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The role of post occupation evaluation in achieving high performance buildings through diagnostics

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Abstract

Buildings are major consumers of energy for heating and cooling. The number of buildings is growing rapidly with demand for energy. To reduce consumption, governments worldwide have implemented codes, standards, and building practices. In New South Wales, Australia the planning department introduced a web-based energy-modelling tool intended to increase the thermal performance of the residential building's envelope prior to development applications. The modelling tool, Building Sustainability Index (BASIX) was introduced in 2004. Building codes and standards in them selfs are not perfect instruments but guidelines to achieve building objectives.

However, there is evidence in literature stating that buildings are not achieving the predicted results in thermal performance leading to increased energy consumption. This research looks into the predicted modelling aspects to the BASIX program for thermal performance and undertaking a diagnostic study in verifying the building envelope meeting its objectives. This study considered the building envelope the key factor in thermal performance, in which building practices may undermine codes and standards delivering sub-optimal performance. The research justifies the need for diagnostics as a tool to evaluate building practices in reducing the performance gap between the modelled and the delivered results. This would provide building professionals, and government bodies in understanding and addressing the cause of performance gaps between the predicted and actual results for thermal performance in future buildings.

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Keywords: Building envelope; diagnostics; thermal performance

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1. Introduction

Buildings are major consumers of energy, especially for mechanical heating and cooling of the built environment [1]. To achieve high-performing buildings the technology of building materials has advanced with the aim of increasing the thermal performance of the building envelope. With the advancement of technology, government bodies globally are also introducing new codes and standards to achieve better performance. The building envelope is the key factor in reducing energy consumption while also achieving thermal comfort.

In Australia, development applications in most states require that accredited modelling software's be used prior to building application at the local council for thermal performance. The modelling tool needs to achieve a set target for heating and cooling loads in order for the building application to proceed. In the state of New South Wales, prior to submission of the development application to the local council, the design has to fulfil the requirements of the Building Sustainability Index (BASIX) web-based tool for thermal performance. The BASIX tool was launched in 2004. Further to BASIX requirements, the building needs to meet the guidelines of the Building Code of Australia (BCA) for building sealing in the construction process. The BASIX tool can be used by the homeowner in the Do It Yourself (DIY) mode or by a certified energy assessor.

In spite of the rigorous requirements, there is growing concern that buildings are not achieving the thermal performance as designed at the post occupation stage [2, 3]. Wray, Walker, Siegel, and Sherman [4] states, California in the United States of America (USA) has one of the most advanced energy codes in the country. In spite of this, houses still do not perform optimally. The modelling results are heavily relied as the optimal performance of the building, and when buildings are completed, it is rarely verified against the modelled criteria. There are limited information of actual case studies of buildings in Australia verifying the results of the post occupation thermal performance for thermal irregularities and other attributes contributing to increased energy use.

Insulation in walls and ceilings forms part of BASIX requirements for thermal performance. Sub-standard on-site practices in insulation installation can significantly reduce the thermal performance of the building. Thermal irregularities are the results of missing and gaps in insulation. Publication by Mosher and McGee of Your Home [5] indicates that small gaps in insulation can reduce the overall R-Value. Thermal irregularities are also the results of thermal bridges, direct connection of materials between the exterior face to the interior wall, gaps between the insulation and the framing structure of timber and steel, which can reduce the thermal performance of the building envelope [6, 7].

Building sealing is a requirement not modelled in the BASIX program, but referred to meet the requirements of the Building Code of Australia (BCA). There is no method of measurement that can be uniformly stated across the building sector in validating the extent of sealing, it is based on professional judgement. If air sealing cannot be measured, then thermal performance of the envelope cannot be managed efficiently. McGee [8] states that air leakage accounts for 15-20% heat loss in winter and a significant coolth loss during the use of air conditioners.

The current setback in achieving post occupation verification can be invasive and destructive. Most of the features of a building envelope that make a home thermally efficient are hidden within the walls. Homes have excess panels on the ceiling to inspect the attic, and some areas can be overlooked due to constricted spaces. There are homes that the ceiling cannot be checked due to the ceiling lying on the same plane of the roof, and the insulations sandwiched in-between. The present destructive nature would deter validation of the building envelope against the modelled outcomes and also lead to wastage and damage to the existing structure. A great amount of energy could be saved if the building quality can be diagnosed non-destructively and rectify any discrepancies for thermal performance to match the design and modelled outcomes. Energy efficiency in buildings is becoming a mainstream requirement and should be meticulously scrutinised for proper compliance.

