
Limited budgets and technical skills required the students to be inventive. A turn to digital technology and the developments of a design to fabrication workflow allowed for basic design parameters and CAD/CAM process to be established. With every new built project, accumulated knowledge allowed for learning from past failures to be avoided. This meant that new students heavily relied on advice from former students, as well as workshop technicians, material suppliers, engineers and design tutors, who had already been involved with the digital design and fabrication class. In this context it was found that prototyping everything from 1:5 models to 1:1 physical mock-ups was an important step within the design process. It served as a means for the students to become familiar and comfortable with the digital technology on the one hand, and to avoid the risk of underestimating the complexities associated with the process of manual assembly.

The concept that one can simply just 'print' component parts or whole designs from a 3D model can be very misleading. It was found, every individual tantalised Radita plywood sheet manufactured in New Zealand varied in dimension and quality and therefore could not be quantified accurately within the digital world. It has been noted by Professor Michael Stacey that architects and engineers enjoy physical testing, as it can provide a source of confidence before final construction takes place (Stacey, 2005). This logic same logic has been applied to the timber technology class and it gives the confidence that they can build.

3.2. The EDFAB research project

The EDFAB: eco – digital fabrication is a research project, with the aim to challenge conventional processes and relationships and propose a radically new but viable design and building alternative. New attitudes towards application of material and the utilisation of digital fabrication methods are employed to produce distinctive, high quality, healthier and cost effective residential buildings that conform to the international passive housing standard.

Today, houses in general can be described as a collection of extensively tested and regulatory approved independent subassemblies. This form of construction is commonly viewed positively, due to the inability for housing to be prototyped and prefabricated. Manufacturers, however, can only realistically test their products with a few common auxiliary details. This can lead to large amount of frustration and liability for builders and designers within the realm of bespoke architecture. In most circumstances, designers are left to refine and coordinate all the sum of building subassemblies through the design, documentation and consent processes. Large projects in contrast, have the luxury to invest in the testing of full scaled mockups as cost normally can be recovered though large project runs (Mark Anderson and Anderson, 2007). This project aims to investigate how digital design and fabrication challenge the way we perceive “off-the-shelf” construction. Is there a way to produce a construction system that can mimic consumer friendly furniture concepts, where the complexity is engineered into the parts, leaving assembly process much simpler?

Early on in the development stage, a decision was made to take a large number of small steps, rather than over running the risk of getting bogged down in detail in one large step. This approach has been deemed successful and in less than a year, the EDFAB group have developed a proof of concept that is close to completion. The need for this prototype to adhere to regulatory code compliance a confined the project to 10m2. Avoid applying for time consuming resource and building consents. At a later date, it is expected to build at a larger 70 to 100m2 dwelling for further examination. The aim of the project was initially to test the potential of a do it yourself approach, and to see if it can conform to the NZ
standards. It was found that extensive specialist and cross disciplinary knowledge was required in its realization.

The design of the EDFAB construction system required the designers to work closely with all consultants including the engineers and the passive house experts. This allowed for building code to be encoded into the design parameters. Drawing on expert knowledge early on in the design process was key to the success of the project. It must be noted, that increasing specialization and experts that was needed for this research project and can be argued that this workflow can be considered to be an expensive one. The pairing of digital technologies and off the shelf material allow for affordable prototyping to occur. In most cases, the time spent designing was greater than the physical testing. As a number of prototypes were conceived, new data was fed into digital models to allow the construction system to evolve. A simple digital work flow allowed development to be easy and all parties involved to be kept well informed about progress.

Figure 2: The process of assembling the modules, fitting them into position and locking them into place with the ‘butterfly’ joint.

The final construction that was developed is similar to Facit Homes, where a 'kit of parts' were simply milled from plywood sheets to form modular panels similar to Facit Homes Chasis Panels. The prototype is divided into three sections, the primary structural modular panels, the secondary external envelope and the tertiary internal lining and fittings. To join and interlock the collection of panels, ‘butterfly plugs’ are hammered into place to form a well-braced structure (figure 2). The external envelope is designed to conform to the building code with off the shelf products. It requires the structure to be wrapped in building paper, followed by battens to form a cavity before being enclosed by timber cladding. Before the commencement of fitting the internal lining, insulation must be blown into the hollow sections within the modular panels. To create a thermally broken interior, insulation-tape will be used to cover all exposed interior joints in lieu of wrapping the internal walls with a vapor barrier membrane. To finish the interior fit out an insulated cavity made up of battens, plasterboard and plywood flooring. Issues like high wind and seismic load were required to take precedence over design details to allow it to meet local building regulations. As a result some elements of buildability and further systems for complex forms had to be sacrificed.
The CAD/CAM process allowed all the components to be CNC milled through simple, but effective production process. These components were assembled to form of the main structure at the Whau Arts festival by local unskilled volunteers. Following Larry Sass principle simple tools such as hammer, mallet and drill were only required and it ultimately lead to a large array of people to participating. The selection of light and durable plywood enabled for easy handling and allowed for mishaps to be easily forgiven. The design principle of symmetry, meant no component or panel could be assembled backwards or in the wrong order. This went along way for the volunteer’s confidence and enabled the sleep out structure to be built at speed.

The ProClima building wrap and for the most part, only required staples and flashing tapes for installation. Drawing attention to the construction of the Warrander Studio project, a trained builder was on hand to ensure to direct and ensure quality of build (MakersofArchitecture, 2014). The importance to use trained professionals during the construction process cannot be understated. The installation of the Diamond steel roofing was surprisingly easy to install, as train roofer was onsite to direct us and preform the more tricky tasks. As the EDFAB structure was built to very close tolerances an exact measurement could be provided to the window and door joiners from the computer model. As the door would be produced via automation, the team was confident that the door would fit. The Smartfit door in fact was the easiest building component to be installed, and only took about 10 minutes to put in place. Obvious problems however did come from the weight of the 2400 x 2500 mm door.

4. Conclusions

The timber technology classes have been successful for the development of UoA students. It serves a purpose and it does it well. The basic knowledge and techniques that were developed were instrumental in developing a digital fabrication culture with plywood at the SoAP. It could be said without it, the researchers of the EDFAB construction system would have spent extra time building that knowledge. It must be noted, the success of the EDFAB project also relied heavily on the cross disciplinary support within and outside the university. It came in the form of advice and recommendations on how to specify and apply off the shelf products. This can be seen in the selection of the Proclima building wrap, the application of the steel roofing and the installation of the Smartfit window.

The adoption of a radically rethought workflow, which involved multiple layers of prototyping, provided a medium for discourse between designer, material suppliers and other consultants. It ultimately led to the building of the 10m2 sleep-out for the purposes of testing the relationship between digital fabrication and social building. The use of simple tools in conjunction with ‘off the shelf’ doors, roofing and flashings to form a bespoke envelope turned out to be a cost effective solution for the project. To date, the sleep-out requires Knauf insulation to be blown into the modular panels by Eco Insulation, along with the fitting of the interior linings and electrical equipment. An oversight in the construction means the insulation should have been blown into the cavities prior to the installation of the interior butterfly joints. As a consequence, it now requires 60mm holes to be punctured into each individual panel to compensate. Missed opportunities in terms of shape and form of the panel modules could have been further explored. It may have reduced the amount of work and material to form the roof structure. Future developments entail making the system code compliant for buildings larger than 10m².
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Theory, Philosophy and Methodology in Architectural Science
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Beyond the front elevation: a conceptual framework for re(thinking) facadism

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Abstract: As the viability of Melbourne’s manufacturing industry declines, the production process is either phased out, or is moved to other areas. In this current economic climate, the pressing notion for redevelopment to privilege a regulated, homogenous new development is favoured. This new construction becomes almost foreign to the idea of an ingrained memory and the rich cultural heritage. The building is preserved, conserved or demolished by adopting the legitimised facadism approach. This paper examines the current established practice of facadism - an architecture designed by preserving the building front elevation with reference to Melbourne’s industrial architecture. By exploring this, it proposes another alternative for the preservation and conservation of heritage value. It argues that the heritage value lies within the functional doings of the building and allowing the latter to evolve, change and adapt is more valuable than that of preserving the heritage façade. The focus is placed on layering of events, appropriating residual space. This is achieved through a proposition of varying levels of indeterminacy, which allows for adaptability and alterations in programmatic trajectories and changing social needs. A living and evolving cultural and social laboratory is proposed in which it maintains its heritage significance and engages within its community.

Keywords: Facadism; industrial architecture; regeneration; preservation.

1. Introduction

The departure of the manufacturing industry in Melbourne is an inevitable result of a capitalist led model. The rise of expanded markets and cheaper method of production produces periodic crises for the industrial enterprise. There is a rising pressure within this sector to drop the less profitable elements of the production process. As this manifests itself within the urban fabric the industrial built form becomes temporarily or permanently useless for the industrial enterprise. These once valued ‘structures’ of a post-industrial era, without a sense of purpose and economic value, now lie as exposed bones nurturing graffiti, violence and crime. Over time, these industrial built forms are left to linger and decay for decades. Whilst others remain within the urban fabric till the first signs of decay emerge allowing for demolition to take place, others are eradicated shortly after their abandonment.
This abandonment tends to be associated with the ugliness and depressing notion of the unwanted buildings of society. These negative impressions are compounded by perceptions about the uses of derelict space where ‘a range of activities are carried out by people commonly identified as undesirable, promoting fear of disorder and crime’ (Kirkwood 2001). However, on the other hand they evoke an aesthetic of disorder, surprise and sensuality affected through time. Together with these aesthetics, the industrial built form used to house a wide range of distinctive industries, allowing a dense social life to occur within its perimeters. This created rich histories through both space and materiality, which are raises the perpetual problem of whether they should be kept within the urban fabric or eliminated. The objective of this paper is to achieve a greater understanding of the current redevelopment trends associated with post-industrial built forms in order to improve the management of it. It focuses on how facadism is adopted as a common design technique and does so by illustrating different current modes of its implementation and offers a conceptual framework other than facadism. However, it is first necessary to review the industrial built form in the modern era, which follows in the following sections.

2. The industrial built form in the modern era

Edensor (2005, p. 6) suggests that such structures ‘are too frequently stripped and cleared to encourage property speculation because dereliction appears as a scar on the landscape which must be erased and then filled in with something more useful’. Perceived as dis-ordered, chaotic, messy and ‘ugly’ sites, they provide a great contrast to the increasingly smooth and highly regulated spaces within the urban fabric. Consequently this privileges homogenous new developments over the realm of surprise. Hence, a tension between the highly regulated space of modernity and the dis-ordered space of the industrial landscape becomes evident. Marshall Berman (1983, p. 165), an urban sociologist, describes this tension as ‘a dialectical process whereby one mode of modernism both energies and exhausts itself trying to annihilate another’. Edensor (2005, p.54) argues that this is ‘increasingly being manifested in modern cities as numerous attempts are being made to regulate urban space, with the prevalence of planning regimes, which determine where and how things, activities and people should be placed’. The designation of abandoned industrial landscapes and derelict land as particular kinds of negative and disordered spaces, slowly start to lose their importance within the modern urban fabric.

David Sibley (1995, p. 410) describes this process as the purification of social spaces, whereby the city slowly rejects the differences and secures its boundaries to maintain homogeneity throughout. The privileged purified spaces allow for conformity within the clear boundaries and a centralised regulated space within the urban fabric. Hence, the delineation of purified space implicitly identifies the industrial derelict built form as the ‘outsider’ or the ‘place out of place’. Rob Shields (1991) advocates that such places are ‘allocated to marginal spaces typically represented and depicted as dangerous, chaotic and dirty and is the antithesis of purified spaces’. However, Rana Kabbani (1986) suggests that such places on the margin are also imagined as realms of desire, permitting interconnection and hybridity. These places also provide ‘potential outlets for unexpected or spontaneous encounters, informal events and alternative activities outside the increasingly commoditized, controlled, and privatized open urban spaces’ (Franck & Stevens 2007). Nevertheless, there is often a strong determination within cities and urban policies to minimise or eradicate abandoned buildings and derelict land, as they are frequently identified and associated with violence and crime while providing an indication of a wider urban cultural malaise or eye sore.

Such a built form becomes almost engrained within the urban fabric of contemporary cities, holding a true heritage of a place. Each and every building is almost unique, it tells a story about the people that
lived before, its use, carrying forward its patina of age, forging the identify of place and the values specific to its predetermined conditions opening up the potential for a romantic aesthetic to be valued. Barron and Mariani (2014, p. 9) also argue that some of the most significant contributing positive attributes were possibilities for unregulated play and recreation, the presence of vegetation and wildlife and ‘an open aspect’ seen by many to be preferable to continuous buildings especially in its role of breaking up the high density built form. Likewise, Philip Kivell et al (1998, p. 121) are of opinion that ‘although a given site was perceived to be in a state of abandonment by former economic uses it was not considered useless because some form of natural regeneration had taken place and people used it unofficially for a variety of informal activities from children’s play, team games, and seeking freedom not existing elsewhere’.

3. The act of preservation

Without a formal sense of purpose and economic value, the negative perception associated with derelict industrial sites together with the modern needs of ‘purification’ slowly diminish these buildings into extinction. The new construction becomes almost foreign to the idea of an ingrained memory. It is common for architecture to demarcate the site boundaries, demolish the existing structure, preserve the heritage façade, replace the interior and build a new. It is a form of instant urban redevelopment and often adopted in heritage preservation, which has been problematized in light of architectural critiques and heritage discourse. Fortunately, this is not the fate of all industrial derelict buildings where some are fortunate enough to forgo the demolition hammer. Instead, they undergo an act of ‘preservation’ or ‘conservation’ or ‘adaptive reuse’. Conservation as defined by The Burra Charter (1999) is the act of retaining the significance of the place, while preservation is the act of maintaining one’s original or existing state. Often the least possible physical intervention: to do as little as possible is advocated as the best approach. The term ‘adaptive reuse’ seeks for the conversion of an existing building site from one use to another allowing for the values of the building to be applied within the present day applications of both program and function.

Adaptive reuse as a design method explores the possibilities that lie between the extremes of demolition or the alternative of ‘preserving’. It provides an opportunity to maintain the historical heritage built fabric, spaces and sites that might otherwise be lost, while at the same time through the careful crafting and designing of the reuse strategy it has the potential to ‘amplify some elements and aspects while downplaying others’ (Heritage Council Victoria 2013, p. 6). When applied specifically to the industrial built form, such design interventions should aim to retain evidence of past technologies, flows of materials and people and the work processes (Department of Environment and Heritage 2004). However, the sense of ‘amplification’ as a reuse strategy regularly alludes solely to the preservation of the fabric or envelope of the building. As a result of this design solution, facadism becomes an adopted design technique.

4. Facadism – as a design technique

Facadism produces an architectural form designed with ‘an emphasis on the façade, or the retention of a preserved building front while demolishing and replacing the remainder behind it’ (Richards 1994, p.7). This is an increasingly growing practice adopted by developers and architects where the existing façade of historically valued buildings are retained while the interior structure is demolished. This design technique manifests itself on a global scale and is becoming more and more prominent within
industrial urbanscape regeneration developments. In Melbourne, the Equity Chamber’s proposed development is a classic example of this tension between CBD redevelopment and the retention of the building’s rich architectural, cultural and historical importance. The existing Equity Chamber is perceived to be architecturally significant for its ‘exotic revival of architectural styles which were adopted in Victoria during the inter-war period’ (Heritage Victoria, 2010). The development, designed by Hayball Architects seeks to integrate the existing building with the new development by retaining the façade and the ground floor, while the remaining floors are transformed into apartments as shown in Figure 1:

![Figure 1: Equity Chambers proposal by Hayball Architects (Source: Hayball, 2015).](image)

Within this proposed development, the sheer weight of the existing building is seen to be offset by the new proposed apartment tower allowing it to be set back. Hayball (2015) describes, that this composition ‘seeks to distinguish the new proposal to the existing by creating a respectful addition’ to the former Equity Chamber building. Similarly, the Shoreham Street Project by Project Orange in Shoreham England adopts a similar design approach where the new addition offset’s itself to the existing building as shown in Figure 2. This specific design methodology adopted by both Hayball and Project Orange can be seen as what Sandord Wood (2012) defines as the ‘scooping façadism method – which involves preserving more than one aspect of the façade by scooping out the middle or interior and inserting a new structure beyond’. In the Shoreham Street project, the design solution sought to rehabilitate an abandoned steel and aluminium warehouse while celebrating its industrial heritage through the use of contrasting materials. Furthermore, one may conclude that the existing buildings act as a podium and base platform where the new proposed building then sits ontop.

![Figure 2: Shoreham street, Shoreham England. (Source Project Orange, 2012).](image)
Similarly, Paul Goldberger had identified this back in 1985 in his critique in The New York Times, ‘where by old buildings were literally becoming a doormat for the towers, a small stoop cringing at the base of a ponderous skyscraper.’ The Water House Hotel in Shanghai, China by Neri and Hu Design Research Office illustrates this in Figure 3. The new built form is carefully crafted to sit on top of the preserved ex Japanese Army three-level headquarters. This redevelopment combines both the new and the old in a clear contrast by allowing the façade of the ex Japanese Army building to act as a base podium.

![Image of Water House Hotel](source)

Figure 3: The Water House Hotel, Shanghai China. (Source: Architectural Review, 2010).

However, facadism as a design technique does not confine itself to producing built forms restricted to that of the ‘scooping out’ method. The Silver Leaf Apartment Project by The Buchan Group and the New Architecture Building at The University of Melbourne by NADAAA and John Wardle seem to produce a different outcome as shown in Figure 4. Both examples allow a new design to emerge and to wrap around the façade almost bookcasing the facades within two new developed ends. Wood (2012), describes this design technique to that of ‘collage – which involves retaining a fragment of the façade while incorporating it into the new building almost like a pattern’. Therefore, this almost provides the existing façade a new skin to breathe through.

![Image of Silver Leaf Apartment](source)


The Granary an ex granary in Gliwice Poland, by Medusa Group adopts a similar approach as seen in Figure 5. The service cores are accentuated in both form and materiality from the existing building. Such an approach, the inverse of what The Buchan Group and NADAA design’s adopted, allows the new design elements to be clearly separated from the historical façade and showcasing its importance. Another interesting design outcome that facadism produces is reflected in the design development for The Windsor Hotel, by Denton Corker Marshall and 466 Collins House by Bates Smart as illustrated in Figure 6.
Both Denton Corker Marshall and Bates Smart have adopted a very similar design technique. It can be seen that their new proposed built form is setback from the existing building and provides a clear distinction between the strong historical presence of the front elevation. Wood (2012) describes this as a ‘sheet’. The developed proposal retains the exterior façade wall in a way that gives an illusion of depth indicating that only the exterior façade wall has been retained. Likewise, the Bradmill Redevelopment in Yarraville, Melbourne (Figure 7) is a classic example of how this technique is commonly used within an industrial built form. All the three examples depicts how the new built form acts as a backdrop to the preserved heritage façade.

These examples illustrate different approaches to how historically valued facades are ‘preserved’ while allowing for contemporary development to occur. Whether a ‘collage, sheet, or scooping out’ design approach is adopted by the architects, at its core agenda it seeks to maintain and preserve the original existing built form. The examples discussed are advocated as a legitimate and acceptable design
solution. Firstly, it recognises the historical context by preserving the historical façade and allowing it to thrive in its exterior existing streetscape. Secondly, it responds and attempts to solve the demands of urban redevelopment and consolidation. And thirdly, it stands within the strict heritage, planning and zonning regulations imposed by the local councils and legislations. Hannah Lewi and Andrew Murray, describes that this common design technique is justified ‘at an urban design level as a realistic compromise between the ever-escalting economic pressures of redevelopment, and an awareness of the value of historical contexts in the wake of preceding decades of modernism and wholesale destruction’ (2014, p. 507). As a result of this design technique, the façade is often stripped to its bare walls, where the interior structure of the building is demolished with no walls, no floors, no ceilings but just one large deep hole as illustrated in The Quay Redevelopment Figure 8 and Dimmey’s Richmond Icon Redevelopment Figure 9.

As portrayed within the two examples, the architecture is reduced to its most superficial element – the front elevation or the 110mm brick wall. Similarly, the former Bank of NSW Façade designed by Joseph Reed at The University of Melbourne’s Architecture building has undergone a similar treatment as illustrated in Figure 8.

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The three examples all have a commonality within: reducing the architecture to that of the façade only. Stephen Georgalis (2013, p. 6), with specific reference to the Joseph Reed façade at The University of Melbourne’s Architecture building describes that ‘a series of tilt metres are installed on the façade during demolition to monitor any movement during the process. The steelwork is secured through the existing window and door openings to a series of permanent steel columns fixed to the rear of the façade’. There is a high importance and emphasis implemented to ‘secure’ and ‘protect’ the façade ensuring that every slight movement is monitored. At the fundamental level, this is preservation at its best where every care is taken to secure and protect the façade with an extensively engineered steel frame. However, Goldeberger (1985) disagrees as, ‘this process of turning an older building of distinction into a fancy front door for a new tower is to respect neither the integrity of the new or that of the old’. This is problematic, as the end design outcome, is seen to under go a ‘cosmetic treatment’ - one where it is preserved, cleaned, propped and re-presented as a small part of a new built.
5. The industrial 110mm façade brick wall

As a general design methodology, this practice seems to promote only the retention of the ‘front face’ of a building which is driven by highly legislated regulations. This general design strategy, at the source of professional debate, neglects the relationship to what has been designed inside or behind the façade. Hence, this implies that the activity within the building and the physical built form of the building is not valued. What is more valued in this instance is ensuring a surface illusion at the street scape while at the same time responding to positive urban attributes of human scale, rhythm, and form. This opens upon an increasing renewed critique that facadism as a design tactic fails to address the body of the building.

Although, facadism as a design technique is well perceived amongst heritage consultants, preservationists, architects and developers as one attempt of preservation, this design technique cannot merely reduce historically valued buildings to nothing but wallpaper thin walls collaged onto new developments. Similarly, Lewi and Murray (2014, p. 515) are of opinion that ‘for keeping only a damaged façade, no matter the strategy, it inevitably denies the preservation of the collective memory and functional workings of a building’s internal light, sound and scale of a complete experience of space.’ With reference to the industrial built form, (Woods, 1996) advocates that the form ‘must be respected as an integrity, embodying a history that must not be denied’ in its act of preservation and conservation. In their damaged states they suggest new forms of thought and comprehension, and suggests new conceptions of space that confirm the potential of the human to integrate itself within. High and Lewis (2007), argue that an industrial infrastructure emerges through the combination of tools, materials, labour and other elements with specific interaction that can be extended through form and scale. This is evident in the Kinear’s Rope Works, Bradmill and the Docklands Cotton Mill. The scale of the built form, has little to no variation as both a large and empty area is required for programmatic reasons.

![Figure 11: Kinnear’s Rope Work Factory, BradMill, Docklands Cotton Mill](image)

This relationship is informed by a formalised industrialised process which generally relies upon the ‘idea that an object must pass through different stages of production, each located in discrete spaces which are connected to each other as a sequence’ (Hardy, 2005). This gives rise to a large main open space allocated for such activities to follow within, while secondary spaces such as amenities and office spaces form part of a wider network into which the factory is internally planned for as illustrated in Figure 12. However, this regimented and orderly fashion arrangement becomes non-existent within the context of a derelict industrial building. Edensor (2005, p. 85), notes that the ‘signs of production with its sequential order become banal as walls erode and rooms appear to be at the center of formless labyrinths.’
6. Development of the conceptual framework

It is imperative to note the strong emphasis made on the internal function of the industrial built form rather than the external face of the building by Edensor (2005), Hardy (2005) and Kirkwood (2001). Hence, the impetus of this conceptual framework will aim at producing a design methodology that allows for the conservation of the latter, rather than focusing on a formal act of preservation. In doing so, it takes the notion that the façade conservation approach is not the priority and argues that the heritage value lies within the functional doings of the building. The merits of this design methodology will allow the latter to evolve, change and adapt rather than preserving and fixing the heritage façade at a specific point in history. To facilitate this, an approach with a static, quick fix and short-term vision is seen as disillusionary and inappropriate since it does not allow for an evolutionary growth of social and cultural values to manifest itself through the functional activities ingrained within an industrial built form. The ambition is to create a place of both production and consumption while bridging on the past, the present, the future and integrating different communities and identities. The challenge that this design framework undertakes into is creating an architectural approach that has the capability of responding when time has expired, or more precisely, when the function and program becomes obsolete. It draws upon Lefebvre’s (1991) conceptualization of space as a social construct that space is continuously under construction through the participative acts of perception, conception and experience. This opens up unlimited potential to abstract elements of space and society, within a particular scale, and allowing objects, relationships, activities and agendas to develop. More importantly, it drives forward a methodology that promotes the significance of the place by extracting upon social, economical, physical, historical and cultural values. This then ensures an approach that is flexible enough to adapt to the evolutionary nature of industrial activities and processes that are undergoing a constant change in both its redevelopment and history within a contemporary context. Unlike a conventional architectural response the design approach is one that is strategic, facilitating social inclusivity, participation within the qualitative richness of the industrial built, and inviting opportunities for diverse uses. It is a methodology of inviting participation through a long-term vision and a framework for decision making that is flexible enough to envision a collection of interventions through the evolutionary process of both time and scale.

This framework envisions to utilise what exists and not to transform it, making most of the building’s physical and aesthetic qualities. It aims to preserve the freedom of space without necessarily partitioning off, while allowing for a maximum spatial freedom. It then aims to capitalize on the emergence of temporal uses to inform a more permanent architecture. It facilitates uncertainties, instabilities while encouraging and inviting participation to occur and stories to be made. The act of
engagement with the built form allows a cultural and social value to be strengthened, reinforced with the memories and stories it generates. This allows the current generation to leave their trace similarly to the older generation. Thus, through this continuous ongoing action, it increases the opportunity for new social and cultural values to emerge while also reflecting upon its ingrained past heritage. The framework seeks to propose an evolutionary heritage through the actions of performance in space while referencing to the core essence of the building; production.

6.1. Phase one – urban foraging

The design framework proposed is phased out across time through three distinctive phases. It begins, with Phase one – urban foraging. On the external surface the industrial built form is almost homogenous and uninviting disregarding the internal richness of productivity, materiality, patina of rust, weathering timber. The intent is to create a walking narrative that re-purposes the building as a framework that allows encounters with both the internal and external spaces. This aims to generate and stimulate a natural regeneration of the site while slowly encouraging interest within by the ‘foraging’ process for future potential. The tactic here is one of creating work that feeds off conversations and differences in opinions as a source of material to progress forward. In the first instance, the built form is used to facilitate participation and stage an arts based ‘performance’. However, this is not the typical exclusive art-based regeneration, which has often been used as a design transformation to post-industrial sites into high-end mixed used developments. It is one that allows and creates an intensity of activity and collective encounter acting as a social catalyst for a performative exchange.

It is crucial to note that this design approach should be flexible enough to allow programmatic indeterminacy, which facilitates an ongoing dialogue of uncertainty, instability and possibility. Throughout this phase of urban foraging, the architectural intervention is more of architectural management where the role of the architect is challenged to that of an event manager, planner, facilitator or even a producer of events. A number of organisations within Arts Victoria have been identified as having a potential to organize events to engage with the broader community. For example, Cultural Development Network is an independent non-profit group that links communities, artists and local councils together through seminars, forums and conferences across Victoria and Australia. Similarly, National Exhibition Touring Support (NETS) Victoria partners with regional galleries, cultural organisations, curators and artists to develop and tour innovative exhibitions and projects of contemporary art, craft and design. These organisations, amongst, many others can use the industrial built form as a platform to host such events. Hence, this design intervention is seen one that is driven by participation as a mechanism to establish the significance of the site and a program that invites a collective involvement through the diversity and variety of events.

6.2. Phase two – urban experimentation

The existing construction is gradually adapted to the new uses. It offers new insights and allows for modifications. The perception of non-use, derelict, and promiscuity, lack of inhabitation slowly disappears through awareness and event engagements. Through the effect of time, phase two can slowly be designed into. This phase – Urban Experimentation, seeks to allow for ‘quick and dirty interventions’ to take place within the realm of developing a creative industry. It engages and invites artists, musicians, performers, and sculptors to use the building as a giant canvas for artistic creation. The design approach is to transform the site into an enormous living and evolving gallery space, providing another layer of use on top the existing industrial activities. It works with the plurality of
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people and opinions, while embracing and accepting the passage of time and its effect on the physical built form. Similarly, as to the urban foraging stage, a number of organisations have been identified as having potential to engage the broader community within. For example, Arts House is an artistic-led organization that presents a yearly curated program of contemporary art workshops featuring performances, exhibitions, installations and cultural events that are intended to inspire and draw a dynamic community engagement. However, Testing Grounds is a more permanent based organisation for artistic development and experimentation that could equally host their artist-in-resident programs as a weekly to monthly ongoing program within an industrial built form context.

As these interventions gain popularity, it becomes crucial to implement essential services such as toilet facilities and electrical services to sustain these activities. These smaller architectural interventions have the potential to draw in a smaller crowd for a longer period of time creating a sense of community engagement. This is most likely to create a positive short term value add to the building. This timed-based design intervention could be seen as an intervention, which aims to create a sense of responsibility and ownership amongst the temporal users. This is seen as a mechanism to provoke creative imagination and evoke the past as a means to speculate the potential future of the existing industrial built form. In this way, the temporary architecture can be tested so that it can later solidify into something more permanent and concrete. Within such a framework, rules do not suffocate, but they create spaces within which a great degree of freedom remains. The approach here is not one where a rigid network of spaces is produced, but one that defines the purpose of space created by proposing both formal and informal spaces generated by previous uses and temporal spaces. Formal spaces are defined by the more regulated and controlled practices that have clearly bounded territories such as toilets, facilities etc, while informal spaces are defined with new movement and temporal interventions undergoing constant change in the propose of creating new identities and allowing new spatial practices to become possible.

6.3. Phase three - permanence

New insights are continuously being introduced and new options are constantly being made available. A place for artistic creation is slowly being created through the process of participatory intervention, engagement and management. The abandoned and the neglect slowly start to show opportunities of habitation and reuse while it retains the significance of its place. The original structure of the building develops the framework for cultural activities to happen, and as a result the potential of the site slowly emerges from the informal and temporal artistic use to a more defined use. Within this framework a combination of old and contemporary are allowed to work hand in hand. The historic structure is exposed – and then allowed to be overtaken by new activities while allowing its beauty and strength to be celebrated. It is anticipated that the temporary spaces will slowly start evolving towards more semi-permanent working studios within the creative industries allowing art and creative ideas to develop and flourish. These creative working studios or working pods would then emerge towards a more permanent architecture occupying certain areas of the building. At this stage it becomes crucial to implement or partner within a leasing and rental facilitator which would allow this to happen. For example, the leasing agreement could follow a similar structure to that of Creative Spaces. Creative Spaces is a program of the City Of Melbourne Arts and Culture branch which develops leases and affordable spaces for the creative industries.

These small-scale interventions aim to outreach into local socio-cultural and economic practices. Individually these interventions may have little impact, however as the intensity of activity on the
factory site increases through time, these interventions could grow into something more tangible – space of production, creativity, consumption and community. Hence, the ultimate objective is to allow an evolution of cultural, social heritage value through the culture of industry and production whilst providing spaces for leisure, cultural consumption and play. This is achieved through a proposition of varying levels of indeterminacy which allows for adaptability and alterations in programmatic trajectories and changing social needs. A living and evolving cultural and social laboratory is proposed in which it maintains its heritage significance and engages with the culture of making within its community.

7. Conclusion

The practice of facadism has been problematized in light of architectural discourse. It is presented as an increasingly growing practice adopted by developers and architects where the existing façade of historically valued buildings are retained while the interior structure is demolished. This compromise values the preservation of heritage fronts and neglects the activity within the building and its interiors. The approach has been to provide a conceptual framework, which seeks beyond facadism in the regeneration of industrial built form. At its core, the framework allows for an evolutionary growth through a process of a natural regeneration across time and space. It is by no means conclusive and static allowing for a more tangible contributory community participation and engagement which bridges the past, present and the future while allowing potential nodes and opportunities to happen. The design strategy seeks to draw upon a performance-led design. This layers across the patina of time through a narrative of industrial history, processes and the multiple re-appropriation of space to form a vision of a potential future.

References


Biomimicry versus machinery: the notion of functionality in design

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Abstract: The range and diversity of approaches in the design of the built environment have reached a productive disarray at the beginning of the twenty-first century. Among these approaches, technology and biomimicry seem to be two pivotal notions. Assessing the technology-based and biomimetic architectural designs reveals the limitations of both notions in producing designed and built structures that fulfil the users and designers’ functional demands. Such an argument is undergirded by our perception of the term ‘function’ in regards to ‘biomimicry’ and ‘technology’ as historical and philosophical themes. In this paper, I will first evaluate the process and products of biomimetic and technology-based architectures on their theoretical and historical grounds in response to the functional demands of users and designers. Second, within the framework of the Actor Network Theory (ANT) and in connection to the object-oriented ontology, I will examine the functionality of biomimetic and technological design approaches.

Keywords: ANT; technology; biomimicry; function.

1. Introduction

Technology and biomimicry define fundamental notions of many design approaches of the current century. Technology has always been available in all forms of architectural design in the past and still today technological and mechanistic innovations are being added rapidly to the existing methods of architectural production (Abel, 2004). One difference between the past and today technology is in the speed of development: slow and in pace with natural evolution in the past, but fast and ahead of the natural evolution today. If in the past a wind catcher made from simple masonry materials found in nature could ventilate a house, today the combination of a manufactured lightweight double skin façade, ceiling vents and mechanical systems can fulfil this task. Compared to technology, biomimicry is a more recent concept with scientific origins in the nineteenth and twentieth centuries, and has been widely pursued during the last two decades as a design approach. In the US, for instance, the number of design schools adopting a biomimetic attitude in design through their sustainability programs is ever increasing: Arizona State University, University of Virginia, Lipscomb University, and Minneapolis College of Art and Design represent only a portion of this trend (Biomimicry 3.8). Peter Head, the chair
of the Global Consulting Planning at Arup, claims that the transition from the industrial age to an ecological age has begun and between now and 2050 biomimicry is going to be one of the main tools in this process (Pawlyn, 2011).

Designers’ approach substantiates this claim and the fact that biomimetic concepts are becoming pivotal in this transition. ‘Biomimetics Network Hessen’ and ‘Association of German Industrial Designers’ (VDID), for instance, are pursuing radical ideas on how the combination of both 3D-Printing technology and biomimetic can generate organic forms for buildings (Ursula, 2015); however, assessing the technology-based and biomimetic architectural designs reveals the limitations of both in producing designed and built structures that fulfil the users and designers’ functional demands. This argument is undergirded by qualitative and quantitative perceptions of the term ‘function’ developed from ‘philosophical,’ ‘historical’ and ‘procedural’ trends of design.

The debate in the last decade over the applicability of the biologically or technologically inspired concepts in fashioning the built environment (Cohen and Naginski, 2014), while substantiating their flaws, has essentially led to the formation of two extremes: being subversive or subservient to either nature or technology. The result will be idolizing the role of nature in design to the point of neglecting the human creativity or imposing the machinery regimes upon human activities to the point of his passivity. An investigation in between the two spheres seems inevitable to reach creative dynamic design approaches. In these approaches, transformative and responsive strategies will aim for ‘making changes’ in the environment as well as ‘responding to these changes’ developed from the context of human society. Here, biomimicry as the abstraction of good design from nature and ‘the conscious emulation of nature’s genius’ (Benyus, 2002) is compared with the machinistic perspective of technological production in nonorganic ways and the potency of human mind for innovations (Kaplinsky, 2006). The former builds like nature by cell division with the aim of continuity, while the later may interrupt natural forces by joining parts together into a unique structure without pursuing continual evolution (Kiesler, 1939). Connected to these interpretations, this essay’s objectives are twofold. First, examining the theory and history of both approaches, through content analysis methodology, to outline their flaws and limitations. Second, developing a theoretical construct to examine the validity of the process and product of designing objects through biomimetic and technology-based architecture. To reach this construct, in the second part of the essay I will draw on the Actor–Network Theory (ANT) and the object-oriented ontology.

Toward this end, I will focus on the notion of function, since in recent decades a current interest in this area has emerged following the advent of sustainability as a socio-economic issue. More precisely, there has been a shift towards building performance as a design paradigm, ‘not solely as a neo-functional approach, but more as a design paradigm concerned with the process of design and form generation’ (Kolarevic and Malkawi, 2005, p. 3). Since investigating the users and designers’ functional demands calls for a separate discussion, here I will only address these demands indirectly by examining the term ‘function’ through its measuring qualities and examples. Nonetheless, the challenge is that our perceptions of function in design will remain capricious. Besides function, I will draw on three key terms in my theoretical-historical investigations: ANT, biomimicry and machine. Actor-Netwrok Theory (ANT) as a fundamental theory for social research in technology investigates the role of objects (actors) in their network of relations. Biomimicry represents the emulation and abstraction of the models, systems, and elements of nature in order to solve complex design problems (Biomimicry 3.8). Lastly, machine is a tool composed of moving part(s) that performs work through externalization of human actions. The
expansion of this definition embraces the notion of technology as a combination of tools and human activities.

2. Biomimicry versus technology: the philosophical origins

The intellectual origins of biomimetic and technological designs, and discussion on their functional efficiency, can be traced back to the golden age of the Greek philosophy (500-300 BC). Plato, for instance, maintains that technology imitates or learns from nature, or Democritus explains that house-building was first invented by imitating spiders and swallows building their nets and nests. Aristotle referred to this theme by repeating Democritus’ examples. (Franssen, 2009). For Aristotle nature was central to scientific investigations evident in his multifarious studies of zoological phenomena in ‘Historia Animalium’ (Mazzoleni and Price, 2013, p.7). Albeit, for Aristotle technology is not solely limited to imitating nature: ‘generally art in some cases completes what nature cannot bring to a finish, and in others imitates nature’ (Anagnostopoulos, 2009; Franssen, 2009). The word ‘technology’ by association, driven from the Greek ‘techne’ and translated as ‘craftsmanship’, ‘craft’ or ‘art’, contributes to this observation. In a more comprehensive outlook, Plotinus in the Enneads (V.8.1) holds the view that the purpose of art is not just a ‘bare reproduction of the thing seen’, the natura naturata, but to return to ‘the ideas from which nature itself derives’, in the natura naturans (Hendrix, 2012).

More recently, Heidegger’s ‘technological understanding of being’ responds precisely to both anthropocentric and ecocentric visions of the argument. In this perception, technology embraces a combination of tools and human activities in which tools will not render human ‘beings’ as passive entities (Heidegger, 1977; Bernstein, 1992). Contrary to this anthropocentric observation, Heidegger also draws on an ecocentric vision by informing us about the danger of using natural sources as ‘standing-reserve’. In Heideggerian terms, ‘Gestell’, literally meaning framing, is the essence of technology. It is not a means to an end, but rather a mode of ‘challenging’ human existence. These varying perspectives stem from the level of agency assigned or gained by each object/subject matter in design that can become accordingly detrimental or constructive to the being of humans, the biosphere, and their relationships. I will return to this theme when discussing the theoretical construct of ANT.

3. Biomimicry versus technology: the historical origins and expansion

The mechanical and organic analogies of the late nineteenth and early twentieth centuries indicate the long history of success and failure of architectural function (Steadman, 2008). Both biomimetic and technological trends, in the meaning of their contemporary applications in environmental design, found origins in the 1920s and the 1930s modern movements. Le Corbusier’s expressed his radical ideas on how architecture should meet the demands of the machine age in his 1923 book ‘Vers Une Architecture’ in which ‘a house’ was claimed as ‘a machine for living in’. This image of machine, Harbison (1997) maintains, can be many things:

- linked sequences of moving parts which perform work; externalizations of human action in stylized form resulting in alien sorts of existence which move in nonorganic ways;
- concentration of ingenuity, device piled on device until they defeat easy comprehension, and of course an escape from feeling into an objective realm. (p.26)

The modern mechanistic perspective of machine, during the 1960s, reached its peak in Archigram movement. For instance, the Walking City theoretically comprised intelligent buildings or robots in the form of self-sufficient living pods capable of roaming the cities. In the form of an insect, though with the
spirit of machinery assemblage, the city was a literal interpretation of Corbusier’s aphorism of a house as a machine for living in (Cook and Archigram, 1999). Such ambitious designs developed from understanding machine as an organic living entity. As Galiano (2000) maintains, in contrast to Harbison’s ‘nonorganic’ perception of ‘machine’, organism and mechanism are the same and the architectural analogies made about them interchangeable. He compares Le Corbusier’s architecture as ‘Heliotechnical’ with Frank Lloyd Wright’s architecture as bioclimatic—representatives of mechanical and organic poetics:

Readily assuming functionalism, both locate the machine-life polemic in a decidedly symbolic realm. Otherwise, organism and mechanism are by all means equivalent, and the architectural analogies made about them interchangeable (pp. 129-130).

This suggests that the lines separating organism and mechanism, although distinct and clear in the symbolic realm, are vague and blurred in the functional field. This ambiguity can make it possible to introduce hybrid concepts such as organic machine.

The idea of organic machine was proposed by Lewis Mumford in the 1930s. This idea and his denunciation of the ‘technocratic perspective’ in the 1950s were signs of reactions against the pervasive use of machine and its destructive impact on the environment in developing the human civilization. His pessimistic outlook towards the notion of mega-machine concerned the human passivity at the dominant presence of machinery in human societies (Stunkel, 2004). The result was the emergence of new concepts at the intersection of biomimicry and technology. For instance, ‘Biotechniques’, attributed to the architect Fredrick Keisler (1939), was an indication of the correspondence between biology and technology, compared to ‘Biotechnic’ as the building techniques of nature.

