Analysis of the design-construction supply chain in the thermal performance of sub-tropical and tropical housing

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Abstract

Background: In sub-tropical and tropical Queensland, a legacy of poor housing design, minimal building regulations with few compliance measures, an absence of post-construction performance evaluation and various social and market factors has led to a high and growing penetration of, and reliance on, air conditioners to provide thermal comfort for occupants. The pervasive reliance on air conditioners has arguably impacted on building forms, changed cultural expectations of comfort and social practices for achieving comfort, and may have resulted in a loss of skills in designing and constructing high performance building envelopes.

Aim: The aim of this paper is to report on initial outcomes of a project that sought to determine how the predicted building thermal performance of twenty-five houses in subtropical and tropical Queensland compared with objective performance measures and comfort performance as perceived by occupants. The purpose of the project was to shed light on the role of various supply chain agents in the realisation of thermal performance outcomes.

Methodology: The case study methodology embraced a socio-technical approach incorporating building science and sociology. Building simulation was used to model thermal performance under controlled comfort assumptions and adaptive comfort conditions. Actual indoor climate conditions were measured by temperature and relative humidity sensors placed throughout each house, whilst occupants' expectations of thermal comfort and their self-reported behaviours were gathered through semi-structured interviews and periodic comfort surveys. Thermal imaging and air infiltration tests, along with building design documents, were analysed to evaluate the influence of various supply chain agents on the actual performance outcomes.

Results: The results clearly show that in the housing supply chain – from designer to constructor to occupant – there is limited understanding from each agent of their role in contributing to, or inhibiting, occupants' comfort.

Keywords: building simulation, housing, post-occupancy evaluation (POE), subtropical and tropical climates, thermal comfort

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1. Background

The minimum energy performance standards set by the Australian Nationwide House Energy Rating Scheme (NatHERS) and incorporated into the National Construction Code (NCC) aim at reducing the heating and cooling energy demand of the residential sector (NatHERS, 2011). The intent of the regulations is to enhance the thermal efficiency of the building envelope in order to minimise the necessity for using appliances to add or extract heat from the internal environment to meet particular comfort needs of occupants. Building simulation software provides a means of taking a lot of the guess work out of predicting the likely space heating and cooling requirements of any particular design in any climate zone. The software protocols adopted by NatHERS allow for a comparative evaluation of different designs in the same climate, or the same design in different climates.

The pervasive reliance on air conditioners for comfort has changed cultural expectations of comfort and social practices for achieving comfort and impacted on building forms (Healy, 2008). A major challenge facing Queensland housing is that a legacy of poor housing design, minimal building regulations with few compliance measures, an absence of post-construction performance evaluation and various social and market factors has lead to a high and growing penetration of, and reliance on, air conditioners to provide thermal comfort for inhabitants. This has placed extreme pressure on the electricity distribution system and contributed to significant rises in the price of electricity (Energex, 2011). These issues were recently explored in a specific subtropical Queensland context showing disparity between inhabitant expectations of the internal thermal environment, design intent and actual building performance (Miller, 2012a), the importance of regulation, design and ethical professional practice in achieving high performance outcomes (Miller, 2012b), the synergies between building performance outcomes and urban design (Miller, 2012c) and the value of holistic systems thinking in performance optimisation (Miller, 2012d).

A second challenge for Queensland housing is the changing climate which is expected to significantly increase the number of extreme heat days. Heat events have killed more people than any other natural hazards experienced in Australia over the past 200 years, and Brisbane (the state’s capital) as already experienced significant deaths in heat events. Modelling of the mid range climate change scenario suggests significantly increased rates of mortality and morbidity than currently experienced, by the middle of the century (Price Waterhouse Coopers, 2011; Huang, Barnett, Want & Tong, 2012). Making housing, and occupants, more resilient to extreme and/or frequent heat events is an important policy issue.

The purpose of this research project is to investigate the post-occupancy thermal performance of subtropical and tropical houses in Queensland and occupants’ self-reported comfort. The aim was to evaluate the role of various supply chain agents in the realisation of housing thermal performance outcomes particularly in hot summer periods.

