Environmental sustainability of prefabricated modular residential buildings compared to traditional equivalent: Two case studies in Perth, Australia.

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Abstract

The share of prefabricated modular residential buildings in the Australian construction market is growing mainly because they are quicker to erect on-site than traditional construction, and often cheaper; but how about their carbon footprint and more particularly their thermal performance?

To bring some light on this question, this paper uses two case studies where existing prefabricated modular buildings (a detached house and a multi-storey residential building) are compared to their equivalent in traditional on-site construction methods. The thermal performance is assessed using 3D modelling and energy simulation, while carbon footprint is assessed by Life Cycle Analysis.

The thermal simulations showed that these prefabricated modular buildings perform better in winter but the study also shows that low inertia modular buildings can require more cooling energy in the summer in certain climate zones. Looking at the overall carbon footprint of the construction elements, the LCA shows that prefabricated buildings are not always less carbon intensive than their traditional equivalent and a wise choice of materials remains a necessity.

The discussion emphasises the importance of the local context and particularly the role of thermal inertia in summer for Mediterranean Climate. It also demonstrates the importance of operating energy in the overall carbon footprint of a building and, more generally, how prefabrication can easily achieve a lower carbon footprint than on-site construction.

Keywords: Prefabricated, Modular, Carbon Footprint, Thermal Performance, Life Cycle Analysis, Energy Efficiency
1. Introduction

Globally, the construction industry is an important consumer of resources and producer of waste (40% of global resources and 40% of global energy according to the 2009 report from the United Nations Environment Programme), while at the same time, construction remains a necessity that grows inevitably with the population growth. The materials and the technology exist to reduce the environmental impact of buildings and early adopters such as Josh Byrne (Byrne, Eon & Newman 2014) have shown that building eco-friendly houses with minimal extra capital investment is possible, but this is not mainstream anywhere in the world and particularly not in Australia.

One solution to mainstream this performance lies in the industrialised construction method, also called off-site construction or simply prefabrication, which has been recognised a leaner and more efficient method of construction (D. Krug, 2013). This paper proposes to analyse the differences in operating energy and carbon footprint of two existing prefabricated modular residential buildings compared to Australian standard-practice equivalent using traditional on-site construction method. More specifically, a detached house and a multi-storey apartment block.

The literature review shows that a few researchers have already addressed the carbon and the energy embodied in the building itself (Monahan and Powell in 2001), and some have shown that operating energy is the most important part of the carbon footprint of a building (Aye et al. 2012). The approach of comparing a prefabricated modular building to a traditional building to assess the carbon footprint difference was found twice in the literature: A study in China (Cao et al. 2015) where the two buildings were of similar typologies but not equivalent; and in the USA (Kim 2008) where the modular house was compared to a traditional equivalent but of very similar specifications. This latter study focused on the difference in the carbon footprint of the construction process rather than on the building itself.

2. Background of the two case studies

The first case study looks at the Stella B17 building of the ADARA project designed and manufactured by the Hickory Group. It was one of the first prefabricated modular multi-storey residential buildings in Western Australia. The building is made of fully finished volumetric modules manufactured in its established Melbourne factory, and shipped to Perth. These modules are equipped with double-glazed windows and walls and floors are made up of steel frame. The floors also received a steel sheet and a plywood board. The building is also constituted of a concrete structure built on-site: the ground level car park and first level floor, as well as two cores integrating the lift shafts and staircases. The 96 modules were then piled up by crane to make 77 units on six floors. After this the façade elements were added to dress up this elegant building.