Biotechnique distinguished between formal-metaphorical imitation and functional emulation of nature. It defines a dynamic mutual relationship between man and his natural and technological environments. Keisler called this relationship ‘correalism’. The term biomimicry which we use today (Benyus, 2002) could be an extension of Biotechnique used by Patrick Geddes, Lewis Mumford, Karel Honzik and Fredrick Kiesler (Braham, 2005). The manifesto of Metabolism movement in 1960 could be a result of this attitude that believed design and technology should be a denotation of human society and merge architectural notions about mega-machines with those of organic biological growth (Lin, 2010). The group was composed of avant-garde Japanese architects, such as Kenzo Tange, Kiyonori Kikutake and Kisho Kurokawa whose designs were essentially theoretical, as in the case of Kikutake’s Marine City (1963), or functionally premature, as in the case of Kurokawa’s Nakagin Capsule Tower (1972). Designed for mass production, the tower not only did not grow, but also was left to deterioration and despair. Such design failures evidenced that the growth and decay of organisms in nature are ‘irreducible’ to those of a building when it comes to fulfilling the users’ needs.

4. Biomimicry versus technology: the procedural trends of design

Procedurally speaking, above philosophical and historical views, the challenges in approaching design problems through biomimetic and technology-based architecture prove their flaws in response to both designers’ and users’ functional demands. Although a contemporary concept in a technological age, biomimicry does not entail the incorporation of complex technology in architecture (Badarna and Kadri, 2014). Biomimetic design strategies embrace two main approaches reviewed by Badarna and Kadri with various terminologies existing in biomimetics.
The first approach seeks a solution from nature for a particular engineering problem. This approach is referenced as problem-based including challenge to biology, top-down, biomimetics by analogy and problem-based. The second approach is solution-based and embraces the value of biology to design, bottom-up, biomimetics by induction and solution-based. These solution-based approaches are inspired by an observation of nature, which leads to a technological design. As Badarna and Kadri extend, however, the major challenge from a biomimetic perspective is the absence of a systematic selective methodology for designers capable of identifying the relevant natural systems and then abstracting their strategies and mechanisms for design. In other words, the transition of a function found in nature to a function appropriate for design concept generation is vague and obscured.

The functional issue of biomimetics is not solely limited to designers, and can affect the users of design. For instance, in reading ‘the ugly side of solar panels’ new research shows in generating electricity, the level of greenhouse gases released through the production of solar panels mimicking green leaves can be higher than the electricity produced by gas (2014). Concerns about the embodied energy and the cost required in the production of solar panels reveal another challenge for both designers and users to think about.

The second challenge to biomimetic design is that of incorporating the concept of natural evolution in design, which removes the designer from the process of design thinking. This challenge stems from the Darwinian analogy in technical evolution that removes the human designer and replaces him with the ‘selective forces’ in the ‘functional environment’ of the designed object. Removing the designer from the scene of design process equals the disappearance of individual choices exercised by the designer in design. The forms of designed objects are conceived as being exclusively the product of their natural environment, the functional context, in which selection acts. This selection process similar to the phrase ‘form follows function’ will no longer be an aesthetic prescription (should follow), becoming a scientific assertion of causality: form materializes as a categorical consequence of function. This is leaving design creativity outside the design thinking process as an outcome of functional determinism (Steadman, 2008). For this reason, advocates of technology-based architecture, arguing that mechanical concepts are the solutions to design problems, question the usefulness of biomimicry.

These advocates prioritize the concept of ‘machine’ over ‘biomimicry’ (Kaplinsky, 2006). They believe that biological languages and analogies through idolizing nature will diminish the real achievement of designers. The evolution within humanity in their belief is grounded in technological innovations rather than ecological evolution. Very little in architectural and urban spheres, these designers claim, of biomimetic architecture has been built. The reason is that the technological advancement of our world has defined a functional conformity for the life that is hard to breach to adapt ourselves with the surrounding biosphere (Spiller, 2007).

5. Function: an irreducible notion

As Kiesler remarks, no one can exactly define what function is, but we may examine what function has meant and will come to mean. In his terms function is ‘a specific nucleus to actions’ (1939, p. 67). In this observation function is perceived as a ‘core or base’ for desired activities, but the inner realm of this nucleus remains undefined for further discovery. Function is a self-evident term difficult to define in a number of words; however, it can be explained through its measuring qualities. As such, Grawbow and Spreckelmeyer (2015) define architectural function as the dialectics established upon three measuring qualities, including purpose (from symbolism to efficiency), materiality (from individualization to standardization) and timeliness (from immediacy to evolution, in response to the physical programming
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of the building). Designers and users’ functional demands vacillate in between these dualities. Nonetheless, such definitions are not comprehensive enough to embrace all the functional features of a certain design product. Separating the realm of what a building ‘does’, as in building’s performance, from what a building ‘does for people’, as in building’s function, might be a helpful strategy for practical analyses, as it is in post occupancy evaluation. However, ‘what a building does’ is evaluated in relation to its user’s standards and demands—and not in vacuum—whereby is still a subcategory of function.

Function, as a self-evident term, is intertwined and ‘irreducible’ to smaller constituents (Kolarevic and Malkawi, 2005). The meaning of functionality in design, although a single entity, becomes multifaceted ‘in relation’ to our perception of its actions as in between several extremes: as that of conceptual and operative, virtual and real (Kolarevic and Malkawi, 2005), process and product, scientific and artistic (Whalley, 2005), optimization and maximization/minimization (Raman, 2005), realm of effect and realm of affect, event mental and event physical (Leatherbarrow, 2005), of form and of ornament (Moussavi and Lopez, 2009; Moussavi and Kubo, 2006), and solution-based and problem-based (Badarna and Kadri, 2014). These twofold understandings substantiate that function, while irreducible, usually finds its meanings ‘in relation’ to another entities, such as form, ornament and mechanical optimization. Similarly, the street that you walk upon, the walls that protect you and all other units of the built environment, while significant for what they are, as Kiesler asserts, also possess nuclear multiple-force and multiple relations:

The common assumption is that these are dead ‘objects’; actually they embody an interplay of action with one another and with nature: They are a constant exchange of anabolic and catabolic forces within themselves, and in their coordination with human beings, through human beings with themselves again, they constitute high potential energy centres (p. 78).

To examine this quote on objects and their multiple-force in relation to function, I draw on my personal reflection on function and functional demands through an example. This examination is for the purpose of this analysis and may not apply more broadly. Assume you are in a downtown area standing by the side of a walkway to cross a street. Functionally, you may cross the street in three methods:

The first, and the most simple, method is to cross the street from your desirable point in space: no matter if you traverse a safe/permission area, since no sign or mark has been installed on the street defining your crossing function. In fact, you are infringing a legal limit by jaywalking, but you are sceptical if you can bring the act of crossing to a finish safely and pleasantly. Even if you are thinking legally, in this case, you have to act illegally against the norms. Will users and designers accept the function that violates, unintentionally or intentionally, our normative beliefs? Or will they consider this in situ legitimized function lack of function?

The second approach to crossing the street is to walk across the pedestrian area defined with only white lines painted on the street: here, signs have been used symbolically to indicate the functional association of the space with pedestrians. To reach the other side of the street, this could be a fast, economic, and efficient method. However, at this point you are only responding to the functional necessities of crossing the street and not more.

The third approach is to cross the street using a pedestrian walkway bridge mingled, interactively, with the shopping malls and plants inserted on its sides. In this case, you will partake in a joyful experience more than just walking across the street. As such, your functional awareness has expanded beyond the limit of the crossing act. Additionally, with access to elevator/escalator you can be
transferred to the pedestrian bridge, to the boon of machine, in a certain and efficient amount of time. The notion of function is both minimized and maximized in this case. Your concern about vulnerability to car accidents is mentally minimized, and the capacity of the space threshold, being exposed to the restaurants and shops on the sides, is physically maximized.

I consider these three attitudes towards function, respectively, lack of function, passive function, and active function. In my notion, the mental and physical level of human involvement in a certain act, from the lens of the users and designers’ demands, define the border between functional passivity and activity. The significance of the individual ‘objects’—such as the street and pedestrians—and the network of ‘forces’ formed among human, nature and technology through design—as in crossing the street—can be investigated through a theoretical construct. I will draw on Actor-Network Theory (ANT) and Object Oriented Ontology (OOO) for such an investigation.

6. Examining design strategies in the context of ANT and OOO

6.1. Description and application of ANT and OOO

Originally developed in the 1980s as a fundamental theory of social research in technology, ANT has recently returned to the forefront of environmental design thinking. A case in point is Yaneva’s architectural theory (2011) that does not take the existing dichotomy of form/function or society/architecture, but takes the design process as it unfolds from an integrated anthropological viewpoint. The combination of ANT and OOO has also formed new theoretical design constructs. Applying this integrative method, Kärrholm has (2013) has reconceptualised ‘building types’ to develop the concept of ‘territorial sorts’ which examines the roles of buildings in everyday life.

ANT gives agency equally to different actors (for example design objects) and the context (for instance function) formed through ‘translation’, ‘relation’ and ‘alliance’ among them (Latour, 2005). Actors denote human and non-human agents, and in a network take shape through their relations. ANT assumes that, first, nothing lies outside the network of relations, second, no difference exists in the ability of technology, humans, nature, animals or other nonhumans to act, and third, there are only enacted alliances; an actor engagement with an actor-network also means its engagement with the web of relations. (MacKenzie and Wajcman, 1999).

While ANT focuses more on the relations formed between things, OOO addresses the existence of things at all scales from atoms (scientific naturalism) to the construction of human behaviour and society (social relativism) (Bogost, 2012). In this philosophy, objects exist independent of each other and their relations, including human perception of objects, where they withdraw themselves from being exhausted. In other words, all relations may distort their related objects, but all objects exist on equal footing at the same time (Harman, 2005).

6.2. Theoretical construct: examining biomimetic and technology-based designs

Bryant (2014) points out that our access to things are descriptions of their actions within a defined assemblage. Meanwhile, our access are always partial accounts as things can interact in different ways in a different assemblage. Indeed, function follows these rules in its own entirety when withdrawing itself from subjection to one singular interpretation from the lens of designers, users and clients. Half a century dispute over prioritizing function or form in design evidences this multifaceted interpretation of the term ‘function’ in relation to the term ‘form’ (Collins, 1959). In pursuit of these fluid relationships,
my aim here is to show how one object—say nature, machine, or design—can draw on flows (effect and affect) from another object to configure and mold it in a variety of ways. Such a mechanism corresponds to the nature of ANT and OOO.

Bryant (2014) observes this flow of mediation among objects through his machine-oriented ontology. Quoting Latour on the ecological issue of the ozone hole, Bryant suggests a simultaneous access to both the discoveries of the social constructivists and the realism that acknowledges the reality of things:

The ozone hole is too social and too narrated to be truly natural; the strategy of industrial firms and heads of state is too full of chemical reactions to be reduced to power and interest; the discourse of the ecosphere is too real and too social to boil down to meaning effects. Is it our fault if the networks are simultaneously real, like nature, narrated, like discourse, and collective, like society? (Latour, 1993, p. 6)

This quote’s relevance is twofold. First, objects cannot be produced only by their relations—as in the relational approaches of biological analogy—leaving the construction of reality to something other more ‘real’ than the designed object per se. While there are real objects in nature and the man-built environment, it is impossible to see the entirety of an object in all its guises or to use it in all possible ways (Kärrholmhas, 2013). As such, the effect of a certain object is contingent upon its relationships with other objects, but every object holds autonomy, an effect that is different from that of its pieces; objects are assemblages where no object is reducible to another object(s) (Harman, 2010). Given this autonomy, the function of biological growth cannot be reduced to the Nakagin Capsule Tower or the self-sufficiency and mobility of a city cannot be reduced to a gigantic walking machine. The functional failures of such designs, either in theory or practice, comes from ignoring the meaning of scalar dimensions both literally and figuratively: the scales of objects are not seen as multiple and produced, but rather as hierarchised and prescribed. Similarly, the hierarchical strategies of biomimicry or machinery, such as the earlier mentioned ‘bottom-up’/‘top-down’ approaches, restrict us to the conformity of the ‘prescribed’ and will impose limits on the production of new objects.

Second, a certain design vision should recognize society on the side of nonhumans as partners for innovation, inspired either by nature or by machine. Both reductionism and holism are problematic. The former ignores the context of the relationships among the designed objects by reducing the whole to isolated irreducible objects, such as nature and machine. The latter focuses only on the context, the society, which embraces the relationships among the objects and neglects the individual contribution of objects in design. This calls for transition from the time of nature and machine to the time of coexistence, not in a metaphorical sense, but in a sense that the social space can lie at the intersection of the anthropocentric and ecocentric interests. To achieve this coexistence it is indispensable to see design as a field of collaboration, where creativity, mechanistic solutions, nature, users and different design disciplines, all are seen as objects holding agency on equal footing with one another. From here, the flow of relations between objects will define the design product: the more diverse the actors connected to the network, the more fluid and all-inclusive the design product in the web of relations will be.

In this setting, function with its dynamic ‘relations’, along nature and machine, play roles both as actor and network in a constant process of change. These are ‘objects’ because of their ‘irreducible’ individualities, but also are ‘networks’ since their ‘acting’ characters will be inactive until expanding their relations to other objects in the network. Their realms of effects and affects, perceived within the
changeful context of society, might be transitory ‘translations’, though these objects will preserve their ‘finitude’. For instance, as mentioned earlier, for Harbinson a ‘nonorganic’ pile would define the image of the machine (1997); in contrast, for Galiano (2000) this is the notion of ‘organic’ that defines the mechanism of a clock, the thermal machine of the steam engine, or the cybernetic machine. The reason for such opposing visions—better to say supplementary—is that ‘relation’ to a machine cannot be ‘translated’ into its direct and complete knowledge. This plural reading develops from the ‘dormant’ qualities of objects for which I suggest constant production of new methods to wake them up or to protect the world from their unwanted effects. One example could be the concept of ‘technological momentum’ defined by the historian Thomas Hughes (1994).

Technological momentum, as in between the two ‘hard’ and ‘soft’ views of technology, incorporates ‘time’ as a unifying factor. In a “soft view,” that is the technological change that drives social change, but at the same time responds discriminately to the social pressures. In contrast, in a ‘hard view’, technological development as an autonomous force and independent of social constraints will drive history. As a dormant quality in early stages of a certain technological progress, deliberate control over the functional scope of the technological momentum is possible and enacted by society. As a technology matures, however, its deterministic force appears since it will increasingly enmesh in the society. Thus, it is imperative to pay heed not just to the design approach, either biomimetic or technological, but also to the social context of design to safeguard the design result against falling into the realm of determinism.

Given the totalizing inclinations of biomimetic and technological design, I believe that ‘Bioconstructivism’ is a more appropriate term to succeed the notion of biomimicry since it may address equally both the relativism and reality of things, in nature, design process and product. By the term ‘reality’ I mean the individual irreducible being of things, and by ‘relativism’ I mean the network of relations among these individualities. Mertins (2004) has explored the term ‘Bioconstructivism’ to distinguish the imitation of the forming and functional principles of nature from its formal mimesis; however, in addition, I suggest the term can connote the social constructivism, which follows the ‘soft’ view of the technological design. Bioconstructivism operates at the intersection of the anthropocentric and ecocentric views, at the midpoint between the hard and soft views of technology.

7. Conclusion

Developing the appropriate design method through the application of technological or biomimetic concepts, before being a design question, is a historical one. The history of design evidences the inadequacy of nature and machine, both metaphorically and functionally, to become the source of inspiration for innovative designs. Those buildings that imitated nature functioned differently compared to their designers’ original intent and could not all satisfy their users’ demands. There are some exceptions to this claim. For instance, Mick Pearce’s Eastgate Harare and CH2 Melbourne buildings are successful architectures; however in extension of the unsuccessful historical precedents, today, these are very few buildings built in the biomimetic field (Mazzoleni and Price, 2013), substantiating the fact that in architectural and urban spheres biological concepts, even if emulated rather than imitated, can hardly turn into design products. For this reason, the advocates of biomimicry still seek a comprehensive systematic approach to develop a strategy capable of identifying and abstracting nature’s function for design function. This criticism does not mean that technology or machine is superior to nature in establishing a design methodology. Ignoring the social dimensions of the built environment in design
and making them subjugated to technological achievements will lead us to another sort of determinism where man and nature become commodities for mass production and consumption.

Designers should consider both the reality of nature and the social dimensions of technology, thereby both the individuality and relativism of the design production and process. A theoretical construct developed from merging ANT and OOO may help designers to examine the validity of a certain design approach. From this view, human, nature, machine, function and all other things are autonomous objects irreducible to each other and stand on equal level of agency in their network of relations. Neither machine is architecture nor is architecture nature. Even function is one object/actor, which also becomes a network as connected to the web of relations among architecture, nature and machine. Idolizing nature or machine over human actors will be against that equal distribution of agency. This leaves human actors functionally passive through the pervasive use of machine or mentally inert through replacing man’s creativity with abstract emulation of natural functions. Multiple perceptions of function endorse that its meaning, while irreducible, moulds ‘in relation’ to another entities, such as form, ornament, art or mechanical optimization. The function of objects is intertwined and multiple as in Kiesler’s ‘nucleus of multiple-force’. These forces are dormant qualities of objects not evident in the early stages of design process or even in the final product. The next step for innovation could be thinking of new design methodologies either to wake up these qualities, or to control them for sustaining the nature and society against their detrimental impacts in future.

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The model and its operative significance in architecture: objects driving evolution in design research

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Abstract: This paper draws upon the distinction between aesthetic and operative characteristics of models set for exploration in scientific and architectural research. Specifically, it weaves a link between Cache’s concept of Objectile and architectural models appointed for studying design’s inner logic also in reference to models describing biological functions. The outcome of this synergy is models that respond dynamically to variable data inputs and designated tasks. However, even when models are primarily applied as highly intellectual devices rather than ones being merely visual, still they cannot be detached from the formal idioms data is presented, compared and implemented with, set in reference to the graphic languages and the communication means by which content of any kind enters the architectural scene. As a response to this apparent incongruity, this paper delves into the operational role of models in the architectural making seen not as aesthetic objects, but rather as testimonial instances of a dynamic system in a continuum of recursive exploration and testing, further prompting to understand design as an experimental process undergoing phases of evolution, and so evincing architecture’s profound affinities with science.

Keywords: Model; objectile; cybernetics; bio-structuralism.

1. Introduction: research models in science and in architecture

Research in science generally assumes applying experimental methods of high reliability in order to produce new knowledge or refine existing one, helping to find proper answers to fully identified problems. Research findings should be stable, useful and repeatable and also, as Glanville (2014) suggests, be consistent with what is commonly approved and stick back together within the larger structures. Models are companions to scientific research, corresponding with the different phases of the exploratory process. Typically, they are made as simplifications of reality, representing variables associated with particular data put under iterative testing, comparison and assessment. As such, models are suitable for tweaking of data through controlled operations, resulting in different outputs produced and reproduced at will.
The above description is pertinent to scientific research directly relating models with a consistent progression of actions, as it also shows affinities with the ways models are appointed for exploration in architectural design. In that case, models may refer to the various means assisting the process of making. They are essentially active, in the sense that they enact, as Picon (2010) notes, negotiation between subjects and objects involved in design such as the designer, the data, the software and the hardware. Architectural models also present their performative character through real-time feedback. Initially they are made to visualize the designer’s intentions, as they are being enriched with more information that enters the working scene, so that the project evolves into more materialized phases gradually leaning towards a design proposition (Figure 1).

Figure 1: Models set to test stripes of land and implementation to a design proposal (source: C. Rowley, Y. Zavoleas, “Mutant body” master’s architectural design studio, The University of Newcastle, 2014).
The kind of models discussed above is different to those produced at the end of the design process to illustrate a project upon completion. There is a clear distinction between models set for exploration to those presenting the aesthetics of the final outcome. This observation applies to models created with either analogue, or digital means. It is worth noting though that the embracing of advanced digital processes in architectural design has rendered the model an exploratory tool assisting progression and decision making, that is, closer to the ways it generally operates in scientific research, whereas various software commonly assisting architectural practice still assumes that the digital tools are mainly ones for documentation and communication across different areas of expertise and working platforms, not so much in relation to the creative phases. In effect, various analogue and digital platforms currently available support multifaceted approaches, favouring equally different ideologies about design research and practice. Apparently, there is a growing separation within the discipline of architecture in reference to the usage of models, the appointed tools and the modes of design, to the point that one is forced asking (Picon, 2010) whether architecture is an aesthetic or a performative discipline, and if in fact it is both, how the often opposite priorities that emerge may be compromised.

In view of the above, this paper outlines what is implicit in the notion of model being symbolic of an augmented view of the drawing and its operative significance in architecture. A response is crafted first, by comparing assumptions related to the aesthetics of architectural models especially since these have largely been influenced by the digital means; second, by focusing on the performative character of models used in design research and their structural analogies with ones describing behavioural functions. An updated notion of the architectural model is proposed as a dynamic intermediate in support of architectural design seen as an evolutionary process that leads to enduring outputs.

2. Models in the design process

2.1. Aesthetics vs. function

Models generally refer to approximations of original phenomena to assist calculations, analysis and predictions. Models omit all but the most essential data, being closely connected to the modes selected to represent that data. The notion of the model in architecture, apart from 3D representations, may also denote, as Glanville (2012) suggests, sketches, diagrams and other graphemes commonly classified under the notion of drawing (Figure 2). Architectural models made for experimentation are not primarily set to portray the geometries about design in a conventional manner, but as Rahim (2009) claims, to further design innovation and produce proliferating cultural effects. Especially with digital operations such as scripting and dynamic simulation it is possible to connect different sorts of data structurally and make them interact in ways that the output may not be appreciated visually, but instead be read in response to rule-based research scopes. Experimental processes related to the computer if applied systematically, may in fact help to envision updated definitions of the architectural model and, as Picon (2010) foresees, create new perspectives on the evolution of design. As such, architectural models are less means for delivering the aesthetics about a project, but ones where form occurs in the first place being the product of synergetic interaction assuming design as a field of (pseudo-) scientific research.

However tempting such a prospect might be, it does not eliminate reservations mainly expressed by traditionally trained practitioners and thinkers, who see in these models and the tools they associate with a lack of aesthetic control by the designer/computer operator, and along with it a conviction to surpass human creative intelligence by constantly promoting extremities, leading – often disappointingly – to meaningless creation of forms easily sorted as different versions of digital mannerism. The
challenge is even greater when these tools act in conjunction with intricate themes of scientific origin, often setting attractive methods for exploring and reproducing complex morphologies, but offering ambiguous outputs when they are eventually implemented to the built environment. For example, the uncritical embracing of references from biology into design has created concerns as to what kind of architecture is produced if organic patterns are automatically set to construct ones in architecture. Initially driven by an admiration towards nature and natural processes expressed by biomimicry and biophilia, models of biological origin are often appointed to suggest forms that present little or no relevance to biological objectives, let alone those establishing architecture as a reputable field of the human intellect. Awkwardness is even greater when the designer applies parametric routines in order to facilitate repetition, but, as Picon (2010) describes, hasn’t fully integrated them in the process of conception to ally with his/her intuition. A result of this kind is described by Hensel (2009) as “parametric ornamentalism,” evoking the morphological articulation of organic patterns such as sponges and algae adapted to form nothing more than mere decoration. Aside from personal preferences, still anyone may accept that the employment of external references, also set of tools and processes, is an ally to creativity, as much as it also raises the risk to impose their characteristics over the outcome in uncontrolled ways. The experimental attitude involved in discovering the proclivities of new modes of practice, unfolds ideally with an equal increasing of the designer’s capacity to tame the related actions and more importantly to stay unbiased in assessing the result.

Figure 2: Analytical diagrams showing layers of data (source: C. Yuen Sim, M. Taylor, Y. Zavoleas, “Temporal topographies” master’s architectural design studio, The University of Newcastle, 2014).
2.2. Dynamic views on form and object

That said, one brings formalism to mind, a persistent threat about architecture, overshadowing any creative movement to be reduced to yet another style. Formalism commonly infers treating references as fixities, whose aesthetic properties are copied into design in ways that visual similarities between input and output are preserved, but the produced forms are generally not consistent with the behavioural traits of the original. The result is viewed as a product of mimicry, a parody of what was meant to be authentic; or, as Kwinter (2008) puts it, a sloppy conflation of the notion of “form” to that of “object.” In response, Kwinter considers form as being inseparable of the mechanisms of its formation, hence yielding a dynamic connotation to it, one that retrieves the actions it sets under its objectified nature. Form should bring those mechanisms together also under a unifying scheme being always somewhat distant, as the object may be a variable manifestation. Kwinter further goes on to describe form as a set of algorithmic rules embedded into the object. As such, form is to its foundation and may only be the most dynamic, extendable expression of an algorithm holding its code of production onto objects as they come into beings, similar to those specified in computational biology.

Figure 3: Topological variations of 3D pieces making a puzzle offering multiple outputs (source: C. Kourtoumi, Y. Zavoleas, K. Katsifaraki, “Design experimentations,” Technical University of Crete, 2005).
The problem is, however, that form may only be verified through an object. The discussion on form is incomplete if it does not include those resources involved in its genesis, which, as de Landa (2001) argues, are being immanent to matter itself, not transcendental. Aiming to disengage form from the properties that render it to the real world may respond at a philosophical level; still, on an actual setting, form and object go together. The answer to this oxymoron must be sought in the conception of the object on terms being equally dynamic to those used to describe form.

In alignment to this view, Cache (1995) identifies the object in a state of constant transformation and so he describes it with the concept of Objectile. As Cache (2013) denotes, the Objectile may be defined as a special kind of technological object, a dynamic topology rather than a static value wherein “fluctuation of the norm replaces the permanence of a law” (Figure 3). The Objectile is an aberration of what is considered as being standard and repetitive, from which harmony emerges as a singularity, not in reference to something universal. Cache’s definition follows a functional model constantly informed by a number of factors – actions, reactions and decisions – influencing the stages of an object’s life. Objects represent nothing more than a moment of densification in the folds of our behaviour that is itself fluctuating; they exist as variations of a “continuum” (Beaucé and Cache, 2007) based on extended flows and relations being essentially parametric.

Moreover, form and object share the same logic of control. For Cache (1995), that logic is a sort of a frame. Framing in this case does not refer to a physical frame or skeleton, but to a set of structural principles that condition the object in a state prior to its formal fixation, described as possibilities about images of flesh without bones, further associated with movement as a precondition to everything. Form is not a preset geometry applied onto matter, but the geometric output of structural constraints at the intersection of which the object is created (Beaucé and Cache, 2007). Experienced by the object’s material status, form resonates and expresses within itself the forces of its formation. The Objectile would demonstrate the range of negotiations among these forces, which, acting together, render the pair form/object a dynamic system (Figure 4).

Figure 4: Progressive transformation of frame structures (source: L. Jones, T. Solman, Y. Zavoleas “Mutant body” master's architectural design studio, The University of Newcastle, 2014).
A systemic definition of the pair form/object calls for the activation of the structural properties being mainly responsible for holding together everything that brought it into being. What appears as fixed in front of our eyes is in fact an open, mobile oscillating system, the palpable effect of computational interaction between internal rules and external pressures maintained in communicative tension together, setting, as Kwinter (2008) proposes, its behaviour as part of a broader ecology. Cache (1995 and 2013) further separates himself from a general understanding of the world as an accumulation of entities being distinct in space and time and so he proposes viewing them as systems interacting with one another, also ones that at any moment and no matter how complex they may be, they still signify parametric data and so they can be calculated. Data of any kind may entail social, legal and cultural factors that influence the system in a variety of ways. Every single bit, whether it is about basic information, a signal, a shape primitive, a curve, a surface, even an idea, is seen as a variable component, ideally summed up to a single formula, laying the foundation of non-standard, modes of production. In effect, the pair form/object refers to what de Landa (2005) identifies as a system mechanism reproducing and activating data under morphogenetic processes that extract multiplicities. The emerging variations refer back to the same system sharing the same code and rules, being also topologically similar; their seeming discrepancy responds to the same list of agents, which may produce alternatives as they are given different values.

3. System models

Systemic views of architecture call for assessing architectural models, those supporting the intermediate phases of exploration and also those illustrating the final design, separately from aesthetic criteria. Form neither has to come and impose itself from the outside (de Landa, 2005), nor has to be an expression of eccentricity. Emphasis is given on the model's operative significance, carrying the architect's thinking along the design process. What is suggested is a paradigm shift, one that involves turning architectural discourse, as Speaks (1995) suggests, to the more pliant, fluid, complex and heterogeneous forms of practice. Especially with the hybridization of the creative phases due to the appointment of digital technologies in representation and manufacture, the scope of design has shifted, Sheil (2012) remarks, from a largely pre-emptive act to an experimental process about form favouring the particular and the unique, under controlled modes of differentiation. The architect's methods should depart from modes of practice prompting aesthetic views upon the model and replace them by a keen interest in the model's aptitude in delivering nominated tasks. The idea is to assume the architectural model as well as the various outputs of the design process as active systems whose primary mission is to prompt negotiations among the design inputs by also supporting the necessary functions, in analogy to system theories speaking about the development and refinement of systems.

The view that architecture is a compilation of active systems has underpinned architectural discourse since the 1960s. Pask (1969) suggested that architecture is an operational research sharing the same philosophy with cybernetics in system management. Around the same period, Doxiadis (1963) stressed out that architects are first and foremost system designers. His working style gradually departed from traditional ones based on aesthetic assessment, also showing his inclination toward scientific modes of research in examining the dynamic connections among various data. Similar views resonate in the works of late-modern architects and particularly those of TEAM 10, who in clear opposition to prevailing ideas and modes of practice after Second World War, were devoted to studying organizing structures about physical space, often leaving the project intentionally unfinished, further claiming that the design is a proposition for handling energies in mutual exchange and a lifelong process that will certainly continue.
after the project is delivered to its occupants. In effect, a building may not simply be viewed in isolation as a set of boundaries and articulated regions. Rather, it is a full-scale model in itself; that is, a system fabricated specifically to interact in real-time with other systems being its inhabitants and the environment, holding other systems locally into itself and being placed within larger systems, making, as Hight (2009) observes, a compound that is hard if not impossible to break apart. This complete model accommodates all kinds of data which are to be linked together as parametric inputs and outputs influencing the development of human settlements at large.

System-orientated thinking in architecture has raised a demand for dynamic models whose directed functionality designates certain behaviours. Dynamic models are nonrepresentational; they are in direct correspondence with the forces of their formation (Rahim, 2009). Models of this kind generally involve abstraction, often being in reduced scale, or in no scale. They leave things intentionally underspecified, tentative and even unpredictable as to how they will be materialized. They expose the options and questions being as important as the value in concluding, further encouraging, as Glanville (2012) has put it, dynamic uncertainty. They are better understood as structural templates connecting the design’s constituent parameters and anticipating change in response to changes of their numeric values. As such, the dynamic model may hold those generative qualities that also act upon it to redefine and evolve it, in so doing fostering its continual reformation (Spyropoulos, 2014). Its beauty resides in its operational ability in relating the data about design, keeping them open as input parameters set dynamically to produce a variety of outputs. The model constantly adjusts eventually reaching equilibrium, a moment when design evolution terminates and the project finalizes.

4. Conclusion: design(-ing) structures of evolution

So far, this paper has stressed out the operative significance of architectural models in assisting the design process. Following their analogies with models in science, architectural models are suitable for identifying and exploring a project’s inner logic, as opposed to sponsoring aesthetically-driven purposes. As it is argued, such a task is factually feasible by describing the functions by which form is produced; in other words, by turning the architectural model from an aesthetic object to a dynamic system activated to eventually suggest its aesthetics being consistent with its formative logic. This task is greatly supported by advanced computing. It may be claimed that digital models are naturally dynamic, a trait they have inherited from the digital medium. In fact, every object on the computer screen is an automatic representation of codified data and so it is a variable per se. Admittedly, digital model’s variable character is often downgraded when the easiness by which data can be translated, modified and multiplied digitally without any of the frictions, or resistances commonly attributed to the material world is not taken into its full account. The undertaking proposed is to completely disengage the digital model from constraints associated with analogue materials and practices alike, especially the ones it suffers when it is appointed to merely respond to analogue-prescribed tasks; accordingly, as de Landa (2001) puts it, to take full advantage of the “digital matter” flowing inside computer simulations, being the basis of Computer Assisted Design (CAD). The contemporary designer, as an emerging type of digital craftsman immersed in the digital era, may invest his/her mastery on the digital model by challenging its limits to approximate behaviours and intuitive responses at micro and macro level also in real-time.

Taken down to its constitution, the digital model simulates data visually, as much as it presumes a structure being a set of specified rules holding data together. Structures support data and their shared functions as defined by the model system. In architectural design, data represent the variables influencing design, whereas functions involve manipulation of these variables also in reference to
schemes that set the general layout, all undergoing mutual compromises leading towards optimal solutions. Moreover, the digital model’s description as a structural scheme underlines its analogies with biological models. The biological model portrays organisms as systems interacting with one another, the result being their interference. An organism’s characteristics are seen as responses to its vital functions, and so they are given parametric significance. Variation is projected onto an organism’s phenotype, being the outcome of interaction between its genotype on the one hand and data and energy exchanges between the organism and its outer environment on the other. Evolution becomes a question of generating and updating the genotype due to limitations that have emerged during exchanging among systems. Consequently, there are operative similarities between digital models in architecture and biological models as instances of the same structure adjusting to data tweaks (Figure 5); a compound process of adaptation and evolution that, according to Spuybroek (2009), offers variations of answers to design problems addressed under a research scope.

As with biology, an evolutionary approach to architectural design presumes delving into the processes of setting a project’s structure that holds variables and their functions together. As Kirschner (2009) suggests, whenever a structure changes, underneath that change is a process of how that structure has been generated. Structure is seen as the primary variable, a kind of bio-structure that adapts to its tasks, a hybrid that evolves in response to new inputs. Architectural design, therefore, seen as a research subject, involves recursive processes of unraveling about variables and structures making up a project and then reconfiguring them back together, and so offering a population of responses gradually leading to comparative selection of the fittest and of which aesthetics may only be the end-effect and a by-product; not the cerebral contrivance of an individual.

Figure 5: Structural models developed as derivatives of a. set of flows, b. polycentric mesh, c. skin (source: Y. Zavoleas, “Bio-structuralism” research project, The University of Newcastle, 2014).
References

Thermal Comfort, Lighting and Acoustics
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A model for the cooling effect of air movement

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Abstract: The importance of the cooling effect of air movement to thermal comfort in hot humid climates is widely acknowledged, however theoretical models of this effect have not been tested in a residential setting. An 11 month longitudinal comfort study of 20 houses in Darwin, Australia yielded 1360 thermal comfort vote responses with corresponding indoor climatic measurements, including air speed. A model to describe the cooling effect of air movement was developed using these data. This model allows for the benefits of natural ventilation and fan use to be accounted for when assessing the indoor thermal environments of climatically designed houses in hot humid conditions.

Keywords: Air movement; thermal comfort; cooling effect; residential.

1. Introduction

Traditional forms of tropical bio-climatic housing are designed to effectively capture and enhance air movement throughout the building, reducing or avoiding the need for air conditioning. The importance of air movement to thermal comfort is widely understood by the occupants of these buildings; however current theoretical models of this effect remain largely untested in residential settings. The aim of the research presented in this paper was to develop a model for the cooling effect of air movement using collected data and to compare it to existing models. This research is relevant because regulatory thermal simulation software in Australia, AccuRate, incorporates a theoretical model which may not adequately allow for the benefits of natural ventilation and fan use in houses in hot humid climates.

1.1 Air movement and thermal comfort

Early studies in hot humid climates emphasised the importance of air movement in achieving thermal comfort (Webb, 1957; McFarlane, 1958). Despite these findings, widely used thermal comfort standards developed in Europe and the United States (US) distinguish air movement as undesirable ‘draft risk’ (Fanger et al., 1988; ISO 7730, 2005). As these standards are increasingly applied worldwide in varying...
climates, researchers are again seeking to recognise the beneficial contribution of air movement to thermal comfort in warm to hot conditions (Zhu et al., 2015; Rupp et al., 2015). The opportunities for providing thermally acceptable conditions through greater air movement is now of increasing interest, particularly in reference to the wider movement to reduce reliance on air conditioning appliances for comfort (Roaf et al., 2010; Brager et al., 2015). Recent studies have shown that there is often a strong demand for higher air velocities in warm and hot conditions (Yang et al., 2009; Cândido et al., 2011; Huang et al., 2013). Whilst much of the recent work incorporating some kind of assessment of air movement in relation to thermal comfort reports on the positive link between thermal sensation and air velocity, none attempt to describe this effect in a manner that can be incorporated into the future assessment of thermal environments. Similarly, very few studies are conducted in residential settings, despite the obvious opportunities for natural ventilation in dwellings. Supporting the need for further work in this area, Brager et al. (2005) conclude a review of contemporary thermal comfort research with;

A major theme has been indoor air movement, a long neglected resource for cooling and air quality, requiring new understanding, products and control approaches. (Brager et al., 2015, p286)

1.2. Measurement of air speed in thermal comfort field surveys

Air movement is one of the four environmental factors required to assess human thermal comfort conditions (ASHRAE, 2013); however it is not often measured in thermal comfort field research because of the expense, delicacy, accuracy and power consumption of anemometer sensors (Nicol et al., 2012). ASHRAE Standard 55-2013 (ASHRAE, 2013) presents stringent requirements for the range and accuracy of air speed measurement instrumentation; however historically methods used to determine air speed are far less precise. Early thermal comfort studies used the laborious Kata thermometer to estimate air speed (Nicol et al.; 2012; Bedford, 1963). More recent research employs thermal anemometers (Melikov et al., 2007), although their use often presents the same limitations as noted above (Nicol et al.; 2012). In cross-sectional thermal comfort surveys researchers are able to mount the monitoring equipment onto a portable base (Cândido et al., 2010); which largely overcomes many of the issues regarding expense and delicacy of sensors. In longitudinal studies where this approach is not appropriate a technique for estimating air speed based on window, fan and air-conditioning operation is commonly employed (Saman et al., 2013; Williamson et al., 1990). These solutions demonstrate the need to develop economical instrumentation for the measurement of air movement for thermal comfort research.


International thermal comfort standards facilitate some increase in the upper boundary of comfort in warm to hot conditions due to elevated air speeds. The effect of elevated air speed is incorporated within the equation of the analytical model for thermal comfort (i.e. PMV-PPD). This paper, however, will focus on adaptive models of thermal comfort which are likely to be more appropriate for application in residential settings (Peeters et al., 2009; Saman et al., 2013; Daniel et al., 2015). The upper boundary of the ASHRAE adaptive model can be extended incrementally by 1.2°C when the average air speed is 0.6m/s, 1.8°C at 0.9m/s and 2.2°C at 1.2m/s, when the prevailing mean outdoor temperature is greater than 25°C (ASHRAE, 2013). Similarly, the CEN adaptive model is able to be extended for air speeds above
0.2m/s when the indoor operative temperature is above 25°C using a convex logarithmic function (CEN Standard 15251, 2007).

The key limitation of both of these models is that they are not dependent on humidity. Previous research (Givoni & Milne, 1981) suggests that the cooling effect of air movement decreases with increasing humidity. Therefore, in a hot humid climate where the conditions indoors are closely linked with outdoor weather, the recognition of humidity is vitally important.

1.4. Cooling effect of air movement in AccuRate

Within the regulatory building performance software, AccuRate, Szokolay’s theoretical model (2000) is used to account for the cooling effect of air movement (Delsante, 2005; Chen, 2011). This model was developed specifically for practical application in the assessment of tropical housing within Australia. The proposed function defined by Equation 1 is derived from the analysis of eight other models (ASHVE, 1932; Drysdale, 1952; Rohles et al., 1974; Arens et al., 1981; ASHRAE, 1985; Arens & Watanabe, 1986; Humphreys & Nicol, 1995). Again, despite the recognition that the cooling affect may diminish with increasing humidity, it is not included in the Szokolay equation. This paper explores a method for taking both air speed and humidity into account.

\[
\frac{dT}{dt} = 6v_e - 1.6v_e^2
\]

Where:
\[
\frac{dT}{dt} = \text{cooling effect (K)}, v = \text{actual air speed (m/s)}, v_e = \text{effective air speed} = v - 0.2m/s
\]

2. Methods

Twenty households located in Darwin, Australia, participated in an 11 month thermal comfort field study from June 2013 to May 2014. The households were chosen to participate in the study because the occupants operated their dwellings as partially or solely naturally ventilated. This fieldwork was conducted as part of a broader research project investigating occupant preferences and behaviour in dwellings of atypical construction within Australia (Daniel et al., 2015).