2. Methodology

This paper's field evaluation of Queensland homes uses quantitative and qualitative methods to collate and examine multiple data sets within a clearly defined climatic and social context, a typical real-world approach of building evaluation (Leaman, Stevenson and Bordass, 2010). The methodology is based on a concept of holism that addresses both the sense of dwelling within a home and the home's environmental performance (Hyde, 2008), and the adaptive model of thermal comfort (de Dear and Brager, 2001).

2.1 Case study climates

Two climate zones were selected for the study: sub-tropical south east Queensland (SEQ) (latitude 26-28^{o} south) and tropical Townsville (19.25^{o} south). The targeted geographic area for recruitment in south-east Queensland were Ipswich suburbs and Brisbane western suburbs, as these inland suburbs have a more extreme climate (hotter in summer and colder in winter) than eastern suburbs that benefit from the moderating effect of the Pacific Ocean. Their climate is arguably best represented, in simulation software used in NatHERS, by climate zone 9 (Amberley). The targeted areas for recruitment in Townsville (climate zone 5) were new housing developments to the north and north-west of the city centre. The typical meteorological year (TMY) climate of zones 5 and 9 are shown in Table 1, whilst the maximum annual space heating and cooling allowance for each zone is shown in Table 2.

Table 1: annual outdoor hours within temperature bands (based on TMY)

Climate Zone	% of annual hours within band				
Temperature band	<15^{o}C	15-17.9 ^{o}C	18-19.9 ^{o}C	20-28 ^{o}C	>28 ^{o}C
Climate 9 (inland sub-tropical)	23.5%	12.9%	11.1%	45.2%	7.3%
Climate 5 (tropical)	8.2%	4.9%	6.7%	74.3%	11.6%

Table 2: star ratings and maximum space heating and cooling allowance

Climate zone	Location	Star Rating / Maximum total annual MJ/m2 for space heating and cooling								
		Star rating	1	3.5	5	6	7	8	9	10
9	Western suburbs and inland SEQ	MJ/m^2	334	132	85	67	52	38	24	12
5	Townsville	MJ/m^2	309	200	153	127	103	81	61	44
Year performance requirement incorporated into National Construction Code Regulation			Nil: typical 1990's	2003	2006	2010	Australia 2012 – 2020?			

2.1 Adaptive comfort band

Taking into account research relating to adaptive comfort, acclimatization and the bioclimatic chart (de Dear and Brager, 2001; Auliciems and Szokolay, 2007), summer and winter comfort bands were calculated for the two locations according to the following equations:

Eq. 1 $T_n = 17.8 + 0.31\ xT_{om}$(January) +/- 2.5^{o}C (90% acceptability)

Eq. 2 $T_n = 17.8 = 0.31xT_{om}$(July) +/- 3.5^{o}C (80% acceptability)

Where T_n = thermal neutrality and T_{om} = mean outdoor monthly temperature (Auliciems and Szokolay, 2007)

These adaptive comfort bands are shown in Table 3 together with the assumed room occupancy hours and heating and cooling thermostat set points applied by NatHERS. The rating scheme's summer neutral cooling temperatures are based on *effective temperature*. NatHERS also assumes a three staged approach to the achievement of comfort in summer: natural means (e.g. operating windows); mechanical ventilation (ceiling fans) and lastly the extraction or provision of heat (artificial heating / cooling). The annual adaptive comfort band is therefore taken to be 18-28^{o}C for south east Queensland, the same range used by Tuohy et al (2001) as one approach for thermal modelling based on adaptive comfort criteria. The comfort band for Townsville is slightly higher (20 - 29^{o}C).