The second case study concerns a group of 22 houses from BGC Residential, prefabricated in its factory in Canning Vale (WA) and erected in Banksia Grove, a suburb North of Perth-metro. BGC Residential belongs to the BGC Group, a major player in the Australian construction industry, who decided a few years ago to start a pilot program to build prefabricated houses. The houses are made up of two or three fully finished modules made of steel frame walls and roof structure, and concrete slab for the floor. They were transported to site and delivered by truck without the need of a crane. The garage and the alfresco are the only elements of the house constructed on-site. The 22 houses are an arrangement of 2 or 3 modules making 7 concepts with different façade colours and orientations.
3. Methodology

3.1 Carbon footprint
In our case, the carbon footprint will be evaluated by calculating the GreenHouse Gases (GHG) emitted during the life of the building, from the extraction of its raw materials down to its deconstruction and transport to the landfill or recycling plant.

Life Cycle Analysis (LCA) is the method chosen here to estimate the amount of GHG of our modular buildings. The unit of measurement used in our LCA is the kilogram of CO2 equivalent per occupant per year of the life of the building, expressed as kgCO2eq/occ/y. This measures the Global Warming Potential (GWP) (US EPA 2013) of various impacts, and means the volume of GHG emitted by the building throughout its life.

The tool used to model the LCA was ETool, a software compliant to ISO14040 2006, ISO14044 2006, BS EN 15978 2011 standards.

For both the multi-storey building and the detached houses, all household energy consumption – beside heating and cooling – and all water consumption were assumed to be the same between the modular buildings and the traditional equivalents.

3.2 Operating Energy
The research being based on the comparison between two equivalent buildings from two different construction methods, the thermal performance of the buildings envelopes – and consequently the heating and cooling loads - are to be the most significant elements to study. Therefore, it was decided to give particular attention to these elements.

The buildings were first digitized as 3D models using Building Information Modelling (BIM) on CYPECAD MEP (from CYPE software. CYPECAD MEP then calculates the yearly heating and cooling demand, by hourly steps, using the EnergyPlus engine, a program developed by the U.S. Department of Energy. This is typically expressed as a function of energy per metre square (kWh/m2).

Weather conditions, from ASHRAE weather files, were factored into the thermal performance modelling to consider how the building will perform in a particular climatic scenario. Additionally, Internal comfort temperatures (set points) have been set to 21°C in winter and 24°C in summer.

The detailed load allowed to study the thermal behaviour of the building and extract important information to understand the yearly results. The yearly results – heating and cooling loads - were then introduced in eTool to estimate the GHG of this part of the operating energy of the buildings.

3.3 The traditional equivalent
For both the LCA and the Energy Simulation, the traditional equivalent was modelled using the specifications given by the respective builders which would correspond to standard-practice aiming at compliance. The equivalent of Hickory apartment block was modelled using concrete external walls without insulation, brick internal walls and single-glazed windows. The BGC modular house equivalents were modelled using double brick cavity external walls, single brick internal walls, thicker on-site poured concrete slab and terra cotta roof tiles on timber structure.

The windows specification did not change (single glazed). The air tightness of the modular and traditional buildings was considered the same.

This base methodology was used in the two case studies but because they happened at different times, the parameters and assumptions were not exactly the same.
3.4 Specificities of the Multi-storey building

The Hickory building, Stella B17, was the first one to be assessed with this method and it was modelled with all the expected internal loads (from the occupants’ bodies, the lighting and appliances) to simulate a building in occupation. In ETool, the occupancy calculator estimated an average occupancy of 124.45 persons in the whole building, and a design life of 150 years for both the modular building and the traditional equivalent.

3.5 Specificities of the detached houses

The BGC project came later and we decided that, for the purpose of a comparison, the houses could be considered without occupancy, thus modelled and simulated with no internal loads.

It was also decided to model and simulate the 22 modular houses for Thermal Performance (TP) but to take only best and worst performing modular houses to model their traditional equivalent for the comparison of TP. Finally, the best performing modular house was chosen to be compared with its traditional equivalent for the assessment of carbon footprint. In ETool, the occupancy calculator estimated an average occupancy of 2.83 persons per house and a design life of 70 years for both the modular house and the traditional equivalent.