2.1. Climate

Darwin has the Köppen climate classification ‘BSh’; hot sub-tropical steppe. The climate has three main seasons; the build-up, the wet (monsoon) and the dry. Average annual rainfall recorded at the closest Bureau of Meteorology (BOM) weather station, Darwin Airport (Station number 014015, 12.42 °S, longitude 130.89 °E), is 1726.5mm. The majority of rainfall is received in the monsoon period through January, February and March. The driest period is through June, July and August where very low amounts of rainfall are recorded (1.9mm, 1.2mm and 5.0mm respectively). Mean daily maximum temperatures have a narrow range from 30.5°C in July (the dry) to 33.3°C in November (the build-up/the wet), while mean daily minimum temperatures have a similarly narrow range from 19.3°C in July to 25.3°C in November and December. Humidity is highest in the wet season with a mean 9am relatively humidity of 83% (February) and lowest in the dry season with a mean 3pm relatively humidity of 37% (July) (BOM, 2013).
2.2. Thermal comfort survey

A paper based comfort vote survey in booklet form was distributed to all households; residents above the age of 18 years old were invited to fill them out on a daily basis. Three widely used subjective measures of thermal comfort were included; sensation 1=Cold to 7=Hot (ASHRAE, 2013); preference 1=Cooler, 2=No change, 3=Warmer (McIntyre, 1982) and; comfort 1=Very uncomfortable to 6=Very comfortable (Brager et al., 1993). The survey also asked the respondents to report their clothing level, activity, and window, fan and artificial heating/cooling operation. A final question asked respondents to identify any source of discomfort not directly related to temperature (i.e. draft, stuffy, dry, humid sensation). Survey responses were collected at the mid-point and at the end of the monitoring period. Responses were manually entered into an Excel spreadsheet with the corresponding environmental measurements at or around the time the respondents completed their survey responses.

2.3. Equipment

Temperature, relative humidity and globe temperature were measured and recorded using the HOBO U12-013 data loggers. At the time of planning the fieldwork no existing systems for measuring and logging air speed were feasible to use. The data collection system needed to be relatively inexpensive, self-sufficient for power for at least six months, unobtrusive, robust and able to measure air movement to a sensitivity of 0.1m/s. In March and April 2013 an experimental system was developed that utilised the open source hardware and software system Arduino™ to connect an Accusense F900 Thermal Air Flow Sensor to the standard HOBO U12-013 logger. A full description of the system and development process was reported in (Daniel et al., 2014).

Two loggers were placed in each household; the logger incorporating the anemometer sensor was located in the household’s primary living area, while a secondary logger was placed either in a subsequent living area or the main bedroom. The loggers were located away from heat sources, out of direct sunlight and, where possible, in a central location within the room at approximately 1.1-1.7m above floor level. In general, data collection meets the requirements of a Class-II field study and the requirements of ASHRAE 55-2013 (ASHRAE, 2013) for data collection.

3. Results

During the monitoring period a total of 2535 thermal comfort vote surveys were completed by 56 subjects from the Darwin households. One thousand, three hundred and sixty of those surveys had corresponding air speed measurements, a basic statistical overview of these data are presented in Table 1. The conditions within the dwellings were predominantly warm to hot with high humidity (see Figure ) whilst the average air speed was relatively low (0.23m/s) at the time that votes were cast (see Table 1). Figure 2 demonstrates the range of air movement achieved within one of the dwellings during July 2013. Note that for the first half of the month the occupants were away and the house was closed up.
Table 1: Descriptive statistics for the thermal comfort votes surveys.

<table>
<thead>
<tr>
<th>Variable</th>
<th>N</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indoor operative temperature (°C)</td>
<td>1360</td>
<td>16.3</td>
<td>36.4</td>
<td>28.3</td>
<td>2.9</td>
</tr>
<tr>
<td>Air velocity (m/s)</td>
<td>1360</td>
<td>0.01</td>
<td>2.01</td>
<td>0.23</td>
<td>0.12</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
<td>1360</td>
<td>20.8</td>
<td>98.3</td>
<td>67.6</td>
<td>17.6</td>
</tr>
<tr>
<td>Outdoors running mean temperature (°C)</td>
<td>1360</td>
<td>23.1</td>
<td>30.5</td>
<td>26.9</td>
<td>1.7</td>
</tr>
<tr>
<td>Thermal sensation vote</td>
<td>1356</td>
<td>1</td>
<td>7</td>
<td>4.1</td>
<td>1.1</td>
</tr>
<tr>
<td>Clothing insulation (clo)</td>
<td>1360</td>
<td>0.04</td>
<td>1.0</td>
<td>0.33</td>
<td>0.20</td>
</tr>
<tr>
<td>Metabolic rate (met)</td>
<td>1360</td>
<td>0.8</td>
<td>2.0</td>
<td>1.3</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Figure 1: Psychrometric chart of the temperature and humidity at the time that “No change” thermal preference votes were recorded. *(Note: dash lines indicate the acceptable range of operative temperature and humidity according to ANSI/ASHRAE 55-2013)*

Figure 2: Hourly air speed measurements in a naturally ventilated Darwin dwelling in July 2013.
3.1. Development of the cooling effect model

The thermal comfort surveys that had corresponding air speed measurements were then used in the development of a model to describe the cooling effect of air movement. A model is proposed for the comfort effect of the form \(dT = f(v_e, \text{RH})\). In order to identify the parameters of this function the surveys where occupants had elected a ‘no change’ preference vote were binned into <75% RH and >75% RH humidity groups. All data were used to represent a central or average humidity group. This approach was taken in order to attempt to account for the influence of humidity in the model.

These groups were then further disaggregated by binning the data by airspeed; <0.2m/s, 0.2-0.3m/s and >0.3m/s. The average operative temperature and air speed was attained for each of these bins. The temperature at 0.2m/s was determined using the equations derived from plotting the average temperature and average air speed at each bin. To get an effective air speed, the average air speed for each bin was subtracted by 0.2 following Szokolay’s methodology. The effective air speed was then plotted against the cooling effect; temperature at 0.2m/s subtracted from the average operative temperature at the 0.2-0.3m/s and >0.3m/s bins respectively, because by “definition” in the Szokolay method there is no cooling effect at zero effective air speed. Each plot in these cases is constrained to pass through the 0.0 point, see Figure 3. The coefficients derived from each humidity bin are presented in Table 2.

<table>
<thead>
<tr>
<th>Humidity bin</th>
<th>Average humidity</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>All RH values</td>
<td>67.1</td>
<td>2.99</td>
</tr>
<tr>
<td>&lt;75RH values</td>
<td>55.0</td>
<td>3.24</td>
</tr>
<tr>
<td>&gt;75RH values</td>
<td>85.4</td>
<td>2.38</td>
</tr>
</tbody>
</table>

Table 2: The average humidity and coefficient of cooling effect (°K) vs. air speed (m/s) for each humidity bin.

The coefficient for each humidity group was then plotted against the average humidity for that group (Figure 4). This yields an equation by which the cooling effect of air movement can be calculated (Equation 2 & 3). The cooling effect for three different humidity levels is compared with Szokolay’s function in Figure 5.

\[
y = 4.86 - 0.029\text{RH} \\
\text{Where:} \\
\text{RH} = \text{relative humidity}
\]

\[
dT = v_e y \\
\text{Where:} \\
dT = \text{cooling effect (°K) as a function of air speed (m/s)}, v_e = \text{effective velocity}
\]
4. Discussion

This model was developed specifically for application in the assessment of residential thermal environments within hot humid climates of Australia. Figure 6 demonstrates how the model could be applied to the ASHRAE adaptive model of thermal comfort. The extension is applied to the upper 80% limit at prevailing mean outdoor temperatures greater than 25.3°C, the temperature corresponding to the greatest proportion of ‘no change’ thermal preference votes. This corresponds well with the
temperature (25.0°C) that both the ASHRAE and CEN adaptive models allow the consideration of the cooling effect of elevated air speeds.

![Graph](image)

Figure 6: Extension to adaptive upper 80% limit. (Note: the extensions are based on effective air speed at 67.6%RH, the average humidity at the time that comfort votes were recorded)

Importantly, this model accounts for the influence of humidity levels in the cooling effect of air movement. At higher humidity levels, the cooling effect is reduced. For example, at 50%RH with an effective air speed of 1.0m/s the upper boundary of comfort could be raised by 3.4°C, while at 75%RH with the same air speed, it would be raised by 2.7°C. In ASHRAE 55-2013, the corresponding increase to the 80% upper limit of the adaptive model is just 2.2°C independent of humidity levels (ASHRAE, 2013). Similarly, comparing Szokolay’s model, the cooling effect is greater than the proposed model at 1.0m/s but then is reduced at 1.5m/s and 2.0m/s. This example demonstrates that current allowances for the cooling effect of air movement may indeed under estimate the benefit afforded to thermal comfort.

5. Conclusions

In the assessment of the thermal performance of naturally ventilated houses in hot humid climates it is critical that the cooling effect of air movement be adequately accounted for when determining acceptable thermal conditions. The proposed model provides greater accuracy in assessing the effect of air movement than the current theoretical model incorporated within the regulatory thermal performance simulation software, AccuRate. The contribution of the research presented in this paper is to encourage more climatically appropriate responses to housing in tropical climates by acknowledging the influential role of natural ventilation in the thermal comfort of the occupants.

The results presented in this paper demonstrate the successful application of a relatively inexpensive experimental air movement sensor. With further development it offers a way by which air speed data can more readily be collected in longitudinal thermal comfort fieldwork studies.

The collection of this data enabled the development of a model to account for the cooling effect of air movement that also takes humidity into consideration. The use of this model allows the benefits of
natural ventilation and fan use to be acknowledged in the assessment of bio-climatically designed tropical housing.

Acknowledgements

The authors would like to thank Mr Andrew Carre for his assistance in the development of the air movement sensor. This research was supported by funding from CSIRO.

References


Comfort models as applied to buildings

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Abstract: This investigation is about applying the ISO-7730 Fanger (static) Comfort model to two fully air-conditioned, yet, differently performing buildings, based on research into on-site comfort performance measurements using comfort carts. The results challenge the common perception that the ISO-7730 model is concerned with a narrow temperature band. Regardless of the environmental variations encountered temporally and spatially throughout real office environments, occupants appear to achieve comfort with reasonable success. The paper explores this flexibility within the ‘static’ model, more than perhaps is commonly realised. We consider the possibilities that many of Australian office buildings can operate under much greater temperature variation than expected and that there are mechanisms for occupants to adapt to varying conditions.

Keywords: Comfort; climate; offices; buildings.

1. Introduction

Thermal comfort is an essential component of occupants’ perceptions of a building. Comfort is formed in part as a function of human physiology, behavioural and psychological encounters (deDear et al., 1997). However, the results of thermal comfort also have many aspects involving the environment and composition of the building spaces themselves, their construction, materials and technologies as well as their social and cultural expectations. Thermal comfort also extends to the individual’s social position and how they pursue it (Nicol and Stevenson, 2013). Therefore, the present investigation and research into comfort in our buildings is complex, yet relevant.

There are several reasons why comfort models (calculations) may not provide the outcome expected at a specific location in a building. One reason rests in the development of the comfort model itself; other reasons are because the building composition and operation are ignored (Nicol and Stevenson, 2013). Other biases of comfort calculation may rest in the parameters selected and applied in the well-known ISO-7730 equation ignoring occupant behaviour or the external environment (Humphreys and Nicol, 2002).

The authors of this paper suggest that more research is required to understand the occupant environment in real buildings and how the level of comfort is achieved. It is also suggested that perhaps
the present PMV model is still appropriate but requires modification according to specific field conditions. A change of the existing ISO-7730 “PMV” comfort model was strongly proposed by reputable comfort scientists who made revisions to the PMV model to include a bias according to actual occupant votes (Humphreys and Nicol, 2002). With the exception of this paper it took over ten years to reinvestigate the application of the PMV model parameters as applied to field measurements of HVAC and naturally ventilated buildings. In addition to this, several authors believe that occupants do not want ‘thermal boredom’ and endorse temporal variation in comfort within a set location (deDear, 2006; Corgnati et al., 2007 (Langevin, J. et. al., 2013).

This paper develops a previous paper (Reference removed to preserve anonymity) into observing the variability of comfort, temporally and spatially, throughout a building level. It explores the variations of comfort experienced in two very different office buildings at different locations and different daytime periods. It challenges our understanding of how our buildings provide for or fail to provide for comfort. What building contributions might be required to ensure comfort?

To better grasp the changing comfort levels experienced by an occupant, throughout the day and at various specific locations, we present this information in a time-series chart. This gives an overall picture of the thermal comfort performance of the building throughout a day in relation to its orientation, ambient temperature, and façade exposure or lack of it. It displays graphically where comfort changes occur. This information consists of measured on-site data (both internal and external) from which comfort indices of PPD (percent predicted dissatisfied) from the ISO-7730 model are calculated. Since the buildings we are investigating are fully air-conditioned and primarily consist of fixed glazed windows we use the ISO-7730 (Fanger) comfort model. However, we consider the flexibility available to the occupants to manage their own comfort in such environments. Indeed, occupants do have some control in fully air-conditioned buildings.

2. The investigation

In an earlier investigation, we measured the climate and comfort of 15 fully air-conditioned office buildings between Brisbane and Melbourne, Australia during brief seasonal periods. Only two of these buildings comply with the narrow comfort band required by the ISO-7730 comfort model. All the others show a more direct relationship with external air temperature, which challenges the omission of this parameter in the ISO-7730 model for HVAC buildings.

In the present investigation, we compare the core (central) building comfort level with comfort levels at other locations on the same floor level on the same day at different time intervals. This investigation allows us to select two very differently performing offices in our discussion of comfort variability and expectations. Both buildings are located in the CBD of Melbourne and are multi-story government office buildings. The first building is typical among office buildings in Australia. It is poorly sealed with air leakage and exhibits a variable air temperature difference across a daily cycle. The second building is one where the temperature variation is tightly controlled. The temperature and comfort measurements are taken at a central ‘core’ of the building to determine the comfort uniformity.

The measurements of both buildings utilise two comfort carts constructed according to the ASHRAE Standard-55 (ASHRAE, 2013), to measure air temperature, globe temperature, and air velocity at 0.1m, 0.6m, 1.1m and 1.7m heights. Air humidity is also measures at 0.6m. One cart is programmed to measure continuously at 15 minute averaged intervals while the second cart is set in a ‘survey’ mode to be relocated for 10 minute sampling at designated locations. Figure 1 is a picture of the comfort carts.
used in the measurements. The survey comfort cart is positioned and allowed to settle for 5 minutes to equilibrium with its environment before the actual measurements are taken in the final 5 minutes.

![Comfort Carts](image)

Figure 1 Comfort Carts as used in the measurements of the project.

### 2.1. Central Building Core Comfort

First, measurements from the building ‘core’, in a central part of a floor level, are investigated. This procedure and its instrumentation are described in (Reference removed to preserve anonymity). Figures 2 and 3 illustrate the comfort levels in the two selected buildings according to a PMV/PPD ISO-7730 (Fanger) comfort model. Measurements from the comfort carts presented in Figure 1 are used in an EXCEL spreadsheet routine to calculate the ISO-7730 (PPD) comfort result.

Both these figures show a ‘clothing comfort band’ according to CLO values from surveying occupants. It was discovered that a ±0.2 CLO difference was the norm, regardless of season, on any given day, across many of the surveyed buildings (reference omitted to preserve anonymity). It is evident that allowing for this ‘CLO range’ shows that the buildings can be comfortable if the standard prescriptions are relaxed.
Throughout a day, the behaviour of the comfort in Building A (Figure 1) is noticeably different from that of Building B (Figure 2). Unfortunately the dataset for Building B was not as large. Regardless of
outdoor temperature changes there is a much larger swing in comfort in Building A. It has also been confirmed, by results not shown here, that this behaviour is independent of whether the assessment is made in winter or summer.

The conclusion is that Building B is more stable in its comfort band because of its operation and construction. Note that this building does exhibit a slight change in its comfort band when it is unoccupied and comfort is irrelevant. However, it appears that Building B possesses an all-round ‘comfortable’ environment. But this conclusion rests on the assumption that the ‘core’ behaviour applies throughout the building. So, an important question is whether the comfort within each of these buildings, at various locations, is uniform and in accordance with the ‘core comfort’ band shown here. In fact, there is a surprising deviation in comfort at various locations throughout the day for each of these buildings.

### 2.1. Surveyed Locations Compared to Building Core

Figures 4 and 5 illustrate the differences in comfort measured at several surveyed locations. Each such location is measured with the survey comfort cart as described above for a duration of 10 minutes three times a day clustered at mid-morning, midday and mid-afternoon. (The figures indicate the ‘PPD comfort vote’ (right heading) calculated for a specific location on the plan shown within the chart. The external air temperature scale is provided on the left hand side of the graph).

![Figure 4: Comfort at Various Locations in Building A](image-url)
These two figures show, in two different air-conditioned buildings, how the predicted percent dissatisfied (PPD) at each time period is scattered rather than clustered closely together. In Building A the PPD ranges from 10% at best to 42% (i.e. off the graph) at worst. Throughout the day, the PPD changes for points on the west of the building. Note the ‘square point’ next to the east wall which is fully glazed from floor to ceiling which is never less than 25% PPD. Such points are characteristic of the building composition (a glazed facade) significantly determining their comfort result. The parameter of mean radiant temperature would heavily influence comfort at this location. For the point on the south the PPD also decreases, but is never less than 20%. For this case, there is a cold pocket with poor air temperature distribution, since this location actually faces an internal corridor.

Figure 5 shows the ‘more stable’ Building B as well as data for a central point in the building monitored continuously throughout the day. This is labelled the “core” PPD, which is always close to 5%. However, the comfort is not as uniform as may be expected, because the PPD away from the core ranges from 7% at best to 23% at worst. However, the three points on the east of the building form a cluster which has a PPD better than 10% at mid-morning and noon, but which is scattered between 10 and 20% in the afternoon. Again, the orientation and location of the measurement at specific times during the day has an impact on comfort.

Do the occupants in such variable environments remain in comfort or not? If adjustments to clothing are accounted for, the ‘clothing comfort band’ allows a PPD less than 10% to be achieved. Table 1 shows the effect on PPD for the mid-morning in Building A as CLO is increased in steps of 0.2 – the effect of adding a light sweater, for example. Wearing a jacket increases CLO by 0.35, and an outdoor coat (or a woollen dressing gown) by 0.6. If occupants are not restricted by dress codes, they have the freedom to control their personal comfort significantly. Japan has had success with the “Cool Biz” policy introduced
in 2005 by Prime Minister Junichiro Koizumi, in which the dress code was relaxed so as to save energy from summer air-conditioning (Cool Biz, 2005).

Table 1: The effect of clothing on PPD

<table>
<thead>
<tr>
<th>Point</th>
<th>CLO = 0.8</th>
<th>CLO = 1.0</th>
<th>CLO = 1.2</th>
<th>CLO = 1.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>42</td>
<td>21</td>
<td>11</td>
<td>6</td>
</tr>
<tr>
<td>B</td>
<td>32</td>
<td>16</td>
<td>8</td>
<td>5</td>
</tr>
<tr>
<td>C</td>
<td>30</td>
<td>14</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td>D</td>
<td>33</td>
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</tr>
<tr>
<td>E</td>
<td>32</td>
<td>16</td>
<td>8</td>
<td>5</td>
</tr>
</tbody>
</table>

3. Discussion

The presented information raises the question as to whether occupants are actually comfortable under variable conditions throughout a day. Unfortunately, other than having clothing surveys filled out, no other comfort questionnaire was taken during these measurements. Nevertheless, there are quite some observations to be made which could provide useful in future research.

The first of these observations is related to the variability of comfort around the same floor level at various locations within a space. This variability indicates that it is in fact erroneous to accept and rely on a single ‘core’ comfort result for an entire floor level. There can be and are huge differences according to the zones (north, east, west or south) of a building and at various times of the day. In fact we can identify the influence of orientation and its exposure (or lack of it) to solar radiation. Factors such as mean radiant temperature and air velocity differences can definitely influence comfort changes at a particular location. However, most of these changes to comfort could be rectified by varying CLO (clothing).

It is useful to investigate more on the façade thermal behaviour in relation to occupant comfort for perimeter building zones. It is indicated that when occupants sitting next to a glazed façade with some control of its shading, can participate to regulate it back into comfort (Anderson and Luther, 2012). Such opportunities constitute a change in occupant behaviour, which removes the stigma of a non-controllable HVAC building.

Interestingly, Figure 6 shows only the air temperature for Building A (Figure 4), which seems to indicate that there is little difference among the various locations measured. Based on this information, one may conclude that other comfort parameters are irrelevant and do not influence the final comfort result. Indeed, Figure 4 shows this is not true. Note that this is a current flaw in NABERS IEQ Comfort assessment where a single wall thermostat temperature reading determines whether comfort is achieved or not.

Furthermore, it should not be forgotten that there are social, behavioural and psychological parameters informing thermal comfort. These, of course, seem to be absent from any comfort model; static or adaptive. However, adaptive models appear to inherently account for and give reason for an occupant’s freedom to adjust their environment for comfort. The two buildings investigated here do not satisfy the requirements to qualify for an ‘adaptive model’ assessment. This is in fact a further issue or problem in the applications of various comfort models where evidently many researchers are applying adaptive models to ‘static’ model buildings. Is it possible that some ‘static’ buildings could be adjusted to allow them to qualify for ‘adaptive model’ assessment? The research of Humphreys and Nicol (2002) and of Langevin et.al. (2013) suggest that it is.
Almost all of our measured buildings had a prime open office space connected with the façade boundary. Back in the day when the ISO-7730 comfort model was developed, (1970’s to 1980’s) many of the buildings consisted of enclosed offices. Although there were ‘open offices’ very few open offices had façade exposure and the office layout was very restricted. In contrast to this, many of our buildings had controllable, manually or automatic blind systems and some had ceiling fans. Several occupants also had their own task lighting at their desks.

The design layout and the behavioural working conditions have changed significantly over the last 30 or more years. Occupants in ‘static’ buildings are gaining some control of their environment and are often permitted to dress accordingly to the weather conditions. HVAC building control strategies are evermore increasing in the application of economizer cycles, night time purges and mixed-mode operation. Controlled daylighting or artificial lighting is increasingly becoming the norm in most office spaces. The entire office design layout itself is changing, allowing occupants to go elsewhere in the building to do their work. The ‘breakout’ or meeting space is included in most office designs. All of these building features would certainly influence the comfort of an occupant and need to be considered in today’s evaluation of an office space.

4. Conclusion

New and endorsing other existing research contribution of our research includes but is not limited to the following:

- While air temperature alone might be uniform throughout a floor level the actual comfort results can vary significantly. This indicates the importance and necessary inclusion of other
parameters that determine comfort. The charting of measured and calculated ISO-7730-PPD (Figure 4) is quite different from Figure 6 showing air temperature alone. This indicates the danger of using air temperature alone to determine occupant comfort, which is so often performed.

- Clothing level (CLO) is a major ‘game changer’ in an occupant’s comfort. Therefore, it is unreasonable to consider a singular CLO value in the use of the ISO-7730 model. Occupants vary their clothing ±0.2 CLO on any given day during any given season.
- Too often single parameters are applied, restricting any provision of a ‘comfort band’ or ‘range’ which appears to exist realistically within buildings.
- Furthermore, our investigation shows that it is unreasonable to consider a single comfort value for an entire floor level.
- In the investigation, the comfort data has been plotted both temporally and spatially. The graphical representation is a good way of showing how we perceive and understand daily comfort variations within a building.

In addition to the above, several authors believe that occupants do not want ‘thermal boredom’ and endorse temporal variation in comfort within a set location (deDear, 2011; Cognati et al. 2007; Humphreys and Hancock, 2007). This study introduces the concept of a ‘comfort band’ to evaluate comfort for HVAC conditioned buildings. Therefore, in rating system calculations, such as NABERS and Green Star, the use of a ‘comfort band’ would be more realistic. Our results indicate that a ‘comfort band’ would provide for a more reasonable assessment in the allowance and planning of comfort.

What is evidently missing from our study are the occupant comfort surveys in relation to the actual measurements. This is unfortunate; however it highlights the importance of a comfort survey in future work. Nevertheless, our rating systems rely on ‘established’ calculations without surveys. It would be interesting to know what is calculated where and when in such evaluations since location and time of day have been shown by this research study to make a significant difference. It should also be recognized that the construction (materials) and design of office buildings vary and have significantly changed from what they used to be. Also, HVAC control systems themselves and their operation have changed since the development of the ISO-7730 static model.

Given the above research, as well as previous research into changes to the ISO-7730 PMV model for field applications, it is crucial to commence and continue with real measurement studies on thermal comfort. We need to understand whether the models are in fact relevant or require adjustment in the near future. It is indicated by others that in fact the ISO-7730 model offers quite some flexibility and allowable variation and can be used for both HVAC and naturally ventilated buildings.

References


Comparing climate based daylight modelling with daylight factor assessment – implications for architects

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Abstract: This paper investigates two different daylight metrics, the commonly used daylight factor (DF) and the new IES approved climate based daylight modelling method (CBDM) IES LM-83-12 in comparison, with regards to their impact on the overall energy demand for heating, cooling and lighting as well as the optimum resulting window size. The assessment has been performed for a typical cellular office room in the climate of Athens, Greece. Different window to floor areas have been compared and the variations have been tested with and without an external overhang for North and South orientation and with an internal roller blind for the assessment of the Spatial Daylight Autonomy. The daylight factor (DF) assessment gives satisfactory results for almost all configurations. The IES LM-83-12 metric requires two criteria to be met, the Spatial Daylight Autonomy (sDA) and the Annual Sunlight Exposure (ASE). While the requirements for Spatial Daylight Autonomy are met for most configurations, the requirements for the Annual Sunlight Exposure are only met on the North façade.

Keywords: Climate based daylight modelling; daylight factor; office; energy demand.

1. Introduction

Daylighting is an important parameter for the assessment of a building's energy performance. Human visual system is extremely well adapted to daylight and the use of daylight in buildings can significantly reduce both peak loads and artificial lighting energy consumption and therefore greenhouse gas emissions.

Traditionally daylight has been evaluated quantitatively, using the daylight factor (DF). The daylight factor is defined as the ratio of internal illuminance to unobstructed horizontal illuminance under standard CIE overcast sky conditions (Moon and Spencer 1942). It is expressed as a percentage of the unobstructed outside illuminance that is available indoors. Although there are various recommendations for typical daylight factor values, an average value around 2% is considered satisfactory. For example In EN 15193:2007 an average value >=2% corresponds to a medium daylight
penetration while in BREEAM, for offices, a good practice daylight criteria is met when an average value of 2% is achieved for 80% of the spaces examined together with a certain value in uniformity. The advantage of the daylight factor evaluation lies in its simplicity, as it can be easily calculated and the assessment can be done in architectural offices alongside the design process. The shortcomings of the daylight factor however are also related to its simplicity. Being expressed as a percentage, the daylight factor does not provide actual illuminance values for the interior space under assessment which could be compared with target values for indoor illuminances. Based on overcast sky conditions, the daylight factor does not consider direct sunlight and it does not provide an indication of potential glare, sun patches, solar angle, intensity and redirection of sunlight. According to Mardaljevic (Mardaljevic 2009), the daylight factor can lead to overglazed buildings that are exposed to high solar heat gains.

In order to overcome the disadvantages of the daylight factor, climate based daylight modelling (CBDM) is a new IES approved approach for daylight evaluation and it is based on two metrics using daylight conditions from typical meteorological years (TMY) as its basis (IES LM 83-12).

1. Spatial Daylight Autonomy (sDA) measures daylight illuminance sufficiency for a given area. It is defined as the percentage of floor area, that meets or exceeds a specified illuminance level (recommended 300 lux on horizontal surfaces, 0.8m above finished floor) for a specified amount of annual hours (recommendation: 50% of the hours from 8am to 6pm). The IES guideline suggests two different quality levels for Spatial Daylight Autonomy, the first being ‘preferred daylight sufficiency’, in case 75% or more of the analysis area meet the above mentioned criteria the second being the ‘nominally accepted daylight sufficiency’, if 55% or more of the analysis area meet the above criteria.

2. Annual Sunlight Exposure (ASE) assesses the potential visual discomfort using as an indicator an illuminance value (>=1000 lux) caused by direct sunlight on the working surface. ASE is defined as the percentage of the analysis area which exceeds 1000 lux for more than 250h per year without the use of any blinds and assuming the operational period between 8am and 6pm.

3. For the calculation of Spatial Daylight Autonomy an interior (blinds or shades) shading system is used which is activated according to the percentage of grid points having direct illuminance values >1000 lux. If more than 2% of the analysis grid points received direct sunlight then, blinds for example, are closed. In addition, if for the activation of the shading system a specific control strategy is used then this strategy should be modelled.

While climate based daylight modelling is potentially more accurate that the daylight factor assessment and combines the quality of the light (i.e. potentially glary sunlight) with qualitative parameters, the shortcoming of this method is a significantly more complicated method of evaluation. The evaluation requires specialised software such as RADIANCE, and the knowledge to operate such a software is not a common skill in architectural practices. As a result climate based daylight modelling assessment is likely to be performed by external consultants, and this requires an additional budget, consumes more time and is less intuitive than the daylight factor assessment.

This paper uses the daylight factor and the climate based daylight modelling assessment comparatively for a typical cellular office room in the climate of Athens, Greece. The aim is to evaluate the impact each metric has on the recommended window size and resulting overall energy consumption for heating, cooling and lighting. Resulting implications for architects will be discussed.
2. The test room

The simulations for this study are based on a typical cellular office room with the properties listed in table 1 and illustrated in figure 1 for the climate of Athens, Greece. For the investigated room 8 different window to floor ratios ranging from 10 to 45% have been modelled as indicated in figure 1, and the orientations North and South have been compared. In all configurations no external obstructions were considered. The interior surface reflectance is 0.5 for walls, 0.7 for ceiling, and 0.2 for the floor.

![Figure 1: Perspective view, front view, cross section and window to floor ratios for the test room.](image)

Internal heat gains have been modelled using the following parameters: People occupancy = 0.1 person/m²; electric lights = 16W/m²; electric equipment = 15W/m²; Hours of operation = from 08:00am to 18:00pm. Heating and cooling temperature set points are considered as 20 and 26 degrees respectively. The room is assumed to be mechanically ventilated. The reference models for energy simulations were constructed to meet the minimum energy codes and standards (U-Values; hours of operations, temperature set-points, etc.) for office buildings according to the thermal legislation of Greece (B' Climatic Zone). An ideal continuous dimming system is used in the room having a minimum input power percentage equal to 15% while the minimum light flux percentage is considered equal to 5%.

For the daylight assessment according to the LM-83/2012, the window unit was equipped with an interior roller shade having visible transmittance and reflectance 5% and 70% respectively. This is somehow a base case scenario when the design team has not defined the exact shading system type.
and properties. The roller control strategy was constructed to meet the minimum requirements according to the IES LM-83.

Table 1: Simulation input geometry.

<table>
<thead>
<tr>
<th>Office room properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (m)</td>
</tr>
<tr>
<td>Width (m)</td>
</tr>
<tr>
<td>Floor to ceiling height (m)</td>
</tr>
<tr>
<td>Façade wall thickness (m)</td>
</tr>
<tr>
<td>Façade wall area (m²)</td>
</tr>
<tr>
<td>Floor area (m²)</td>
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<table>
<thead>
<tr>
<th>Window properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
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<td>U-Factor (W/m²K)</td>
</tr>
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<td>Visible Transmittance (%)</td>
</tr>
<tr>
<td>SHGC</td>
</tr>
<tr>
<td>height (m)</td>
</tr>
<tr>
<td>Width (m)</td>
</tr>
<tr>
<td>Window sill (m)</td>
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<tr>
<td>Length (m)</td>
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<td>Distance from the window (m)</td>
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</tbody>
</table>

3. Simulation setup

Figure 2 illustrates the modelling of the test room in DaySim as well as EnergyPlus. The methodology used is described with details in the following steps:

1. Two DaySim (DaySim 2013) simulations (with and without the interior roller fully deployed) on hourly basis were performed using the following RADIANCE (Desktop RADIANCE) parameters (-ab 6 –ad 2000 –as 500 –ar 300 –aa 0.1 -dds) and Athens, Greece weather file. Illuminance values were obtained on a grid of 0.2m x 0.2m.

2. One DaySim simulation (DaySim/RADIANCE parameters used –ab 0 –dds) to determine the Annual Sunlight Exposure in the room based on the direct illuminance as provided in the weather file.

3. For every hour, using the results from the step 1 simulations, a new file is created. On each particularly hour, if 2% or more of calculation grid points (step 2 simulation) receive solar direct illuminance more than 1000 lux, the results from the simulation with interior shading fully deployed are used, otherwise the results with no shading are used. This new file is used for the assessment of the Spatial Daylight Autonomy (sDA) with values >= 75% preferred,
Comparing climate based daylight modelling with daylight factor assessment – implications for architects

>=55% accepted and <55% categorised as insufficient. At this point, a schedule for the operation of the interior shading system is created.

As a fourth step EnergyPlus (DOE 2013) simulations have been performed, based on the same weather file used in DaySim/RADIANCE and shading operational schedule derived from the third step. The results have been evaluated with regards to the resulting energy demand for heating, cooling and lighting.

![Diagram of simulation setup with DaySim and EnergyPlus](image)

4. Results

Figures 3 to 5 illustrate the results for the lighting and energy demand for the North and the South orientation. In each of these graphs, the daylight assessment results are visualised in the markers connected by dotted or continuous lines for daylight factor, Spatial Daylight Autonomy as well as Annual Sunlight Exposure. These are measured by in % as indicated on the vertical axis on the left hand side of the graph. The bars are visualising the resulting energy demand in kWh/m² related to the vertical axis on the right hand side of the graph. The energy demand for each of the 8 different window to floor rations is evaluated without (left bar) and with (right bar) activated roller blind, resulting in a set of two bars for each configuration.
4.1. Daylight assessment results for the North orientation

The results in figure 3 show, that for the North orientation and a window to floor ratio of 20% and above, the room configurations with or without external overhang result in a Spatial Daylight Autonomy (sDA) of 55% and more and thus satisfy the ‘acceptable’ condition. Without overhang window to floor areas of 30% and more and with overhang window to floor areas of 35% also meet the criterion of 75% for ‘preferred’ conditions.

With regards to the Annual Sunlight Exposure (ASE), values for North orientations for all window to floor ratios range between 0 and 2.08%. Although IES LM 83-12 acknowledges that additional research on target values for ASE would be required, as a guideline, an acceptability threshold of <3% and an unsatisfactory threshold of >10% is suggested. The Annual Sunlight Exposure results on the North orientation are both well below this threshold. It can be concluded that on the North side, all investigated configurations meet the requirements of the IES daylight metric as long as the window to floor area is larger than 20%. In comparison, the daylight factor analysis based on a threshold of 2% produces results of >2% for all investigated window to floor ratios from 10% to 45%. When using the DF and the IES metric as a design guideline to determine the optimum window area, it can be concluded that for the North side, the IES LM 83-12 metric leads to larger window areas compared to the daylight factor.

Figure 3: Simulation results for the test room, base case vs. base case with roller without overhang for North orientation.

4.2. Daylight assessment results for the South orientation

Orientated to the South, window to floor areas of 20% and above result in a Spatial Daylight Autonomy of 55% or more, and thus meet the criterion for acceptable conditions. Without external overhang (figure 4), configurations with a window to floor area of 25% also meet the Spatial Daylight Autonomy
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threshold of 75% which is considered as preferred conditions. With an external overhang (width = 3.4m, length = 1m, distance from the window head = 0m) however (figure 5), only the configuration with window to floor area of 45% has a Spatial Daylight Autonomy of more than 75%.

When evaluating the resulting Annual Sunlight Exposure for the South orientation, without the external overhang, only the window to floor area of 10% results in Annual Sunlight Exposure (ASE) below the recommended value of 10%. For window to floor areas between 10% and 25% the ASE gradually increases until it reaches a relatively consistent value of 24-25% for window to floor areas of 25-45%. For the configurations with an external overhang, the window to floor areas of 10 and 15% lead to ASE values below 10% and thus fulfil this criterion. Window to floor areas of 20% and larger lead to ASE values of 13 to 21%. For this configuration, the ASE values are relatively consistent between 19 and 21% for window to floor areas of 30% and above. This pattern is consistent with the configuration without the overhang. When evaluating the Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE) criteria together it can be concluded that none of the investigated configurations meets the requirements of the IES metric for the examined case (meaning internal roller with Tvis=5%). This is because for small window to floor ratios, the resulting Spatial Daylight Autonomy is too low, and for larger window to floor ratios the Annual Sunlight Exposure is too high. The daylight factor analysis however suggests satisfactory conditions for all investigated configurations without external overhang, and all configurations with a window to floor area of 15% and more in case of an external overhang. It can be concluded that while the two metric daylight factor and IES show relatively consistent results for a north orientated room, they deliver contradictory results for a South orientation.

![Daylight Metric Performance vs Energy Demand](image)

Figure 4: Simulation results for the test room, base case vs. base case with roller without overhang for South orientation.
4.3. Energy performance

The bars in figures 3 to 5 illustrate the energy demand for the investigated configurations with and without activated shading. Several observations can be made:

For the North orientation, the difference in energy demand between the configuration with and without activated roller is almost negligible. As this orientation does not get any direct sunlight, shading as determined based on the ASE assessment, is only activated for about 1% of the hours of the year. For the South orientation, shading is activated for about 20% of the 8760 hours of the year for both configurations with and without external overhang and the majority of window to floor ratios. The activated roller, although in some cases slightly decreasing the energy demand for cooling, reduces the daylight provision in the space and thus increases the energy demand for lighting and the total energy demand. For the South orientation, the presence of an external overhang significantly reduces the resulting energy demand for cooling as well as the total energy demand, especially for the larger window to floor ratios.

For the North orientation, the configuration with 20% window to floor area and without activated roller has the lowest overall energy demand of about 60kWh/m², and the configuration with 10% window to floor ratio and activated roller results in the highest overall energy demand of about 73kWh/m². The smallest window sizes lead to the highest energy demand, the energy demand then decreases with increasing window size to the lowest values for 20% window to floor area without overhang. For larger window sizes the total energy demand gradually increases with window size. The lowest overall energy demand occurs in both cases around the window to floor area that also satisfies the 55% criteria for Spatial Daylight Autonomy.
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For the South orientation without overhang, the configuration with 15% window to floor area and without activated roller has the lowest overall energy demand of about 62kWh/m², and the configuration with 45% window to floor ratio and activated roller results in the highest overall energy demand of about 115kWh/m². With an added overhang, the configuration with 20% window to floor ratio has the lowest total energy demand of about 56kWh/m², and the configuration with 45% window to floor ratio and activated roller results in the highest overall energy demand of about 86kWh/m². As can be expected for the South orientation, the configuration with an overhang leads to significantly lower total energy consumption, especially for larger window to floor areas. Similar to the North side, it is not the configuration with the smallest window area that leads to the lowest total energy consumption, but the configuration with a minimum window to floor area of 15% without and 20% with overhang. After that and similar to the North side, total energy consumption increases with window to floor ratio. Similar to the North side, the configuration that is closest to the 55% criteria for Spatial Daylight Autonomy is the one resulting in lowest overall energy demand.

5. Discussion

This paper compares the two metrics for a typical cellular office room with different window to floor ratios, with and without external shading. The aim is to identify how the two metrics perform in comparison, with regards to their accuracy in daylight prediction, energy performance and related implications for architects.

For the North orientation, and when comparing both, energy demand and daylight autonomy it can be observed that the IES LM 83-12 metric seems to produce similar, however more detailed results. Almost all configurations for the North orientation, meet the daylight factor criteria of 2% even with window to floor areas as low as 10-15%. In order to meet the requirements of the IES metric for the North orientation, a minimum window to floor area of 20-25% is required and this window size also coincides with the lowest total energy demand. Apart from the difference in recommended minimum window size for both metrics, it can be concluded that both metrics agree that the daylight situation is satisfactory under the majority of the investigated conditions.

For the South orientation in contrast, none of the investigated configurations meet the IES requirements. For small window to floor ratios, the Spatial Daylight Autonomy (sDA) is too low, even though the Annual Sunlight Exposure (ASE) requirements might be met and for the larger window to floor ratios, the Spatial Daylight Autonomy is sufficient, however the Annual Sunlight Exposure is too large. At the same time the daylight factor analysis suggests that almost all configurations are provided with satisfactory daylight levels. The reason for these contradictory results is based on the fact that the IES metric takes direct sunlight into account whereas the daylight factor analysis is purely based on overcast sky conditions, as it is the Annual Sunlight Exposure which does not meet the requirements for most configurations. From the perspective of architects this study indicates the following conclusions:

- The daylight analysis based on the IES metric is more accurate in its evaluation as it considers not only overcast sky as in the daylight factor analysis, but also direct sunlight which can cause glare. However, it is significantly more time consuming than the daylight factor analysis. It involves special expertise to operate software like RADIANCE / DaySim and significant computing power. In most architectural offices this expertise is not readily available, and as a result climate based daylight modelling based on the IES assessment is likely to be
subcontracted to external experts. This derives architects of the intuition for daylighting that could be developed from a consistent use of the much simpler daylight factor analysis.

- For the North oriented room, the climate based daylight modelling according to and the daylight factor analysis produced relatively similar results. Due to the significant additional effort that an IES LM 83-12 analysis requires compared to the daylight factor (DF) analysis, it could be concluded that for the North orientation which does not get direct sunlight, the DF analysis is sufficiently accurate.

- For the South orientation, the investigated configurations indicate potential similarities between daylight factor and Spatial Daylight Autonomy results. A 55% or higher Spatial Daylight Autonomy (IES requirement) seemed to coincide with a DF of 3% or more. Further research and validation would be required, however similar to findings from the North orientation, this can lead to the interpretation that the Spatial Daylight Autonomy, which requires significantly more effort to evaluate is not significantly more accurate than the DF.

- The Annual Sunlight Exposure helps to evaluate the presence of sunlight in a room and the potential for glare, and this information is not available using the simple daylight factor analysis. IES LM 83-12 recommends that a maximum of 3% of the analysis area can exceed 1000lux for more than 250h per year without the use of any blinds and assuming the operational period between 8am and 6pm. This target could not be met with the investigated configurations for the South orientation. It should be noted in this context that this study was based on a roller as internal shading. Further testing and validation would be required to evaluate whether e.g. venetian blinds would perform differently.