Thermal irregularities and reduced infiltration are not tangible attributes that can be visually observed when buildings are completed. It is difficult for homeowners or governing bodies to determine if the thermal requirements in the built stage have been achieved. In most cases, the measured energy consumption is taken as the determinant factor in verifying the performance of the building envelope, which can lead to bias results. For example, two similar houses, House A with poor thermal envelope may use less energy due to occupant behaviour and of the lower socio economic group, concerned with increasing energy costs, compared to House B, which is a better thermal performing envelope of a higher socio economic group with the increased use of space heating and cooling. Based on the energy consumption results between House A and House B, it may indicate that House A has better thermal

performance. Therefore, the building envelope needs to be validated against the built quality for thermal performance in achieving the intended targets of the BASIX goals for the lifespan of the building.

With increasing demand for better thermal performance of the building envelope, the construction sector is faced with the greater challenge in delivering the design expectations at the post occupation stage [9]. Achieving high performing building requires a multi- disciplinary approach from all building professionals involved in the construction of the building [10]. The International Energy Agency [11] states that quantifying the actual performance and achieving positive energy buildings can only be effectively realised by in-situ testing. Lerum [12] also states that numerous buildings by highly acclaimed architects use two to three times more energy against the predicted values. He further states that it is not about stricter regulations; it is more about the actual performance. The final performance of the building cannot be measured by the theoretical results and high-energy ratings. It is the design, modelling and ultimately the quality of the completed building that delivers high-performing goals. According to the BASIX's help notes, the thermal loads of a building is based on the dwelling's construction and insulation, including floors, walls, ceilings and roof. This indicates that the built quality is an important contributing factor in the thermal performance requirements and needs to be validated.

The aim of this research is to diagnose any discrepancy between the modelled attributes of BASIX tool against the completed building at post occupation stage by using non-destructive diagnostic tools to verify the integrity of the building envelope for thermal irregularities. The research would provide important knowledge of present buildings in understanding the extent of reduced infiltration required by the Building Code of Australia (BCA). The BASIX tool does not model air infiltration generally referred as building sealing, instead refers to the requirements of the BCA in building sealing. There are no set levels of building sealing requirements in the BCA just professional judgement.

1.1. Building diagnostics

Diagnostic is an ancient concept used in the health care sector in diagnosing the root cause of health problems. The same concept with advancements in instrument technology can now be efficiently used in the built environment in diagnosing building quality. It is also a systematic approach in investigating building failures [13]. Building diagnostics can become a mainstream concept in verifying defects of the building envelope for thermal performance [14, 15] and can be used efficiently with minimum time and costs. The concept would not only diagnose building defects but would send a strong message to building professionals to deliver quality-building practices due to possible audits in built quality. The diagnostic equipment consists of a high-performance infrared camera and fan pressurisation equipment known as a blower door. The infrared camera used, is a FLIR B660 especially designed for building use with 680 x 480 pixels and an accuracy of $\pm 1^0$ C or ±1% of readings. The blower door is a Retrotec 3000 series software driven to comply with EN 13829 (Thermal performance of Buildings-Determination of Air Permeability of Buildings-Fan pressurization method 2015).

1.2. Factors affecting thermal performance

The study focuses on the building envelope and the factors contributing to energy consumption based on Fig.1. Appliances, including lighting, water heater, HVAC and fenestration have their set energy performance ratings and consumption levels set by the manufacturer, which is beyond the control over the building professionals in altering the ratings or consumption.

The attributes of the building envelope such as infiltration, built quality, thermal bridges and insulation are all relied upon by the building professional's expertise in constructing them together to achieve optimal thermal performance. Insulation is installed with an energy rating, which is an R-Value, but can change due to poor built quality in the construction processes.

The building envelope with increased infiltration will have an effect on thermal performance due to the following:

a) Cold draughts in winter exacerbated by the stack effect in drawing cold air from the lower parts of the house as warm air rises.
b) Increasing air-conditioning loads especially demand load caused by stop start cycle due to infiltration air.
c) Increased latent cooling due to infiltration bringing in humid air in the warm season.
d) Loss of energy through exfiltration.