Table 3: Comfort bands and NatHERS heating / cooling schedules and set points

	Summer Comfort		Winter Comfort	
Location	Adaptive comfort band	Cooling thermostat setting and time schedule	Adaptive comfort band	Heating thermostat setting and time schedule
South-east Queensland inland / western suburbs	22.0 – 27.9 ^{o}C	26.0^{o}C **Living spaces** 2400-0700 - no cooling 0700-2400 - cooling **Sleeping spaces** 1600-0900 – cooling 090001600 – no cooling	18.2 – 23.2 ^{o}C	**Living spaces** 2400-0700 -no heating 0700-2400 - 20 ^{o}C **Sleeping spaces** 2400 – 0700: 15 ^{o}C 0700-0900: 18 ^{o}C 0900-1600: no heating 16:00-2400: 18 ^{o}C
Townsville	23.6 – 28.6 ^{o}C	26.5 ^{o}C (Schedule above)	20.1 – 27.1 ^{o}C	

2.2 Case study homes

Twenty-six households were recruited in Queensland – 20 in south east Queensland and 6 in tropical Townsville. Selection criteria consisted of dwellings constructed since 2006 and dwellings smaller than the median house size (253m^2) for new Queensland homes in 2008/9. Participants were recruited through direct mail campaigns and neighbourhood newsletters in targeted suburbs, email distribution lists and word of mouth. Participation was requested for 12 months. In addition to the case study homes, some display homes in the vicinity of the participating homes were also measured and/or simulated to gauge a comparison of existing homes with new homes.

The participating households represent a broad spectrum of household types found in Queensland: 2 adults (31%); 2 adults + 2 children (31%) and 3 adults (18%); single adult (4%); 2 adults 1 child (4%); 1 adult 2 children (4%); 1 adult 1 child (4%) and 2 adults 2 children (4%). The mean household size was 3. A quarter of participating households had children under school age. Fifty percent of the households were single income households. No households had an annual gross income of less than $50,000 and half of the households had an annual gross income greater than $110,000.

The recruited homes represent the diversity of housing that make up the Queensland housing market, as shown in Table 3.

Table 3: housing types participating in study

Feature	Year (number of houses)
Construction year	2006 (5); 2007 (2); 2008 (5); 2009 (6); 2010 (3); 2011 (5)
Building foundation	1/3 of the homes are elevated construction whilst the remainder are slab-on-ground.
Construction type	1/3 of the homes are light weight construction, with the remainder heavy weight construction (brick veneer or cement block)
House form and ceiling height	Most homes a single storey. 2.4 m ceilings for homes constructed prior to 2010. Minimum ceiling height of 2.7m for homes approved and constructed post 2010.
Air conditioner penetration	25% of SEQ had no air conditioning (consistent with regional statistics). All Townsville homes had at least one air conditioner.
Air conditioner type	Split systems were the predominant air conditioner type (46% of houses). Other types: window/wall box units (17%); ducted systems (12%)
Air conditioner placement	Four households (20% of air conditioned houses) had an air conditioner in the living room only. Of those houses with more than one air-conditioner, the majority had a split system in each of the bedrooms
Other cooling appliances	The majority of houses had ceiling fans in living areas and bedrooms.

2.3 Monitoring equipment

Temperature sensors (*Maxim ibuttons*), programmed to record every 15 minutes, were installed in the main living room (temperature and humidity); the air conditioner outlet in the main living room (temperature); the main bedroom (temperature); a second bedroom or office (temperature) and a covered outdoor living area (temperature). Recorded data was downloaded approximately every 80 – 90 days and the sensors reprogrammed for the next monitoring period.

2.4 House simulation

Where building plans were available, house designs were simulated using BERS PRO 4.2, NatHERS accredited software commonly used in Queensland for housing regulatory purposes (i.e. a simulated energy performance certificate is one way to meet requirements for building approval).

2.5 Thermography

Eleven of the homes in SEQ and two of the Townsville homes (plus 2 display homes in Townsville) were subject to thermal imaging and air infiltration tests. The testing was carried out by a certified Building Science Thermographer and Air Leakage Technician, and member of the Australian Professional Thermography Association (AUSPTA). Thermal imaging utilised a *FLIR E50bx* camera. Air leakage testing was conducted using a *Retrotec 2000* fan, and in accordance with the following standards:

- ATTMA TS1 Issue 2 – Measuring Air Permeability of Building Envelopes
- BS EN13829:2001 Thermal Performance of Buildings
- BINDT – Quality Procedures and Explanatory Notes for Air Tightness Testing