- This investigation for this paper has been limited to the North and South orientation only. An additional investigation for the East and West orientation will be helpful to achieve a better overview on the impact of different orientations on the two metrics.

References

Illuminating engineering society (2012) Approved method: IES Spatial Daylight Autonomy (sDA) and Annual Sunlight Exposure (ASE), IES LM-83-12, Illuminating Engineering Society of North America, NY, USA.
Daylight enhancement and lighting retrofits in educational buildings

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Abstract: According to the International Energy Agency, lighting makes up about 19% (~3000 TWh) of the global electric consumption. Often the lighting energy savings cannot be provided in new buildings with new lighting systems. Therefore, major potential in lighting energy savings can be found in the existing building stock (older than 25 years). Educational environments such as schools, colleges, universities /campuses cover a significant percentage of the existing non-residential building stock. This study focuses on lighting solutions for the retrofitting of educational buildings, with a particular emphasis on two University lecture halls which are located in Turkey/Konya and Germany/Stuttgart. Evaluations of the pre-retrofitting lighting performance are based on the measurements and observations. After a detailed performance analysis, the best lighting retrofitting options were identified. The retrofitting scenarios were simulated in virtual environment and their impact in terms of identifying the most efficient are discussed. The cost of retrofit estimation is done using the Relight tool which is developed as a part of IEA- SHC Task 50 Subtask C.

Keywords: Lighting retrofitting; daylighting; campus; education buildings.

1. Introduction

The place of learning should be a secure, safe and comfortable environment conducive to teaching and learning. The students, teachers and lecturers are more alert and ready to work if appropriate comfort conditions are provided. All educational spaces should use the available daylight as the primary light source. Good lighting provides the best visual effectiveness, minimizes the use of energy while giving people satisfaction.

Recent studies have estimated that European schools contribute 15% of the public sector carbon footprint. It is assumed that approximately 20-30% of energy use comes from artificial lighting in educational buildings. This is a current important research topic, revealing more environmental and sustainable educational buildings. The primary energy consumption of schools in Luxemburg has
increased due to the higher electricity usage (Thewes et al., 2014). The trend of increasing electricity use in Scottish schools was discussed by Dobson and Cater (2010), while approximately 46% of total electricity demand of the American educational buildings is from office equipment and lighting (Appel, 2010). Most of these studies try to detect the efficiencies and potential improvements which allow reduction in energy use.

The lighting for a lecture hall must supply the correct amount of light during the day. Tasks and activities are generally carried out on a table/desk or on white/blackboards. Therefore, good horizontal and vertical lighting is essential. Furthermore, controllable lighting and shading systems should be able to adapt lighting conditions when visual equipment, (i.e., data projectors), are used. Even though daylight contribution is significant for educational spaces, it is of variable nature and mostly provides only a portion of the required light level.

Glare is a common problem in classrooms and lecture halls, which happens when part of the visual scene is much brighter than the overall brightness of the rest of the field of view. Glare can be divided into two types: Disability glare, defined as a decrease in a visual performance due to light scatters within the eye; and, Discomfort glare, a subjective feeling of disturbance. Although the glare issue has been studied over a long period, there are still many unresolved questions. One common finding is that people consider a bright surface as disturbing. It is also believed that some glare can be tolerated if the work place contains a view to the outside (Osterhaus, 2001; Velds, 2000; Wienolds and Christoffersen, 2006).

2. Method

The main aim of this study is to investigate the effect of daylight availability on visual comfort and estimate potential savings on lighting electricity in educational spaces. Interior daylight illuminance measurements were carried out in lecture halls at the Stuttgart University of Applied Sciences, Germany and KTO Karatay University, Turkey. The unobstructed horizontal outdoor illuminance data and the internal measurements were acquired simultaneously. During the monitoring of the luminous environment, a user satisfaction questionnaire (IEA-SHC-Task 50 Subtask D3) was answered by students. The purpose of the questionnaire was to obtain inputs such as the indoor comfort levels of occupants in the context of light intensity. High Dynamic Range (HDR) imaging was used to collect luminance information at the lecture hall in Stuttgart. All collected momentary illuminance, luminance data, computer simulation outputs such as climate based annual lighting analysis and occupant feedback through questionnaires were used to evaluate visual comfort and glare.

In a first step, the luminance and illuminance in the lecture rooms with daylight and artificial light were measured. In Konya, the measurements were conducted during the last week of May 2015, with illuminance levels recorded every 15 minutes. The illuminance measurements in Stuttgart were taken three times a day, on a weekly basis, during the winter semester. The luminance measurements were performed with a high dynamic range (HDR) camera with a fisheye-objective. The images were evaluated with the LMK 2000 software. In both locations, all illuminance measurements were taken with HOBO illumination/temperature data loggers (U12). This device has a range of 0 – 320,000 lx and an accuracy level of ±2.5% at 25°C.

As daylight factor (DF) threshold measures are not sufficient to assess the daylight performance, climate based daylight modelling was used to analyse the lecture rooms. In order to conduct climate based daylight modelling, standardized meteorological files were used for specific geographical locations. Three computer simulation tools were used to model the daylight performance for the
present study. Three dimensional geometries, including the rooms’ surroundings were built in Ecotect Analysis 2011. The numeric simulation results were also visualized via the same tool. Radiance 3P7 for Windows was used for current moment daylighting analysis. Climate based annual lighting analysis were performed via Daysim 3.1 for Windows (Daysim 3.1, 2013). Additionally, energy analysis of the existing lighting system and suitable renovation suggestions including cost comparison was generated by reLight.

It is reliable to have measured data and comparable simulated data to assist the investigation and analysis of a space (Maile T. et al., 2010). Nevertheless, the complexity of the lighting environment requires documentation of user experiences to better understand the nature of the light and especially to discover unpleasant occurrences such as glare, distribution of light intensity use of control systems etc. To obtain data, students were asked to fill in a user questionnaire (IEA-SHC-Task 50 Subtask D3). All collected data was digitalized and analysed in an excel spreadsheet and the average score was found for the questions.

2.1. Room(s) description

The study was carried out in two lecture halls in Konya and Stuttgart in the month of May, 2015. The lecture halls have different dimensions and are furnished differently. Therefore different measuring grids were used for each lecture hall: in Konya a 3x3 grid, in Stuttgart a 4x4 grid. However, measurement results of both can be easily compared considering the general room form.

2.1.1. Stuttgart, Germany

The test space is a lecture hall in Building 3 of the University of Applied Sciences Stuttgart, Germany, geographically located at 48°68'N latitude and 9°22'E longitude. The duration of sunshine varies between 1300 and 2000 hours, while the global radiation varies between 780 and 1240 kWh/m². During the winter, Stuttgart’s daylight can range from 8 and a half to 9 hours. In summer the average amount of daylight is almost 16 hours.

![Figure 1: Bird’s-eye view of the building and floor plan of the lecture room in Stuttgart.](image)

The main facade of the lecture room is oriented towards Southwest. The test room dimensions are 10.1 m x 9.7 m x 3.8 m - width x depth x height). Location of the building and floor plan and of the test room is shown in the Figure 1. The centre of each desk was selected as a measurement point, this results in grid dimension of 1.60 m x 1.60 m in the lecture hall. Window-to-wall-ratio of the lecture hall facade is 40%. The room surface reflectance values are: Rceiling = 80%, Rwalls =50%, Rfloor = 30%,
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R\text{furniture} = 50\%. The windows consist of two layers of clear glass resulting in visible transmittance (Vt) of 72%.

2.1.2. Konya, Turkey

The classroom from KTO Karatay University, as shown in Figure 2, was located in Konya, Turkey at 37°52'N latitude and 32°35'E. Konya is a city in the Central Anatolia Region of Turkey. The average duration of sunshine is 2630 hours and the global radiation varies between 760 and 2530 kWh/m\textsuperscript{2}a. Winter has an average of 9 and a half hours of daylight in Konya and in summer the average amount of daylight is 14 and a half hours. The facade of the measured classroom is oriented towards west. The dimensions of are 10.50 m x 9.45 m x 3.60 m - width x depth x height). Window to wall ratio of the lecture hall façade is 60%. Floor plan and sections of measured classroom are shown in the Figure 3. The surface reflectance values are obtained from on-site auditing: R\text{ceiling} = 85\%, R\text{walls} = 65\%, R\text{floor} = 35\%, R\text{furniture} = 50\% and Window Visible Transmittance = 72%.

Figure 2: Layout plan of KTO Karatay University and floor plan of the measured classroom in Konya.

The classroom from KTO Karatay University, as shown in Figure 2, was located in Konya, Turkey at 37°52'N latitude and 32°35'E. Konya is a city in the Central Anatolia Region of Turkey. The average duration of sunshine is 2630 hours and the global radiation varies between 760 and 2530 kWh/m\textsuperscript{2}a. Winter has an average of 9 and a half hours of daylight in Konya and in summer the average amount of daylight is 14 and a half hours. The facade of the measured classroom is oriented towards west. The dimensions of are 10.50 m x 9.45 m x 3.60 m - width x depth x height). Window to wall ratio of the lecture hall façade is 60%. Floor plan and sections of measured classroom are shown in the Figure 3. The surface reflectance values are obtained from on-site auditing: R\text{ceiling} = 85\%, R\text{walls} = 65\%, R\text{floor} = 35\%, R\text{furniture} = 50\% and Window Visible Transmittance = 72%.

Figure 3: Daily mean direct normal illuminance and daily mean diffuse horizontal illuminance values of Konya and Stuttgart.

2.2. Illuminance distribution

In order to quantify the daylighting performance of the lecture halls, it is helpful to see the differences between illuminance data for each city. Figure 4 represents the diffuse horizontal illuminance and the
Daylight enhancement and lighting retrofits in educational buildings

Direct normal illuminance magnitude difference between Konya and Stuttgart. According to the data, it was observed that both direct and diffuse illuminance values are higher in Konya than in Stuttgart.

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Figure 4: Horizontal illuminance at working plane grid in Stuttgart and Konya.

Inside the lecture halls, measurements were taken on sixteen points (Stuttgart) and nine points (Konya), respectively, to evaluate internal illuminance. In this paper, the findings of the first experiments are presented. The results deal with the impact of geographical position and sky/climate conditions. Figure 5 indicates a comparison of illuminance measurements in two lecture rooms under different sky conditions on similar days. Measurements were taken at 11:00h, 13:30h and 17:30h.

The columns show the illumination level of each measurement point. Unobstructed horizontal exterior illuminance levels (EIL) were also measured and noted in to the Figure 4. Under cloudy sky, the illuminance levels do not greatly differ between the first measurement row and the rear rows of the room. Under clear and sunny sky, the sensors were affected by direct sun light and shadow in both lecture halls. This effect causes high illuminance level differences between measurements points and may be the main cause of the glare problem. Moreover, in daylighting distribution was observed under changing sky conditions (clear, cloudy, and covered). Under sunny sky the fluctuation is more remarkable compare to cloudy sky conditions.
2.3. Existing lighting system inspection and suitable renovation suggestions

To enable a precise analysis, it is essential to adequately assess the existing lighting system. The reLight tool (V1.04) was used to evaluate the existing lighting system, to provide suitable lighting renovation suggestions and to cost each of the different proposals.

First, a simplistic qualitative analysis of the lecture halls, (i.e., room proportion, facade type), was completed. The main space usage categories were defined and the pre-parameterization and verification logic was established to ensure that no invalid data sets were created. Relevant system components such as lamps, control equipment and luminaires were created within the database together with their characteristic values for energy use and efficiency. As a second stage, the lamp and luminary properties were defined. Additional information, for instance; typical service life of lamps and/or the necessary illumination level for the different spaces were also added to the database. To provide renovation options with a comparative analysis, appropriate lamp and spatial data was input into the relight (V1.04) application. Finally different renovation options per lecture room were combined into an overall renovation, in order to obtain optimum energy and/or cost-efficiency results and viewed in a graphical format.

3. Results

3.1. Luminance and illuminance distribution from the observers’ point of view

During the monitoring of the luminous environment, the user satisfaction questionnaire (IEA-SHC-Task 50 Subtask D3) was answered by students. The questionnaire consists of four parts: general questionnaire (remarks and light level questions); light experience questionnaire; daily experience; and, semi-structured interview. The general questions were rated from 1 (Low/little) to 7 (High/ Much). In the semi-structured interview, questions covered attitudes and behaviours, light environment, control system and eye symptoms.

In Konya, 50 students were part time users of the classroom, with 8 hours per week. 80 % of the students found the lighting level in the room and on the desk satisfactory or better than satisfactory. On the other hand 30% of the students mentioned bright areas and glare problems. Half of the students found the classroom and lighting control system unsatisfactory and not good enough. They describe lighting experience of classroom as light, pleasant, colourless, strong, spread, warm, clear, monotonous and bright.

In Stuttgart, 14 students answered the questionnaire during the measurements. 36% of the students rated the light distribution with 3 and 64% were rated 4. The light environment defined as middle and the lighting system optimization was not necessary required. 9% of the students didn’t find any gloomy areas in the lecture room. 55% of them rated the gloomy areas with 7, 27% of them with 4 and 9% with 3. Bright area was assessed with 4, from 27 % of the contributors. 9% were not affected by bright areas. 27 % of the respondents found glare as a problem and rated the outcome with 4 or 5.

3.2. Daylight autonomy and electric lighting use

Climate based annual daylight simulation were completed in Daysim 3.1, with illuminance values analysed using the “Useful Daylight Illuminance” (UDI) scheme (Nabil and Mardaljevic 2005). UDI is the annual occurrence of illuminance across the grid system that considered in three categories, namely; illuminance level less than 100 lx, greater than 100 lx and less than 2000 lx, and greater than 2000 lx.
Figure 5 shows the related UDI distributions for the two lecture halls in this study. UDI>2000 is meant to represent times when an oversupply of daylighting might lead to glare and / or visual discomfort. The useful daylight indicates for the lecture rooms are; in Stuttgart 87% and in Konya 65%. The UDI100-2000 that represents “useful” daylight was achieved with 6% in Stuttgart and only 1% in Konya.

![Figure 5: Useful Daylight Illuminance comparison.](image)

500 lx were specified as the daylight autonomy threshold and 65% of all illuminance work plane sensors have a DA$_{con 500}$ above 60% in Stuttgart. The investigated space in Konya 100% of all illuminance sensors have a DA$_{con 500}$ above 80%.

### 3.3. Possible lighting solutions and cost of retrofitting variations

The existing lighting systems (B) of both lecture halls are defined in Table 1. The best way to reduce the cost of the operating an older lighting system is to replace it with a newer, more efficient one. This can be achieved with upgrading the lamps, ballast, fixtures and control systems (http://www.facilitiesnet.com).

Four different retrofitting alternatives were calculated using reLight and compared them in order to attain lower energy use and save utility costs. In the first retrofitting suggestions (V2a), the number of the luminaries stayed the same but lamp types were changed (per luminaire Stuttgart: 30.8 W and 2262 lm, price: € 134, Konya: 37.0 W und 3900 lm, price: 280 €). The second alternative, (V2b), provided similar illuminance levels on working plane with less luminaires and lamps (Stuttgart: 59.4 W and 4550 lm, 150 € Konya: 59.4 W and 4500 lm, 162 €). In the third alternative (V3), additional to the second one, the daylight and occupancy control system were proposed. For sun and glare protection, a light-
directing system was proposed as a supplementary system to the lighting control system, in fourth alternative (V4).

In Stuttgart, the existing system’s total cost including investment, energy and service/maintenance over the 20 years period is 57.52 €/m². With first retrofitting alternative, the energy and service cost can be saved but investment cost are high compared to existing system. The total energy costs are 30% lower in second alternative. Using of the control systems and sun/glare protection systems 20.5 % and 15.5% of the total costs can be saved.

Table 1: The existing lighting system of the lecture halls in Stuttgart and Konya.

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</tr>
<tr>
<td>Mounting Style</td>
<td>Mounted</td>
<td>Recessed</td>
</tr>
<tr>
<td>Type of lighting</td>
<td>Direct</td>
<td>Direct</td>
</tr>
<tr>
<td>Luminaire shape</td>
<td>Rectangular (long)</td>
<td>Rectangular (middle)</td>
</tr>
<tr>
<td>optical system</td>
<td>Glossy grid</td>
<td>Glossy grid</td>
</tr>
<tr>
<td>Number of luminaire</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Number of lamps per luminaire</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Lamp type</td>
<td>T8 fluorescent lamp</td>
<td>T5 fluorescent lamp</td>
</tr>
<tr>
<td>Ballast</td>
<td>Magnetic</td>
<td>Electronic</td>
</tr>
<tr>
<td>Lamp power [W]</td>
<td>58</td>
<td>18</td>
</tr>
<tr>
<td>Solar shading</td>
<td>No sun/ glare protection</td>
<td>No sun/ glare protection</td>
</tr>
<tr>
<td>Lighting management</td>
<td>No lighting management</td>
<td>No lighting management</td>
</tr>
</tbody>
</table>

Comparing the total costs in Konya, the alternative costs are higher than in Stuttgart. That means less cost reduction can be provided by suggested retrofitting alternatives. The saving potential is 18 % in the second, 7.5% third and just 1.6% in the fourth alternative.

Figure 6: Specific annual primary energy demand comparisons for retrofitting alternatives.
In order to evaluate the influence of the retrofitting alternatives on the energy balance, the primary energy is calculated. The annual primary energy demand comparison is given in Figure 6. The highest energy demand is needed in existing conditions for both locations. The difference between the third and the fourth alternative is small even though the lowest primary energy demand has been sustained from different retrofitting scenarios in Konya and Stuttgart. The comparison between V2a and V2b leads to the following conclusion: In Konya, there is a large reduction in energy demand by using energy efficient lamps. On the other hand, a higher reduction in energy demand was observed in Stuttgart, by using 8 efficient luminaries instead of 15 and T5 lamps.

4. Discussion and conclusion

Based on the literature review, it was established that there is a large amount of energy consumption from artificial lighting in educational buildings. At the same time, it is strategic to explore and quantify the benefits of daylight contribution and compare the energy saving from retrofitting alternative lighting systems.

Nowadays, there are increasingly capable lighting simulation tools available for comparing the performance and energy efficiency of lighting systems. In this study, the daylight availability and visual comfort conditions were calculated and evaluated by users in two different lecture halls in Germany and Turkey. This method included the definition of the energy efficiency potential via analysis of the existing situation by measurements and questionnaire, evaluation of software tool outputs and the comparison of retrofitting scenarios. The analyses of the daylight availability and energy saving potential of existing lighting have been evaluated based on real use conditions in order to understand the positive and negative attributes of the system of the system. During the measurements, the following weak points were found: the lack of the measurement equipment (different numbers of sensors were used in the lecture halls), the lack of a luminance camera in on location (Konya) and sometimes inconsistent answers of respondents.

After monitoring the existing situation, the lecture halls were modelled in a computer environment, with annual daylighting simulations undertaken for both locations. The outputs like Daylight Autonomy and Useful Daylight Illuminance, which indicate the percentage of occupied hours when sensor point was above or between certain lux thresholds, were displayed and compared. According to the simulation results, the predicted annual lighting energy demand in the investigated lecture room in Stuttgart is 22.1 kWh/m²a. In Konya the predicted annual lighting energy demand is 7.9 kWh/m²a. In both cases the installed specific lighting power is 11.48 W/m².

The large windows do not mean that the light is automatically better. It causes mostly glare problems which could be eliminated by using of sun/ glare protections elements such as lamellas and blinds. The luminance camera was used in Stuttgart to quantify the luminance level and evaluate the glare. However the absence of the luminance camera in Konya, meant the comparative glare analysis couldn’t be completed but is planned for the future.

The energy saving percentage for the retrofitting scenarios was calculated for each location. Besides energy efficiency of the lighting system the productivity and satisfaction of the users are important, especially in lecture halls of university buildings. Considering the result of the user satisfaction questionnaire it is possible to conclude that the main visual discomfort is caused by disability glare in the classrooms, perceived especially in places close to the windows. For this reason shading systems are recommended.
In conclusion, the retrofitting of the lighting system generally assures a more efficient use of artificial lighting, the proper daylight contribution and a higher visual comfort level. Moreover, in order to improve the daylight limitations; more illuminance and luminance levels can be provided in different time of the year and under various sky conditions. Finally, in order to improve the computer model characterisation; user behaviour definition can be monitored.

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References

Designing with thermal comfort indices in outdoor sites

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Abstract: Design of outdoor sites for improved thermal comfort will contribute to greater use and value of these environments. Whilst there are many available thermal comfort indices, the complexity of external sites makes the useful application of these in outdoor site design difficult. This paper discusses two case studies: phase 5 of Masdar City in the United Arab Emirates and the Danginri Thermal City in Seoul, South Korea to illustrate the use of different thermal comfort indices in the design of open space. These case studies highlight the value of using indices when combined with other design tools and processes including multidisciplinary collaborative practices and digital technologies such as Computational Fluid Dynamic (CFD) modelling. Importantly this combination of approaches shifts the emphasis from a focus on achieving specific thermal comfort measures, to a more comprehensive design approach. This shift demonstrates how design can work with relative change to extend the experience and use of outdoor space.

Keywords: Thermal comfort; design; outdoor.

1. Introduction

The design of external space for thermal comfort performance is gaining increased attention. This is most notable in urban environments where enhanced temperatures affect large and growing populations (Chen and Ng, 2012; Norton et al., 2013; Zinn and Fitzsimons, 2014; Brown et al., 2015). Globally, climate change is altering outdoor environmental conditions through temperature increases and heat waves, both of which are linked to severe discomfort, heat stress and mortality (Norton et al., 2013; BOM and CSIRO, 2014). The experience of these conditions limits the usefulness of external open space and is a significant restriction to the value of outdoor environments. Yet at the same time, increased urbanism and density means access to quality open space is of great importance. New land developments are expanding into challenging environmental territories, such as the Masdar city scheme in the United Arab Emirates. As the quality of outdoor space contributes to both human and ecological wellbeing, open space can deliver critical environmental and social infrastructure to urban environments provided that design is able to respond to these needs (VAG, 2014; Brown et al., 2015). This means
addressing the potentials of open space, including improved thermal comfort in a wide range of sites and conditions.

This paper aims to demonstrate the challenges in the use of thermal comfort indices for informing design of external sites. This is developed through an examination of a range of frequently used thermal comfort indices and the variance in the information they provide. This point is expanded through discussion of two case study examples that demonstrate the use of different thermal comfort indices in conjunction with other design tools. The case studies reveal the benefits and limitations of quantifying thermal comfort in design processes. This suggests an alternative use of thermal comfort indices for design as predictive tools of relative change rather than explicitly quantified measurements.

2. Designing for thermal comfort

Thermal comfort is a subjective measure of people’s psychological response to the heat balance of the human body within different environmental conditions. The effects of the thermal environment on different people can vary greatly and this makes assessing the thermal comfort of many users a complex issue. In an outdoor environment the key variables affecting thermal comfort are air temperature, air speed, relative humidity and radiant temperatures (Rose et al., 2010; Jendritzky et al., 2012; Johansson et al., 2014). These principle drivers are shared by indoor and outdoor space, however in external environments they are subject to more extreme, complex and irregular relational changes that vary according to geographic area and climate type, as well as localized physical characteristics. Further challenges of assessing thermal comfort levels in external space include a high variation in individual perceptions and preferences for outdoor temperatures which results in a much greater range of thermal comfort acceptability. These preferences are also influenced by geographic area and acclimatisation of users to certain conditions (Givoni et al., 2003; Johansson et al., 2014; Brown et al., 2015).

For designers attempting to influence the thermal comfort in outdoor environments, there is a lack of control of many of these variables. This challenges the usefulness of different indices for design feedback. For instance, the Pierce two-node model measures the human body at skin and core levels. This measure can give a very accurate indication of an individual’s thermal comfort; however, designers must consider external space as accessible to several users and realistically have limited ability to monitor individual subjects to this level of detail (Chen and Ng, 2012). Further, the influence of design on many meteorological variables is beyond explicit control. For instance, ambient air temperature and relative humidity may be modified through very large scale interventions such as regional parks however, in most design scenarios the scale required to influence these factors is unachievable, particularly within existing urban site conditions (Brown et al., 2015). Factors affecting comfort that are more easily manipulated are air speed, radiant heat and solar exposure, in the conditions set by ambient temperature and humidity. So, whilst design interventions cannot modify all of the conditions related to thermal comfort, the combination of dynamic meteorological properties still needs to be understood and accounted for in influencing thermal sensation in outdoor sites (Rose et al., 2010). Design that aims to influence thermal comfort in external space is faced with these concurrent challenges: an understanding of the relationships of thermal comfort factors in different climatic scenarios; the limited control of these factors and; highly variable responses of users.

In design, it is necessary to understand the different types of output that outdoor thermal comfort indices will provide. For instance, the measurement of thermal comfort is different from thermal stress. As Spagnolo and De Dear explain, the “application of indices from the hazardous periphery to the comfortable central region would seem to be a case of applying a tool with the wrong resolution.
Comfort is about subtle, finely graded perceptual details, whereas thermal stress is at the gross margins” (Spagnolo and De Dear, 2002). Here the understanding of what is being measured forms a critical judgment on the usefulness of an indices and how it might be applied in design.

The further challenge for design is the proposal of new spatial arrangements, which implies the need to predict future change as well as measuring existing site conditions. The limitations of design of outdoor sites suggest that in many scenarios desirable comfort levels may not be achievable. Similarly, large scale climatic factors may make it impossible to avoid thermal stress at all times. An indication of difference or relative change may be more useful for designers than a precise measurement. This shifts the emphasis of design using thermal comfort indices from measurement of conditions or people to the performative qualities of specific sites (Rose et al., 2010; Brown et al., 2015). Thus, designers need an appropriate index for use as a predictive tool that will suggest relative differences on how a site will perform in relation to variable conditions (Givoni et al., 2003; Chen and Ng, 2012).

The range of frequently used thermal comfort indices offer several ways for informing design, however these vary in how they address specific demands of site, scale, existing conditions and resources. There are many examples of arguments for the need for standardization of thermal comfort assessment methods and indices (Jendritzky et al., 2012; Johansson et al., 2014). There are currently no recommendations for suitable thermal comfort indices for specific conditions or guidance on how to integrate these into design, thus the use of indices as predictive design tools remains an area for further research (Chen and Ng, 2012; Johansson et al., 2014; Brown et al., 2015).

3. Thermal comfort indices

There are over 100 indices developed to represent thermal comfort in hot and cold conditions. Many of these are simplified versions of air temperature combined with a secondary parameter, though the complexity of these indices has increased in recent years (Jendritzky et al., 2012; Johansson et al., 2014). Thermal comfort indices tend to be divided into either rational or empirical guides. The rational are based on heat transfer and energy balance of a typical human body in relation to spatial conditions. Many of these indices have been developed specifically for internal environments where it is possible to maintain constant conditions. The second type of indices is based on empirical studies of subjective experience of thermal comfort in relation to meteorological phenomena. Many examples of both of these types are based on steady state models which assume that users have reached a thermal equilibrium within an ambient climatic environment. Steady state models such as the commonly used Predicted Mean Vote (PMV), Outdoor Standard Effective Temperature (OUT_SET*) and Physiologically Equivalent Temperature (PET) can be problematic when used in external environments where it is difficult to account for the dynamic aspects of adaptation to external environments (Chen and Ng, 2012; Johansson et al., 2014). However, the alternative adaptive assessment methods are largely based on the Pierce Two-Node model of the human body that requires extensive monitoring of subjects which is not feasible in most outdoor scenarios (Chen and Ng, 2012). Based on the practicality of working in external space, commonly used thermal comfort indices for outdoors environments often make a necessary number of assumptions or standardise variables. Table 1 summarizes some of the more commonly used thermal comfort indices which are applied in outdoor environments.
Table 1: Common thermal comfort indices used in external space studies. (source: Fanger, 1970; Steadman, 1984; Spagnolo and De Dear, 2002; Davis et al., 2006; Rose et al., 2010; Chen and Ng, 2012; Johansson et al., 2014).

<table>
<thead>
<tr>
<th>Index</th>
<th>Usage</th>
<th>Description</th>
<th>Expressed</th>
<th>Indication</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent Temperature</td>
<td>Outdoors</td>
<td>$AT = T + 0.33e - 0.7</td>
<td>U</td>
<td>- 4$</td>
</tr>
<tr>
<td>Predicted Mean Vote (PMV)</td>
<td>Indoors</td>
<td>Meteorological Variables: Air Temp, humidity, wind speed, mean radiant temp + clothing and activity</td>
<td>Scale between -3 to +3</td>
<td>Quantifies Discomfort</td>
</tr>
<tr>
<td>Standard Predicted Mean Vote (SPMV) Physiologically Equivalent Temperature (PET)</td>
<td>Outdoors</td>
<td>Adjusted PMV to include more extreme humidity Four meteorological variables. Standardized clothing and activity for indoor activity.</td>
<td>Scale between -3 to +3, where 0 is neutral Temperature Degrees Celsius</td>
<td>Quantity of comfort</td>
</tr>
<tr>
<td>Outdoor Standard Effective Temperature (OUT_SET*)</td>
<td>Outdoors</td>
<td>Derived from SET with simplified mean radiant temperature. Assumes activity and clothing value for outdoor uses.</td>
<td>Temperature Degrees Celsius</td>
<td>As with SET*</td>
</tr>
<tr>
<td>Thermal Sensation Index (TSI) Universal Thermal Climate Index (UTCI)</td>
<td>Outdoors</td>
<td>Air temperature, Solar radiation and Wind Speed; Air temperature, Mean temperature wind speed, water vapour pressure or relative humidity. Can be coupled with clothing model.</td>
<td>Scale between 1 – 7, where 4 is neutral Temperature Degrees Celsius</td>
<td>Quantifies discomfort</td>
</tr>
</tbody>
</table>

### 3.1. Predicted Mean Vote (PMV) and Standard Predicted Mean Vote (SPMV)

One of the most widely used indices of thermal comfort, the Predicted Mean Vote (PMV) calculates the mean thermal response of large groups of people (Fanger, 1970; Chen and Ng, 2012). This equation uses heat transfer to calculate the equilibrium thermal balance between a person and their surroundings based on meteorological variables (air temperature, air humidity, wind speed and mean radiant...
temperature) as well as clothing insulation and activity levels. Despite being developed as a measure of indoor thermal comfort, PMV has been frequently applied in outdoor studies (Chen and Ng, 2012). PMV is measured across a scale of 7 with -3 being cold to +3 being hot. This scale was developed to describe thermal discomfort which is more precise in indoor conditions than variable outdoor environments and may not be appropriate for assessment of outdoor thermal comfort (Spagnolo and De Dear, 2002; Chen and Ng, 2012). The PMV model has been adjusted for the outdoor environment to include the effects of extreme humidity. This version of the PMV model is the Standard Predicted Mean Vote (SPMV) which takes into account the standard effective temperature (SET*) in the heat balance (Gagge et al., 1986; Rose et al., 2010).

3.2. Physiologically Equivalent Temperature (PET)

Developed specifically for outdoor environments the Physiologically Equivalent Temperature (PET) is the air temperature required in an outdoor environment to reproduce a standardized indoor setting, for a standardized individual. This is the air temperature required to balance the heat budget of the human body with the same skin and core temperatures in complex outdoor conditions (Höppe, 1999; Matzarakis A and B, 2008). The calculation of PET is based on four meteorological variables (Höppe, 1999; 2002). As with SET* and OUT_SET* this measure standardizes clothing and activity values. Here, the standardized individual is assumed to have a work metabolism of 80 W of light activity in addition to basic metabolism and 0.9 clo of heat resistance from clothing (Matzarakis A and B, 2008). The indoor reference climate is based on the following; mean radiant temperature equal to air temperature, air velocity (wind speed) is fixed at $v = 0.1$ m/s and water vapour pressure is set to 12 hPa (approximately equivalent to a relative humidity of 50% at 20°C). The thermal conditions of the body are then calculated using the Munich energy balance model for individuals (MEMI), which in turn are substituted in to the energy balance equation system to produce the PET air temperature measurement.

3.3. Standard Effective Temperature SET* and OUT_SET*

Also developed for indoor environments, the Standard Effective Temperature (SET*) is a model for calculating the dry-bulb temperature which relates the real conditions of an environment to the (effective) temperature assuming standard clothing, metabolic rate and 50% relative humidity. SET* uses skin temperature and skin wettedness as the limiting factors (Blazejczyk et al., 2012). This assessment gives an equivalent air temperature measurement to compare thermal sensations in a range of conditions and from this the effective temperature can be related to a subjective thermal comfort response. OUT_SET* is the outdoor variant of SET* which simplifies the complex mean outdoor radiant temperature conditions down to a mean radiant temperature with all other variables maintained as in SET* (Pickup and de Dear, 2000; Jendritzky et al., 2012).

3.4. Thermal Sensation Index TSI

The Thermal Sensation Index (TSI) determines a measure between 0 and 7, with 4 as the most comfortable condition (Givoni et al., 2003). TSI was developed from research in Japan through formalized testing of subjects positioned in outdoor environments for set periods of time. Subjects were asked to complete a questionnaire of thermal sensation indicating discomfort, neutral and pleasurable conditions. These experiments were conducted under various solar and wind conditions to quantify the experience of outdoor climatic variables in relation to the subject’s experience. Regression analysis of
the data from this experiment led to the development of an equation expressing thermal sensation as a function of five variables including surface temperatures of surrounding materials and humidity. This was further analysed to produce a simplified equation to be used as a predictive formula taking into account air temperature, solar radiation and wind speed (Givoni et al., 2003). This predictive formula was used in the Danginri case study discussed below.

### 3.5. Universal Thermal Climate Index UTCI

In 2000, the Universal Thermal Climate Index (UTCI) was developed by a commission established by the International Society of Biometeorology. The primary aim was to create an index that would be accurate in all climates, seasons and scales, and be independent of personal characteristics such as age, gender, specific activities and clothing (Jendritzky et al., 2012).

The UTCI is defined as the air temperature in the reference condition (50% humidity, still air and full shade) that causes the same physiological response as the actual observed conditions. The range and classification of UTCI is given in Table 2.

<table>
<thead>
<tr>
<th>Case</th>
<th>Air Temperature (°C)</th>
<th>Wind Speed at 10m (m/s)</th>
<th>Global Solar Radiation (W/m²)</th>
<th>UTCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unshaded, low wind</td>
<td>36</td>
<td>1.5</td>
<td>1045 (full sun)</td>
<td>46.5°C</td>
</tr>
<tr>
<td>Shaded, low wind</td>
<td>36</td>
<td>1.5</td>
<td>114 (shade)</td>
<td>38.3°C</td>
</tr>
<tr>
<td>Unshaded, acceptable wind</td>
<td>36</td>
<td>4.0</td>
<td>1045 (full sun)</td>
<td>43.3°C</td>
</tr>
<tr>
<td>Shaded, acceptable wind</td>
<td>36</td>
<td>4.0</td>
<td>114 (shade)</td>
<td>36.4°C</td>
</tr>
</tbody>
</table>

Table 3 summarizes the UTCI if a person were to be in full sun or full shade in open ground for a warm, low wind speed day in Adelaide. In addition, the probable UTCI rating using 4m/s wind at ground level (the limit for acceptable wind speed for long periods of sitting based on the Lawson criteria) is also provided for reference. This higher wind speed is likely to result in the most comfortable conditions for the simulated air temperature and associated level of shade.

These examples illustrate how different thermal comfort models provide various indications of comfort or stress. Whilst many of these are expressed as a temperature in degrees Celsius, they are incompatible. For example, the PET air temperature for comfort is between 18°C – 23°C whilst SET* (an indoor measure) reports a much greater range of 17°C – 30°C and UTCI suggests between 9°C to 26°C (Blazejczyk et al., 2012). This is because they are each reporting on different things. This highlights the
need for outdoor specific models; however, with the variability of external conditions there remains a necessity for standardizing certain variables which again limits precise testing in some areas. Further, the influence of different climates and user groups has been found to greatly alter the range of responses for thermal comfort calculations (Chen and Ng, 2012; Niu et al., 2015). As discussed above, the value of different indices for design is in the indication of potential changes within microclimates. This requires an integration of the appropriate index with other design tools. Following are two case studies of design of outdoor space for improved thermal comfort using indices through complimentary design tools.

4. Design case studies

Design of external space occurs in numerous contexts from very small interventions to the redevelopment of existing space and master planning of entirely new developments. Each of these scenarios provides different constraints and opportunities for thermal comfort control. Following are two case studies; phase 5 of Masdar City in the United Arab Emirates and Danginri Thermal City in Seoul, Korea. Masdar City is located in Abu Dhabi, United Arab Emirates. Abu Dhabi experiences very little rain throughout the year, with an average of 20mm of rain in February but less than 10mm for every other month of the year. The dry climate has an average summer temperature of nearly 35°C, with highs exceeding 40°C for 9 months of the year (Böer, 1997; Islam et al., 2009). In contrast, Seoul, in which Danginri Thermal City is located, is much cooler. Average winter temperatures fall in January to -4°C and summer temperatures average between 21°C and 24°C without days exceeding 30°C (NOAA, 2014; KMA, 2015). Whereas Abu Dhabi is very dry throughout the year, Seoul averages nearly 400mm of rain in the month of July. These two case studies provide an interesting juxtaposition to one another as design challenges. These examples demonstrate variance in design processes, and as a discussion around different strategies for intervention and application of thermal comfort assessment and feedback into design decision making.

4.1. Design case study 1: Masdar City Phase 5. AECOM

Masdar City in Abu Dhabi has used the fundamental principles of thermal comfort to develop a master plan that has the best chance of resulting in comfortable conditions for what aspires to be the world’s most sustainable city. The 6km² developments, when completed, will house commercial, education, residential and industrial facilities. This case study is restricted to Phase 5 of the master plan which is mostly residential, consisting of townhouses and villas. However the same principles were used for the whole development site. With a huge focus on Masdar City being a cycling and pedestrian friendly neighbourhood, it has been imperative to understand not only the impacts of the local climate, i.e. the surrounding hot, arid desert, on the development, but also the impacts that a development can have on the local microclimate.

Although exposure to the sun’s rays is the driving variable for thermal comfort, arguably, the built form has the biggest impact on wind patterns through any development, particularly at the scale of the Masdar City development. It has therefore been critical to develop this master plan with wind flows in mind to ensure that as much air as possible is directed through the site. In terms of the other remaining comfort variables, the built form provides shading, with local features such as canopies and awnings incorporated to shade pedestrians from the intense summer sun. The use of low albedo materials in the construction of the villas and townhouses will reduce the amount of heat stored in the material from
solar radiation in the day. This heat gets released as soon as the wall temperature is above the outdoor temperature, contributing to high temperatures. Finally, humidity can be influenced by the use of vegetation and water. However, any change in humidity is dependent on the humidity of the incoming air.

At the early stages of master plan design, getting building layout and massing correct is crucial to the success of providing a comfortable thermal environment. If done incorrectly, wind flows through the streets become limited, resulting in stagnant air pockets and excessive heat build-up. An analysis of local meteorological conditions will therefore dictate street orientation and placement of tall buildings. Throughout the year, the winds in Abu Dhabi come mostly from the North West, with occasional winds from the east and south. As the aim is to reduce the impacts of excessive temperatures, winds during summer are most significant; especially those during the afternoon and evening when temperatures are higher and pedestrians are most likely to move from one part of the city to the other. Prevailing winds change throughout the day with overnight and morning winds during summer being easterly to southerly. From noon onwards however, winds predominantly come from the North West. This provides the first design principle of aligning main streets along a north west to south east access. In addition, orienting streets in this way will result in cooler overnight street temperatures as winds purge the heat that builds up in the streets during the day. Building on the encouragement of prevailing winds through the site, much work was done in the early design stages on the importance of urban canyon aspect ratios: street width to building height. The current master plan design maintains wide streets, and uses green infrastructure along these streets to further reduce the temperature of incoming air movement.

Phase 5 of Masdar City is bounded to the north and west by ‘Khalifa City A’ – a similar residential development of single and two storey villas and townhouses. As winds flow from the North West, ‘Khalifa City A’ is exposed to the breeze, however this will result in a low speed sheltered wake region behind the development. This is one of the primary reasons that Phase 5 of Masdar City uses graded street levels. By raising streets above the standard ground level (approximately 4m above sea level) by up to 2m in parts, the wind availability is increased, and the likelihood of more comfortable conditions is increased.

With these main principles in mind, four master plan concept designs were worked up by the project architects. High level, coarse CFD models were created at a building massing level of detail (1m – 2m model resolution) to assist the design team in visualizing the benefits that certain features and layouts could have when the development is subject to prevailing north westerly winds. At this stage, only wind flows were simulated, and the ratio of local street level wind speeds to open ground wind speed analysed. Compared to most standard CFD modelling exercise, these concept CFD models were run for less than 12 hours each, and so whilst the accuracy of simulated wind speeds could be questioned, general flow patterns were unlikely to significantly change with a more accurate and refined model.

One of the key outcomes from the early CFD modelling was the effect of location of the taller multi-unit residential blocks within the development. As with the sheltering effect of ‘Khalifa City A’, placing taller buildings at the north west of the site created a slow moving air region behind the building, extending half way through the development in some cases. One of the other options had the multi-residential unit located towards the centre of the site. This resulted in improved air flows throughout the development, as whilst winds skimmed across the lower villas and townhouses, they flowed down the taller building envelopes, drawing air down to ground level. While this can be detrimental in some climates due to highly accelerated winds, the extent of the downwash in Masdar City is unlikely to be as
significant, as the tall buildings are only five to six storeys tall, and therefore do not draw significant air volumes down to ground level.