Buildings modelled in BASIX require a follow through in the construction process in meeting the theoretical objectives in the practical stage. Achieving optimal thermal performance of the building envelope is the results of building quality by on site building professionals in reducing gaps causing thermal irregularities, considering and mitigating steps to avoid thermal breaks and reducing infiltration. Achieving these would reduce the heating and cooling loads required by the occupants resulting in better thermal performance of the building envelope.

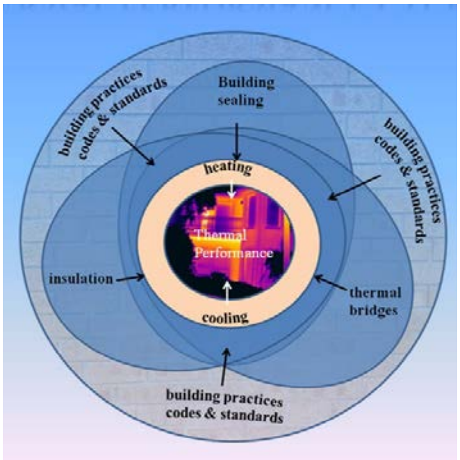


Fig.1. Thermal performance cycle.

1.2. Building thermal performance diagnostics to inform BASIX assessment

1.3.

There is growing evidence that buildings are not performing as modelled, creating a performance gap Fig.2. The performance gaps refer to the disparity between the modelled building and the completed building for thermal performance. When buildings are modelled in BASIX, it is assumed that the completed building resembles the modelled outcome. Most of the attributes relating to thermal performance are concealed, such as insulation, thermal breaks and infiltration, which are not visible for building certifiers to verify. This assumes that the building has fully complied with BASIX requirements. Poor monitoring and feedback from the post occupation stage, results in defects being unknown and jeopardises future improvements to the modelling tool, related codes and standards. Performing diagnostic investigation, anomalies related to thermal performance will be verified so that decisions can be made to provide optimal thermal performance to future buildings.

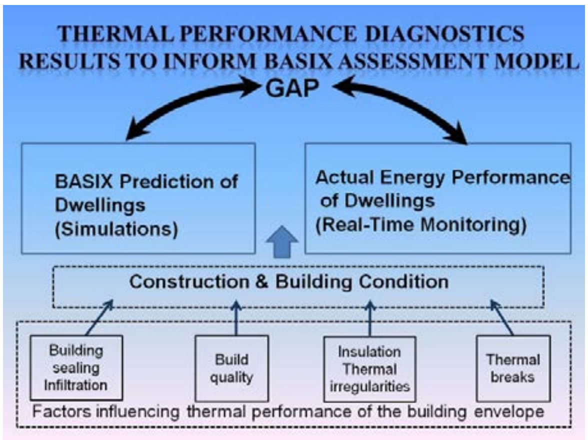


Fig.2. The performance gap

2. Development of a diagnostic model for thermal performance assessment of the building envelope

2.1. Identification of key variables

The attributes in the key variable chart may have an effect individually or jointly in changing the thermal performance outcomes. The building envelope serves the main function in maintaining a comfortable environment to the occupants. The attributes are listed in Fig. 3 the key variables chart.