4. Results and discussion

4.1 Multi-storey residential building

4.1.1 Heating and Cooling loads

The results for Perth Weather are represented in Table 1 below:

Table 1: Comparison of Thermal Performance of Stella B17 in Perth weather

<table>
<thead>
<tr>
<th></th>
<th>MODULAR</th>
<th>TRADITIONAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[MWh]</td>
<td>[kWh/m²]</td>
</tr>
<tr>
<td>Heating</td>
<td>26.59</td>
<td>4.94</td>
</tr>
<tr>
<td>Cooling</td>
<td>340.59</td>
<td>63.28</td>
</tr>
<tr>
<td>TOTAL</td>
<td>68.22</td>
<td>62.83</td>
</tr>
</tbody>
</table>

Unexpectedly, the modular construction is not performing as well as the traditional one despite the thermal insulation in the external walls and the double-glazed windows. These elements assist the thermal performance in winter but something is missing in summer. To understand what can explain this difference in cooling load, the same two buildings were simulated in different climate than the Class 4 “warm temperate” of Perth (Building Code of Australia (BCA)). They were simulated in Port Hedland, Class 1 “Hot humid summer, warm winter” and in Melbourne, Class 6 “Mild temperate”. The results are represented in Table 2 and Table 3 below:
Environmental sustainability of prefabricated modular residential buildings compared to traditional equivalent: Two case studies in Perth, Australia.

In both cases, the modular version performs better than the traditional. Heating being not required in Port Hedland the result is not significant for the comparison, but this time the cooling load is lower for the modular building. On the contrary, the thermal performance in Melbourne follows the same trend as in Perth (modular performing better than traditional in winter but worse in summer) even if the overall performance is, this time, to the advantage of the modular building.

These results lead us to analyse the particularity of the summer conditions in these three locations, and the two major differences were the humidity and the variance between night and day temperatures. The latter made us think that the lack of thermal inertia in the modular building compared to the all-concrete (walls and floors) traditional equivalent didn’t allow to make the most of the lower nocturnal temperatures in Perth and Melbourne.

This hypothesis was verified by simulating internal walls made of bricks and finding 8% reduction in cooling load. The approach of using bricks in the modular building to increase thermal mass is technically feasible but not workable in terms of the construction process, cost and transport. The second factor that influences cooling energy demand is solar gain, which is the amount of heat that penetrates inside the building through the windows. Reducing solar gain can easily be achieved by tinting the windows as shown in Table 4 below. In summer, solar rays penetrate the building the most when the sun is the lowest in the sky, at sunrise and sunset, through the east facing and the west facing sides of the building.

Table 2: Thermal performance of Stella B17 in Port Hedland compared to Perth

<table>
<thead>
<tr>
<th>MODULAR</th>
<th>PERTH [MWh]</th>
<th>[kWh/m²]</th>
<th>PORT HEDLAND [MWh]</th>
<th>[kWh/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>26.59</td>
<td>4.94</td>
<td>0</td>
<td>0</td>
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<tr>
<td>Cooling</td>
<td>340.59</td>
<td>63.28</td>
<td>1113.22</td>
<td>206.83</td>
</tr>
<tr>
<td>TOTAL</td>
<td>68.22</td>
<td></td>
<td>206.83</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TRADITIONAL</th>
<th>PERTH [MWh]</th>
<th>[kWh/m²]</th>
<th>PORT HEDLAND [MWh]</th>
<th>[kWh/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>39.78</td>
<td>7.39</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Cooling</td>
<td>298.39</td>
<td>55.44</td>
<td>1175.65</td>
<td>218.43</td>
</tr>
<tr>
<td>TOTAL</td>
<td>62.83</td>
<td></td>
<td>218.43</td>
<td></td>
</tr>
</tbody>
</table>