As well as a CFD model, an analysis of hourly local weather data and thermal comfort metrics was done to demonstrate the impacts of increasing and decreasing wind speed. The apparent temperature metric was used as this enabled approximations to be made based on the variables the were accessible; air temperature, speed and humidity, with two different equations depending on whether comfort is estimated in full sun or shade. Assuming that local features would be incorporated in pedestrian heavy areas, the baseline thermal comfort, i.e. in open ground but fully shaded was calculated at pedestrian head height using the atmospheric boundary layer approximation. Adjustments were then made to account for a 50% increase or 50% decrease in wind. The apparent temperature calculation showed that adjusting wind speeds could achieve a relative thermal comfort difference of ±2°C. This demonstrates that considering thermal comfort during early stage design and manipulation of important metrological variables can make the local microclimate more acceptable than surrounding areas.

Future work on Masdar City will include full thermal comfort simulation using CFD. This will provide guidelines for surface materials, local shade and green and blue infrastructure as the development progresses to individual plot design.

4.2. Design case study 2: Danginri Thermal City. PARKKIM

Thermal Comfort was also a major design consideration for PARKKIM’s entry to the 2013 competition for the Danginri Power Plant redevelopment in Seoul, Korea. Situated in Mapo-gu, Seoul, located next to the Han River the competition brief asked for ecological and cultural significance to be addressed in the landscape design of this post-industrial site. The redevelopment is to move the existing ground level thermal power plant, built in the 1930’s to underground at the same location. The upgraded power plant is due to be completed in 2016 and will be the world’s first large scale combined power station located underground. The above ground space will be transformed into a cultural complex including libraries, museums and 8350m² of public open space (Daesung, 2011).

PARKKIM’s Thermal City scheme was not successful in the final competition; however their strategy provides useful insights into the use of thermal comfort indices in design validation. The scheme proposed to control thermal comfort to increase the use of the open space in both summer and winter conditions. Whilst Seoul’s climate is relatively mild it is changing towards more extreme conditions with hotter and more intense summers and very cold winters (NOAA, 2014). The necessity for open space to be habitable in those extreme times provided an important design consideration (PARKKIM, 2014).

In the final design proposal, topographic features were aligned to capture cool airflows from the bordering Han River for summer cooling. Further vegetation provided both shade in summer and barriers to the winds in winter. During winter it was proposed that the excess heated water from the power plant would be channelled through pipes to stone surfaces within the park. These stone features would absorb the heat from the water to produce warm seating and small microclimates within the park. This process would also cool the water and address the environmental damage of pumping hot water directing into the river. The system of under-surface heating is a reference to a traditional Korean architecture convention of channelling wood smoke through an under floor system to heat sleeping and living areas (Walliss and Rahmann, 2015).

During the design development, PARKKIM used Autodesk Ecotect analysis software to simulate sun, shade and wind behaviour to test new landform and facilitate the siting of vegetation. The initial
simulations were run on test plots which were unable to convey the full complexity of the site. However, this initial testing was able to provide insight into performative qualities for influencing thermal comfort at the early stages of design and suggest tactics for further development.

Once the proposal had been short listed, PARKKIM engaged the consulting engineers ARUP for more detailed analysis of thermal comfort performance of the design against the existing and proposed site conditions (Walliss and Rahmann, 2015). This more advanced stage of the design development used multiple soft wares and the Thermal Sensation Index (TSI) equation to calculate and simulate the effects of air temperature, solar radiation and wind speed.

The detailed analysis of the existing site and proposed design undertaken by ARUP was tested for critical times in the height of summer in June between 2-5pm and winter in December between 2-5pm. The results show the design extends the areas measuring closest to 4 (most comfortable) using the TSI in the summer months into the central open space. Whilst in the winter the areas with the most comfortable spaces aligned with the heated stone (Walliss and Rahmann, 2015). This testing facilitated a design process of iterative feedback between the simulation analysis and the designers to further develop the landform and features that would enhance the thermal comfort performance of the scheme (PARKKIM, 2014).

Using a combination of design tools including a relevant thermal comfort equation, the emphasis of the design proposal was focused on the key tactics of wind management, shade, shelter and the warming capacity of the stone seating structures to produce microclimatic change. Whilst the designers were seeking to extend use of the park in the extreme climatic conditions of summer and winter the broader climatic conditions severely limited the ability to achieve a reading of 4 (most comfortable) across the site. This is especially evident in winter where it is most challenging to warm the external environment. However, the designers were able to work with a relative change of conditions specific to the surrounding environment. Through the management of key variables certain microclimate conditions could be enhanced, such as the warm stone benches. Whilst the majority of the park remains unaffected, opportunities for use of the space in the most extreme scenarios emerged in the smaller interventions.

5. Tools for predicting difference

These case studies illustrate the benefits of using a predictive tool to inform design and the usefulness of working with projected relative change of thermal sensation in the design of external environments. The existing site conditions in these examples were already at extreme or very uncomfortable thermal ranges so that the design responses were implicitly restricted in the ability to achieve a desirable thermal comfort range. Whilst in both circumstances the proposals are not always able to achieve a perfect measure of thermal comfort, the design schemes are able to effect relative change at the sites and extend the potential use of the space. This suggests a move away from generalizations of thermal comfort ranges to methods for working with information about existing site conditions and effecting change within those. This shift provides a broader range of outcomes that are more suitable to design in external sites where knowledge of desired thresholds remains valuable but may or may not be precisely achievable depending on the particular site and climate.

Both of the case studies also show how digital modelling and simulation technology can reveal complex environmental phenomena and provide behavioural analysis of climate conditions. In these instances simulation is essential for communicating with the design teams and conveying the relationships between spatial interventions and the critical forces dictating thermal comfort. In both
examples computational fluid dynamic (CFD) modelling was used as a critical design tool for analysis but also as a responsive strategy for the design teams to test and reflect on design moves. The integration of CFD into the design processes, which is different from a post-design report, facilitated the development of specific potentials. This is best demonstrated in the Masdar City Phase 5 development, where the integration of CFD into the design process influenced how this technology was used. In this case a faster and therefore potentially less precise result was required to allow for the design to develop concurrently with the CFD findings.

Finally, in these examples the value of working in cross-disciplinary teams is evident. Not all designers have the in-house skills or disciplinary knowledge to select and apply appropriate thermal comfort indices or use CFD and other simulation tools. These case studies both utilize engineering expertise to extend standard design practices. The simulation model is used as a critical design tool as a point of communication between designers and engineers and for applying the findings of the thermal comfort indices. The use of technology in these instances flags the importance of shared knowledge of design tools.

6. Conclusion

The use of thermal comfort indices in design of external space can provide important knowledge of the relationships between the key variables which affect thermal sensation. However, the usefulness of these is dependent on the aim in particular situations, the selection of an appropriate measure and the method in which the index is applied. The case studies shown here suggest the use of indices is valuable for designers as a predictive tool for change. This is apparent when used within a design process where designers can test spatial design proposals against different scenarios and predict a result. Here the value of simulation technologies such as CFD modelling is clear, where this tool works as a means for accessing complex information, predicting change and as a communications tool.

It is evident that designers need to address the issues of thermal performance in external space to ensure these kinds of sites remain useful in the future. There are many existing and emerging tools and methods through which to work with the variables that impact on thermal comfort, including established thermal comfort indices. How these tools are best applied into design processes is an important and necessary area for further research in the area of performative external space design.

References


Improving the impact of luminance contrast on the window appearance in a conventional office room: using supplementary lighting strategies

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Abstract: High contrast ratios between windows and surrounding surfaces could cause reduced visibility or discomfort for occupants. Consequently, building users may choose to intervene in lighting conditions through closing blinds and turning on the lamps in order to enhance indoor visual comfort. Such interventions increase projected electric lighting use in buildings. One simple method to prevent these problematic issues is increasing the luminance of the areas surrounding to the bright surface of windows through the use of energy-efficient supplementary lighting, such Light Emitting Diodes (LEDs). This paper reports on the results of a pilot study in conventional office in Brisbane, Australia. The outcomes of this study indicated that a supplementary LED system of approximately 18 W could reduce the luminance contrast on the window wall from values in the order of 117:1 to 33:1. In addition, the results of this experiment suggested that this supplementary strategy could increase the subjective scale appraisal of window appearance by approximately 33%, as well as reducing the likelihood of users’ intention to turn on the ceiling lights by about 27%. It could also diminish the likelihood of occupants’ intention to move the blind down by more than 90%.

Keywords: Window design; visual discomfort; office room; LED (light emitting diode).

1. Introduction

Office workers generally spend most of their working time inside the buildings in which they work (Schweizer et al., 2007). It is well understood that improving Indoor environmental quality (IEQ) of office buildings can enhance work performance and reduce absenteeism of office workers, besides reducing energy consumption of buildings (Fisk et al., 2011).

Indoor lighting quality as part of IEQ is one of the most significant attributes of a working environment (Ne'eman et al., 1984). Optimal or at least acceptable indoor lighting quality, which relies on daylight and/ or electric lights, can be achieved through providing high level of visual performance and avoiding visual discomfort for occupants (Boyce, 2003).
Office buildings generally rely on vertical windows for daylight harvesting, particularly in high-rise cities (Huang et al., 2014), and they are considerably favoured in working environments for access to daylight and an outside view (Veitch et al., 1993). Vertical windows also characterise energy consumption and visual comfort patterns in buildings (Ochoa et al., 2012). For instance, research suggests that a building with a typical façade, which has about 30% window to external wall, is likely to consume less energy than a building with fully glazed façade (Kevin Van Den and Meek, 2015).

The ubiquity of high contrast ratios between windows and the surrounding surfaces of the window especially when they are limited in a portion of wall can lead to reduced visibility and discomfort glare (Alrubaih et al., 2013). Prolonged exposure to poor visual conditions may cause headache, visual stress, and eyestrain; besides negatively affecting satisfaction and productivity of office workers (Boubekri, 1995). Consequently, building users may intervene by closing blinds and turning on additional lamps to improve indoor visual comfort (Aschehoug et al., 2000). For instance, a study among 123 buildings with installed photosensor-control systems illustrated that there is a comparatively monotonous relationship between the amount of illuminance from windows and turning on the lights by occupants, in particular when dimming control systems work perfectly (Heschong et al., 2005). This study showed that as the window illuminance increases, the probability of switching on the lights will also increase to up to 60% to reduce luminance contrast between the window and surrounding areas. Evidently, occupants’ interventions in lighting conditions increase electricity consumption of buildings.

The aim of this study is to improve user acceptance and visual comfort of typical day-lit offices, and to reduce negative occupant interventions in these spaces. It is presumed that one simple and efficient strategy to achieve this is to reduce the luminance contrast on the window wall by increasing the luminance of the areas surrounding the window using supplementary lighting, such as LED.

Preliminary small pilot study investigated potential energy saving offered by using supplementary LED system in an office room (Amirkhani et al., 2015). It evaluated subjective responses, as well as using the DAYSIM engine within ECOTECT to assess annual energy consumption of the test office room. The results of this study indicated that increased electricity usage of an approximately 18 W LED lighting strategy, which was not chosen because of its energy efficiency, is offset where there is roughly one-fourth reduction in users’ intention to intervene in lighting conditions.

The purpose of this study is assessing subjects’ acceptance for luminance ratios on the window wall under different lighting conditions using a simple rating scale (self-reported data). Physical lighting measurements are combined with occupant surveys to provide a better understanding of discomfort caused by high contrast ratios between windows and the surrounding window wall when they are in the field of view of occupants. In addition, different solutions that could reduce any apparent discomfort have also been tested. The results from this survey present valuable information for the design of more comfortable and glare-free office environments.

2. Method

2.1. Experiment settings

The test is conducted in an individual test office room on the first floor of a 2 storey building located in Brisbane central business distinct (CBD), Australia during June 2015. The test room is 3.17 m deep by 3.64 m wide and 3.85 m high. Figure 1 illustrates the plan and sections of this room. This room is facing South-West and its window has ceiling height at 3.6 m and a sill height at 1 m while the width of that is 1.23 m. The walls and ceiling are white and the flooring is grey. Daylight penetration is controlled by a
fabric roller blind, and the room is furnished with a desk and chair, which are located in front of the window. This room has 2 x 28 W fluorescent luminaires, suspended 1.3 m from the ceiling. These luminaires can be switched on or off separately.

Cool-light LED strips, which have matched CCT to sunlight (5600 K-7000 K), were chosen to diminish luminance contrast in the field of view of subjects through distributing light on surfaces around the window. They were pre-assembled in a channel diffuser to reduce bright spots generally associated with strip LEDs and to distribute light evenly. Each of pre-assembled LED light strip has 30 mm width, 12 mm height, and 513 mm length. Each LED strip has luminaire power of 9 W and needs a constant-voltage driver to convert main voltage to 12 V. They were also equipped with a suitable compatible dimmer switch to be able to adjust light level from 0% to 100%. LED strip cases were mounted on the window sides with sill height of 2.1 m and the bottom of window surface (see figure 1). It should be noted that the proposed LED system in this study was chosen as merely an easy method to conduct the test and not for its energy efficiency.

![Figure 1: Plan and sections of the test office room in Brisbane, Australia.](image)

The test room relies on reflected sunlight (from adjacent buildings) and diffuse skylight for indoor daylight harvesting due to its orientation. Thus, the blind were fully opened during the experiment to have maximum indoor natural light.

### 2.2. Questionnaire

The survey was divided into three sections; date and time of conducting the experiment, basic demographic data from the subject, and some scales to rate participants’ preferences for window appearance under different lighting conditions. The number of questions used in this survey was carefully considered to minimise fatiguing or boring the respondent, while still capturing the significant information required.

The second part of the survey collected demographic and personal information relevant to the participant’s glare susceptibility. This included the participant’s age, whether they wear corrective lenses, and whether the participant considers himself or herself as a glare-sensitive person.

The third section of the survey related to the participant’s opinion and preference on the lighting in the test room. It was divided into four stages: no supplementary lighting, and LED wall-washing of the
window surrounds at 3 different power levels (9 W, 18 W and 27 W). The questions in each stage were designed to find whether the use of the supplementary lighting system influenced feeling discomfort glare from windows and subjects’ decision to turn on top lights.

It is frequently challenging to find predictable practical relationships between physical stimulus and subjective reaction in the field of lighting (Houser and Tiller, 2003). However, some studies have grouped perceived discomfort glare from daylight into bins of imperceptible, perceptible, disturbing, and intolerable (Suk and Schiler, 2013). The first question at each stage asks participants to rate the level of perceived discomfort glare from the window when it is in their field of view among these four groups.

Currently, there are different techniques that can be used to relate subjective responses to physical parameters in lighting research, including questionnaire, rating scales, magnitude estimation strategies, and paired comparison (Tifler and Rea, 1992; Houser and Tiller, 2003). However, according to Houser & Tiller (2003) paired comparison and semantic differential (SD) scaling are two of the most widely techniques used in lighting research. SD consists of a set of bipolar adjectives. The ends of each scale are defined through polar opposite adjectives which are separated through a seven-point scale (Monette et al., 2013). The number of points to the scale can be varied between seven, five, or even three (Barbara Sommer, 2006). Therefore, the second question at each stage uses SD scaling to rate indoor visual comfort on a scale of 1-5 (one meaning very dissatisfied and five meaning very satisfied).

The last two questions at each stage ask subjects whether they want to move the blind down or turn on the ceiling lights (yes/no answer). If they respond yes to turn on lights, further question asks how many they would like to switch on (one or both of the ceiling lights).

2.3. Procedure

Thirty five people participated in this investigation and they were surveyed individually in the test office room. They were office workers with normal or corrected to normal vision and representative in age and sex of the general office worker population. Before starting the experiment, each subject was clearly informed of the purpose of the research, and shown the light measurement equipment. Each participant was asked to sit facing the window, around 2.2 m from the window surface and the experimenter stood somewhat behind the subject. They were also asked to fill in the first and second section of the survey themselves; while the researcher led the remainder of the survey, adjusting light levels and asking questions for a verbal response from the participant.

To start the first stage of each experiment, all the ceiling lights and the LED supplementary system were switched off. The experiment followed the same process during each stage, whereas the luminaire power of the LED supplementary system was increased by 9 W at the start of stages 2 to 4. Participants were given one minute to adapt to light level changes before the survey started at each stage. Quantitative data was collected using a Nikon Coolpix 8400 digital camera (calibrated for luminance measurement (Coyne et al., 2008)), Konica Minolta LS100 luminance meter, and Konica Minolta T-10 illuminance meter prior to asking the questions of each stage.

The digital camera was used to take High Dynamic Range (HDR) images to observe the luminance distribution at the window and surrounding surfaces. In order to capture a field of view that is relatively similar to human eye, an FC-E9 fisheye lens (focal length = 5.6 mm, 190° field of view) was used. The camera was located as practicable as possible to the head of subjects through using a tripod. Multiple pictures of the same scene were captured during each experiment to achieve a single HDR image with relative luminance through using Photosphere. In addition, the luminance meter (LS100) was used to
measure the luminance value of a single white spot inside the room for HDR calibration in Photosphere. Photosphere remembers the response curve of camera and attached lens. Therefore, it was not essential to measure luminance values of more than one spot. The illuminance meter was used to record the luminance measurement on the working plane (the desk in the test room), which was 0.72 m above the floor and 1.5 m from the window. After collecting quantitative lighting information at the beginning of each stage while the participant was adapting to the change in lighting, the experimenter completed the questionnaire by directly asking the survey questions of the participants.

3. Results and discussion

Table 1 illustrates mean illuminance measurements at the desk level during each stage. There was a little variation in exterior lighting conditions across all experiments. For example, the mean standard variation of horizontal illuminance at the desk level across all test conditions was 18. Accordingly, about 95% of values were less than 36 lux away from the mean illuminance measurements during each test condition.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Ceiling lights are off</th>
<th>One Ceiling light is on</th>
<th>Two Ceiling lights are on</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean illuminance (lux)</td>
<td>Std. deviation (lux)</td>
<td>mean illuminance (lux)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Std. deviation (lux)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Std. deviation (lux)</td>
</tr>
<tr>
<td>1</td>
<td>159</td>
<td>13</td>
<td>250</td>
</tr>
<tr>
<td>2</td>
<td>160</td>
<td>15</td>
<td>251</td>
</tr>
<tr>
<td>3</td>
<td>169</td>
<td>17</td>
<td>261</td>
</tr>
<tr>
<td>4</td>
<td>180</td>
<td>18</td>
<td>275</td>
</tr>
</tbody>
</table>

Calibrated HDR images of each stage of all experiments were resized for calculation. Figure 2 shows an example of a HDR image captured by the digital camera when overhead lights and supplementary system were off. This image shows the 12 areas that were targeted for luminance spot measurements using calibrated HDR images, as well as the illuminance meter located on top of the desk. To obtain the value of the window to wall luminance ratio, readings 1 to 6 are averaged (to give window luminance) and compared to the average of readings 7 to 12 (for the surrounding wall luminance). These ratios are presented in Table 8 below.

![Figure 2: Captured HDR image from the test office room.](image-url)
Table 8 illustrates that as the luminaire power of proposed LED system increases, the luminance contrast between the bright surface of the window and surrounding walls decreases by about 72% and 81% during stage 3 and 4 to compare with stage 1, respectively.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Mean window luminance (cd/m²)</th>
<th>Mean wall luminance (cd/m²)</th>
<th>Luminance ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2331</td>
<td>20</td>
<td>117</td>
</tr>
<tr>
<td>2</td>
<td>2406</td>
<td>38</td>
<td>63</td>
</tr>
<tr>
<td>3</td>
<td>2192</td>
<td>66</td>
<td>33</td>
</tr>
<tr>
<td>4</td>
<td>2289</td>
<td>103</td>
<td>22</td>
</tr>
</tbody>
</table>

Figure 3 plots participants’ response for feeling discomfort glare from the window at the beginning of each stage during 35 experiments. It illustrates that the spread of variables during stage 1 generally fall within disturbing and perceptible, whereas the middle half responses for feeling discomfort glare falls within perceptible and imperceptible during stage 3 and stage 4. In addition, this figure indicates that although the median report for feeling discomfort glare during the first three stages remains the same and is perceptible, it is imperceptible during stage 4. Furthermore, only one person reported intolerable discomfort glare from the window throughout all stages. Overall, this figure suggests that feeling discomfort glare from windows can be reduced by about 33% through using proposed LED lighting system.

Figure 4 and 5 show the mean subjects’ scores of indoor visual comfort at the begging of each stage and also in association with reported discomfort glare from window. Figure 4 shows that participants’ satisfaction of indoor lighting level increased by around 17% and 24% throughout stage 3 and 4 in comparison with stage 1. Figure 5 illustrates that the mean participants’ satisfaction for indoor visual comfort improved by 24% when they did not feel discomfort glare from the window in comparison with when their responses for feeling discomfort glare from the window was disturbing. Finally, these line graphs indicate that the mean score (about 3.7) for indoor visual comfort during stage 4 is similar to when reported discomfort glare from windows is imperceptible.
Improving the impact of luminance contrast on the window appearance in a conventional office room: using supplementary lighting strategies

Figure 4: Mean subjects’ satisfaction for indoor visual comfort during each stage.

Figure 5: The relationship between mean subjects’ satisfaction for indoor visual comfort and their responses for feeling discomfort glare from the window.

Figure 6 plots luminance ratio on the window wall when subjects’ response for feeling discomfort glare from window is intolerable, disturbing, perceptible and imperceptible. It indicates that subjects did not report discomfort glare from window when the median luminance contrast between the window and surrounding surfaces is about 32, which is close to the mean and median window wall luminance ratio during stage 3 (around 34 and 31 respectively).
The results of the survey shown in figure 7 indicate that decreasing the luminance ratio between the window and immediate walls affect participants wanting to whether switch on or off top lights or to close blinds. This study suggested that the mean possibility of subjects’ intention to turn on one or both ceiling lights decreased by about 27% when their responses for feeling discomfort glare from window were imperceptible. Approximately 53% of subjects wanted to turn on both overhead luminaires when they perceived discomfort glare from window. However, only 23% of subjects wanted to turn on both ceiling lights when they did not perceive discomfort glare from window. Figure 7 also indicates that the probability of moving the blind down decreased by about 77% and 97% when subjects’ responses for feeling discomfort glare from window were perceptible and imperceptible to compare with when it was intolerable. In addition, the likelihood of moving the blind down diminished by about 96% when participants did not feel discomfort glare from window in comparison with when their responses for feeling discomfort glare from the window were disturbing.
Table 3 shows some demographic data of participants, including the number of participants who wore corrective lenses, participant age, and how many considered themselves to be glare sensitive. The results suggested that there is no relationship between responses of subjects who wore perception glasses and who did not wear for feeling discomfort glare at the beginning of each stage. The results also did not indicate any significant relationship between age and reported discomfort glare in the test room. In addition, there is not any significant difference between the responses of subjects who considered themselves to be glare sensitive person and those who did not.

<table>
<thead>
<tr>
<th>Question</th>
<th>Options</th>
<th>Number of subjects</th>
<th>Percentage</th>
<th>Median response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Perception glasses</td>
<td>Reading</td>
<td>4</td>
<td>11.5</td>
<td>All the time</td>
</tr>
<tr>
<td></td>
<td>Driving</td>
<td>3</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>All the time</td>
<td>11</td>
<td>31.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Never</td>
<td>17</td>
<td>48.5</td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>Less than 30</td>
<td>19</td>
<td>54.5</td>
<td>Less than 30</td>
</tr>
<tr>
<td></td>
<td>Between 30 and 50</td>
<td>13</td>
<td>37</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Between 50 and 65</td>
<td>3</td>
<td>8.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>More than 65</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Glare sensitive</td>
<td>Yes</td>
<td>22</td>
<td>63</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>No</td>
<td>13</td>
<td>37</td>
<td></td>
</tr>
</tbody>
</table>

4. Conclusion and future work

This study investigated users’ acceptance for the luminance ratio on the window wall using a supplementary lighting strategy. A simple LED system was proposed for the supplementary lighting strategy. The main aim of this study was to test the impact of proposed LED system on subjects’ intention to intervene in lighting conditions through moving the blind down or turning on the ceiling lights. The results from this study indicated that the proposed LED system could significantly diminish the luminance contrast between the window as a daylight source and surrounding surfaces by about 3.6 fold (from 117 to 33) during stage 3 and around 5.5 fold (from 117 to 22) during stage 4. The study also suggested that the mean indoor visual satisfaction increases by about 24% when the luminance ratio of window to wall reduces from values in order of 117:1 during stage 1 to 33:1 during stage 3. In addition, the results of this research indicated that the median report of discomfort glare from the window is imperceptible, while using proposed LED lighting system with approximately 18 W luminaire power (stage 3). Consequently, the mean users’ intention to switch on ceiling lights diminished by about 27% and to move the blind down by more than 90% through using a supplementary LED strategy with about 18 W luminaire power. Furthermore, this investigation indicated that there is a monotonous relationship between feeling discomfort glare from windows and indoor visual comfort.

The tests in this study were not conducted randomly. This research also focused on a small conventional office room without any specific daylighting system. Further study is needed to investigate on more rigorous testing of occupants’ perception using supplementary strategies in various test office environments with different office layout and window types. In addition, more investigation is needed to improve the energy efficacy of proposed supplementary system to considerably increase the energy savings available for this design system.
References


Introducing the SAMBA indoor environmental quality monitoring system

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Abstract: To date the sustainable commercial building sector in Australia has focused primarily on energy, due in large part to the mandatory disclosure provisions of the National Australian Built Environment Rating System (NABERS). Other dimensions of building sustainability such as Indoor Environmental Quality (IEQ) are less well developed. But widespread concerns about occupant productivity is shifting the spotlight onto building IEQ performance. Our new approach to IEQ measurement centres on small, low-cost, desk-based monitors (SAMBA) with sensors for thermal comfort (air and radiant temperatures, air speed and humidity), acoustics (SPL), lighting (lux) and air quality (CO₂, CO, TVOC, Formaldehyde and PM10). Low unit costs make it feasible to place SAMBAs in each HVAC zone of complex commercial buildings. The SAMBA network architecture is based on a self-forming mesh network that does not require access to the host organisation’s ICT infrastructure. Measurements are relayed wirelessly to a central SAMBA gateway within the building that transmits data through the cellular network to the IEQ Laboratory's server every 15 minutes. Various IEQ indices and compliance metrics are calculated in real-time before being presented to an online IEQ dashboard to which the building operator has access.

Keywords: Indoor environmental quality; acoustics; indoor air quality; thermal comfort.

1. Introduction
In the past couple of years the Australian commercial building sector has begun paying more attention to Indoor Environmental Quality (IEQ) issues largely because indoor environment is believed to impact productivity and performance of office workforces. Even though the scientific evidence of this link remains highly contentious (e.g. de Dear et al., 2013) there seems little doubt that more satisfied building occupants with higher levels of wellbeing generally translate into better outcomes for the organizations leasing the building (e.g. Newsham, Veitch, & Charles, 2008). Sustainability rating tools such as Green Buildings Council Australia’s “Green Star - Performance” (GBCA 2015), and the National
Australian Built Environment Rating System “Indoor Environment” (NABERS 2015) specifically assess indoor environmental quality of buildings using two broad strategies – occupant questionnaires called Post-Occupancy Evaluations (POE), and instrumental measurements. The latter are retained simply because of the lingering suspicion that non-building issues such as industrial relations, staff morale etc may also influence how an office population will rate their workplace environment on a POE questionnaire. Instrumental data are seen as “ground-truthing” subjective evaluations captured by POE. Measurement of IEQ inside a building reduces to a spatio-temporal sampling problem. Many of the key IEQ parameters are characterised by significant variability in spatial and temporal dimensions, and to accurately capture that variability in a sample of instrumental IEQ measurements inside a building poses several technical and logistical challenges.

The spatial scale of IEQ variations can be at the HVAC zone level (perimeter versus core zones, east versus west zones in morning and afternoon, north versus south zones in summer versus winter). Some IEQ parameters demonstrate variances on an even smaller spatial scale, for example, in terms of metres in the case of air speed which is directly related to air-supply vents and the often complex flow patterns within a room filled with air. Specific IAQ parameters such as Total Volatile Organic Compounds (TVOC) can also demonstrate sharp spatial gradients and variations, depending on proximity to individual emission sources such as cleaning detergents, particular pieces of furniture, or even particular fit-out materials such as drapes. Mean radiant temperature within a space can also demonstrate significant spatial heterogeneity, depending on proximity to heat-emitting appliances such as computer terminals or photocopiers, or complex and changing patterns of direct solar penetration onto the building floor-plate through large expanses of un-shaded perimeter glazing that is so popular in contemporary office building architecture. Indeed, it was this inherent spatial heterogeneity of mean radiant temperature that was successfully used to argue for the exclusion of that parameter from the NABERs Indoor Environment rating scheme (2015), despite the fact that mean radiant temperature is as important as air temperature in determining human thermal comfort sensations (ASHRAE 2015).

As with spatial scales, the temporal dimension of IEQ parameters within buildings is characterised by considerable variability, including cycles and random variations across multiple timescales ranging from second-to-second turbulence, through diurnal cycles, up to synoptic-scale changes in the daily weather conditions outside the building, up to seasonal-scale variations in solar position, deciduous tree shading, and general outdoor meteorological environment. Air temperature time-series within office buildings demonstrate complex ebbs and flows as HVAC systems start-up and switch-off at either end of the working day. Likewise with indoor air quality bellwether parameters such as CO₂ concentrations that reflects the tidal flows of building occupants at the start, middle and end of the working day. The mix of daylight to artificial lighting inside a building responds to the sun path arc from one side of a building to the other through the course of a day, and the background noise level inside a contemporary sealed-façade office building is overwhelmingly dominated by occupant density that fluctuates wildly throughout the day.

2. Previous instrument solutions to the IEQ sampling problem

In view of the inherent spatial and temporal heterogeneity of IEQ parameters within a building it is perhaps surprising that some IEQ rating tools have deemed a one-day sampling strategy to be sufficient to characterise the indoor environmental quality of a building. For example, Australia’s NABERS IE (2015) allows a consultant to do a one day walk-through sample of the key IEQ parameters on a random selection of floors in morning and afternoon periods. Apart from missing many if not most of the spatio-
temporal variability described above, a one-day on-site measurement campaign encourages the unscrupulous building operator or owner to “game the system” i.e. temporarily optimise the building management system settings for the duration of the measurement campaign and then revert to less-than-ideal settings in order to minimise energy consumption once the IEQ rating has been made.

The ASHRAE/USGBC/CIBSE Performance Measurement Protocols (PMP) (2010) prescribes three levels of measurement detail: Basic, Intermediate and Advanced. Instrumental measurements prescribed in the Basic protocol include spot measurements with a hand-held temperature, humidity, air speed, illuminance and sound pressure level meters. The Intermediate PMP protocol requires time-series (datalogger) observations of air and mean radiant temperatures, relative humidity, occupied zone air speed, CO\textsubscript{2}, and vertical plus horizontal surface light-level measurements. The required acoustic measurements include sound pressure level with parallel octave band filters and a noise source for calculation of background noise and reverberation time respectively (Kim, 2012). The Advanced PMP level (ASHRAE 2010) requires air and radiant temperatures, humidity, air speed, CO\textsubscript{2}, PM2.5, and TVOCs sensors to be logged continuously for a defined period, while the requisite lighting measurements include a High Dynamic Range (HDR) camera and software. Advanced PMP requires a sound pressure level meter equipped with a parallel one-third octave band filters and loudspeakers for evaluations of speech privacy, speech communication, sound and vibration isolation respectively (Kim, 2012).

IEQ researchers have developed a variety of solutions to the problem of registering spot measurements inside buildings. Typically they have involved a mobile cart of some sort with an on-board data-logger into which the various transducers have been wired. The cart is typically wheeled around inside the building and the data-logger is randomly triggered to perform a sweep of all transducers. Figures 1 and 2 depict some examples of various carts from the recent research literature.

![Figure 1: Left - a mobile IEQ cart used to field-test the ASHRAE/USGBC/CIBSE performance Measurement Protocols (Kim, 2012); right - a mobile IEQ cart with telescopic mast of temperature sensors designed to specifically commission underfloor air distribution systems (Webster et al., 2007).](image-url)
Figure 2: Perhaps the most sophisticated mobile IEQ cart to date includes most transducers required by the ASHRAE/USGBC/CIBSE PMP Advanced Level protocol (Newsham et al., 2013).

In all these mobile cart examples (Figures 1 and 2) the design strategy has simply been to select off-the-shelf, laboratory-grade instruments for each one of the individual IEQ parameters of interest, and then hard-wire them into a centralised datalogger. The end result, without exception, has been a prohibitively expensive apparatus that requires a human operator to wheel through the space and to periodically trigger the datalogger to sweep all of the transducers, time-stamp their data, and store it all in memory for safe retrieval after a day “on the job.” The prohibitive expense of this IEQ measurement solution arises from three main causes:

- The individual off-the-shelf instruments themselves are usually exorbitantly priced because of the relatively small market, even if the actual transducer component being used is abundantly available and modestly priced (e.g. a turnkey hand-held CO$_2$ instrument can easily cost two orders of magnitude more than the actual non-dispersive infra-red sensor component at its centre).
- Mobile IEQ measurement carts require a human operator to steer them along their “random sampling trajectory” within a building. The labour cost, including associated on-costs such as worker insurance and payroll tax, for a technically skilled engineer or research assistant conspire to make each day on-site a very expensive proposition.
- Logistical complexities (inter-city air freight or even just intra-city road transport) and the associated insurance costs of placing an elaborate and extremely delicate scientific apparatus
Introducing the SAMBA indoor environmental quality monitoring system

(e.g. Figures 1 and 2) on-site, all add significantly to the overall costs of a day of IEQ sampling inside a building.

As a result of these factors, measurement of a building’s IEQ is prohibitively expensive and beyond the reach of most building owners in the Australian commercial buildings sector. There are only a handful of IEQ consultants operating in the Australian market and the mainstay of their business is collection of the requisite data for NABERS IE ratings. But the demand for NABERS IE ratings has been very low since its inception, prompting the NABERS organisation to fundamentally redesign the IE rating protocol in 2014/15 (NABERS, 2015). The stated aim of that review was to reduce the costs of collecting the IEQ data and applying for the IE rating.

3. Introducing SAMBA IEQ monitoring stations

The basic aim of the SAMBA project (Sentient Ambient Monitoring of Buildings in Australia) was to design a small, low-cost, autonomous IEQ monitoring device that could be placed permanently at multiple sampling points across the occupied zone of a building floor-plate (spatial sampling) and on multiple levels of a multi-storey building (vertical sampling). Permanent placement of such devices could allow longitudinal measurements through time (i.e. all occupied hours for weeks, months, seasons or even years). In this way it is possible to collect a truly representative picture of a building’s IEQ performance – not just on “a good day.”

The expected Australian end-users of such a system for IEQ performance monitoring and improvement include, but will not be limited to;

- Building owners seeking market advantage in the highly competitive commercial property sector (includes portfolio and individual building owners).
- Commercial building tenants seeking to ensure that the building they are leasing is providing an indoor environment at a quality level specified in their lease.
- Building services engineering firms.
- Architectural and interior design firms.
- Office fit-out firms.
- The Property Council of Australia.
- Green Building Council of Australia (Green Star-Performance).
- National Australian Built Environment Rating System (NABERS Indoor Environment).
- Facilities Management firms and consultants.
- Building services and FM accredited assessors for NABERS IEQ and Green Star-Performance.

3.1. SAMBA’s sensors

Decisions about which sensors to include in SAMBA were made largely on the basis of the specifications in Australia’s NABERS Indoor Environment (IE) rating tool (2015), but also on component costings. The list of IEQ parameters can be found in Table 1 and cover the four key IEQ areas of thermal comfort, indoor air quality, lighting and acoustics. The SAMBA hardware design integrates a low-cost suite of sensors into a small monitoring station that is intended to be placed on the desk surface (i.e. occupied zone) in a random selection of workstations throughout the building. Rather than focusing on laboratory-grade measurement practices which are appropriate for detailed workplace health audits and perhaps forensic investigations (see Figures 1 and 2 above), SAMBA’s sensing capabilities have been
scaled to the application at hand – ‘good-enough’ real-time data – thus allowing very substantial reductions in both hardware costs and also on-site technical personnel costs.

3.2. Calibration of SAMBA’s sensors

SAMBA comes with the caveat that it is not intended to be a laboratory-grade IEQ data acquisition system. Referring to the ASHRAE/USGBC/CIBSE nomenclature for performance measurement protocols SAMBA would qualify at the BASIC measurement protocol, with parts of the INTERMEDIATE protocol covered as well. SAMBA definitely would not withstand legal scrutiny in a forensic context. Nevertheless we have conducted a series of in-house calibration of the SAMBA sensors against laboratory-grade reference instruments across the range of parameters reasonably expected inside office buildings (Kim, 2012). On the basis of explained variance (R2) of the relationship between SAMBA sensor and the relevant calibrated laboratory-grade reference instrument listed in Table 1, the suite of sensors selected for SAMBA are consistent with the performance specifications of ASHRAE/USGBC/CIBSE Basic Level (ASHRAE 2010). To safeguard against calibration drift, the SAMBA device is swapped over, new for old, at the end of every 12 months in service. Each new SAMBA device is laboratory-calibrated using the reference equipment described in Table 1 before being sent out into the field.

Table 1: The suite of transducers selected for SAMBA and their calibration performance against relevant laboratory-grade reference instruments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SAMBA Transducer Type</th>
<th>Measurement Range</th>
<th>Resolution</th>
<th>Accuracy</th>
<th>Calibration Reference Instrument</th>
<th>Calibration R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air temperature</td>
<td>NTC thermistor</td>
<td>-40 to 125°C</td>
<td>0.04°C</td>
<td>±0.3°C</td>
<td>Innova 1221 Comfort Logger w/ MM0034 air temperature transducer</td>
<td>0.99</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>Capacitive humidity sensor</td>
<td>0 to 100%</td>
<td>0.1%</td>
<td>±2%</td>
<td>Innova 1221 Comfort Logger w/ MM0037 air humidity transducer</td>
<td>0.98</td>
</tr>
<tr>
<td>Globe temperature</td>
<td>NTC thermistor</td>
<td>-40 to 125°C</td>
<td>0.04°C</td>
<td>±0.2°C</td>
<td>Innova 1221 Comfort Logger w/ MM0034 air temperature transducer</td>
<td>0.99</td>
</tr>
<tr>
<td>Air speed</td>
<td>Hot-wire anemometer</td>
<td>0 to 2m/s</td>
<td>0.01m/s</td>
<td>±5%</td>
<td>Dantec 54T21 omni-directional anemometer</td>
<td>0.98</td>
</tr>
<tr>
<td>Carbon dioxide</td>
<td>Non-dispersive infrared</td>
<td>0 to 5000ppm</td>
<td>1ppm</td>
<td>±30ppm</td>
<td>CET AST-IS infrared CO2 sensor</td>
<td>0.97</td>
</tr>
<tr>
<td>Particulate Matter</td>
<td>Photodiode</td>
<td>0.001 to 1 mg/m³</td>
<td>0.001mg/m³</td>
<td>-</td>
<td>TSI Dusttrak II Aerosol Monitor 8532</td>
<td>0.99</td>
</tr>
</tbody>
</table>
Introducing the SAMBA indoor environmental quality monitoring system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SAMBA Transducer Type</th>
<th>Measurement Range</th>
<th>Resolution</th>
<th>Accuracy</th>
<th>Calibration Reference Instrument</th>
<th>Calibration R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>TVOC</td>
<td>Photo-Ionisation Detector</td>
<td>0.001 to 50ppm</td>
<td>0.01ppm</td>
<td>-</td>
<td>N/A</td>
<td>-</td>
</tr>
<tr>
<td>Carbon Monoxide</td>
<td>Electrochemical</td>
<td>0 to 500ppm</td>
<td>1ppm</td>
<td>-</td>
<td>N/A</td>
<td>-</td>
</tr>
<tr>
<td>Formaldehyde</td>
<td>Electro-chemical</td>
<td>0 to 5ppm</td>
<td>0.01ppm</td>
<td>-</td>
<td>N/A</td>
<td>-</td>
</tr>
<tr>
<td>Sound Pressure Level</td>
<td>Electret condenser microphone</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>N/A</td>
<td>-</td>
</tr>
<tr>
<td>Illuminance</td>
<td>Broadband photodiode</td>
<td>0 to 40,000 lx</td>
<td>0.1 lx</td>
<td>±3 lx</td>
<td>Konica T10A Konica minan Meter</td>
<td>0.99</td>
</tr>
</tbody>
</table>

3.3. SAMBA hubs

SAMBA’s autonomous IEQ performance data acquisition and transmission does not require access to or cause disruption to any of the host building’s existing services or information/communication networks. Data network autonomy was a design priority because of the extremely sensitive nature of many of the host buildings’ data operations. As depicted in Figure 3, SAMBA’s IEQ data stream is periodically transferred, using our own ad hoc wireless mesh network, back to a ‘hub’ that is centrally located within a building. A single hub is configured to service all SAMBA monitoring stations within each building. The hub collates time-series data from all nearby SAMBAs and transmits them through the public cellular telephone network to a remote server for quality assurance and subsequent assimilation into the IEQ Lab’s cumulative database.
3.4. IEQ analytics dashboard

Once on our server the SAMBA’s data exports undergo some automated statistical analyses and visualization scripts for our on-line reporting procedures. The online portal, shown in Figure 4, has been specifically designed for interpretation by building facility managers (often non-technical personnel in Australia’s commercial buildings sector), and delivers prompt and concise visualization of all measured IEQ parameters. All data are compared alongside the relevant IEQ standards and rating criteria (e.g. GreenStar “Performance” and NABERS “IE”) to give building operators, owners and their tenants timely and intelligible reports on their building’s IEQ performance. The IEQ Analytics portal was designed after extensive consultation and with a large sample (over two dozen) of industry stakeholders during three months of pilot testing in Sydney and Melbourne commercial office buildings.
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Figure 4: The IEQ Analytics dashboard is a website that displays a building’s real-time IEQ performance data (SAMBA data) in a format that is intelligible to, and useful for a building facility manager.