2.6 Household surveys and periodic comfort surveys

Households participated in a general questionnaire at the beginning of the study, gathering general demographic information as well as more detailed information about their behaviour to manage their comfort during hot weather: thermostat set points, frequency and time of use of air conditioner and other comfort strategies they used (e.g. opening or closing doors and windows / window dressings; changing clothing; using fans; having a shower/bath; using a swimming pool; relaxing outside etc). Throughout the study, and particularly during periods of hot weather, participants were asked to complete a short comfort survey (via SmartPhone, online or paper) indicating their current location (e.g. which room of the house), comfort level, comfort preference and clothing level. At the end of a minimum of a full year of monitoring for all houses (March 2013) these comfort surveys will be correlated with measured temperature data from each of the houses.

3. Results

3.1 Building documentation

In general, the study revealed very poor levels of housing documentation. 50% of occupants did not have copies of their house plans (building documents) despite all homes being relatively new (generally less than 6 years old) and mostly owner-occupied. Only three households could provide a copy of the energy certificate for the house or provide information on the expected thermal performance of the house (e.g. the star rating). Sales staff at display homes were also not able to show building documentation and energy certificates in response to requests for information about the energy efficiency of the houses. The lack of building documentation raises the need for further research to understand and quantify potential risks and liabilities for both sellers and buyers.

3.2 Building Simulation

House construction plans were obtained, from owners or estate developers, for 18 of the 26 homes. Of the twenty SEQ homes, only five were designed above minimum performance standards set by regulation. All five of these homes were non-airconditioned. (Future analysis will include a comparison of all simulation files, and an analysis of simulated versus actual performance for each house). In Townsville, the ‘as designed’ plans of nine display homes were simulated by an independent rating assessor, and compared with the building documentation supplied by the display homes. Five of the nine homes showed a discrepancy in building rating of 2 stars or more (i.e. the display homes over-claimed the actual rating performance). Six of the display homes had under-represented the actual housing floor area in the simulation software by more than 10%, affecting the calculation of the space cooling requirement. Four of the nine homes had underestimated the cooling requirement by more than 10%. Additionally, each of the nine homes, plus an additional 10 display homes, was re-rated after incorporating 3-5 minor design improvements suggested by the independent assessor. Design improvements, and estimated costs (2012), are shown in table 4. Applying these design improvements resulted in a star rating improvement of 0.5 to 2 stars, or, in energy terms, a space cooling reduction of 16-45MJ/m^2.

Table 4: housing design improvements and associated costs (no rebates applied)

Improvement	Light colour (roof and walls)	Additional ceiling insulation	Sarking to roof sheeting	Ventilate roof space	Low-e glass
Cost	$0	$300	$1,200	$950	$1300

3.3 Temperature measurements

Preliminary analysis was conducted for several SEQ homes for the summer period February 28 – March 2, 2012. These dates presented four consecutive days where the maximum temperature was over 30^{o}C, as recorded by the Bureau of Meteorology (BOM) at weather station 040004 (Amberley), approximately 22 km north-west of the location of these six homes at Springfield Lakes (Table 5). The table shows that whilst the diurnal temperature range of Amberley and Springfield Lakes was similar (average 14.3 and 13.6^{o}C respectively), Springfield Lakes’ temperature extremes were higher than the BOM weather station. This is not unusual as housing estates are likely to suffer from the urban heat island effect due to higher radiant heat and restricted ventilation due to urban forms (building and road materials and urban layout). The data recorded in this study shows higher minimum temperatures (about 4^{o}C) and higher maximum temperatures (about 3^{o}C), resulting in a mean temperature (for these 4 days) 2.4^{o}C hotter than Amberley. This is significant because housing regulations are based on simulated performance according to BOM TMY data and do not incorporate the heating effects of urban forms nor the changing climate.