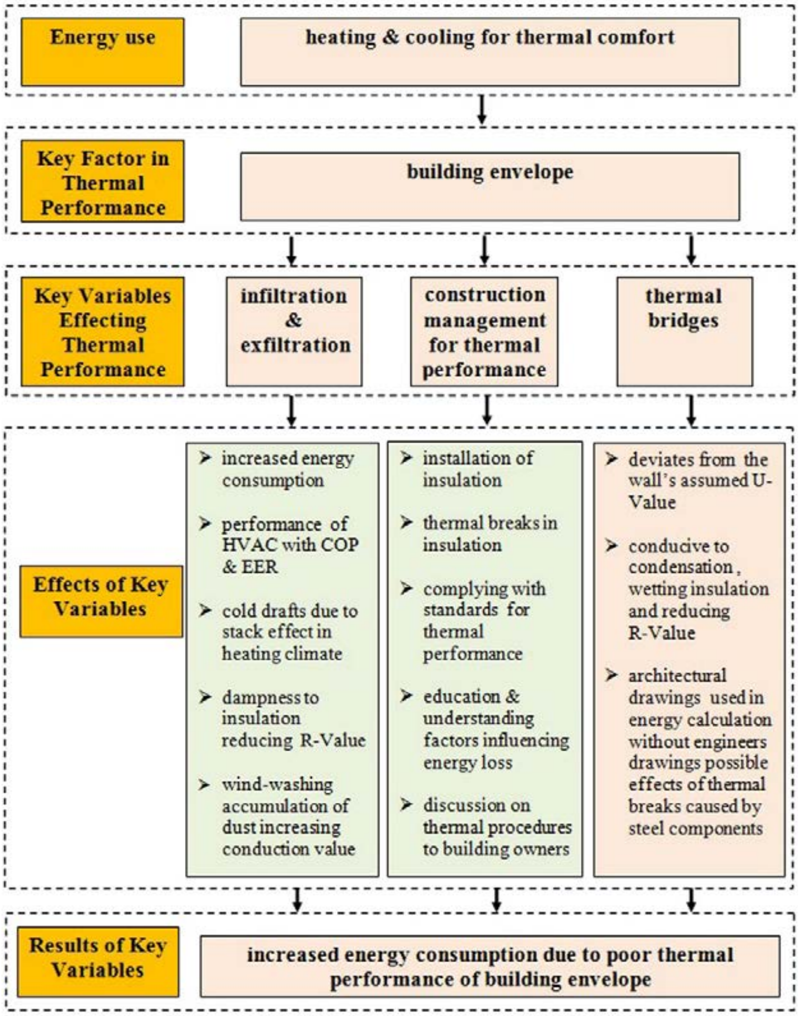


Fig.3. Key variable chart

2.2. The diagnostic methodology

The diagnostic methodology Fig.4 considered four houses as part of this study. The diagnostic procedure included infiltration testing which is air sealing, verifying thermal irregularities in insulation, thermal breaks and building a data base of the floor, windows and wall area.

The infiltration test would be performed using a blower door, which will measure the air leakage of the whole

house. The building will be depressurised at 50 Pascal to measure the Air Change per Hour (ACH_{50}) following the guidelines of the European Standards, EN 13829 (Thermal performance of buildings-Determination of air permeability of buildings-Fan pressurization method 2015). Thermal irregularities would be qualitatively analysed using a high-end thermal camera FLIR B660 on the walls and ceiling. The floor, windows and wall area would be extracted from the drawing and recorded in a database.

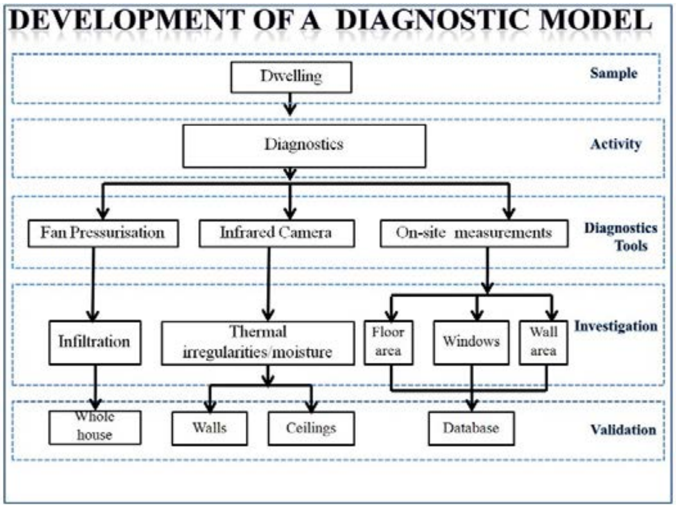


Fig.4. Diagnostic methodology

3. Diagnostic and analysis of four BASIX compliant dwellings

3.1. Data collection

The four homes selected are slab on ground brick-veneer, timber framed and internal plasterboard lining, a common construction method in Australia. The roof covering is of concrete tiles with radiant barrier. The houses are located in the western part of Sydney. The house numbers are in no particular order and from a larger database. The house numbering refers to their respective file name and listed accordingly. House 5 is a two storey in Penrith, House 8 is a single storey in Emu Plain, House 15 a two storey in The Ponds and House 25 a two storey in Penrith.