Table 3: Thermal performance of Stella B17 in Melbourne compared to Perth

<table>
<thead>
<tr>
<th>MODULAR</th>
<th>PERTH [MWh]</th>
<th>[kWh/m²]</th>
<th>MELBOURNE [MWh]</th>
<th>[kWh/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>26.59</td>
<td>4.94</td>
<td>182.84</td>
<td>33.97</td>
</tr>
<tr>
<td>Cooling</td>
<td>340.59</td>
<td>63.28</td>
<td>119.16</td>
<td>22.14</td>
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<td>TOTAL</td>
<td>68.22</td>
<td></td>
<td>56.11</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>TRADITIONAL</th>
<th>PERTH [MWh]</th>
<th>[kWh/m²]</th>
<th>MELBOURNE [MWh]</th>
<th>[kWh/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heating</td>
<td>39.78</td>
<td>7.39</td>
<td>268.20</td>
<td>49.83</td>
</tr>
<tr>
<td>Cooling</td>
<td>298.39</td>
<td>55.44</td>
<td>83.53</td>
<td>15.52</td>
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<tr>
<td>TOTAL</td>
<td>62.83</td>
<td></td>
<td>65.35</td>
<td></td>
</tr>
</tbody>
</table>

In both cases, the modular version performs better than the traditional. Heating being not required in Port Hedland the result is not significant for the comparison, but this time the cooling load is lower for the modular building. On the contrary, the thermal performance in Melbourne follows the same trend as in Perth (modular performing better than traditional in winter but worse in summer) even if the overall performance is, this time, to the advantage of the modular building.

This hypothesis was verified by simulating internal walls made of bricks and finding 8% reduction in cooling load. The approach of using bricks in the modular building to increase thermal mass is technically feasible but not workable in terms of the construction process, cost and transport. The second factor that influences cooling energy demand is solar gain, which is the amount of heat that penetrates inside the building through the windows. Reducing solar gain can easily be achieved by tinting the windows as shown in Table 4 below. In summer, solar rays penetrate the building the most when the sun is the lowest in the sky, at sunrise and sunset, through the east facing and the west facing sides of the building.
Table 4: Thermal Performance of the modular building with East and West windows tinted

<table>
<thead>
<tr>
<th></th>
<th>MODULAR TEST 4</th>
<th></th>
<th>TRADITIONAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[MWh]</td>
<td>[kWh/m²]</td>
<td>[MWh]</td>
</tr>
<tr>
<td>Heating</td>
<td>26.59</td>
<td>4.94</td>
<td>33.37</td>
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<tr>
<td>Cooling</td>
<td>340.59</td>
<td>63.28</td>
<td>280.36</td>
</tr>
<tr>
<td>TOTAL</td>
<td><strong>68.22</strong></td>
<td><strong>58.29</strong></td>
<td>39.78</td>
</tr>
<tr>
<td></td>
<td>298.39</td>
<td>55.44</td>
<td></td>
</tr>
</tbody>
</table>

This low cost and easy fix solution improved drastically the performance of the building in summer though it reduced slightly its performance in winter.

4.1.2 Carbon footprint

The Figure 1 below shows the carbon footprint, expressed as Global Warming Potential (GWP) of the modular building compared to the traditional equivalent:

![Figure 1: GWP over the whole life of Stella B17 Modular vs Traditional equivalent](image-url)

The GHG from the building elements (foundations, envelop, fit-out, appliances, building services…) happen only once, at the construction stage, and their carbon footprint is broken down through-out the life of the building. However, the GHG from the production of the operating energy and water used during the life of the building happen every year. This graph reveals that over the life of a building, the impact of the operating energy, dominated by heating and cooling, is predominant in the whole carbon footprint of the building.
To better visualise the differences in construction between modular and traditional, we have removed from the graph the operating energy and water, as shown in Figure 2 below:

Looking at all the materials and services involved in fabricating, transporting and erecting these buildings, the modular building has a carbon footprint 6% more than it’s equivalent in traditional construction. To better understand this situation, the next graph Figure 3 shows the same comparison but this time focusing on the elements of the buildings that are different between the two construction methods:

In this graph, we have removed elements similar to the two buildings and we see that steel frame, plywood and bathroom structure; all three specific to the modular construction, account for 30% of these selected materials and services. The modules’ structure is made of steel frame and steel sheets for the floors (aggregated under “Steel frame” in the graphs). Moreover, this modular building uses quite a lot of concrete for the ground floor and the two cores. Consequently, the carbon footprint of the structural elements of the modular building is higher that the concrete used in the traditional equivalent.

In a second order comes the additional carbon footprint of the double-gazing and the insulation in the walls, but these elements participate to reducing the operating energy which, as we saw, is more important than the carbon footprint of construction materials. Finally, the transport of the modules, from Melbourne to Perth for that particular project, also add to the overall deficit of the modular building.
For this particular project and without changing drastically the original design, one of the low hanging fruits would be to replace carbon intensive materials with a mainstream low carbon equivalent. For example, replacing the carpets with a timber floor.

### 4.2 The detached houses

#### 4.2.1 Heating and Cooling loads

The 22 modular houses were modelled, along with their next neighbouring buildings to simulate the shadow, to calculate the heating and cooling loads for Perth weather.

The best and worst performing modular houses, number 21 and 12, were selected to be compared to their traditional equivalent (after modelling them) as shown in Table 1 below.

<table>
<thead>
<tr>
<th>Construction</th>
<th>House #</th>
<th>HEATING [kWh/m²]</th>
<th>COOLING [kWh/m²]</th>
<th>TOTAL [kWh/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modular</td>
<td>21</td>
<td>35.57</td>
<td>4.18</td>
<td>39.75</td>
</tr>
<tr>
<td><strong>Traditional</strong></td>
<td>21</td>
<td>61.63</td>
<td>1.73</td>
<td>63.36</td>
</tr>
<tr>
<td>Modular</td>
<td>12</td>
<td>42.06</td>
<td>5.44</td>
<td>47.50</td>
</tr>
<tr>
<td><strong>Traditional</strong></td>
<td>12</td>
<td>65.53</td>
<td>1.87</td>
<td>67.40</td>
</tr>
</tbody>
</table>

The added insulation of the modular houses (in the walls) helps contain the heat better in the winter and requires less energy to keep the house at 21°C. From Table 1 we see that house 21 modular requires 42% less energy in winter than its equivalent in traditional construction and house 12 modular 36% less than traditional. Both constructions benefit from a concrete floor slab and have similar low inertia ceilings, but the traditional house has a heavier thermal inertia thanks to its brick walls (external and internal) compared to the light steel-frame construction of modular. This added inertia helps retain the coolness of the night in summer, hence requiring less energy to keep the house at 24°C. From Table 1 we see that house 21 traditional requires 59% and house 12 traditional 56% less energy in summer than its equivalent in modular construction. Though this lower performance in summer has a minimal impact on the overall annual energy load.

#### 4.2.2 Carbon footprint

Figure 4 below shows the carbon footprint, expressed as Global Warming Potential (GWP) measured in kgCO2eq/occ/y, of the modular house #21 compared to its traditional equivalent:
As for the multi-storey building, the carbon footprint of operational energy is dominant in the life cycle assessment of the building.