Table 5 Amberley BOM (and Springfield Lakes) weather observations for study period

	28 Feb 2012	**29 Feb 2012**	**1 Mar 2012**	**2 Mar 2012**

Minimum temperature (°C)	17.9 (22.16)	16.2 (21.66)	17.3(21.16)	16.9(20.66)
Maximum temperature (°C)	30.4 (35.16)	32 (34.66)	31.9(34.16)	33.2(36.16)
Mean temperature (°C)	24.15(26.5)	24.1(26.86)	24.6(26.99)	25.06(27.19)
9am Temperature (°C)	26.1(25.6)	23.8 (27.17)	25.6(27.17)	25.8(27.17)
9am relative humidity (%)	73	83	72	62
3pm Temperature (°C)	29.5 (34.67)	31.4 (34.66)	31.4(33.66)	32.4(35.16)
3pm relative humidity (%)	48	46	39	39

Histograms were developed for each of monitored spaces of each house. Figure 1 shows the hours that each space in House 2 was at different temperature bands during the four days (96 hours). The green zones represent temperature bands within the adaptive comfort band (18-28°C). The graph shows that both the main bedroom and the living room experienced more hours outside of the comfort band than the external temperature.

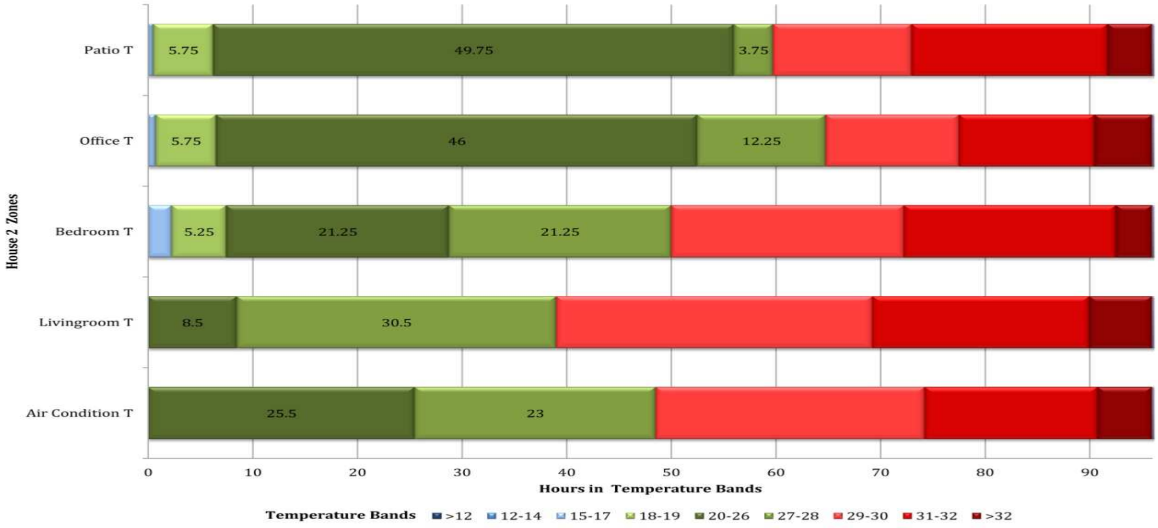


Figure 1: temperature histogram of House 2 Feb 28 – Mar 2, 2012

A comparison of the thermal performance of the main bedrooms of these six houses with each other and the external temperature (Figure 2) shows several important points. With the exception of H1 which was air conditioned overnight, none of the bedrooms cooled to the same extent as the external air. The slow rate of cooling in these rooms would seem to indicate that night ventilation / cooling strategies are either not available (e.g. poor design) or are not being utilised by occupants (e.g. not opening windows overnight). H1 was air conditioned overnight, but not during the day (8am – 5pm). The internal temperature seems to lag approximately 2 hours behind the external temperature, and continues to rise after the external temperature starts to decline. This would seem to indicate that the house design and construction properties are not being effective in limiting heat transfer into the building.