The diagnostic investigation was undertaken during the summer month of January. Summer is the warmest period of all seasons which will result in greater thermal movements within the building envelopes from the exterior into the interior due to reduced environmental conditions such as excessive wind and heat source within the internal space. Generally, occupants try to maintain a comfortable temperature compared to the warm exterior in summer. The lower internal temperature and wind free environment, which otherwise would have a cooling effect on the surface, thermal patterns of the wall and ceiling will be clearly visible, especially due to solar heat gain. The ceiling would produce a larger thermal pattern due to the horizontal nature of the roof to the sun receiving high levels of solar heat gain.

Thermal imagining can be undertaken in winter, preferably late in the night at the exterior where heat is travelling out of the building envelope. Due to security and privacy reasons, this option was not considered. Cool breezes on the building envelope at night can also provide bias results to the thermal camera. During autumn and spring the temperature differences between the interior and exterior is minimal, which would reduce the thermal movements.

The blower door test was done simultaneously to reduce site visits. Blower door test can be performed in all seasons except in extreme windy conditions, which may affect the results. In this study, the conditions were within the requirements of the respective standards in performing blower door tests.

A high end thermal camera FLIR B660 was used with a wide-angle lens to record maximum amount of depth of the surfaces. The blower door was a Retrotec 3000 series with a hard panel assembly to reduce site time. The

weather conditions were measured with a Testo 417 Rotating Vane Anemometer. The anemometer records the temperature, wind speed and relative humidity in-situ prior to testing. The pre-test results listed in Table 1 were within guidelines in performing the diagnostic study. Temperature and humidity sensors were also placed in the test homes to obtain data in comparison with the external. The external temperature was obtained from the local weather station. Sensors were placed in the electric distribution board to gather usage data of the air-conditioning system.

Table 1. Pre-test results.

Test house	Average Indoor Temperature/(°C)	Outdoor Temperature /(°C)	Wind speed /(m/s)	Relative Humidity/(%)
House 5	24	26	4.8	58
House 8	26	29	5.0	57
House 15	25	29	4.5	60
House 25	25	29	4.8	58

3.2. Results of the sensors

The predicted modelling and actual results of energy consumption for thermal comfort varied greatly within the four test houses. The results are shown in (Fig.5). Predicted data was not available for House 5, however, it consumed higher energy. The results are based upon a cooling period for six months from October to March.

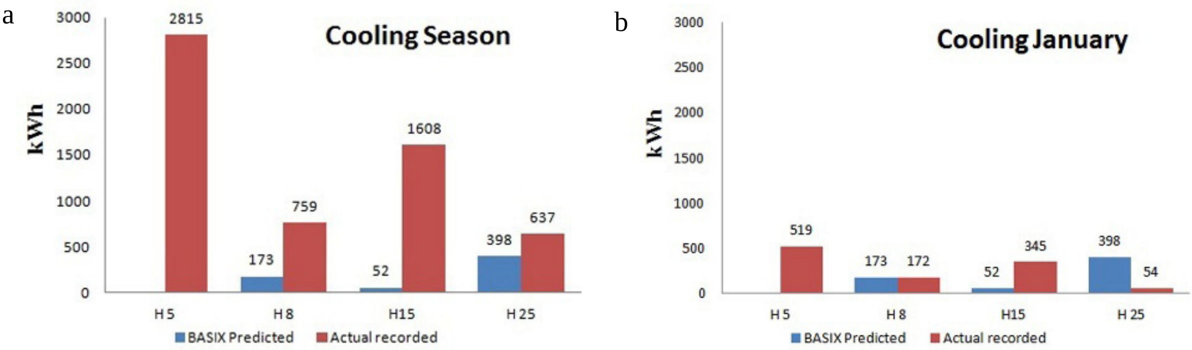


Fig.5. (a) Cooling season energy consumption; (b) January energy consumption

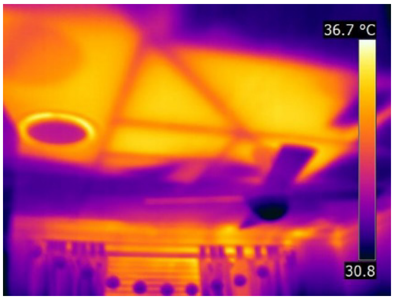
The energy consumption for January in some test homes almost reached the seasonal cooling load allowed in the modelling software (Fig.5). January, in which the diagnostic study was performed, had cooler periods than warm. In spite of this, there were high levels of mechanical cooling in some test homes.