Again the operating energy and water are removed from the graph Figure 5 in order to better visualise the differences in construction between modular and traditional:

Looking at all the materials and services involved in fabricating, transporting and erecting these two houses, the modular building has a carbon footprint 26% less important than it’s equivalent in traditional construction. The next graph Figure 6 shows the same comparison but this time focusing on the elements of the houses that are different between the two construction methods:

In this graph, we have removed elements similar between the two houses. We observe that the mineral-based construction elements of the traditional house, namely the concrete, the roof tiles, the bricks and the mortar, account for the major part of the difference between modular and traditional constructions. These are carbon intensive materials mainly due to their energy intensive fabrication process. A focus on the roof shows that despite the fact that the timber structure of the traditional house is three times less carbon intensive than the steel-frame of the modular house, the weight of the terra cotta roof tiles makes this carbon intensive element predominant in the roof category.
Additionally, the People & Equipment category is 29% less carbon intensive for modular. That is because modular benefits from an industrialised fabrication process involving less staff and less equipment. For example, the prefab concrete slab takes less staff than the traditional slab with on-the-spot custom-made formworks. Steel roof structures are easier to assemble in a factory than timber structures on-site, and the same can be said for the steel structure of the walls compared to the on-site erection of traditional walls brick by brick or the use of plasterboards versus hand laid plaster for finish. But more importantly, the fabrication and installation process of modular being 126 days shorter than for traditional, that is 126 round trips the staff doesn’t have to make to work on this one house, hence less carbon emissions from their vehicles. For this particular project and without changing drastically the original design, the modular house could improve its carbon footprint even more by adopting a prefabricated roof structure made of timber trusses.

5. Conclusion and lessons learned

Other studies have looked at different factors of sustainability between modular and traditional construction, such as construction waste, embodied energy, construction time and cost. These two case studies comparing two similar buildings of two different construction methods teach us some lessons from the thermal performance and carbon footprint perspective.

On the thermal performance:

1. If the lighter construction of modular buildings has many advantages, it also represents in general a weak point for the thermal performance in summer.
2. More specifically, this weakness is particularly impacting the high-rise building typology rather than the low-rise house typology, because of the higher window area and compactness. Indeed, multi-storey buildings are less shaded by eaves and surrounding built or natural environment. Moreover, compared to a house, average units tend to have less surfaces in contact with the exterior (heating load) and still a fair amount of glazing (cooling load).
3. But thermal inertia is beneficial to summer thermal performance only when night temperatures drop low enough below day temperatures. The thermal performance results of the multi-residential building in the 3 different climate zones showed us that there were significant differences. The lesson to draw is consideration of the local context is necessary.
4. That same case study also showed that solar gain is a key to easy thermal performance improvement and should be considered right from design stage to limit cost and ensure elegant integration of solar design.

On Carbon footprint:

1. Operating energy is a predominant element of the carbon footprint of a building in its life cycle. Unless the building is near passive house standard (i.e. close to zero operating energy from heating and cooling), then operating energy is the low hanging fruit to reduce Global Warming Potential of buildings over their life time.
2. Consideration of the carbon intensity of materials should be given right from the design stage to allow for exploration of environmentally friendly alternatives at minimum, if not zero, extra cost.

These lessons are the result of the study of these 2 particular projects and further research is necessary to refine and generalise this knowledge.

The author believes that off-site construction can offer a real advantage over on-site construction when it comes to carbon footprint and operating energy; while still retaining the other more outspoken benefits (waste, time ...).

The manufacturing process of off-site construction being more repetitive and controlled than on-site construction, it naturally welcomes continuous improvement. Therefore, off-site construction
appears to be the key to achieve the evolution required from the building sector to play its role in reducing the national level of GreenHouse Gas emissions in line with the target set recently in Paris (COP21).

The Hickory group has embraced continuous improvement from the start, both for their manufacturing process and their products. They learned very quickly from the Stella B17 experience and the next generation of modules was already designed to achieve better summer performance and use less carbon intensive materials.

To take this topic further, the author has engaged in a doctoral research to identify and define the links between off-site construction and operating energy.

6. References


7. Annexes

Annexe 1 Architect view of Hickory's Stella B17 building

Annexe 2 3D Model for Thermal Performance Simulation
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Annexe 3 Lay out of the 22 modular houses

Annexe 4 Street view of a BGC modular house
Annexe 5 Model of a modular house for Thermal Performance Simulation