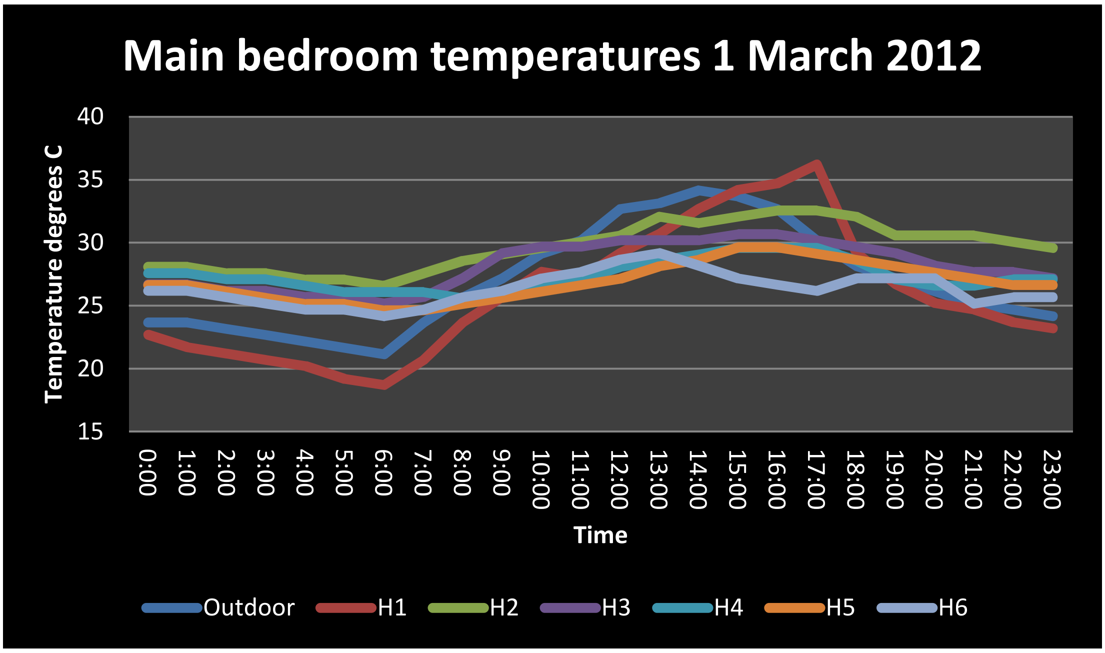
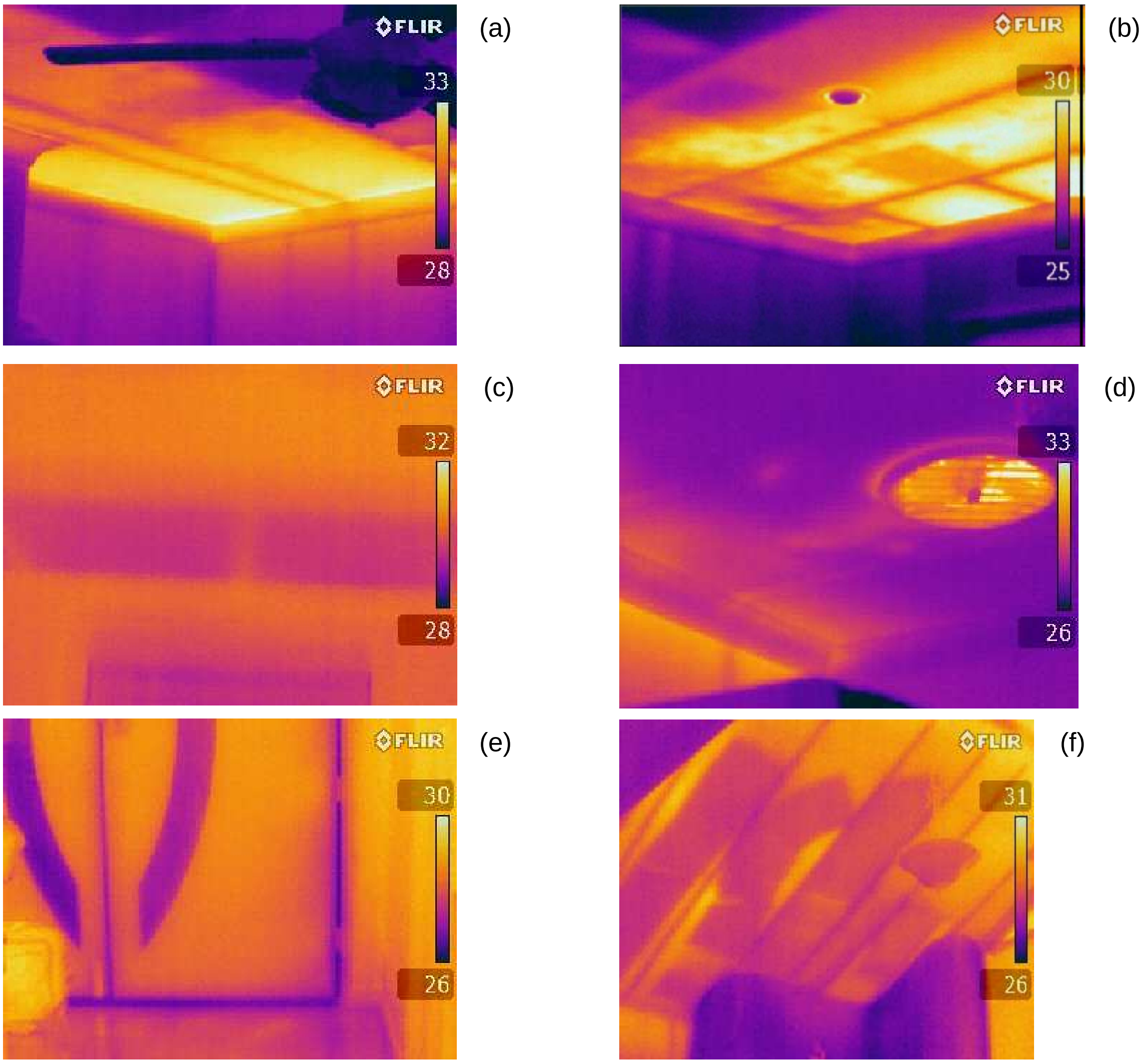