Apart from displaying measured parameters the dashboard also displays some derived comfort indices. For example, in the thermal comfort section of the dashboard is a real-time stream of PMV/PPD calculations (ASHRAE 2013). SAMBA collects all the requisite environmental parameters for PMV/PPD (air temperature, globe temperature, air speed and relative humidity). Once the data have been transmitted to the server, the first three parameters are used to calculate a mean radiant temperature. Apart from four environmental parameters PMV/PPD requires estimates of two so-called personal parameters, namely building occupants’ metabolic rate and the intrinsic insulation value of the clothing ensembles being worn indoors. On the basis of extensive surveys in office buildings across Australia that have been collated together in the ASHRAE Global Thermal Comfort Database (de Dear, 1998) an estimate of 1.2 met units has been adopted in SAMBA’s index calculations. Building occupant clothing insulation is estimated in real-time using ASHRAE Standard 55’s statistical clothing model that is based on a running mean of outdoor air temperature, the latter being supplied by the closest automatic weather station and scraped from the internet by our servers on an hourly basis.

4. Research opportunities created by SAMBA

SAMBA provides a method for the efficient data acquisition of IEQ parameters en masse. Apart from providing timely and actionable IEQ data to building operators and facility managers, it opens up rich new possibilities for building science research. First and foremost SAMBA will feed the world’s largest commercial building IEQ performance database. Such an extensive database of IEQ measurements will allow for a range of scientific investigations through data-mining, particularly when combined with subjective IEQ measurements from building occupants. For example, the database could be used to identify trends such as recently discussed “indoor climate change” – the observation that indoor summertime air conditioning temperatures have been drifting lower in Australia and North America, in
contrast to upward trends across most of Asia (de Dear, 2012). Exploration of the multimodal interaction effects of different IEQ vectors in commercial buildings would also be possible. This research topic is underdeveloped partly due to the methodological difficulties in collecting the appropriate data from the field. The research potential is not limited to commercial office buildings either – SAMBA affords the possibility of conducting investigations of IEQ in residential settings, health-care facilities, retail facilities, or educational institutions. SAMBA therefore marks a paradigm shift in indoor environmental quality research that will enable a range of interesting research avenues in the near future.

References
Investigating energy and indoor environmental performance of aquatic centres

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Abstract: Aquatic centres are popular recreational facilities in Australia and other developed countries. These buildings have experienced exponential demand over the past few decades. The growing desire for better indoor environmental quality in aquatic centres has resulted in a marked increase in energy consumption in this sector. Community expectations in relation to aquatic centres are rising and these spaces are associated with wellness and health. Energy consumption in indoor swimming pool buildings is high due to the high indoor air temperatures, increased ventilation heat losses and the need to disinfect water. This study investigates the energy consumption and indoor environmental quality of seven aquatic centres in Australia. The construction and various energy consuming systems of the facilities are analysed and compared against the energy consumption. Thermal comfort data is collected through measuring the indoor environmental parameters. Building envelopes were found to be leaky in most of the buildings resulting in energy wastage. The main indicators for energy consumption were gross floor area, area of pool surface, and number of visitors. It was found that the set point temperatures were significantly high in some of the buildings resulting in high level of discomfort for the spectators and staff.

Keywords: Aquatic centre; energy; thermal comfort.

1. Introduction

Aquatic centres are popular recreational and sports facilities in Australia. The growing desire for better indoor environmental quality in the indoor aquatic centres has resulted in a marked increase in energy consumption in this building sector. Around 1900 aquatic centres in Australia attract approximately 263 million visits per year, with 64% of Australians aged 15 and over participating in physical activities for recreation or exercise (Australian Bureau of Statistics, 2011). The high energy consumption of aquatic and recreation centres offers challenges for energy conservation and improvement of indoor environmental conditions. To identify opportunities for energy conservation and further improvement
of indoor environmental quality, the first key step is to compare the performance of aquatic centres to establish benchmark data and best practice. This study compares the energy and indoor environmental quality of seven aquatic centres in Australia. The outcome of this study provides insights about the design and operational practices of aquatic centres.

2. Literature review

Although aquatic centres share some characteristics with offices and commercial buildings, due to different activity types, functions, ownerships, unique comfort requirements and complex environmental conditions, the level of energy consumption is significantly higher compared to a typical commercial building. Currently there are no benchmark standards for aquatic centres in Australia, whereas benchmarks for other building types such as offices, shopping centres, hotels and data centres are established leading to the development of national rating systems (NABERS, 2012). In a study of 978 municipal service facilities (offices, schools, libraries, hospitals, sports facilities etc.) in Barcelona, Oliver-Sola et al. (2013) reported that indoor swimming pool had the highest average energy consumption ranging from 48 kWh/m² to 5273 kWh/m² with an average of 666 kWh/m². A recent study in Australia found that aquatic centres are seven times more energy intensive than a commercial office building (Rajagopalan, 2014). Several studies have been conducted in naturally and mechanically ventilated office buildings to examine the indoor environmental quality. But studies on the indoor environmental quality of aquatic centres is very limited. These buildings have some of the most specialized indoor environmental requirements. The temperature of the air and the water need to be linked and balanced, so as to achieve the right humidity to minimise evaporation from the pool water. It is necessary to control the pool water temperature, air temperature, relative humidity, ventilation, lighting and water pumping, in order to provide a healthier indoor environment for different types of users such as swimmers, spectators and staff with different clothing types and various activity levels.

There has been a consistent trend towards higher water temperatures in recent years, due to the substantial growth in aquatic leisure activities. Table 1 shows the recommended indoor environmental conditions as per the Pool Operators’ Handbook (2008) and Australian Standards (2002). A safe, comfortable and appealing internal environment is crucial to attract and sustain customers. Higher temperature can cause discomfort to swimmers thereby limiting vigorous swimming. This increases the water pollution through sweat and body oil contamination. Higher water and air temperatures increase direct and indirect energy cost. With higher temperature, moisture level in the pool increases, even when relative humidity is controlled at the same level. This causes risk of condensation, and possibly corrosion and deterioration of the building fabric, structure and equipment. This will also increase the rate of chloramine formation (PWTAG, n.d). Even though new advanced heating, ventilation and air conditioning (HVAC) systems have replaced old systems, the community expectation towards the overall indoor comfort in aquatic centres has not been adequately met.

<table>
<thead>
<tr>
<th>Air Temperature</th>
<th>Humidity</th>
<th>Pool water temperature</th>
<th>Ventilation</th>
</tr>
</thead>
<tbody>
<tr>
<td>27°C in the pool hall, not more than 29°C</td>
<td>50-60%</td>
<td>26-30°C for lap pools 26-30°C for leisure pools 28-32°C for spa and hydrotherapy</td>
<td>10 l/s for sports hall 10 l/s for pool and deck areas 15 l/s for spa and hydrotherapy</td>
</tr>
</tbody>
</table>

Table 1: Recommended indoor environmental conditions.
3. Methodology

Energy consumption data and other pertinent information such as physical, occupancy and operational data were collected from seven aquatic centres. Energy consumption data was collected through utility bills and sub-meters installed at various centres. Information about the physical characteristics such as floor area, water surface area and building envelopes were obtained from architectural drawings and detailed site inspection. Thermal comfort measurements were conducted in the pool hall using a movable thermal comfort cart. The cart was fitted with various sensors that measure air temperature, mean radiant temperature, humidity and wind speed at the occupant levels. The data was analysed to understand the interrelationship between numerous factors that contribute to the energy consumption of these facilities and to determine the significant drivers of building energy use on a site energy basis.

4. Description of the aquatic centres

Six buildings were located in the state of Victoria and one building was located in the state of New South Wales where the air temperature is slightly higher. These buildings represent the wider population of aquatic centres in Victoria in terms of the floor area, area of functional spaces, number of visitors, etc. Aquatic centres generally consist of both dry and wet areas. There are large variations between the facilities in terms of the size of wet and dry areas. Each of the facility has three or more water bodies within the wet area. They include a lap pool with multiple lap lanes, either 25 m or 50 m long, a program pool for swimming lessons, leisure pool and wellness program pool. Program pools are separate pools with less than one meter depth and they have a large surface-area-to-volume ratio. In addition, two facilities have outdoor pools. Table 2 shows the range of floor areas and number of visitors.

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Floor area</td>
<td>2,944 to 11,000 m²</td>
</tr>
<tr>
<td>Water surface area</td>
<td>640 to 2,760 m²</td>
</tr>
<tr>
<td>Pool hall area</td>
<td>1,300 to 3,300 m²</td>
</tr>
<tr>
<td>Annual visitors</td>
<td>168,000 to 1,200,000 people</td>
</tr>
</tbody>
</table>

5. Results

5.1. Building fabric

The construction of old and new buildings varied considerably. The buildings constructed after year 2006 have to comply with BCA section J requirements for the envelope. The new buildings are well insulated, with double glazed windows, whereas old buildings are poorly insulated, with lots of gaps in between joints, window frames and mullions. Table 3 shows the envelope construction of various buildings. Air pressure testing was conducted in two of the facilities (B3 and B5) to measure the permeability rating. Building envelope permeability rate is a measure of the amount of air that permeates through gaps, cracks and leaks in the building envelope when driven by an external forces such as wind or the thermal stack effect. It is expressed in cubic metres of air per hour that passes through each square metre of the building façade (m³/hr/m²). The results of the test can show the integrity of the building envelope, with respect to leakage through penetrations, around door seals and
windows and joints in the building façade. The uncontrolled air movement has a significant impact on the energy consumption as the HVAC system need to work harder to treat the air.

Table 3: Type of building fabric.

<table>
<thead>
<tr>
<th>Facilities</th>
<th>Age of buildings</th>
<th>Building fabric</th>
<th>R value (m²K/W) /SHGC</th>
<th>Energy efficiency rankings</th>
<th>Permeability rating (m³/hr/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building 1</td>
<td>20</td>
<td>Insulated walls with no sealing, single glazed windows with air gaps in mullions/window frames</td>
<td>1-1.2 for walls, 0.9 for windows/SHGC 0.8</td>
<td>4</td>
<td>not measured</td>
</tr>
<tr>
<td>Building 2</td>
<td>35</td>
<td>Minimal insulation, with air gaps, single glazed windows with air gaps in mullions/window frames</td>
<td>1-1.2 for walls, 0.9 for windows/SHGC 0.8</td>
<td>5</td>
<td>not measured</td>
</tr>
<tr>
<td>Building 3</td>
<td>1</td>
<td>Part J compliant, well-sealed walls and roofs, double glazed windows</td>
<td>1.8-2.8 for walls, 1.6-1.8 for windows/SHGC 0.6</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Building 4</td>
<td>11</td>
<td>Insulated walls and no sealing, single glazed windows with air gaps in mullions/window frames</td>
<td>1-1.2 for walls, 0.9 for windows/SHGC 0.8</td>
<td>4</td>
<td>not measured</td>
</tr>
<tr>
<td>Building 5</td>
<td>18</td>
<td>Insulated walls reasonable sealing single glazed and sealed windows</td>
<td>1.2-1.5 for walls, 0.9-1.2 for windows/SHGC 0.8</td>
<td>3</td>
<td>22.5</td>
</tr>
<tr>
<td>Building 6</td>
<td>3</td>
<td>Part J compliant, well-sealed walls and roofs, double glazed windows</td>
<td>1.8-2.8 for walls, 1.6-1.8 for windows/SHGC 0.6</td>
<td>2</td>
<td>not measured</td>
</tr>
<tr>
<td>Building 7</td>
<td>36</td>
<td>Minimal insulation, with air gaps, single glazed windows with air gaps in mullions/window frames</td>
<td>1-1.2 for walls, 0.9 for windows/SHGC 0.8</td>
<td>4</td>
<td>not measured</td>
</tr>
</tbody>
</table>

Table 4 shows different permeability rates as specified by the Air Tightness Testing and Measurement Association (ATTMA TSL2 standard, 2010). ATTMA is a professional association based in United Kingdom, dedicated to promoting technical excellence and commercial effectiveness in all air tightness testing and air leakage measurement applications. Previous studies have shown that air leakage rates in Australia are much higher than those reported in Europe and USA (Egan, 2011). It can be seen from Table 3 that B3 constructed in 2014 has air permeability rating of 10 m³/hr/m². Building B5, with medium age has a permeability rating of 22.5 m³/hr/m². Reducing leakage from 22.5 m³/hr/m² to below 15 m³/hr/m² requires careful sealing of all air gaps. The permeability rating of other five buildings are not measured. Correlating the permeability rating with the façade construction, it can be deduced that B1, B2, B4 and B7 can have a much higher value for permeability rating and B6 can have a permeability rating closer to 10 m³/hr/m². A simple ranking for energy efficiency based on the façade construction is conducted and is shown in Table 3.
Table 4: Permeability rating as per ATTMA TSL2 standard.

<table>
<thead>
<tr>
<th>Type of facilities</th>
<th>Air permeability (best practice)</th>
<th>Air permeability (good practice)</th>
</tr>
</thead>
<tbody>
<tr>
<td>New Leisure &amp; Aquatic Centres</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>20 year+ old Leisure &amp; Aquatic Centres</td>
<td>5</td>
<td>15</td>
</tr>
</tbody>
</table>

5.2. Mechanical system

The air distribution system in the seven buildings varied considerably. Some of the facilities had minimum air distribution showing evidence of condensation. New buildings were found to have no condensation experience. Table 5 shows the fresh air percentage and type of heat recovery systems. Four of the facilities have no heat recovery systems, whereas B3, B5 and B6 have full heat recovery in the form of heat wheel, run-around heat coil and cross flow respectively.

Mechanical system for the pool plant is particularly important. Large volumes of water need to be continuously filtered, treated and heated. Heated water at specific temperatures is required for a wide range of activities as shown in Table 1. The provision of water for an infant ‘Learn to Swim’ class requires different conditions from that of competitive swimming training. The needs of the leisure swimmer and rehabilitation program are different. Selecting a heating system that will cater for such differing comfort needs is a complex task. It is important to carefully design each of the sub-systems including circulation pumps, filtration and backwash, UV treatment plant and the control of total dissolved solids (TDS) levels.

Table 5: Type of mechanical system.

<table>
<thead>
<tr>
<th>Facilities</th>
<th>Fresh air</th>
<th>Heat recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building 1</td>
<td>100% fresh air</td>
<td>no</td>
</tr>
<tr>
<td>Building 2</td>
<td>100% recycled air</td>
<td>no</td>
</tr>
<tr>
<td>Building 3</td>
<td>100% fresh air with Heat Recovery</td>
<td>Full Heat Recovery Heat Wheel</td>
</tr>
<tr>
<td>Building 4</td>
<td>50-50 recycled air</td>
<td>no</td>
</tr>
<tr>
<td>Building 5</td>
<td>100% fresh air with Heat Recovery</td>
<td>Run-around heat coil</td>
</tr>
<tr>
<td>Building 6</td>
<td>100% fresh air with Heat Recovery</td>
<td>Full Heat Recovery Cross flow</td>
</tr>
<tr>
<td>Building 7</td>
<td>100% fresh air</td>
<td>no</td>
</tr>
</tbody>
</table>

5.3. Energy consumption

The main components of energy consumption include heating the pool water and pool hall air, heating and cooling gym, crèche and administrative offices, operating pool equipment such as pumps and water filtration system, heating hot water for toilets and café as well as lighting and equipment. The proportion of each of these components will vary from building to building. According to Sydney water (2011) the water heating constitute around 64% of the total energy followed by pool equipment (18%). This is expected to be different in Victorian facilities due to the weather conditions that require considerably more heating.

The most common methods of producing heat include cogeneration units, condensing boilers, standard boilers and heat pumps. The seasonal efficiencies of these systems vary. Condensing boilers are more effective than standard boilers. Heat pumps are probably most cost-effective as part of a heat recovery/dehumidification system. The most important factors to be considered in the selection of fuel
are the availability and convenience of the fuel, the efficiency of the heat production method and the price. The environmental effects and greenhouse gas emission of different fuel options also should be taken into account. There are large variations between the seven facilities in terms of consumption patterns and air and water heating methods as shown in Table 6. Two of the facilities (B1 & B3) use cogeneration system to produce electricity and gas. B2 and B7 use electric heat pumps whereas the rest of the facilities use gas fired boilers to heat the pool hall air and pool water. The type of fuel used depends on the councils’ environmental policies, existing contracts with the energy providers and price of gas and electricity. Cogeneration system will significantly change the energy and emissions profile of the facilities and councils. Pools utilizing cogeneration aim to use more gas but less electricity resulting in fewer greenhouse gas emissions. It is to be noted that savings largely depend on the size and effectiveness of the cogeneration system. In order to achieve the maximum efficiency of cogeneration units, they need to run at full load for as many hours as possible.

<table>
<thead>
<tr>
<th>Facilities</th>
<th>Fuel type</th>
<th>Heating system</th>
<th>Pool details</th>
<th>Pool hall area (m²)</th>
<th>Water surface area (m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Building 1</td>
<td>gas</td>
<td>condensing boiler with cogeneration</td>
<td>25 metre pool, Beach entry pool, Toddlers' pool, Learners' Pool Indoor waterslide</td>
<td>1700</td>
<td>640</td>
</tr>
<tr>
<td>Building 2</td>
<td>electricity</td>
<td>heat pump</td>
<td>50 metre pool, spa and sauna, toddler pool, hydrotherapy pool, waterslide</td>
<td>2430</td>
<td>1072</td>
</tr>
<tr>
<td>Building 3</td>
<td>gas</td>
<td>condensing boiler with cogeneration</td>
<td>25 m outdoor pool, 25 m indoor pool, leisure pool, warm water program pool, spa</td>
<td>2930</td>
<td>1882</td>
</tr>
<tr>
<td>Building 4</td>
<td>gas</td>
<td>Standard boiler</td>
<td>25m pool, Toddlers' pool, leisure &quot;SPLASH&quot; pool, Learn to swim pool</td>
<td>1315</td>
<td>703</td>
</tr>
<tr>
<td>Building 5</td>
<td>gas</td>
<td>condensing boiler</td>
<td>50 m pool, Wave pool, Learn to swim pool, Toddlers pool, Spa-sauna</td>
<td>3000</td>
<td>1438</td>
</tr>
<tr>
<td>Building 6</td>
<td>gas</td>
<td>Condensing boiler</td>
<td>50 m outdoor pool, 25 m indoor pool, hot water program pool, leisure pool, big water sides, spa</td>
<td>3000</td>
<td>2760</td>
</tr>
<tr>
<td>Building 7</td>
<td>electricity</td>
<td>heat pump</td>
<td>50 m pool, learners pool</td>
<td>3300</td>
<td>1648</td>
</tr>
</tbody>
</table>

The total energy consumption along with CO₂ emissions are plotted in Figure 1. Emission factors were assumed as 1.18 Kg CO₂-e/kWh for electricity and 3.9 Kg CO₂-e/GJ for gas (Department of the Environment, 2014). Subsequently, various factors for normalizing the energy consumption were identified. They include total floor area, pool surface area, and total number of visitors. B6 has the highest energy consumption and greenhouse has emission. B6 has the highest number of visitors (1.2 million per year) and largest floor area, therefore the high electricity and gas consumption is justified. B3 has similar number of visitors and total floor area to B6, but the energy consumption is comparatively lower probably because of the higher water surface area. The greenhouse gas emission for B3 is much lower than B6, mainly because of the use of cogeneration system resulting in less electricity consumption. B2 and B4 have the lowest energy and greenhouse gas emission. The floor area
and number of visitors for B2 are double that of B4. B4 has the lowest gross floor (3520 m$^2$) area and least number of visitors (167,600) therefore has relatively high energy use intensity.

Figure 1: Total energy consumption and CO$_2$ emission.

Figure 2: Total energy consumption and normalised energy consumption.

Figure 2 shows the total energy consumption and normalized consumption with respect to the gross floor area and number of visitors. The energy usage intensity ranged from 507 kWh/m$^2$ to 1662 kWh/m$^2$. Normalising with number of visitors, the energy usage intensity ranged from 6 to 21 kWh/visit. B4 has the highest energy usage intensity with respect to the number of visitors. B1 had highest energy usage intensity with respect to the gross floor area and second highest with respect to number of visitors. A closer look at the other indicators revealed that this facility has the lowest pool surface area and the high energy usage intensity is not justified and need to be further investigated.
5.4. Thermal comfort

Thermal comfort measurements were conducted over two days period at various locations inside the pool halls. Predicted mean vote (PMV) was calculated using an excel spread sheet as per the heat balance equations (Fanger, 1970). It should be noted that thermal comfort is very sensitive to clothing and activity levels. Based on the clothing and activity levels, the users are categorised into three types: swimmers with minimum clothing and high activity level, staff with moderate clothing and moderate activity, spectators or carers of young children with high levels of clothing and low activity level. Assigning a metabolic rate for swimmers is challenging. ANSI/ASHRAE standard 55 (2013) recommends a time weighted metabolic rate for individuals with activities that vary. However, ANSI/ASHRAE standard 55 does not apply to occupants with high metabolic rate whose time averaged metabolic rate is higher than 2.0 met. Therefore, a met value of 2.0 is considered for swimmers and this should be taken into consideration while looking at the results.

![Figure 3: PMV values.](image)

Figure 3 shows the mean PMV of swimmers, staff and spectators along with the air temperatures of various facilities. When the PMV is within the range of −0.5 to 0.5, it is believed that the environments are thermally comfortable. The PMV for swimmers are generally towards warmer sensation, ranging from ‘slightly warm’ to ‘warm’, except for B2 and B7. The lower temperature setting for B2 should be related back to the low energy consumption for this facility. The Mean PMVs for B3 and B4 were 1.69 and 1.64 respectively. It is to be noted that the mean air temperature of B3 and B4 are set as 29°C which is quite high in comparison to other buildings. B7 is different from other six buildings in terms of its location.

6. Discussions

Aquatic centres use vast amount of energy and water. Environmental design standards for aquatic centres have generally been overlooked due to the complex nature of these buildings. Through analysis of energy consumption data, various normalization factors were identified. They include total floor area, pool surface area, and total number of visitors. Selecting the most suitable indicator that can accurately predict the energy consumption is very challenging and requires rigorous statistical analysis involving a
large number of samples. Majority of the buildings constructed before year 2006 had leaky facades resulting in energy wastage. The impact of building envelope and infiltration on energy consumption for these building typologies need to be further investigated through energy simulation.

Achieving thermal comfort has always been challenging especially with the multiple user groups. The results of the thermal comfort measurement showed that indoor parameter settings vary across the seven buildings. As a result of this, comfort experiences were different in the seven buildings. Each parameter has some implication on the energy consumption of the building, particularly heating energy. There are very limited studies comparing the thermal comfort conditions of indoor aquatic facilities. The existing comfort models have limitations in terms of metabolic rate limiting its adoption for activity levels more than 2.0 Met, hence not suitable for predicting the comfort of swimmers. A previous study conducted in two facilities (a swimming pool and a sports hall) showed that it was possible to apply PMV model without a specific correction after 10 min post-swimming (Marco Revel and Arnesano, 2014). However, for wet swimmers, the heat balance for the evaluation of the PMV requires the addition of the evaporative term. The comfort models need to be further extended and simplified to cater the wet swimmers. It may be argued that pool halls are designed for the comfort of swimmers, and the other user groups will have to sacrifice to some extent or come with certain expectations about the temperature and then possibly adapt through clothing. If it is possible to have some optimum temperature setting where every user group can achieve reasonable level of comfort, as in the case of B5, it need to be further explored.

The set point temperatures of the pool halls were up to 29°C in some buildings. Huge amount of energy is required to heat the air from 10°C to 29°C and to keep the water also at similar temperatures. However evaporation loss will be more if the air temperature is set low.

7. Conclusions

This study provided some insights into the complexity of aquatic centres and their variability in terms of design and operations. The main indicators for energy consumption are identified as gross floor area, area of pool surface, and number of visitors. The energy usage intensity ranged from 507 kWh/m² to 1662 kWh/m³. Normalising with number of visitors, the energy usage intensity ranged from 6 to 21 kWh/visit. It was found that the set point temperatures are high in some of the buildings resulting in high level of discomfort for the spectators and staff. In summary, the three main inter-related aspects for these buildings are energy consumption, indoor environmental quality and the integrity of the building structure. The influence of the indoor parameters on the building fabric and equipment is time dependent as long term exposure to high humidity and chloramines will cause facility corrosion. Due to the variability in the age of the studied building, such comparison between the buildings was not possible.

This study is part of a research project that aims to investigate the correlation between energy and indoor environmental performance of aquatic centres in order to discover the optimum balance between energy and indoor environmental performance. The results will help to develop guidelines for the design and operation of aquatic centres in Australia. Further work is being conducted to correlate the thermal comfort results with the HVAC energy consumption of each of the facility in order to establish the optimum balance between energy and thermal comfort. In addition, the air quality and occupant exposure to trichloramine levels will be investigated. More work is being carried out involving more number of samples to develop a comprehensive benchmark. The benchmarking system will assist local government to manage energy consumption and system design through better informed day to
day management of operations, as well as guiding environmental performance during the design of new or refurbished infrastructure.

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References

Investigation of the effect of balconies on natural ventilation of dwellings in high-rise residential buildings in subtropical climate

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Abstract: Balconies, as one of the main architectural features in subtropical climates, are assumed to enhance the ventilation performance of buildings by redirecting the wind. Although there are some studies on the effect of balconies on natural ventilation inside buildings, the majority have been conducted on single zone buildings with simple geometries. The purpose of this study is to explore the effect of balconies on the internal air flow pattern and ventilation performance of multi-storey residential buildings with internal partitions. To this end, a sample residential unit was selected for investigation and three different conditions tested, base case (no balcony), an open balcony and a semi-enclosed balcony. Computational Fluid Dynamics is used as an analysis method due to its accuracy and ability to provide detailed results. The cases are analysed in terms of average velocity, flow uniformity and number of Air Changes per Hour (ACH). The results suggest the introduction of a semi-enclosed balcony into high-rise dwellings improves the average velocity and flow uniformity. Integrating an open balcony results in reduction of the aforementioned parameters at 0° wind incidence.

Keywords: Natural ventilation; balcony; high-rise residential; CFD.

1. Introduction

Natural ventilation is considered as an effective passive strategy for cooling and reducing buildings’ energy consumption especially in tropical and subtropical climates. As natural ventilation does not consume any fossil fuels, it can significantly reduce CO₂ emissions while maintaining good indoor air quality. Energy consumption in high-rise buildings can be accelerated with an inappropriate design and contribute to higher urban energy consumption in overall (Kennedy et al., 2015). Hence, implementing passive strategies such as natural ventilation and daylighting for designing high-rise buildings could lead to significant energy savings. Furthermore, high-rise buildings are exposed to higher speed wind profiles due to their height and less obstructed surroundings. Thus, implementation of natural ventilation is more feasible.
While natural ventilation is a passive cooling strategy, relying on natural ventilation as a sole cooling strategy in climates with extreme weather conditions including high temperature and humidity for the most portion of a year could be quite unpractical. However, in mild climates such as Brisbane, where more than 60% of the year is within the comfort zone (temperature of 18 to 28°C) natural ventilation could be considered as an effective passive cooling system (Shah Nazari, 2014).

There are various influential parameters that have effect on natural ventilation in buildings. Some depend on the climate and the environment and cannot be controlled by architects such as wind speed, direction and temperature, while some can be addressed through an appropriate design. These parameters include building height and orientation, size and configuration of openings, internal obstacles and façade design. Researchers who explored these parameters and their influence on natural ventilation include (Mak et al., 2007; Gao and Lee, 2011b; Fung and Lee, 2014).

One of the façade design features that can affect natural ventilation performance of buildings is balcony. Balconies are one of the main architectural features in subtropical climates (Buys et al., 2008), being used as a private outdoor space, while potentially providing benefits to indoor air flows. There are some studies investigating the impact of the provision of balconies on indoor airflow in low-rise buildings. Prianto and Depcker (Prianto and Depecker, 2002) pointed out balconies have significant influence on indoor air movement and they will result in increase in internal air velocity. Chand et al. (Chand et al., 1998) conducted an experiment to investigate the effect of balcony provision on pressure distribution on the building façade. They found wind pressure distribution alters on the windward side but not significantly on the leeward side and provision of balcony would result in increase in wind pressure in most cases they studied. Additionally, Ai et al. (Ai et al., 2011b) used their experiment to research the impact of balconies on internal average velocity and mass flow rate. They concluded in single-sided ventilation, the addition of a balcony on the leeward side would lead to an increase in mass flow rate, while in cross ventilation no significant changes were observed for 0° and 45° wind incidences.

A good body of literature can be found around balconies and their effect on thermal comfort and energy performance in buildings (Prianto and Depecker, 2003; Chan and Chow, 2010; Ai et al., 2011a). However little work has been done on examining the influence on introducing balconies to high-rise dwellings on natural ventilation in subtropical climates.

This study uses CFD to evaluate the influence of balconies on ventilation performance and flow distribution of an entire unit in a high-rise residential building in a subtropical climate. This method has been used in many similar studies (Jiang et al., 2003; Gao and Lee, 2011b; Chu and Chiang, 2013; Fung and Lee, 2014). Grid sensitivity analysis was conducted to eliminate the errors associated with the grid size. A sample residential unit without a balcony is taken as the base case. The same unit layout, with an open and a semi-enclosed balcony were then explored and compared to the base case. This was to investigate the effect of different balcony types on internal airflow distribution and natural ventilation. Performance is analysed based on relative values of average air velocity, flow uniformity and the number of ACH.

2. Case Study

In order to conduct this study, a unit in a multi-storey dwelling design, which was constructed from a charrette (Kennedy and Thompson, 2011), was chosen as the case study. The main design intention for these case studies were to provide ample daylighting and natural ventilation by allocating proper length for daylighting (Garcia Hansen et al., 2012) and providing cross ventilation in order to facilitate natural ventilation. The chosen apartment building consists of 17 floors, each floor contains four residential
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units, and it is designed for a site located in Brisbane, Australia. Figure 1 shows the original floor plan and an elevation of the selected unit for this study.

Figure 1: The original case study floor plan from charrette design.

Detailed explanation of the charrette designs can be found in (Omrani et al., 2014). For the current study, the original floor plan was modified into a symmetrical plan layout in order to limit the variables. It contains two bedrooms, two bathrooms, a living area and two balconies at opposite sides that allow cross ventilation through the unit. The length of each balcony attached to the living room is three meters.

In order to assess the effect of balconies on natural ventilation, three case studies were used for this research: selected residential unit with open balconies, semi-enclosed balconies and without balconies. These three cases are explained below.

Case 1: the primary design without any balconies.

Case 2: the primary design with two balconies at two sides of living room. Eastern balcony wall is adjacent to the bedroom and the height of parapet wall at two other sides is one meter from floor.

Case 3: similar to Case 2, the only difference is height of balconies western walls which is from floor to ceiling (three meters).

3. Methodology

This study uses CFD to investigate flow behaviour in the three case studies. CFD is the most used method for evaluating air flow behaviour inside and outside the buildings due to the relatively low cost compared with experimental tests, its effectiveness as a design stage tool, and its accuracy (Chen, 2009). Hence, several studies have implemented CFD as a method for natural ventilation evaluation in buildings (Jiang et al., 2003; Gao and Lee, 2011b; Chu and Chiang, 2013; Fung and Lee, 2014).

In this study, the commercial CFD code FLUENT was employed for all simulations. Turbulence has been modelled with the two-equation RNG k-ε, which is one of the most common turbulence models for wind driven natural ventilation studies (Jiru and Bitsuamlak, 2010). The pressure-velocity coupling
scheme was selected and spatial discretization parameters were set to second order upwind. The simulations were conducted in steady-state mode and gravity was activated.

Some simplifications and idealisations were applied to the simulations such as neglecting the furniture, modelling the apartment building as a bulk except for the unit of interest, neglecting the effect of surrounding buildings and assuming the openings are fully open. The assumptions were kept the same for all the three case studies. As the aim of this paper is to compare different balcony types to each other rather than obtaining absolute values, retaining the same conditions for all case studies limits the effect of idealised assumptions on outcomes.

3.1. Computational domain

A three dimensional full-scale model of the whole apartment within its computational domain was constructed using AutoCAD software. The domain size was based on a previous study by Gao and Lee (Gao and Lee, 2011a) with overall dimensions of 5Length x 5Width x 5Height of the building.

3.2. Mesh and grid sensitivity analysis

An unstructured quad dominant mesh was generated for this study using the ICEM CFD (Posbic and Rever, 2000) meshing software. A grid sensitivity analysis was conducted in order to obtain a grid independent solution. Three cases of coarse, medium and fine mesh consisting of about 1.5, 2.5 and 3.5 million elements respectively were generated. Grid density was increased near crucial parts such as unit of interest volume, walls and openings, in order to more accurately capture the fluid dynamic behaviour. The generated meshes were applied to the base case (without balcony) and results were compared in terms of average velocity through the entire unit. The average velocity differed by 6.4% from coarse to medium meshes and only 1.6% from medium to fine meshes. Due to excessive computational time required for the fine mesh, medium mesh was adopted for the three case studies.

3.3. Boundary condition

An inlet boundary layer profile was considered for an upwind boundary condition using the power law equation:

\[
\frac{V_z}{V_{ref}} = \left( \frac{Z}{Z_{ref}} \right)^\alpha
\]

Where \(V_z\) is the mean velocity (m.s\(^{-1}\)) at height \(Z\) (m), \(V_{ref}\) is the velocity (m.s\(^{-1}\)) at reference height and \(\alpha\) is the power law exponent characteristic of terrain roughness. In this study \(V_{ref}\) is an average of Brisbane wind speed at 30°C temperature which was measured at reference height of 10m (\(Z_{ref}\)) extracted from Brisbane 30-minute weather data over 15 years collected by Australian bureau of meteorology. Furthermore, the \(\alpha\) exponent was set to 0.25 based on Aynsley et al. (Aynsley et al., 1977) who suggest this value for suburban areas. Additionally, the wind angle was set to 0° (perpendicular to the openings) in order to study the air flow through the building at optimum orientation.

The same boundary conditions were set for all three cases. The outlet boundary condition was set to pressure outlet, top and side boundaries were set to symmetry and the ground boundary condition was defined as a wall.
4. Results and Discussion

The results from the CFD simulations are presented in terms of average velocity, flow uniformity and number of Air Changes per Hour (ACH) in three different cases. The number of ACH (h⁻¹) is calculated as below:

\[ ACH = \frac{3600Q}{Vol} \]  

Where \( Q \) (m³.s⁻¹) is volumetric flow rate and \( Vol \) (m³) is the total volume of the space.

The results of each case study were demonstrated in three layers at different heights of 0.6 m, 1.2 m and 1.8 m from the unit floor. These heights were selected as they are within the breathable zone and can be referred to human body sleeping, sitting and standing position height respectively. For each scenario, the air flow distribution is shown on three vertical sections, two sections through bedrooms and one in the living area (refer to Figure 1). The bathroom doors were assumed to be closed, therefore no air movement is evident in those zones. Figure 4 illustrates the air velocity magnitude and air flow distribution at the selected heights. Dark blue refers to zero velocity magnitude and the red colour illustrates the highest velocity magnitude (6.0 m.s⁻¹). Black vectors represent the flow direction at each point of the space. Although Case 1 does not have any balconies, the areas allocated to the balconies in other cases are also presented in Case 1 plans in order to allow the comparison of flow behaviour within these areas in all three cases. The wind direction

The following observations can be interpreted from Figures 3 and 4:

- The most uniform air flow distribution is through Case 3 and the least air flow uniformity is through Case 2, regardless of the height. This can be explained by the redirecting effect the western balcony wall has in Case 3.
- By looking at the Figure 3 graphs, the lowest average velocity can be seen in Case 2 at all three studied heights. The average velocity in Case 3 is higher than the average velocity in Case 1 near the ground (0.6 m) then it decreases and falls slightly below that of in Case 1 at the height of 1.2 m and eventually they reach equal values at the height of 1.8 m (1.5 m.s⁻¹).
- The lowest average velocity among the investigated heights can be observed at the height of 1.8 m for all cases. As the openings end at heights of 2.1 m and 2.7 m for living area and bedrooms respectively, this would cause minimal air flow movement at higher heights and recirculation zones above the openings.
- Given the dark blue as 0 m.s⁻¹ velocity magnitude, the first bedroom in all cases has minimal air movement at the height of 0.6 m where it is most required. It can be related to the height of bedroom opening, which starts from 1.2 m above the unit floor. Furthermore, a high-speed air flow region can be observed through the second bedroom which is not desirable. It can be the result of total air flow entered from bedroom one window, passing through bedroom two, through a comparatively small opening. It may also be the influence of some portion of air from the living space passing through this area as well.
- In Case 2, there is a high speed air flow region on the windward side balcony at height of 1.8 m which cannot be seen in other cases. This could be because the balcony wall resists the air flow and directs the air through the gap between the ceiling and the balcony wall. Even though there is a similar gap in Case 3, the wall on the western side of the balcony prevents the high speed air flow on the balcony.
Not having any obstacles in the balcony area in Case 1 results in a high speed air flow which travels almost diagonally through the balcony area. This leads to an inconsistent air flow in the living area i.e. a stream of air will travel at a high speed near the living area wall.

Figure 2: The average velocity at three heights (0.6 m, 1.2 m and 1.8 m) for the three case studies.

Figure 5 represents the velocity magnitude and air flow pattern on three sections through each case. One section passes through the middle of the living area (Section A-A), one from the bedroom doors (Section B-B) and the other close to the bedrooms western wall (Section C-C) - refer to Figure 1. The following observations can be drawn from figure 5:

- The obstruction that the balcony parapet wall makes on the windward side results in less uniform air flow through the living area section and higher air velocity near the unit’s floor in the two cases with balconies (Case 2 and Case 3). It also explains the highest average velocity in the 0.6 m plan for Case 2 and Case 3 compare to the 1.2 m and 1.8 m plans.
- The highest average velocity in bedroom sections can be seen in Case 2. This is considered to be the result of high pressure in adjacent zones in living area.
- Despite the difference in average velocity in the sections through the bedrooms doors (B), no noticeable difference in average velocity in the other sections (C) from the bedrooms is evident among the case studies.

Considering Case 1 as the base case, investigation of ACH shows 24% and 3% less performance in Case 2 and Case 3 respectively. The idealised assumptions that were made in the simulations (i.e. fully open openings) resulted in high number of the ACH. Hence, ACH in the case studies was only discussed relatively to each other.
Figure 3: Velocity magnitude at heights of 0.6 m, 1.2 m and 1.8 m for the three case studies.
Figure 4: Velocity magnitude on sections through living area, bedroom doors and bedrooms close to western wall.

As can be seen in Table 1, Case 3 has the highest average velocity in the whole unit volume and the lowest average velocity is evident in Case 2.
Table 4: Average velocity in case studies volume.

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Velocity (m.s(^{-1}))</td>
<td>1.5</td>
<td>1.3</td>
</tr>
</tbody>
</table>

5. Conclusion

This study investigated the influence of the provision of balconies in high-rise residential buildings in subtropical climates using CFD as an analysis method. ACH, flow uniformity and average velocity were used as criteria to assess ventilation performance of three case studies.

Among the three examined case studies, Case 3 with the semi-enclosed balcony had the best performance in terms of flow uniformity and average velocity. Case 2, however, with an open balcony had the worst performance in all defined criteria. Although the amount of ACH in Case 1 is slightly higher than that of in Case 3, taking into account other criteria, it can be suggested that integrating the semi enclosed balconies into high-rise residential buildings would enhance the ventilation performance at 0° wind incidence. However, further studies need to be done considering various wind angles.

This study assessed the air flow at three different levels regarding human body height while sleeping, sitting and standing. The minimum air movement observed in the bedrooms at the height of 0.6m emphasises on the importance of designing openings sill height or other design considerations regarding the space function and the human body height for intended activities in each space.

These results contribute to the understanding of the effect of three different balcony types on natural ventilation in high-rise residential buildings given the limited body of literature in this area.

6. Limitations and Future work

In the presented analysis, some simplifications and assumptions were made to limit the influential variables, such as modelling the whole apartment building as a bulk without any openings except for the unit of interest, assuming the openings are fully open and not considering surrounding buildings. These simplifications may have led to idealizing the simulation results and higher air velocity and hence, higher ventilation rate. However, as the main purpose of this study is to compare the effect of three different balcony types, these idealizations may have limited effect on the outcomes as the relative values were considered rather than absolute values. This paper is a part of an ongoing study and simulation validation through full-scale measurements will be the next step. Investigation of various wind angles and different opening configurations will be also undertaken.

Acknowledgements

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Shah Nazari, H. (2014) Examining the potential for design and renewable energy to contribute to zero energy housing in Queensland.
Negotiating technology change: the challenge of designing lighting with LEDs for domestic settings

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Abstract: The focus of this paper is on the shift from the GLS (incandescent) technologies that dominated 20th century experience of light, to Light Emitting Diodes (LEDs). It argues that expectations, based upon the performance and behaviour of 20th century lighting technologies, have profoundly influenced the direction taken in developing LED technologies for lighting design applications. However, the light from LEDs, stubbornly refuses to conform to the norms of previous forms of lighting. As a light source the LED is completely different in feeling, form and technological delivery, and does not easily create the same lighting conditions as the 20th century light sources. The profound differences between GLS and LED lighting mean that the expectations of both designers and consumers are often inappropriate, and contribute to unsatisfactory applications of the technology. This paper reports on findings from experimental, practice-based research into approaches to lighting design using LED technologies. The research posed a series of questions around designing with LEDs: How can designers come to grips with the challenges and potential of LED technology? What changes in attitudes and expectations for lighting does this new technology require from designers and consumers? What radically different possibilities for lighting design might emerge once we move beyond the conditioning and practices established by 20th century light sources?