3.3. Results of thermal irregularities

The thermal imaging Fig.6 indicates poor quality of insulation management consistent in all homes, including walls and the ceilings. The thermal patterns on the ceiling and walls should be homogenous as designed and modelled with some minor changes within the ceiling joists and wall studs due to thermal breaks but in this instant, there are large inconsistencies. The temperature of the internal and external of the houses as recorded is listed in (Table 1). Temperature variations at the ceiling and walls ranged from a low 25.4^{0}C to a high of 41^{0}C.

The homes indicate that thermal irregularities are present on the walls and ceiling reducing the thermal performance of the building envelope. The areas of high thermal patterns are an indication of sub–standard practices in insulation management and in some areas, thermal breaks.

a



b

Fig.6. (a) Thermal irregularities at ceiling; (b) Thermal irregularities at walls and ceiling

3.4. Results of blower door

The blower door test resulted in leakage of homes tested at ACH_{50} with various results from 8.96 to 12.6 air changes per hour Table 2, which also included the building data. International guidelines are well below these results.

Table 2. Blower door testing.

Test house	Average/ (m^2)	Total Envelope area/ (m^2)	Fenestration area/ (m^2)	Building volume/ (m^3)	Air change rate per hour @ACH_{50}
House 5	435	420	70	1044	11.97
House 8	180	250	33	432	8.96
House 15	248	308	51	595	12.6
House 25	231	278	35	554	10.33

3.5. Summary of findings

This study indicates that all test homes have large heat gain through ceilings and some walls. Insulation in the attic space is critical as temperature can reach in excess 50^0C. All test homes have sub-standard quality of insulation within the ceiling space. The ceilings and some areas of the walls are producing increased levels of heat and performing as a radiant heater in the warm summer months. Areas of lighting, air-conditioning supply vents and exhaust fans have insulation removed and displaced. The thermal images also indicate greater heat transfer at the cornice of exterior walls. This is due to the insulation not crossing the top plate in the ceiling area but rather stops short, allowing greater heat transfer from the roof tiles to the wall plate which is transferring the heat to the cornice area.

Some walls in the test homes are of cladding observed in House 25 (Fig.6b). Insulation placed in the cladding walls seems to have the same R-Value of insulation as the brick-veneered area. Insulation placed within cladding walls should have higher R-Value to compensate for the increased heat transfer. Thermal bridges of the test homes are at minimal, mostly caused by the timber framing which may have a small impact on energy consumption. Reducing cluster studs by changing the design is an option in reducing thermal bridging.

Based on the global infiltration practices, there is room for further tightness in homes built in New South Wales. Air leaks were notable within the electric power points of all homes at an average of 1m/s (meter per second) when depressurised at 50 Pascal. Large air leaks were also observed at the inter-leading door between the garage and the main dwelling. Further research would be required to establish a safe level of infiltration, balancing energy and indoor air quality.

Air-conditioning duct leaks within the attic space can have a significant impact on energy use. Thermal images of the ceiling indicate cold spots which may be related to duct leaks. This would require further research in establishing the level of tightness of the air-conditioning duct, and the impact on energy due to coolth loss.

4. Conclusion and future work

The goal of this study meant to establish if diagnostic can be used to verify any inconsistencies in the building envelope leading to poor thermal performance, undermining the codes and standards. It is shown throughout this study that diagnostics can be used successfully in verifying the thermal performance of the building envelope at the completion stage and can be used efficiently with minimum time and costs.

BASIX cannot control the construction of the building but provide the ground work in achieving thermal performance. Building professionals in command of projects have to pay greater attention to details in delivering better build quality. During the project cycle, the build quality for thermal performance would require close attention in managing infiltration, insulation and thermal breaks associated with thermal performance. Buildings are put together by complex elements and by various building professionals. There is no specific trade relating to energy efficiency but put together by all building professionals the key stakeholders in the thermal performance journey. To achieve high-performing buildings, training and education is the key to success. Training and education, especially in the area of infiltration, the impact of insulation by all building professionals and aspects of thermal bridging should be of high priority. Random auditing of buildings for build quality should be part of the BASIX requirements. In order to have a greater understanding of the built environment, future work will include in-depth analysis of more BASIX compliant dwellings through diagnostics.

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