Figure 2: comparison of six bedroom temperatures March 1, 2012

3.4 Thermal imaging

All of the 15 houses and 3 display homes subjected to thermal imaging had issues that would make them non-compliant (minor to serious) with the current building regulations and impact negatively, to varying degrees, on the thermal performance of the building. The common issues relating to insulation and thermal leakage are shown in Figure 3 (a-f).



a) Poor perimeter coverage (typically 300-600mm around perimeter of internal ceilings), with particularly poor coverage in the corners of hip roof designs

b) Patchy (or absent) ceiling coverage in general

c) Entry hallways, utility rooms (e.g. bathrooms, laundry) and bulkheads often not insulated correctly (similar with garage ceilings and walls adjoining main house)

d) Poor insulation around exhaust fans (pictured), lights, roof access covers

e) Leakage around doors (pictured) and windows

f) Two of the homes revealed extensive and serious non-compliance issues that required house owners to seek restitution from the relevant builders.

Figure 3 Common insulation and thermal leakage issues

3.5 Occupant management of thermal comfort

As expected, occupants have different strategies for managing their comfort. Preliminary analysis of the occupant behaviour in six Springfield Lakes houses (section 3.3.) shows that their reported behaviour reasonably matches the assumptions made by NatHERS i.e. that occupants will manage their comfort by firstly using natural means (e.g. window operation), secondly by using mechanical means (e.g. ceiling fans) and lastly by removing excess heat (e.g. air conditioning). The cooling set points of the air conditioners, though, are not reflective of their stated decision points to operate the air conditioner, nor the NatHERS setpoints, but rather appear to be a reflection of government and utility messages that seem to convey that 24-25^{o}C is the optimal temperature for operating air conditioners (Miller, 2012a).

Table 6 Demographic, construction and experiential variables of 6 houses

Indicator	**Range/ Variables**					
	House 1	House 2	House 3	House 4	House 5	House 6
Occupancy	Work from home	Pre-school children at home	Pre-school children at home	Generally unoccupied daytime	Shift work	Shift work
AC use during summer	Day: office & living room; whole house when hot weather predicted	Day: living room when >32^{o}; night – bedrooms	Living room when >28^{0}	Living room when >26^{0}	Living room and main bed when >30^{o}	Living room and main bed when>30^{0}
AC thermostat set point	24^{o}C	24^{o}C	24^{o}C	24^{o}C	25^{o}C	24^{o}C
Use of window openings for cross ventilation	Not in summer	Yes; close when AC on	Yes; close when AC on	Sometimes	Sometimes	Sometimes