Keywords: Light; light emitting diodes; lighting design.

1. Introduction

How we interpret visual experience is strongly influenced by what we have already seen – a process some researchers liken to recognition – using the data base of previous images in the visual cortex (Julian, 2011). Similarly, the way we interpret spatial experience is shaped by previous experience. This conditioning of expectations by experience plays out in reactions to technology change. New technologies that play into our expectations, enabling better delivery of a valued perceptual experience, are rapidly incorporated into our environments and practices. Those that deliver less immediate benefits, and that challenge perceptual expectations, struggle to gain a foothold in our lives.
Light Emitting Diodes (LEDs) belong to the latter category, at least in respect of their penetration into domestic space. The contrasting rapidity with which they have transformed urban night-life, re-energising the role of artists in city-branding, and proliferating light festivals, speaks to the proximity of LED lighting effects to visual expectations of festival atmosphere and display; that is, a play of intense, spectacular and constantly changing colour against the contrasting blackness of the night. Expectations of light in domestic space are very different. While LEDs rapidly supplant fireworks and neon as a source of the spectacular in public night-life, the demand that they likewise supplant the General Lighting Service (GLS) technologies that have dominated lighting in the domestic sphere for the past century, has met with less success. The reason for this difference lies in the technology. LEDs generate intense light; GLS fittings generate abundant light. The significance of this difference for domestic lighting design is only beginning to be appreciated.

LEDs offer greater energy efficiency and longevity than other light sources and are being adopted across the lighting market (Shur and Zukauskas, 2005). The residential sector is a substantial part of the lighting market overall, currently estimated at 40% globally (McKinsey, 2012). For the full benefits of energy efficiency to be obtained, the residential market needs to engage with LED technology.

If we are to design successfully for LEDs in domestic space we must understand the relationship between LED lighting effects and our expectations of visual pleasure and task facilitation through lighting in the home. Equally, designers of domestic light fittings and lighting effects need to re-examine the assumptions that have shaped their approach to design. Culturally, our expectations of the relationship between light fitting and lighting effect have been shaped by GLS technologies. LEDs behave very differently.

This paper reports on findings from practice-led research into the design of domestic light fittings for LED light sources. Iterative experimental development and trial of LED-based light fittings, informed by user feedback on lived experience of the lit spaces, raised unanticipated questions concerning design approach. A starting assumption of the research, that ‘the problem of designing for LEDs’ would be (relatively easily) solved through the production of a fitting - a beautiful, light-distributing form, similar in conception to the iconic light fittings of the 20th century - proved overly-optimistic (see Figure 1). What was quickly revealed by the research was a need not only for technical understanding of the behaviour of LEDs, but for insight into our expectations of light, and into the strategies by which those expectations have been met in contexts beyond those lit by GLS technology.

The argument of the paper proceeds in three steps: first, a discussion of the way that GLS technology has shaped both consumer and designer expectations of domestic lighting over the past century; second, a discussion of the new paradigm presented by the intense light of LEDs; and third, an account of the practice-led research, and of the mixture of practical, technical and historical understandings that informed it. The paper concludes with a discussion of possible directions for the development of LED fittings in domestic settings.

2. General lighting service

2.1. The GLS: an all-purpose light source

The light from GLS is created by burning a tungsten filament in a vacuum. This incandescence emits a spectrum of light similar to that of the sun and other burning sources such as fire. Humans have evolved with this spectrum, and it is comfortable for our eyes. The GLS spectral distribution is smooth and the
colour rendering quality is excellent (Tregenza and Loe, 1998). By contrast the spectrum from artificial light generated by LEDs is uneven, which impacts colour rendering (Shur and Zukauskas, 2005).

The colour temperature of the GLS lamp hovers in the warmer tones of 2800K, creating what has been called “incandescent coziness” (Kellog, 2009). These warmer tones are similar to the colour of late afternoon light, and are registered by our senses as appropriate to end-of-day activities (Czeisler, 2013). Research into light quality has revealed that we find warm light especially attractive at night; particularly in places intended for relaxation and social activity so GLS technology fits well into expectations within the domestic sphere (Hopkinson and Collins, 1970). In terms of the behaviour of the light, the most influential characteristic of the GLS lamp is its ability to emit light evenly in all directions – only interrupted by the socket.

In summary, the GLS lamp produces light that is comfortable and attractive to our eyes, renders colour well, and disperses light evenly. Joined to these qualities, and definitive in its impact, is the abundance of light produced by this source. In contrast to the scarce light of pre-industrial times, the light produced by the GLS lamp is plentiful, high intensity, and flows generously out in all directions. Supported by the industrial technologies of centralised power generation and distributive grid, that supply abundant electricity to outlets in every residence on demand, GLS lighting transformed 20th century domestic life. It can be seen as one of the constitutive technologies of embodied experience within cultural modernity.

2.2. Expectations of lit domestic space in the GLS era

Historically, GLS technologies completed a transition that had commenced with the introduction of gas, from portable light sources such as candles and lamps to lighting that belonged to the infrastructure of each space. Rather than transport light from one space to another, we became accustomed to move unencumbered through lit spaces, from task to task and from room to room. GLS light fittings in domestic environments are capable of flooding a room with light, rather than lighting just the task or immediate personal space.

An important dimension to this transition was the reorganisation of fuel provision. Pre-industrial lighting involved the burning of fuel as an immediate source of light. Provision of fuel for lighting had been a part of everyday domestic economy; even the wealthy practiced frugality in consumption of this valued resource (O’Dea, 1951). Lavish lighting of interiors was reserved for occasions of significant display, such as public assemblies or private parties (Crowe Leviner, 2000). The centralised production and distribution of gas and electricity, with embedded infrastructure to enable ready access, transformed this domestic economy. Establishment of a remote and apparently unlimited source of energy removed constraint on local production of light, and rendered redundant the habits of frugal consumption.

A third dimension of this transformation of spatial experience was the development of an aesthetic that excluded deep shadow. While GLS technologies made the banishment of shadows possible, it was the hygiene movement that made such banishment culturally desirable (Ryczynski, 1986). The GLS incandescent lamp, in contrast to previous light technologies, provided light that was instantaneous and clean, with no unwanted by-products such as stained walls, smells or messy wax. A new desire to flood interior spaces with abundant light was extended, through GLS technologies, beyond the hours of daylight and into the evening. For the moderns, architectural beauty was reconceived as ‘the magnificent play of masses brought together in light’ (LeCorbusier, 1946, p. 186). The white walls of
modernist interiors relied upon both ample daylight, and abundant light at night, for their aesthetic impact.

An important participant in this new spatial aesthetic was the unrestricted and mobile modern body, moving freely from one space to the next. Differences in atmosphere between one space and another, between occupied space and unoccupied space, between interior and exterior, were banished wherever possible. Light that flowed evenly throughout a dwelling, and that eliminated boundaries and distinctions, played a central role in shaping the embodied experience of modern life. The sculptural forms of GLS luminaires, suspended in architectural space from ceiling fixtures, reproduced in miniature the new aesthetic preference for detached, free-floating and unencumbered objects, bathed in light.

The shift to bright, even lighting in the home paralleled the ideas being developed by illumination engineers for working situations (Cuttle, 2012). Homes were no longer the cosy retreats of the 19th century. Rather, they were to be the dwelling place of reason, fitness and efficiency. The house was to be ‘a machine for living in’ (LeCorbusier, 1946, p.95) Reform movements, such as the domestic science movement influenced by the writings of Frederick Taylor, focussed on efficiency and hygiene (Taylor, 1913). Domestic spaces of production and cleanliness, such as the kitchen and bathroom, reflected the uniformly illuminated aesthetic of the efficient modern workplace.

As the 20th century progressed, designers came to understand, and exploit, the freedom created by electric light. The technology that underpins GLS lamps is simple, easily available and relatively inexpensive. As light is abundantly produced, there is no need for craft in optimising scarce light. The light quality itself is pleasing, so there is less need to mediate glare. Further, GLS lamps (like fluorescents) perform well at higher temperatures, so heat management is relatively simple. Heat generated by the light is easily dispersed by air, and is not a concern as long as there is sufficient distance between the lamp and any combustible or heat absorbing material.

These properties of the GLS lamp allow, if not demand, a three-dimensional response, where the shape and form of the lamp is integrated into design of the fitting. GLS luminaires are often three-dimensional, glowing objects in space (Figure 1). Lighting typologies that have evolved since the introduction of GLS illumination are now so familiar as to be taken for granted; hanging pendants (often centrally in a room), standing lamps with conical or drum shades, wall brackets, table lamps, ceiling “oyster” lamps.

Figure 1: Iconic luminaires for GLS lamps by 20th C. designers: 1a) Poul Henningsen, 1b) Isamu Noguchi, 1c) Issey Miyake.
If GLS technology was a crucial contributor to development of a spatial aesthetic of openness and light in European modernism of the 1920s and 30s, it played an equally central role in the colourful pop and consumer cultures of the 1960s and 70s.

The post-World War II availability of plastics made possible a wider range of sculptural shapes and brilliant colours for use in conjunction with GLS lamps. Like plastic, the flexible nature of GLS illumination lends itself to playful experimentation. Designers of luminaires rapidly moved beyond a concern with utility and comfort: a light fitting now could be almost anything; a sculpture, an artwork, a symbol of style, fashion or status. Increasingly designers saw their role as being to ‘dress’ the light source, rather than to focus on optical principles or performance (Artemide, 2014). Designers with no particular knowledge of lighting or light sources were able to create popular and attractive light fittings.

A whole sector of the lighting design industry has developed to showcase such work, with new ranges of enticing light fittings being launched every year at events such as Euroluce in Milan or Light and Build in Frankfurt. Success for lighting designers, both professional and commercial, is grasped through these events. It is unsurprising that designers, as they begin to work with LEDs, should aim to display their work in such settings. However the expectation that LED should lend itself to the lighting typologies of GLS, or that they are amenable to display at lighting showcase events, overlooks the profound differences between these two lighting technologies.

Designers have been struggling to work with LED because the landscapes of interior light enabled by GLS have set in place taken-for-granted expectations of the forms and effects at which lighting design should aim. That designers have been able to work easily with light, without specialised technical knowledge, was a bonus of GLS. Working with LED presents wholly unanticipated challenges.

### 3. New lighting technologies

#### 3.1. What is an LED?

An LED is a light producing semi-conductor device that is comprised of a layer of electron-rich material (p) separated from a layer of electron deficient material (n). When voltage is applied, electrons flow from the (p) area to the (n) area. Each electron flow emits a photon of light. Importantly, another effect of the electron flow is the production of heat at the junction of the (p) and (n) layers (Shur & Zukauskas, 2005).

In the early days of the technology (1970s) only green and red light could be created and LEDs were most commonly used as indicator lights and for signage. It was not possible at that stage to produce blue or white light.

The breakthrough came in 1996 with the announcement from an engineer, Shuji Nakamura, that a bright blue LED had been created using InGaN (Indium Gallium Nitrate) in the substrate (Johnstone, 2007). When the InGaN chip is mounted into a package and a phosphor (similar to that used in fluorescent technology) is added, white light is created. The package includes a lens, known as the primary optic, which directs and shapes the light for its intended application. The package provides protection for the LED chip and also acts as a conductive path to extract heat from the junction via a thermal pad (Hansen, 2011).

Nakamura’s invention was important, not only because it enables production of blue and white light, but also because the light source itself is relatively bright. LEDs could now be explored as a source of architectural lighting.
3.2. Intense light – a new paradigm

“[The] appreciation of specific material qualities of light, the ecstasies of the bulb’s colour reproduction and temperature, the patina and multi-sensuality of orchestrating lightscapes through the shadows … is at the heart of understanding the contestation against adopting a new technology” (Bille, 2012).

Light from different light sources has a particular feel and behaviour. The carefully husbanded, scarce light of pre-industrial times was only able to illuminate specific areas. Outside the circle of comforting candle or lamp light, darkness reigned. The light sources introduced during the industrial revolution (advanced oil lamps, gas lighting and electric lighting) produced light that was progressively more abundant in volume and quality. The light flowed out to illuminate larger areas and even whole rooms from a single source.

The light from LEDs is different: it is neither scarce nor abundant, and yet has characteristics of both. As for pre-industrial light sources, LEDs can only illuminate specific areas. The amount of light flowing from an LED is high, but is narrowly directional and piercingly intense. LED light is crisp and glarey, with a sharp divide between intense pinpoints of light and unrelieved shadow. As the LED has no distribution of light across a filament or tube at the source, as do incandescent and fluorescent lamps, discomfort is experienced when the intense pinpoint of an LED light source is directly viewed (Lay, 1974). By contrast, GLS lamps distribute light evenly from the source along the tungsten filament, so discomfort glare is less pronounced. The even distribution of light from GLS lamps means that transitions between illuminated areas and darker areas are relatively gradual, with soft edges.

When LEDs were introduced into the architectural market, the light compared poorly to incandescent light in terms of colour temperature and colour rendering. Since that time there have been improvements in these areas, as predicted by researchers (Azevedo et al., 2009). However, despite improvements to the colour of LED light, the experience of light from an LED light source remains uncomfortable.

To put the issue briefly, designing for LED light sources is comprehensively different to working with GLS lamps. LEDs are technically more complex, and demand that the designer understand issues like thermal management, driver technology, and lens technology. Conditions of general illumination, easily generated by the omni-directional and generous spread of incandescent light, cannot be easily created with LEDs. The narrow stream of light is generated from an intense, pinpoint source that has no fixed form. Designers need to work out how to organise the LEDs, how many to use, and in what arrangement. There is no sensuously shaped GLS lamp to build a light fitting around. The whole paradigm of an illuminated glowing object in space is challenged by LED technology.

The narrow distribution of light from LEDs means these light sources need different placement within interiors, and different strategies to give volume to the light. Designers need to develop expertise in the use of optical principles to refract, reflect and diffuse intense light. Historical research into the mediation of earlier light sources through application of these general optical principles provides some guidance, but few easy answers. The requirement for mediation is completely different. What LEDs require is not the magnification of light, as in conditions of scarce light; or gentle moderation, as for abundant light. Further, the intensity of light produced by the LED means that material choices for use in mediating this light source are more limited than when working with earlier lighting technologies. For example, conventional diffusing materials such as frosted glass or acrylic do not work well with LEDs (Lau, 2013).
LEDs are a relatively new light source and we have, as yet, no innate understanding of how they behave. We have no history or tradition of light fittings for this source from which we can learn; there are no iconic shapes or traditional forms for LED technology. The typologies of light fitting that we are familiar with, and instinctively draw upon, were developed for abundant light and have limited application for LEDs.

3.3. The response of the lighting industry

Historically, each new light source has created new conditions for lighting. The early users of a new light source have instinctively tried to adapt it to match their pre-existing expectations of lighting effect and behaviour. This was true even of the transition from scarce to abundant light (Bluhm and Lippincott, 2000). Currently, our cultural expectations of lighting in domestic interiors, as well as our skills in, and knowledge of, the design of appropriate light fittings, are being challenged by LEDs.

The considerable energy directed by the lighting industry into the adaptation of LED technology to domestic settings, has been frustrated by the difficulty of making LEDs conform to expectations shaped by GLS lighting. For the mass domestic lighting market there has been an emphasis on retaining existing light fittings, and retrofitting them with LED lamps. This strategy locates LEDs in typologies of light fitting that are not only unsuitable for the light produced by LEDs but, due to the different requirements for heat management, do not allow the LEDs to perform well (Willmorth, 2014).

The focus on retrofit has led the industry to develop versions of the LED that mimic, as closely as possible, both the visual form and the maintenance requirements of the GLS lamp. Two examples are the E27 retrofit and COB (Chip On Board) lamps, which have a degree of omni-directionality and also fit into the sockets of existing light fittings. However, this approach produces significant technical and performance issues; poor thermal management and poor optical distribution, to name just two.

It is concerning that a great deal of effort is being put into addressing the technical and aesthetic problems attendant upon the retrofit approach, despite its unsuitability to LED technology. Drivers for this approach include the desire to protect existing investment, not only of consumers, whose dwellings were fitted upon construction with electrical outlets appropriate to the installation of pendant, standard and table lamps, and whose stylistic preferences have been exercised in their choice of luminaires; but also of producers, who have made significant investments in resource networks and in tooling for the manufacture of existing lighting typologies. However retrofit is a short-term approach and works to the detriment of the long-term (Hansen, 2011; Willmorth, 2014a). Recognising this, some writers have
drawn parallels with the demise of Kodak, following its refusal to engage with digital camera technologies until too late (Chopra, 2010).

3.4. The way forward

Lighting expert and editor Kevin Willmorth (2014b, p.80) describes the pre-LED world of lighting design as “a mix of pure instinct, artistic flare and just a dash of verification” and candidly admits to enjoying the freedom of designing “like kids playing in the park.” However, as Willmorth reminds us, the lighting sector now makes far greater technical demands. The freedoms enjoyed by designers of previous light sources have not really prepared them, or the industry, for working with the new light source.

4. Discussion

4.1. The practice

“Light is the experience of inhabiting the world of the visible, and its qualities – of brilliance and shade, tint and colour and saturation – are a variation upon this experience” (Ingold, 2000)

Light is an experiential phenomenon. Whilst it is possible to describe it in quantitative terms (lumen, colour temperature, etc), qualitative issues are to the fore in our difficulty in adapting to LED. An experimental, practice-led approach allowed direct engagement with qualitative and experiential outcomes of different approaches to luminaire design for LED.

There are a number of functions that luminaires or light fittings need to fulfill. These include provision of protection for the actual light source, enclosing cabling for safety and supporting any associated control gear (Tregenza and Loe, 1998). Light fittings also provide a visual link between the light source and the surrounding architecture. Finally, light fittings need to provide optical control so that the light is distributed according to the required function. Due to the challenges inherent in the light created by LEDs, light fittings using this light source need to provide a degree of mediation of the light - possibly to a larger extent than they necessary for incandescent light sources which already have an acceptable quality of light.

There are a number of methods of providing optical control of light commonly used in light fittings or in architectural lighting approaches (Tregenza and Loe, 1998; Rea, 2000). The principle of obstruction uses masking to control light. In terms of light fittings this can be seen in the use of louvres to protect the viewer from glare. Obstruction is also used in architecture where coves can be used to mask a light source or in the beautiful perforated screens used in Islamic architecture to mediate bright exterior light.

Reflection occurs when light falls on a surface and is then redirected back - the angle, amount and spread of the reflected light depends on the shape and material of the surface (Rea, 2000). The principle of reflection can be seen in downlights where omni-directional light sources are given a downward direction by the use of reflective material. Reflection can be seen in architectural applications – particularly in colder climates where scarce sunlight is reflected into interiors by the use of light shelves (Norberg-Schulz, 1996).

Refraction describes the behavior of light when it changes direction at the junction of two transparent materials of different optical densities such as air and glass (Rea, 2000). If the surfaces where the light emerges are cut at a variety of angles, the light is then “scattered”. The most spectacular
examples are the 18th century lead crystal chandeliers where the scattering effect gave volume to the scarce light of candles. In current times, refractive plastic surfaces with diamond shaped patterns are used to mediate the light from a variety of light sources.

Diffusion occurs when the light passes through a material and is spread in many directions by small particles within the material itself. Light fittings with diffusing material such as paper, textile, frosted glass and translucent plastic use the principle of diffusion to mediate light.

[Author’s name redacted], who conducted practice-led research into designing for LEDs as the focus of her doctoral project, experimented with a number of different strategies for mediating the light from LEDs, using these principles. In this paper we focus upon a series of experiments that took adjustable louvres, such as venetian blinds, as a starting point for thinking about the moderation of intense light within domestic settings. The mediation and regulation of intense sunlight through adjustable louvres, either by shutters or blinds, has been familiar from ancient times. In this situation of venetian blinds the optical principles employed in this mediation are obstruction, where the direct sunlight is blocked, and reflection where a small amount of light is reflected into the interior.

[Author’s name redacted] had also observed historical examples where reflective surfaces were attached to walls to enhance the light of candles and oil lamps. With the understanding that the narrowly focused light of LEDs needed to given volume, this practice planned to use the whole wall as a reflective surface.

This practice also considered how the light fitting may enhance the lighting in a particular space – in this situation it was a corridor. Research has found that impression of spaciousness can also be reinforced by the use of peripheral lighting such as illuminated walls and is particularly useful in corridors, lobbies and circulation areas (Flynn, 1988). It has also been found that, in lighting human subjects, light from the side is preferred to that from directly above (Marsden, 1972).

This practice took advantage of the very compact size of LEDs to create a discrete fitting that would sit neatly against the wall, thus complementing the architectural form of the interior. The effect aimed at was very different to that of the even, general illumination created by a centrally situated GLS light source.

In early experimentation the simple curved profile of a venetian blind louvre was adopted. A large single blade was back-lit by LEDs, reflecting light to the adjacent wall surface. Rotation of the light source and of the louvre was to achieve a spread of light.

![Image](image_url)

Figure 3: The light-louvre concept: curved blade mock-up (left and top right); gull wing mock-up (bottom right) (Source: the author).
It was realised early in the development of the curve-profile, rotating louvre of perforated metal, which was the first experimental form tested, that this form would expose the viewer to glare from LEDs without offering advantages in terms of light spread. Additionally it was recognised that a rotating mechanism would be difficult to develop within the resources of the project. The light spread from a fixed curved shape was quite limited, as illustrated by the mock-up (Figure 3, top right).

A second experiment focused on generating as great a spread of light as possible. To this end a ‘gull-wing’ shape was mocked-up using cardboard and wire, for testing. Following the success of tests, a set of 3 more formally realised versions of the gull-wing approach were created using a range of acrylics; 2a) a solid acrylic with a reflective under-surface, 2b) clear acrylic, painted white on the upper surface, and 2c) an opalescent acrylic, as used in light boxes and retail situations. Material experimentation was limited to different types of acrylic, at this stage, for cost reasons. That quality of materials is an issue, quickly became apparent. The opalescent acrylic of Model 2c looked cheap, as did the solid acrylic of 2a. The clear acrylic painted white on the upper side of model 2b, had a more neutral appearance and created a better spread of light. Painted acrylic was therefore taken forward into further translucent models. Model 2a, which blocked all light, was developed into a solid metal version made from brushed stainless steel, to give this fitting a higher quality finish. The use of translucent acrylics introduced the principle of diffusion into the practice.

In the third stage of experimentation, the focus was on development of a flat and continuous light source. Ribbon-style Nichia LEDs were mounted on an aluminium strip for thermal management, and attached to a board that simulated a flat wall surface. An escutcheon around the module prevented accidental exposure of naked LEDs, to the eye. The small size of the LEDs was important to the success of the light-louvre fitting. Using a different linear light source, such as a small fluorescent, would have necessitated mounting the louvre at a greater distance from the wall, destroying the elegant aesthetic that was sought.

In developing the light-louvers, initial spacing of the LEDs was too great, creating ‘spots of light’. When diffusion was attempted the individual light sources remained distinct, which detracted from the effect. A tailored light source comprising a continuous strip of LEDs, was integrated into the diffusion model more successfully. It became evident that to achieve better light spread, and to use the gull-wing shape effectively, sophisticated lenses would need to be developed and the light flow calculated using photometric software.

Figure 4: From left: Model 2a, Model 2b, Model 2c (Source: the author).
4.2. What was learned from this practice?

As Fredrik Nystrom from Danish lighting manufacturer Louis Poulsen, has commented, when designing with LEDs you need to ‘design the light source’ (personal communication, 2009). LEDs are essentially a formless light source, and the designer must group or manipulate them to achieve the desired effect. But it is not just a matter of grouping the LEDs; better understanding of optics is required. The requirement for technical expertise constrains easy entry to the field of designers without specific training in lighting design.

The light-louvre project also highlighted the sensitivity necessary in material choice when working with LEDs. Slight changes in material can significantly influence the lighting effect. The material of the fitting needs to add quality to the ‘feel’ of the light when designing for LEDs. This is in contrast to designing for GLS sources where a wide range of materials could be used very effectively.

In this series of experiments, different types of plastic were tried for the diffusion model, before deciding upon back-painted clear acrylic. Similarly, different finishes were tried for the metal louvres. The early examples used a softer metal finish on the underside. The final version (Figure 6 right) had a highly polished finish that created a more spectacular light spread, but may be too hard-edged for some applications. More resources would be needed to find just the right finish and material – the correct balance of diffuse and specular finish.

![Image of light-louvre models](source: the author)

Figure 5: Reflection+Diffusion louvre (left). Reflection+Obstruction louvre (right) (Source: the author).

Author took a ‘back to front’ approach to the design of the light-louvre, with lighting effect being the prime consideration in giving shape to the luminaire. This approach is also suggested by Italian designer Michele de Lucchi who has recommended that designers working with this technology should create a system of light, which then creates the shape of the light fitting (Artemide, 2014). This contrasts with the approach to design of many light fittings of the 20th century, where the priority was on explorations of form, material or cultural ideas.

Author made no attempt to create conditions of general illumination through the light-louvres. Artefacts such as these would need to exist within a system of other LED lights; cove lighting, portable work lights, wall lights, suspended lights and other, yet-to-be-developed typologies of light fitting, each catering to a specific lighting need within the space.
4.3. The role of evaluation

Experimental practice using LEDs within exhibition or festival contexts, provides limited opportunity for feedback and evaluation. The very different temporality of experience of light in domestic spaces, makes possible a more formal approach to incorporation of user feedback in the design process. It was considered particularly important to get feedback on the ‘liveability’ of the quality of light produced by the light-louvre, and their suitability for domestic use.

There is little precedent for in-situ evaluation of domestic light fittings. Most formal qualitative evaluation of lighting has been undertaken under laboratory conditions or within work-based situations (Veitch, 2006). For evaluation of the light-louvre, a new method was developed to obtain feedback from lay (non-professional) research participants.

Canter (1974) observed that much light exists below the level of consciousness. In recognition of this it was decided to sensitise the research participants to specific dimensions of light quality, and so to enhance their awareness of particular light effects. A first step in this process was to obtain subjective responses to various forms of lighting through a method known as semantic differential scaling, developed by John Flynn and based on the work of Osgood et al (Flynn et al., 1973). The second part of the process employed a technique called ‘domestication.’ This involves leaving experimental prototypes in a household for a period of time to allow inhabitants of those spaces an opportunity to develop a feel for, and relation to, the artefacts. Participants are interviewed about their response to, and opinion of, the experimental prototype at the end of the process (Routarinne and Redström, 2007). The adaptation of these two processes to evaluation of the light-louvre has been covered in more detail in [author’s publication redacted to maintain anonymity].

4.4. Feedback

Two light-louvre prototypes were tested; one developed from the back-painted clear acrylic gull-wing model (2b) that combined reflection and diffusion to moderate the LEDs, and the other a metal version of the solid acrylic gull-wing (2a), that combined reflection and partial obstruction to moderate light.

In feedback, light from the ‘reflection + diffusion’ model was seen to have some warmth and create a relaxed, calm ambience in the area in which was placed. Expressions such as lightweight, soft, and halo-effect were used. A shift worker commented that this light-louvre created a pleasing connection between darkness of early morning and daylight. Others commented that it provided a connection between different light levels (verandah and living room, for example). There was generally positive feedback on the way the light functioned within the space, the atmosphere created, and the way the light radiated out from the light-louvre, washing across the wall. One participant even commented that light coming from the side was “more romantic – something to do with sunsets.” Another described the reflection + diffusion model as “a good hall light.” Others also suggested placement of this model in hallways and vestibules. A very long version of the reflection + diffusion model that could connect different floors in a stairwell was suggested, to take advantage of the modularity of LEDs. Horizontal placement (above bookshelves, for example) and ceiling-based placements were also suggested.

On the other hand, as one research participant noted, you either loved or hated the reflection + obstruction model. Whilst there were some positive words (festive, fancy, dramatic, complex, interesting) to describe the light, it was perceived to be less comfortable and less functional than the reflection + diffusion model. Some thought it more of an artwork than a light fitting. The long strip of light created by this fitting was controversial. Interestingly, many research participants expressed
appreciation of this unusual effect, which provoked comment from visitors and household inhabitants. However the reflection + obstruction fitting was considered suitable only to “a particular approach to interior design” whilst the reflection + diffusion model was thought to be more generally acceptable.

5. Conclusions

The aim of the practice-led research was to better understand LEDs as a light source, and to use these understandings to develop new design approaches to domestic lighting using LEDs.

Tacit acceptance of general illumination as a goal, when lighting interiors, is thrown into question by the behaviour of LEDs, which are resistant to this approach. Recognition of the extent to which aesthetics of early 20th century architecture has shaped attitudes to the illumination of interiors, led to research into pre-industrial lighting and lighting in non-western cultures. Tanizaki’s ode to scarce light in traditional Japanese dwellings, and Bille’s discussion of the hygge in Denmark, helped establish the potential desirability of lighting cultures other than those established by GLS, and opened the practice to non-uniform approaches to lighting interiors (Tanizaki, 1933; Bille and Sorenson, 2007).

Findings from the experimentation with light-louvres, together with other lighting artefacts generated as part of the doctoral research project, point to a future where lighting may become more particular to each interior. The all-purpose, omni-directional light source creating conditions of general illumination may be superseded by a variety of new lighting artefacts, each achieving a different effect and performing a different function.

Are people ready to live with scattered light sources with differing intensities of light, when they are used to the uniform light of GLS? Whilst there is research to support a preference for non-uniform light sources (Marsden, 1972) the cultural conditioning of the last one hundred years may make it a difficult transition.

References

Simulating the thermal and daylight performances of a folded porous double façade for an office building in Cairo

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Abstract: The application of Double Skin Facades (DSFs) in hot climates is limited and their potential benefits are still under investigation. Moreover, daylight and thermal performances of the double façade are rarely studied together. In this paper a set of parameters are optimized for the design of a folded porous double façade for an existing office building in Cairo, with an aim of reducing cooling loads while maintaining daylight needs. The design and optimization processes take place using parametric design software, specifically Grasshopper Plugin for Rhino 3D modeller. These software tools were chosen due to the possibility of using evolutionary algorithms for multi-objective optimization, and environmental simulation plugins that provide real-time feedback during the early design phase. The existing building acts as a reference case to which the proposed façade is compared to evaluate its performance in South-East and North-West orientations. It is also compared to a conventional double façade. The paper discusses the effect of the design parameters on the thermal and daylight performances of the façade highlighting their preferred numerical range. Limitations of the software used are addressed, requiring verification of results using CFD simulations in future work.

Keywords: Double facades; hot climates; optimization; environmental performance.

1. Introduction

Façade design plays an important role in the thermal comfort of interior spaces of buildings. Double skin facades (DSFs) in particular are becoming increasingly popular in cold, temperate climates for aesthetic reasons and also for energy efficiency among other advantages (Poirazis, 2006). Most of design guidelines and recommendations of double facades are for temperate climates and aim at the enhancement of buoyancy-driven airflow (Barbosa and Ip, 2014), thus having a big temperature difference between the cavity and external temperature isn’t a major problem. A higher cavity temperature enhances the buoyancy effect and natural ventilation. However, having such an increase in cavity temperature will not be favourable in hot areas where specific attention is made to the reduction of cooling loads as much as possible. This is one of the major differences between designing DSFs for hot and cold climates.
Moreover, the daylight performance of DSFs has been rarely addressed alongside its thermal performance in other researches. This is particularly important in hot climatic areas where shading devices or highly reflective glazing (which clearly affect daylight performance) are needed in order to reduce heat gain in the cavity.

2. Aim and methodology

The paper aims at reducing heat gain in the double façade cavity by designing a folded surface that provides self-shading thus reducing direct solar radiation. The folded surface also has perforations distributed throughout the façade area for natural ventilation of the cavity thus increasing heat loss by convection. This is done while taking into consideration its daylighting performance as well.

A recent paper by the authors (El Ahmar and Fioravanti, 2015) addressed the design process behind this proposal and compared its thermal and daylight performances to a room in an existing office building in Cairo (reference case) in the South-East orientation only. Results showed a potential reduction of cooling loads by around 14%, however the daylight performance needed improvement. This paper continues the investigation where modifications are made for improved daylight. To evaluate the thermal and daylight performances of the proposal, they are compared to those of the existing building façade and to a flat DSF to see whether or not they have improved. These comparisons were done in both South-East (SE) and North-West (NW) orientations. The flat double façade is designed based on recommendations concluded from reviewing DSFs in hot climates as will be explained.

This paper represents an exploratory research in which a set of design parameters are optimized using evolutionary multi-objective optimization to achieve a balance between the conflicting thermal and daylight requirements. The optimization process is performed then a solution is chosen for each orientation to compare it with the reference case and flat DSF. The influence of design parameters on both daylight and thermal performances is discussed, and based on them the preferred range of each design parameter is given. The tools used are Grasshopper Plug-in for Rhino 3D modeler v.5 SR8, Octopus plug-in for evolutionary optimization, Archsim plug-in for thermal simulations which runs on EnergyPlus v.8.2 and DIVA v.3 plug-in for daylight simulations which runs on Radiance and Daysim.

3. Literature review

Since most of the research about double façades was in temperate climatic areas as mentioned earlier (Barbosa & Ip 2014; Poirazis 2006), an exploration of examples in hot climates was necessary.

Hamza et al. (2007) compared thermal and daylight performances of a continuous-type DSF (in which there were no obstructions in the cavity) with a corridor-type in which there were perforated walkways (50% open) every two floors. They both had air openings at the top and bottom of the cavity but no shading devices were used. Only the corridor-type had air openings in the outer façade layer at each floor level. Simulations were done on a summer day in the climate of Cairo. They compared thermal and daylight performances of the two cases in East and West orientations. Their results showed that direct solar radiation is the main heat gain source compared to surface radiation and convection heat fluxes in both orientations. The corridor type cavity temperature was 1.5°C lower than the continuous one. This shows the importance of multiple openings for ventilation throughout the height of the façade and not just at the top and bottom.
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Figure 1: The corridor (left) and continuous (right) double facades compared by Hamza, et al., (2007).

However the corridor type resulted in a darker indoor environment indicating the need of more use of artificial light. In both orientations; they resulted in glare problems near the windows which will require the use of blinds. It represented an interesting example as it showed that despite the potential energy savings due to improved thermal performance, they were associated with increased energy use for artificial lighting. Hamza (2008) conducted another study in Cairo, comparing a single façade that had single-pane clear glazing, and a DSF that had vents at the top and bottom. Cooling loads were compared for the four orientations using different glazing properties for the outer façade layer. Reflective glazing provided the most reduction in cooling loads (32% in all orientations) compared to double clear and double tinted glazing which produced a 7% increase and 11% decrease respectively.

Another study took place in the extreme hot climate of the United Arab Emirates. Radhi et al. (2013) modelled an existing building with a double façade, and compared it with a single façade. The double façade had air openings at each floor level, and at the top and bottom of the cavity. They performed these comparisons in four orientations. They also compared different glazing properties and cavity depths to see their influences on cavity temperature, airflow and cooling loads. The double façade resulted in lower cooling loads in all orientations except in the North where a 3% increase was estimated. Cavity temperatures were generally not much different than the air temperature outside due to the presence of openings along the cavity height. They recommended cavity depths between 0.7m and 1.2m and that the solar heat gain coefficient (SHGC) and U-value of the outer glazing layer are very important. They estimated a 17% reduction in cooling loads due to the presence of the double façade.

Hashemi et al. (2010) also modelled an existing double façade in Tehran and compared the cavity temperatures and cooling loads to that of a single façade in four orientations. The double façade had Aluminum vents which were 1.5m high distributed throughout the façade height. Their results showed that cooling loads in daytime were reduced, however during the night they increased due to the lack of night ventilation in the office rooms. Despite the lack of shading devices, and the use of single glazing in both the outer and inner facades layers, natural ventilation alone was able to improve the overall performance in the climate of Tehran. After reviewing the mentioned examples among others
(Baldinelli, 2009; Papadaki et al. 2014; Barbosa and Ip 2014), the following considerations are seen as the most important for the architectural design of DSFs in hot climates:

- Multiple air openings along the height of the outer facade layer to prevent over heating
- The glazing properties of the DSF (balance between low U-Value and low Solar Heat Gain Coefficient) especially if no shading is used.
- Since solar radiation is the main heat gain source, it is highly recommended to use shading devices.
- Shading elements are preferably placed externally and not in the cavity
- Recommended cavity depth range: 0.7 m to 1.2 m.
- Cavity should be higher than ground level and higher than roof level.

It is important to note that studying the daylight performance along with different façade configurations was only addressed by Hamza et al. (2007). It was the only example found (to the authors’ knowledge) that studied both daylighting and thermal performances of double facades in a hot climatic area.

4. Reference case & flat DSF

![Reference case: B19 office building in the Smart Village, Cairo. Architect: Engineering Consultants Group (ECG).](image)

The Smart Village in Cairo is a contemporary business district that represents state of the art in office building design in Egypt. One of these buildings was chosen for this study (Figure 2), which has a blue-tinted curtain wall façade having the same material specifications as all other buildings in the Village; non-operable double-pane tinted glazing (with a light transmittance of 0.37 and solar transmittance of 0.43) and aluminum cladding. Building drawings, façade material specifications, and readings of monthly cooling energy consumption (for the year 2014) were obtained. Only one office room is addressed in this paper, representing a typical mid-floor space with the dimensions of 5 m in width, 8 m deep, and 4.1 m high. It is studied in SE and NW orientations as in the existing building. Digital simulations of annual cooling loads in SE and NW orientations predicted a consumption of 121 KWh/m$^2$ and 112 KWh/m$^2$ respectively, which was in close accordance with actual readings of the building which indicated that average annual consumption is 113 KWh/m$^2$. 
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Figure 3: Cross-sections illustrating the geometric and glazing properties of each façade: A) Existing reference case, B) Flat double façade with air openings at each floor level and at top, C) Folded façade showing the parameters used in the optimization process (the 3rd fold depth omitted for simplification).

A flat double façade is proposed that is very similar to that proposed by Hamza et al. (2007) as it was also designed in Cairo. Figure 3(B) describes its geometrical configuration and the glazing materials used. It is a fully glazed double façade, 9 m wide, 13.3 m high with a 0.8 m wide cavity including perforated (80%) walkways and air openings at each floor level. Air openings are present also at the top.

5. Proposed folded porous DSF

Many possible folding patterns can achieve the desired effect of self-shading. For this design proposal the triangular Pinwheel pattern has been chosen (Figure 4). It is seen as aesthetically pleasing and also folded surfaces would be triangular and therefore flat, making it relatively easy to construct compared to other double-curved folded surfaces. It is an iterative fractal pattern that takes an input triangle and divides it in a certain way (1st iteration), then a certain point in the triangle is moved perpendicularly to its plane, creating the folding effect (Figure 4B), this moved distance is called the fold depth. The same division logic is applied again to the resulting triangles and so on (subsequent iterations). When applied to the double façade, the first iteration was extracted to act as the main structural elements that would bear the load of the façade and also contain a network of small 2.5x2.5 cm perforations creating the intended porous effect. The overall dimensions are 9x13 m as the flat DSF.

The geometrical design parameters that control the DSF configuration (Figure 3C in red) and affect the performance of the façade are; depth of the 1st, 2nd, and 3rd fold iterations, cavity depth, glazing scale factor, distance between the façade perforations (which controls their density), and a scale factor for air openings at the top of the façade. It is important to clarify that the glazing scale factor represents the biggest possible number to be used to scale down the size of each triangular face to create a glazed
opening. This list of numbers (scale factors) is set to be inversely proportional to value of insolation on each face. Thus the bigger the insolation the smaller the glazing scale factor and vice versa.

Figure 4: A) Hierarchy of 3 iterations of the triangular pinwheel pattern, in black, grey and light grey respectively. B) Adding a third dimension to the pattern. A point in each subdivided triangle is moved perpendicularly to its plane to have a folding effect. The moved distance is called the fold depth. Each iteration can have a different fold depth that could be positive (outwards) or negative (inwards). C) The pattern applied on part of the building façade where one room is studied. Overall dimensions are 9 m by 13 m. The 1st iteration (in red) includes perforations.

The performance criteria chosen to evaluate the performance of the double façade are the cavity temperature and the percentage of the room area with a Daylight Factor (DF) greater than 2 in the office room. The DF is used only in the evolutionary optimization phase as an indicator of better/worse daylight performances so that the solver would select the best performing solutions in a given generation to proceed to the next. Afterwards a final solution is selected when the optimization process is finished, and the more accurate Daylight Autonomy (DA) metric is used instead of the DF.

All of the design parameters affect the performance criteria in different ways. At first a preliminary testing phase was performed. The design parameters were all given default values and then each one was tested individually to have a basic understanding of its influence, and consequently assign a suitable search range in the optimization process. For example the preliminary testing showed that the presence of the perforations together with openings at the top increase airflow and could decrease the cavity temperature by up to 2°C. Therefore their search ranges were restricted to the values achieving relatively bigger surface area of openings. There are many possible combinations among these parameters and it is very difficult to manually test each combination and to see its effect on the conflicting performance criteria. This encouraged the use of evolutionary algorithms for multi-objective optimization, to help in finding a solution achieving a good balance between the required criteria. The preliminary testing phase helped in setting the search ranges of each parameter, to avoid wasting time in solutions that have low performances.