4. Discussion

The growth in the reliance on the electricity market to provide occupant comfort by pumping out excess heat has significant economic, ecological and social implications (Miller and Buys, 2012a and c). The expected increase in extreme heat days throughout Queensland, with resultant public health impacts, adds to these concerns. The initial analysis of the results of this study (still in operation) already raises significant concerns about the efficacy of current building regulations and housing industry practices in protecting the health, wellbeing and economic investment of housing occupants and electricity infrastructure. The low level of building documentation (section 3.1), especially relating to the energy rating, appears to indicate a lack of understanding about the importance of those documents in informing potential buyers and current occupants on the thermal performance of the house and hence their own personal thermal comfort. There was no evidence revealed in this study, that occupants, builders or sales agents understood that the star rating system required for building approvals was in any way linked to occupant thermal comfort and associated risks.

The prevalence of houses designed to only meet the minimum regulated performance standards (section 3.2) would appear to add support to findings from previous research: that the housing industry (design, construction and sales) and consumers may (i) misunderstand the intent of regulations (i.e. they represent minimum performance and do not equate to adequate comfort) and (ii) have a very limited perception and experience of the potential and benefits of high thermal performance buildings (Miller, 2012 a,b). Analysis of the simulation results of the display homes in Townsville (section 3.2) showed (a) that the simulation software was poorly and incorrectly used by the industry, misrepresenting the energy performance of the houses, and (b) that the housing industry had not incorporated no cost and low cost opportunities to significantly improve the energy performance of their homes, leading to an under-representation of housing comfort potential to the many display homes visitors.

Over-representation of the thermal performance of the house designs was exacerbated by Queensland regulation that currently permits the 6 star building requirement to be met by a mixture of building envelope efficiency, covered external living area and/or solar power systems. That is, the Queensland government has permitted a level of trade-off of thermal efficiency of the building envelope, for outdoor living areas and renewable energy generation. This regulatory decision appears to have added to market confusion about the differences between building envelope thermal efficiency (and hence indoor thermal performance), occupant options for managing the indoor environment (e.g. using an outdoor living area) and options for reducing the greenhouse gas emissions from electricity consumption (renewable energy). House buyers may think they are obtaining a 6 star house (127MJ/m^2 -Townsville) but in reality the building envelope itself can be as low as 4 ½ stars (168MJ/m^2). This could be considered misrepresentation, and affects both internal thermal conditions and the operational costs to achieve occupant comfort. Added to the above concerns is the strong evidence of very poor industry practices in relation to insulation installation. Of equal concern is that each of these houses has been independently certified, supposedly in accordance with Queensland legislation, as (a) being constructed as designed, and (b) complying with the building regulations, including the energy efficiency requirements. This compliance failure needs further investigation.

The limited performance analysis of the homes to date has already revealed evidence of overheating in summer. The thermal performance of bedrooms in particular needs addressing as our early analysis shows a high use of bedrooms during daytime hours (e.g. shift workers, young children, bedrooms as offices). This multiple-functionality of rooms raises the possibility of changes to the NatHERS protocols and assumptions to treat all rooms as living spaces that are required to meet occupant comfort levels 24 hours per day, eliminating current differences between living spaces and sleeping spaces. Finally, the disparity between the thermostat settings incorporated into the NatHERS protocols and the thermostat settings recommended by government and the electricity industry needs to be resolved. The current practices appear to be contributing to market confusion.

5. Conclusion

The aim of this study was to evaluate the role of various supply chain agents in the realisation of housing thermal performance outcomes particularly in hot summer periods. Preliminary post-occupancy evaluation of twenty-six sub-tropical and tropical homes in Queensland has raised significant concerns about the efficacy of current building regulations in protecting the health and wellbeing of housing occupants, about the ability of the housing industry (design, construction and sales) to deliver minimum requirements and promote higher levels of occupant comfort, and about the way occupants respond to mixed messages (from government, electricity industry and housing industry) about thermal comfort. Data collection for this project will continue to March 2013 and further analysis is expected to contribute to a greater understanding of occupant thermal comfort in Queensland homes.

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