6. Optimization Process

Using Octopus Plugin for Grasshopper, this process was done once for each of the SE and NW orientations on a typical summer day with an average ambient temperature of 32°C and average wind
speed of 4.9 m/s. The results were exported to excel files then viewed in Pollination (Roudsari, et al. 2015) web application for exploring multi-dimensional data. It was particularly useful due to the ability of choosing a certain value or a range of values of any parameter/criterion and see the corresponding other parameters of that solution. For example in Figure 5, results were narrowed down to those having the least cavity temperatures enabling the observation of possible tendencies of the design parameters that led to these results.

6.1 Effect of parameters on cavity temperature

The range of cavity temperature values was very narrow (33.64°C to 33.91°C) and air change rates were generally high (40 ach to 150 ach), this is due to the search range of each variable that has been narrowed down. The glazing scale factor, even in its highest value (0.99) corresponded to a window-to-wall ratio (WWR) of 0.44, so a considerable amount of shading is still applied anyway which reduces cavity temperatures compared to a fully glazed DSF. Fold depths strongly influenced both thermal and daylight performances. The numerical value of each fold depth on its own does not count as much as the differences in directions among them. Bigger air opening areas were always associated with higher air change rates and less temperatures. But when they exceeded around 45 ach, no improvement to the temperature was observed. The parameter ranges that led to lowest temperatures were:

- Folds: tended towards opposite extremes (folds in opposite directions); first and third fold depths had maximum positive values (1 m and 0.4 m), while the second had maximum negative value (-0.5 m).
- Cavity depth: tended towards higher values and ranged between 1.4 m and 1.5 m.
- Glazing area scale factor: tended towards minimum (corresponding to a WWR=0.2), which was an expected result.
- Air openings: tended to have mid-range values (corresponding to a total area of 4.4m² for openings at the top and 0.9 m² for perforations).

Figure 5: Results of optimization process that achieved the minimum cavity temperature values. Results visualized using Pollination web application (Roudsari, et al., 2015). The upper and lower limits for the design parameters represent their search ranges in the evolutionary solver.
6.2 Effect of parameters on Daylight

Despite the expected effects of glazing area on cavity temperatures and room daylighting, the same glazing area could result in different performances if the rest of the variables are changed. For example a high glazing scale factor of 0.98 (WWR=0.44) can result in 22% or 13% of room area having a DF greater than 2, when different fold configurations were used. The main difference observed was that of the first fold depth which was 0.8m and -0.4m respectively. This shows the strong influence of folds on daylight performance, especially the first fold depth as it is the largest in the facade. The highest DF performance reached was 22% of the space, corresponding with a temperature range between 33.6°C and 33.9°C. The design parameters that led to highest daylight performances were:

- Folds: first fold depth clearly tended towards maximum positive values (0.9 to 1.0 m). The second and third fold depths did not show a clear value range but they were either near zero or positive values. In general, they tended not to be folded in opposite directions.
- Cavity depth: ranged between 0.97 m and 1.29 m.
- Glazing area scale factor: tended towards maximum values ranging between 0.97% and 0.99% (corresponding to a WWR=0.42 to 0.44).

The aforementioned observations were for the SE orientation. Very similar tendencies were observed in the NW; the main differences were that the fold depths did not show the clear tendency towards opposite extremes, cavity temperatures were slightly less and there were more possible solutions achieving good trade-offs between daylight and temperature. In general, for both orientations, many different combinations of parameters produced very similar results. This gives the architect some freedom to choose according to other preferences (aesthetic, structural, etc.).

6.3 Modifications to improve daylight performance

During the optimization process, the glazing of the inner façade was initially left as that used in the reference case. This justifies the poor daylight performance. In practical terms, if one would decide to build a double façade like this, then the choice for glazing specifications of the inner façade layer would not be a tinted one that only transmits 37% of light inside as that used in the reference case. This is because the inner façade layer has already become shaded by the added layer which reduces the amount of light entering the office spaces. Consequently, it has been decided to use a different inner glazing which is double Low-E clear glazing (Figure 3C).

7. Comparison with reference case and flat DSF

A solution was selected for of each orientation. More accurate simulations of daily cooling loads for the whole month of July, and Daylight Autonomy (DA) have been performed as seen in Figure 6. It is important to note that the flat DSF was assigned an outer glazing different from that of the folded one. It transmits less light and solar energy to compensate for the lack of shading devices. The folded one however is in itself a shading device, so it did not need the same glazing properties (as in Figure 3).
The reference case in the SE barely achieves the DA benchmark (LEED v.4), which is 50% of the space receiving at least 300 lux for half of the occupied time, and is slightly below it in the NW. In the reference and flat DSF cases a considerable amount of the space is over-lit near the windows, receiving more than 3000 lux for at least half of the occupied time. This requires the use of blinds and thus more energy for artificial lighting. The flat DSF slightly decreased DA, with slight improvement to the glare problem, and decreased cooling loads by only 4% and 2% in the SE and NW respectively. This means that shading devices or higher reflective glazing is required to improve the thermal performance, but it will be at the expense of even less DA.

Figure 7 shows that the cavity temperatures in the folded DSF were always higher than ambient temperatures by only 2°C and around 1.7°C lower than the flat DSF despite changing wind speed and direction. Consequently the folded DSF showed better improvement to cooling loads as they were decreased by 9% and 12% in SE and NW orientations. This decrease was associated with better DA, in fact better performance was observed in both orientations with a considerable reduction in the over-lit area as light was better distributed reaching deeper into the space. The modified glazing properties of the inner façade layer were important to achieve this DA performance; when the inner glazing was left as in the reference case, reduction in cooling loads reached 15% but was associated with a DA of only 45% of the space (El Ahmar and Fioravanti, 2015).
7.1 Software limitations

Digitally modelling a double façade cavity is a complicated task since airflow, air temperature, and daylight interact with each other and affect the resulting behaviour (Poirazis, 2006). Based on the level of resolution of the simulations, they can be categorized into macroscopic; dealing with whole building systems over periods of time like EnergyPlus and microscopic which focuses on smaller spatial and time scales, Computational Fluid Dynamics (CFD) are typically used in this level (Hensen, 2002). Despite the advantages of CFD, it is difficult to use in early design phases as it is too detailed, it needs high computation power and advanced user knowledge. The use of EnergyPlus in simulating double façades is debatable as it uses the Airflow Network model which assumes that each thermal zone has a uniform temperature distribution, and it doesn’t consider the cavity airflow pattern (EnergyPlus, 2014). Several studies (Zhang, et al., 2013; Sabooni, et al., 2012; Kim and Park, 2011) recommend coupling EnergyPlus with a CFD tool to complement each other’s limitations.

8. Conclusion

The thermal performance of DSFs is still not widely studied in hot climates as those in cold ones, and their resulting daylight performance is rarely addressed. The paper presented an exploratory investigation of the application of an irregular DSF for the improvement of thermal and daylight performances of an office room in Cairo. The proposal was compared to the reference case as well as a flat DSF designed based on observations from previous studies. To attempt to find a trade-off between conflicting daylight and thermal performances of the folded DSF, evolutionary search algorithms were used. The tools proved very useful in finding a suitable combination of the numerous design parameters, to achieve a balance among the performance criteria.

Results showed that the folded morphology which provides self-shading, in addition to air openings and perforations that improve cavity airflow are important in reducing the cavity temperature. Cooling loads were reduced while improving daylight performance. The selection of glazing properties was important to achieve these results. This encourages further explorations into irregular DSF configurations for higher reduction in cooling loads. Future work also includes the verification of the results simulated by EnergyPlus using CFD. It is expected that there will be inaccuracies in EnergyPlus results. However the purpose is to know the degree of inaccuracy and whether EnergyPlus can be relied on in differentiating between best and worst-performing solutions. This is quite important since the use
of CFD is still not practical in early design phases. In all cases the physical phenomena occurring within the cavity of a DSF are complex to accurately simulate using computers, even with CFD, especially with complex geometrical façade configurations.

References


Thermal perceptions and microclimates of educational urban precincts in two different seasons in Melbourne

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Abstract: This paper assesses the levels of comfort within outdoor educational urban precincts in Melbourne. Three urban spaces, in relatively close proximity to each other were investigated in two different seasons: spring 2014 and summer 2015. In total, 368 and 413 comfort responses were collected in the spring and summer seasons, respectively. The preliminary results show the characteristics of thermal perceptions, using the 7-point scales of thermal sensation votes (TSV) and comfort scale 'affective evaluation'. In addition, the Physiological Equivalent Temperature (PET) index was also used to predict the thermal comfort for a large number of space users. While the mean temperature for spring was recorded as 21.55 °C, it reached up to 24.75 °C in summer. The overall thermal sensation votes for both seasons were toward the slightly warm side of the scale and its value moved from 0.47 in spring to 0.78 in summer. However, comfort responses, using 7-point comfort scale, on average, were from moderately to slightly comfortable conditions in spring, which changed to between just right and slightly uncomfortable conditions in summer. The changes found in the results of two seasons illustrate the extent of seasonal changes impacting thermal perceptions. Adopting the PET as a thermal comfort indicator, the results prove the reliability of this index for the study periods.

Keywords: Thermal comfort assessment; microclimates; urban precincts; outdoor environments.

1. Introduction

People’s outdoor thermal comfort is influenced by surrounding microclimate, and people’s usage of outdoor spaces is impacted by their thermal perceptions. Therefore, providing thermally comfortable open spaces for the users needs to be considered. Urban precincts may be considered as enclosures with different physical characteristics and focused activities. They provide much needed open outdoor areas, particularly in high density spaces. However, these open spaces are subject to a range of ecological issues, including but not limited to, urban heat island effects. In Australia, recent trends in urban planning suggest redevelopment of the urban precincts to minimise adverse environmental, social
and economic consequences such as climate change, energy consumption and pollution. Therefore, it is imperative to understand thermal comfort requirements during different times of a year to enhance the experience of users within outdoor environments. According to ASHRAE 55 (2010), thermal comfort is a “condition of mind which expresses satisfactions with the thermal environment”.

1.1. Outdoor thermal comfort

Several thermal comfort indices and methodologies have been applied to investigate thermal comfort in outdoor settings. Both heat balance and adaptive based approaches have been developed and applied with some success in outdoor settings (Nikolopoulou and Lykoudis, 2006; Ng and Cheng, 2012). While the heat balance approach has been long used and still used to assess thermal comfort, there exist some shortcomings in terms of non-thermal factors that are addressed in adaptive theory.

To date, a number of studies have been conducted in Melbourne, Australia to analyse the thermal comfort requirements for different types of outdoor users (Spagnolo and de Dear, 2003; Loughnan et al., 2012; Kenawy, 2013; Lam et al., 2014). Each of these studies has focused on a population target with the view of characterising their thermal comfort conditions. Also, the thermal comfort conditions may vary depending on the season of the year as people can adapt to prevailing climate conditions (de Dear et al., 1997; Lin et al., 2011). The comfort requirements may also differ among various user groups; including, tourists, students and pedestrians. No study has considered outdoor thermal comfort assessment in educational precincts with a population consisting of university students and staff in Australia. While study of educational precincts is novel, the underlying concepts may be applied to any outdoor urban setting. The concept of educational precincts refers to those built environments that feature outdoor spaces, surrounded by educational buildings. These built environments give a sense of enclosure with different physical characteristics and focused activities. In Australia, recent trends of urban planning and management such as Melbourne @ 2030 (Victorian Government, 2008) suggest development of urban precincts to minimise adverse environmental, social and economic consequences (d’Argent, 2012). Some studies have focused on the temporal impact of physical characteristics of educational precincts on comfort conditions in other parts of the world (Wong et al., 2007; Xi et al., 2012).

This paper explores the effect of seasonal thermal conditions on the users’ thermal perception in educational precincts in two seasons. The paper is based on a preliminary analysis of data collected for a doctoral study, which identifies some of the wider determinants of outdoor thermal comfort in educational urban precincts. The study aims to understand the ability of different thermal indices in the prediction of thermal comfort along with other cultural and social drivers, and site specific urban morphology in understanding thermal perception and microclimates in educational precincts. This paper is restricted to an initial exploration using the Physiological Equivalent Temperature (PET) index as the main yardstick of measure. This study also tries to inform the guideline used by universities on provision of thermally comfortable educational outdoor environments for university students and staff as well as other users.

2. Method used for this study

The conditions of thermal comfort outdoor spaces were assessed according to a concurrent measurement of major microclimatic parameters: air temperature (Ta), wind velocity (Va), relative humidity (RH) and globe temperature (Tg), and a questionnaire survey on human thermal responses
using ISO standards (ISO 7730, 2006). The values of these parameters were measured using Testo 480 IAQ Pro Measurement Kit that was placed close to the participants, and the data logger was set to collect variables at 1-min intervals. The sensors were mounted on the kit’s tripod at different heights: Ta (95 cm), RH (95 cm), Tg (95 cm) and Va (110 cm). Subjective assessment was conducted at the 3 sites to understand the effect of seasonal change on thermal comfort requirements. In each season 15 days were allocated to conduct field surveys in the study sites: from 9:00 am to 5:00 pm in November 2014 (spring time) and February 2015 (summertime). Also, a concurrent measurement of Ta and RH was carried out across the sties during each season using a stationary measuring system (HOBO Pro v2 temp/RH U23-00). The method used in this study is considered as a standard practice to assess outdoor thermal comfort that has been adopted in previous studies (Spagnolo and de Dear, 2003; Lin et al., 2011; Johansson et al., 2014)

2.1. Study sites

This study was conducted in Melbourne, which has an oceanic climate and Cfb according to the most updated Köppen-Geiger classification (Peel et al., 2007). Melbourne has highly changeable weather conditions due to its specific location situated on the borderline of extremely hot inland region and cool southern ocean (BoM, 2014). The thermal variability is greatest in the spring and summer months due to the formation of cold fronts from the northwest, west and south. Three urban environments within an educational campus were selected as the case study for this research. The selection criteria were based on their characteristics representing common outdoor spaces with similar urban forms to those of the inner city of Melbourne. The study sites were situated in the heart of central Melbourne which is subject to UHI effects caused by surrounding high-rise buildings, densely urbanized hard surfaces with less evapotranspiration and crowded spaces with higher anthropogenic heat production (Coutts et al., 2007). The majority of space users are university students and staff who belong to the young ages (18-35 years old) that use the sties either to pass by to another place, use the space for work or for leisure.

All the sites were located in the premises of the RMIT University City Campus (RUCC) and their specifications are presented below:

- **Site 1:** University Lawn which is used as a recreational space by university students and staff. This venue has a varied surface coverage, water features and a natural green space. The compact design of University Lawn makes it representative of many recreational outdoor spaces in the inner city.

- **Site 2:** Ellis court in RUCC is differentiated from the other two sites as it acts a thoroughfare and a main path to other parts of the campus. This site includes a range of urban elements that collectively affect thermal conditions and resemble many other urban precincts in the City of Melbourne.

- **Site 3:** RMIT A’Beckett Urban Square is recreational space, which provides multi-functional courts for outdoor activities, green spaces and shading features. This site resembling many commercial outdoor settings in inner-city which is surrounded by high rise buildings and is open to the public. The microclimate conditions of these sites during the two field survey (Table 1) and in a 10 day period (Figure 1) are presented below. As can be observed, there were noticeable variations in the climate variables during the field survey in both seasons. However, the changes did not necessarily share a same trend in the three study sites.
Thermal perceptions and microclimates of educational urban precincts in two different seasons in Melbourne

Table 1: Summary of the climate variables monitored at study sites during the field survey (mobile weather station).

<table>
<thead>
<tr>
<th>Site</th>
<th>Variable</th>
<th>Unit</th>
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<td>Spring</td>
<td>Summer</td>
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Figure 1: Thermal conditions of the three study sites (Ta) in two seasons (Stationary station).

2.2. Outdoor thermal index, PET

Among several thermal comfort indices, the Physiological Equivalent Temperature (PET) was used in the study. This index is specifically designed for outdoor conditions and has been recently adopted in many
outdoor comfort studies. PET is expressed in degrees centigrade and easy to be understood by designers and urban planners. Use of this index eases the comparison between the results of this study and those of others. Also, the results in the form of PET can be integrated with other PET-based studies to form a global database on thermal comfort requirements.

PET is built up on the basis of Munich Energy-balance Model for Individuals (MIMI) in 1987 and is technically linked with the Gagge’s two-node model parameters (Höppe, 1999). The theory behind this index is to transfer the actual thermal conditions in an equivalent indoor setting, where similar thermal perception is assumed (Thorsson et al., 2007a) and therefore is fit to be used outdoors (Chen and Ng, 2012). PET was calculated using Rayman Software Package 1.2 that assumes the constant values for the level of activity (80 W) and clothing insulation (0.9 Clo for spring and 0.5 Clo for summer). Also, Mean Radiant Temperature (\(T_{\text{mr}}\)) is also calculated to be input into Rayman software using \(T_a\), \(T_g\) and \(V_a\) (ISO 7730, 2006). \(T_{\text{mr}}\) indicates the radiative exchange between the human body and the given environment (Thorsson et al., 2007b). To reduce the effect size of individual differences the calculated PETs were put into 1 °C intervals (bins) and thermal sensation votes (TSVs) were averaged against each interval called mean thermal sensation vote (MTSV) (de Dear and Fountain, 1994).

2.3. Thermal perceptions

The participants in this study were among university students and staff who were asked to complete a questionnaire that took less than five minutes with 14 questions. They were briefed about the aim of research before participating in the survey. Two descriptors of thermal perceptions were used in this study: thermal sensation and thermal comfort. The subjective perception was measured using two 7-point scales: thermal sensation and comfort scale ‘affective evaluation that was tailored to 7-point to match with thermal sensation points. The TSV was judged on the ASHRAE 7-point scale (ASHRAE 55 2010) and has a range of “cold (-3), cool (-2), slightly cool (-1), neutral (0), slightly warm (+1), warm (+2) and hot (+3)”’. The comfort 7-point scale, which is an extension of 4-point scale of ISO 10551 (1995), ranges from “very uncomfortable” (1), “moderately uncomfortable”(2), “slightly uncomfortable”(3), “just right”(4) to “slightly comfortable”(5), “moderately comfortable” (6) and “very uncomfortable”(7) that correspond to the thermal sensation scale.

3. Results

3.1. Characteristics of the sample size

In total 781 thermal responses were collected from two field surveys conducted during 18 days from November 2014 to February 2015 at the study sites. In the spring, of the total 368, male and female participants were accounted for 67% (N= 246) and 33% (N= 122), respectively. The same percentages were also observed in the summer, where out of 413 participants, 69% (N= 257) and 38% (N=142) were male and female, respectively. Also, over 54% and 63% of participants were within the range of less than 18 to 30 years old in the spring and summer, respectively. The age group distribution indicates the type of the study site users who were mostly young people.

3.2. Thermal sensation votes

While the mean temperature for spring was recorded at 21.55 °C and reached up to 24.75 °C in summer, the distribution of TSVs shows relatively alike trends (Figure 2). However, the percentage of
votes to the right side of the scale (warmer conditions) was always higher (60.10 %) in summertime compared to the conditions in the spring (53.80%). Likewise, for the left side of the scale (cooler conditions), spring’s TSVs outnumbered that of summertime. The overall TSV (the arithmetic average of thermal votes) for both seasons were toward the slightly warm side of the scale and its value moved from 0.47 in spring to 0.78 in summer. However, comfort responses, using a 7-point comfort scale, on average, were from moderately to slightly comfortable conditions in spring, which changed to between just right and slightly uncomfortable conditions in summer.

3.3. Actual and Predicted thermal perception

To validate the accuracy of predicted thermal comfort conditions, mean thermal sensation votes (MTSV) were plotted against predicted PET values. As shown in Figure 3, the prediction power of PET noticeably changed during the two seasons (R² = 0.77 in spring to R² = 0.93 in summer, P<0.05). Also, the findings suggest the fact that while in summer above 90% of the variation in the users’ thermal sensation is explained by the thermal conditions, in spring users were less sensitive to weather conditions and other non-thermal factors matter. In the two seasons an increase in PET values caused TSVs shifted towards the warmer end of the scale.

Figure 2: Distribution of thermal sensation votes in two seasons.
Figure 3: The dependence of actual thermal sensation (MTSV) on predicted thermal comfort (PET) in two seasons.

The comfort level was also cross-tabulated against PET for the two seasons (Figure 4). The results of simple linear regression show a weak relationship between the concept of comfort and thermal conditions in spring ($R^2 = 0.14$, $P<0.05$) and summertime ($R^2 = 0.13$, $P<0.05$). The results also show that comfort conditions were equally a function of thermal conditions in the two seasons.

Figure 4: Cross-tabulation of comfort levels and predicted thermal comfort (PET) in two seasons.

4. **Discussion**

The requirements of thermal comfort in outdoor spaces vary depending on some factors including seasonal change. This study evaluates the impact of seasonal change on the thermal perceptions to understand the essence of changes across the two seasons. In doing so, two comfort field surveys were conducted in a spring (November 2014) and in summer (February 2015). In total, 368 and 413 comfort
responses were collected in the spring and summer seasons, respectively. The overall TSVs for both seasons were toward the slightly warm side of the scale and its value moved from 0.47 in spring to 0.78 in summer. These findings suggest the impact of seasonal change on the outdoor thermal perceptions, yet in small grades, in two subsequent seasons.

Cross-tabulating TSV with PET values indicates the strong impact of climate conditions on thermal sensation. However, this impact was proved to be varying across the seasons; more effective in summer and less in spring. The varying effect of climate conditions on TSV implicates the role of seasonal change on outdoor users’ thermal perception; where the comparatively severe thermal conditions in summer induced higher sensitivity to thermal conditions among users. The results of cross-tabulation between PET and comfort levels points to the difference between the concept of comfort and thermal sensation. This difference is already recognised in a study in Queensland (de Freitas, 1985) where the holiday makers had different thermal preference and comfort compared to what they indicated as thermal sensation. This difference also underlines the importance of other non-thermal factors contributing to the status of comfort in outdoor spaces (Brager and de Dear, 1998).

5. Conclusion

The outcome of the present study contributes to empirical data used to assess thermal comfort in outdoor areas in a temperate climate such as Melbourne. Despite the growing demand for understanding the dynamic of thermal comfort, such empirical data are yet to be investigated and the links to urban planning yet to be explored. This shortcoming has been also recognised in the previous studies (Spagnolo and de Dear, 2003; Kenawy, 2013) that suggest further studies are required to shed light on different aspects of thermal comfort in outdoor conditions. The preliminary findings of this study illustrate the role of other players in achieving comfort in outdoor environments. Furthermore, the likelihood of changes in comfort conditions throughout a year calls for the need for standard assessment of thermal comfort during different seasons. This, together with results of previous studies can lead to defining the requirements of thermal comfort in urban spaces and setting up of a standardised approach to measuring thermal comfort in the outdoors. The empirical findings of the research also raise the awareness for the use of climate sensitive design principles, which allows spatial managers to maximize the use of comfortable outdoor environments including educational precincts. Further studies are highly recommended to gain an insight into the dynamic of the concept of comfort in use of outdoor spaces; the factors that are influential in thermal perceptions.

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Understanding the changing thermal comfort requirements and preferences of older Australians

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Abstract: Australia is faced with the challenge of housing and caring for an increasingly ageing population. As the human body ages its sensitivity to changes in the thermal environment diminishes. This paper discusses a recent survey of older people living in Adelaide, South Australia, about the conditions of their living environment, their general health conditions and the ways in which they operate their houses. Selected dwellings are being monitored to record indoor temperatures and humidity while a long term thermal comfort survey of the occupants is being conducted. This paper will discuss preliminary results of this thermal comfort survey for the summer period. The results found that in general the selected occupants perceived their dwellings to be thermally acceptable; however there are some potentially hazardous trends around the use (or not) of heating and cooling. Overall, the thermal comfort surveys in conjunction with the temperature and humidity data indicate a preference among older people for cooler temperatures than typically considered comfortable by the healthy adult population. Balancing these preferences for both temperature and mechanical heating and cooling usage is vital for creating an environment for health and comfort in later life.

Keywords: Thermal comfort; health; ageing population.

1. Introduction

As Australia’s population ages, a number of challenges must be overcome to ensure a healthy later life for a large proportion of the population. One of these challenges is that of housing; having enough housing that meets the needs and wants of older people and provides a healthy environment as they age.

As the body ages, changes in the way that it adapts to different thermal conditions begin to appear. Studies into the thermoregulatory responses of older people have shown that sweating starts at higher temperatures than in younger adults, while shivering starts at colder temperatures than in younger adults (Anderson et al., 1996). Both of these responses are also less vigorous than might be expected in younger people. Older people feel the cold more slowly than healthy adults – i.e., it must be a colder temperature before they will report feeling ‘cold’ than in younger test subjects (Yochihara et al., 1993).
The result of this is a reduced capacity to maintain a healthy body temperature in both hot and cold conditions, potentially leading to hypo- or hyperthermia and associated health problems. Trends toward increased morbidity and mortality amongst older people during periods of hot and cold weather are well established and continue despite public health campaigns aimed at alerting older people to the health risks associated with extremes in weather (reference).

The effect of housing on the health and wellbeing of its occupants is well documented (Evans et al., 2003; Howden-Chapman, 2004; Lawrence, 2004). This effect is multifaceted, and determinants can include physical factors such as cool temperatures, damp and lack of ventilation (Martin et al., 1987; Williamson et al., 1997). Extremes in both heat and cold have led to increases in hospital admissions and mortality of the elderly. Cold and damp conditions lead to exacerbation of respiratory diseases such as asthma (Williamson et al., 1997), and extreme heat can cause renal and cardiovascular problems (Hansen et al., 2008; Nitschke et al., 2011). The degree to which occupants’ experience these conditions as opposed to how the conditions themselves affect health is also of interest to researchers. As the perception of temperature and the physiological response to it change with age it is possible that an older person may perceive an environment to be thermally comfortable when in fact it may pose threats to their health. Whilst there are clear correlations between hospital admissions and external temperature and climate conditions, there has been little research on the indoor environment of the dwellings of the elderly, particularly on the effect of the occupants’ perceptions of this environment on their health. In the home environment, thermal comfort models (eg ASHRAE, 2013) have been developed to predict the range of conditions most comfortable for occupants, both in air-conditioned and naturally-ventilated modes. Whilst these models have been used to determine the thermal comfort and occupant satisfaction levels of several cohorts, information about how those aged over 65 experience their thermal environment is scarce and whether these models are applicable to this cohort is still questionable.

Through cooperation between architecture and public health researchers, the research aims to examine the relationship between the thermal environment of homes of older people, their thermal comfort perceptions and their health. This paper presents the preliminary results of the study, conducted in Adelaide, South Australia, amongst independently living people aged over 65. The paper will discuss the general opinions of the respondents regarding their housing and health, as well as some detailed thermal comfort data from a small cohort participating in a thermal comfort survey.

2. Background

Whilst older people are particularly susceptible to extremes in heat and cold, there is little known about their experiences of their thermal environment, and indeed there is some controversy in the available research regarding the effect of age on perceptions of thermal comfort. A number of studies have shown that older people in general prefer a lower temperature than would be predicted by the PMD/PPV model of thermal comfort (Collins and Hoinville, 1980; Tsuzuki and Iwata, 2002), which contradicts expectations of a preference for warmer temperatures in those with lower activity levels. Another study found that older adults prefer a temperature within the PMV comfort range (Turnquist and Volmer, 1980). The general conclusion drawn by van Hoof and Hensen (2006) is that older people tend to perceive thermal comfort differently from the young, due to a combination of behavioural factors such as clothing and activity level, and physical factors due to the ageing process. What is not yet clear from the research is what effects this altered perception of thermal comfort has on health. For
instance, an older person may not perceive the environment as being too hot, but the conditions may be hotter or more humid than is healthy for them.

There is however, evidence that the outdoor temperature is connected to health, especially in older people. A number of studies have shown increased health problems during periods of extreme heat and cold, including an increase in hospitalisations, ambulance call outs, and emergency department visits during heatwaves (Mayner et al., 2010; Hansen et al., 2011; Toloo et al., 2014). There is also research that indicates cold weather is likely to increase the risk of falls in older people, especially older women (Lindemann et al., 2014). This is of particular concern for older people who live alone, as 50% of older people are unable to get up after a fall without assistance, and thus these falls can be a cause of accidental hypothermia as well as other serious ongoing health problems (Voermans et al., 2007).

There is very little research available on links between thermal comfort and health, particularly of the elderly. A report produced by the World Health Organisation (WHO) (Goromosov, 1968) concluded that the human body could only compensate for external temperature in a narrow range, given as between 15 and 25 degrees Celsius, with minimal energy expenditure. A further WHO study (WHO Working Group, 1982) showed minimal risk to health of sedentary people, such as the elderly, when housing was kept at a temperature of between 18 and 24 degrees Celsius. Whilst it is an important aspect of thermal comfort, there are other factors that determine whether a person finds their indoor environment comfortable. There have been studies into some of these factors individually, such as humidity and ventilation, but there is little research on all factors collectively, their link to occupant satisfaction, and health.

3. Methodology

This study has been carried out in two stages – a questionnaire and a field study. In the first stage, people in the target age group of 65+ years living independently in Adelaide, South Australia, were asked to complete a survey about their housing and health. Participants for this survey were recruited by contacting targeted local government Home and Community Care (HACC) centres, local church groups, and University of the Third Age chapters. A ‘hot desk’ set up was also utilized in the local government community centres who assisted in survey distribution to assist those who might have questions about the survey or struggle with the length of the questionnaire. This stage was conducted as a paper questionnaire. This survey included questions about house construction and materials, the kind of heating and cooling installed and how this was used, the ability of the occupants to use various passive heating and cooling as well as mechanical systems, and questions about general health as well as specific symptoms during hot and cold weather. These symptoms included headaches, joint pain, dizziness, anxiety, respiratory and circulatory problems and fatigue. General demographic questions such as age, sex, income and country of origin were also included, as well as a request for the approximate yearly gas and electricity expenditure. Areas of the Adelaide metropolitan region identified as having higher vulnerability to heatwaves as determined by the heat related vulnerability index (Loughnan et al., 2013) were targeted for participation.

Participants of the survey were subsequently invited to join the second stage of the study which aimed to investigate the thermal conditions in their homes and possible relationship with their health. This field study involved the installation of unobtrusive indoor data loggers in the participants’ living and bed rooms to record air temperature, relative humidity and globe temperature every 15 minutes. Whilst these loggers were installed in the houses the participants were asked to regularly fill out a comfort vote survey based on section 7 of ASHRAE standard 55-2013. This is a short survey including the ASHRAE 7-
point thermal sensation vote, McIntyre’s three point preference scale, as well as questions regarding the acceptability of the current conditions, clothing being worn, factors influencing their thermal comfort (for example, doors and windows being open, fans and cooling or heating operating) and the participants activity level immediately prior to completing the survey. In addition, the survey also asked whether the participants experienced heat or cold related symptoms in the 24-hours prior to the time they responded. The answers to these surveys were then matched with the data from the loggers to determine what conditions the participants find thermally comfortable and acceptable. Data were also analysed to investigate the relationship between the thermal condition of the space, the participants’ thermal requirements and preferences, and their health condition.

4. General Survey Results

At the time this paper was being prepared, 59 surveys had been completed. The study is continuing and more participants are still being recruited. Out of those who have responded, females made up 74.5% (n=41) of respondents with 25.5% being male (n=14), with 4 respondents failing to indicate their gender. The majority of the respondents were aged between 65 and 80 (n=44), with only a small number (n=14) aged 81 years or older, and one participant failing to indicate their age bracket. Over 70% (n=41) were on either a full or part government pension, which accounts for the modal income being between $20,001 and $40,000. Despite having a slightly lower household income than the median reported by the ABS, household expenditure on electricity and gas was roughly equal to the national household average (Australian Bureau of Statistics, 2012) at approximately $32 per week.

Of the survey respondents, 4 noted not having any cooling installed, whilst all participants had some form of heating in their home. When asked about their heating or cooling use, 33% of respondents reported avoiding using their heating and/or cooling despite feeling uncomfortable. The majority (78%) of these respondents reported either not being able to afford the usage or not wanting to spend money on gas or electricity as their reasons for avoidance. Other reasons given included health concerns and a desire to ‘save the environment’. One respondent reported that their air conditioner didn’t work.

Most respondents reported only using their heating and cooling in response to their own comfort needs, with ‘only when I feel too hot/cold’ (45 and 53% of responses respectively) and ‘only when it gets hot/cold inside’ (29 and 25% of responses respectively) being the top responses. Very few (<5%) used their heating and cooling around the clock to create a constant thermal environment. The modal thermostat temperatures were 23 degrees in summer and 22 degrees in winter. Use of heating or cooling in the evenings before bed was also quite common, especially in the winter months with a third of respondents reporting this practice. Despite the pattern of mechanical heating and cooling usage, a majority of respondents reported their houses were ‘always’ or ‘mostly’ comfortable during both winter and summer.

5. Preliminary field study results

5.1. Participants and their houses

Of the 59 survey respondents, 23 were interested in joining the field study. Of these, 11 have had loggers installed in their homes so far but only six of these households have data reported in this paper due to the timing of installation and subsequent collection of data. The households represented in this paper include five two-person households and two single person households. Despite the option for two members to complete comfort votes, in these six households so far all votes have been completed by
Understanding the changing thermal comfort requirements and preferences of older Australians

one participant only, with four females and two males completing comfort votes. All participants reported either ‘good’ or ‘very good’ health, although all respondents reported being on medications for chronic health conditions.

All participants lived in detached houses of either double brick (n=5) or brick veneer (n=1) type construction. All were long term residents with length of residence ranging from 13 – 48 years. All houses had some form of mechanical cooling and heating installed; however, three of those reported avoiding cooler use at least occasionally. Of the six houses, three had insulation in the ceiling and walls, two had insulation in the ceiling only and 1 had no insulation. All had external and internal window treatments on at least some windows. Five of the houses had ceiling fans installed in the main bedroom and the living area, with two houses having additional ceiling fans in the kitchen and other bedrooms. All houses had at least some windows which were able to be opened.

The monitoring period reported in this paper was 09/02/2015 – 25/05/2015. This encompassed both hot summer weather and some unseasonably cool autumn weather. Participants’ houses were on average 2 degrees warmer than the average daily outside air temperature. On the hottest day during the logging period (average outside temperature of 34 degrees, maximum temperature of 41.6 degrees, low of 26.5 degrees) the houses were on average 7.1 degrees cooler than the average outdoor temperature, and on the coldest day (average outside temperature 10.3 degrees, low of 4.8 degrees, high of 15.7 degrees) on average the houses were 5.3 degrees warmer than outside air temperature. At their coolest period, the houses were 5 degrees cooler, and at their warmest 6.5 degrees warmer than the outdoor temperature.

5.2. Thermal Comfort Votes

A total of 452 thermal comfort votes were received from the six participants from whom data was collected. Of these votes, 40% were completed at conditions the participants felt were ‘just right’ (neutral vote of 4 out of 7-point scale), with an additional 37% occurring during conditions considered ‘slightly warm’ or ‘slightly cool’, 17% when conditions were ‘cool’, 5% when ‘cold’, and less than 1% each at ‘warm’ and ‘hot’. Average thermal sensation vote (TSV) was found to increase with indoor temperature. Figure 1 shows the average thermal sensation vote (TSV) compared with indoor temperature interval. Using the linear regression equation of $TSV = 0.1897 Ti + 0.5287$, an average neutral temperature would be reached at 23.9 degrees.

![Figure 1: Average thermal sensation votes (TSV) compared with indoor temperature.](image-url)
At the extremes of thermal sensation vote, some interesting trends have been observed. When reporting ‘warm’ or ‘hot’ conditions, participants were more likely to indicate a preference for change (75% and 100% respectively) than they were when they considered the conditions ‘cool’ or ‘cold’ (54 and 59% respectively). Even when voted ‘slightly warm’ more participants expressed a desire for change (57%) than when reporting feeling ‘slightly cool’ (24%). This indicates a preference for cooler conditions rather than warmer, and also a greater acceptability of cooler temperatures than warmer temperatures. It is worth noting, however, that there were a greater number of cooler days than warm days during the monitoring period, despite the fact that it was conducted during later part of summer to autumn, and therefore there were fewer thermal comfort votes during which people stated feeling ‘warm’ or ‘hot’ (see Figure 2).

![Preference for change during sensations of cold through to hot.](image)

Participants were more likely to operate cooling during hot weather than they were to operate heating during cold weather. The largest percentage of responses who answered that yes, they had heating operating was 44% when the daily average was only 11 degrees. In contrast, at temperatures about 28 degrees and above 50% or more of respondents had cooling operating, with 100% having cooling operating at daily average temperatures of 31 and 33 degrees. This tends to once again indicate that cooler temperatures are more acceptable (therefore not requiring mechanical change) than warmer temperatures for the older people in this cohort.

This preference is confirmed when the thermal comfort vote data is entered into the Adaptive Thermal Comfort model. A larger number (43%) of neutral thermal sensation votes (slightly warm, just right, slightly cool) than expected are clustered below the usual 80% acceptability limits, indicating a preference for cooler conditions. When the 90% acceptability limits are examined, 60% of the votes fall below this line (see Figure 3).
When the indoor air temperatures and prevailing mean outdoor temperature are examined at times when participants indicated no desire for change in their thermal comfort levels, there are once again more votes clustered around the cooler end of the spectrum (42% lower than 80% acceptability, 59% lower than 90% acceptability) than expected (see figure 4).
These results exclude votes at the highest activity levels and the lowest and highest clothing ranges, meaning these preferences were not due to increased activity level or heavy clothing. This reduces the effect that adaptive behaviours may have on the results.

6. Discussion

6.1. General Survey

Results from the general survey indicate that the older people in this cohort do not consider their thermal needs as being any different from the general population. Heating and cooling was used in response to their own comfort, rather than in a way that creates a more consistent environment. Whilst this is reasonable for the general population, if there are indeed age-related changes in thermoregulation and temperature sensitivity taking place, this pattern of heating and cooling use may not be appropriate. Whilst many did not shy away from using their heating and cooling, concern must be raised about those who do avoid their usage when they are uncomfortable. This is especially true of those who are concerned about the financial impact of using these devices. Whilst frugality and resilience are common attributes amongst the older population (Hughes et al 2008, Abrahamson et al 2009), with increasing electricity prices there is concern that those with lower incomes may be more at risk during extreme heat and cold.

A further concern is the trend of many older people to keep the thermostat on their heating and cooling at the same temperature year round. For those concerned about the price of electricity, a thermostat set at 22 or 23 degrees in the winter may be having a dramatic impact on their energy usage. Estimates published by the Australian Government suggest every extra degree can impact heating and cooling energy use by 5-10% (Milne et al., 2010). As long as the thermal needs of the older population can be met at lower temperatures, these should be considered, especially by those wishing to reduce their electricity bills.

6.2. Thermal Comfort Field Study

Overall the results from the field study show a trend toward the preferences of older people for cooler temperatures. There are a number of reasons that these older people’s preferences may fall outside of expected norms. These include behavioural and attitudinal factors as well as changes in physiology which occur in later life. At this stage, however, any reasoning as to which factors are specifically at play amongst this cohort is pure conjecture, and future research is needed to determine which attitudinal or physiological factors have a greater influence over the preferences and perceptions of thermal comfort amongst older people.

In a recent study (Tod et al., 2012) of attitudes toward cold in older people in the UK, particular values emerged which may be relevant to the results seen in this study. Firstly, amongst some older people, there was an idea that central heating could be detrimental to health. Rooms which were too warm were considered ‘bad for you’ and led people to live in colder conditions than they might otherwise. Secondly, there was an attitude of resilience and not seeing a need to change behaviours that had been acceptable all their lives. This is quite possibly linked to the well-established fact that people often don’t see themselves as being ‘old’ (Abrahamson et al., 2009) and therefore dissociating from the specific needs that come with age. The results of this thermal comfort study show cooler indoor conditions to be preferred, rather than simply being ‘put up with’, however the degree to which the two attitudes are related is complicated and warrants further investigation. Whilst attitudes of
resilience and stoicism may influence a person’s preference for particular conditions, the possibility of physiological factors being at play cannot be excluded. The participants in this study all but one reported good health, however, the fact that they are of an older age may mean various changes in physiological thermoregulation can occur. A lack of adequate thermal sensitivity in older people may potentially compromise health and wellbeing and may become a public health issue warranting help for older people to understand how best to manage their health in these conditions.

The current methodology does not allow for differences between physiological and attitudinal responses and further investigation is required once more participants have been identified and recruited. Of particular importance is whether the personal preferences of older people for these cooler temperatures are leading to a greater number of health problems for this population. Whilst a question relating to hot and cold symptoms was included in the thermal comfort vote survey in this study, there is so far insufficient data to determine whether a link between thermal comfort and health exists in this cohort. If so, there may be a need for strategies that can be implemented to address the thermal conditions of houses to create healthy indoor environments. Finding the balance between how older people prefer to feel and what is best for their long term health is the difficult but necessary task that is faced when dealing with an increasingly ageing population both now and in the future.

7. Conclusion

Overall, this study finds a high degree of satisfaction with the thermal conditions in their home amongst the older cohort examined. The older people studied accepted and preferred much cooler temperatures than what would be expected in a healthy younger adult population as predicted by the thermal comfort standard such as ASHRAE 55. Whether this has to do with personal behaviours and attitudes or a general change in physiological perception of the cold is not able to be determined in this study at this stage, nor are any potential health impacts of this preference. Ultimately, a balance between the preferences of the older people concerned as well as the relationship between thermal environment and health will need to be struck in order to provide the best housing solutions for older people.

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