Thermal Mavericks in Australia: A Study of Occupant Preferences in Dwellings of Atypical Construction

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Abstract

The preferences and behaviour of occupants are critically important in the environmental performance assessment of proposed and existing dwellings. Performance assessment should respond to both the needs of the occupants as well as societal goals, and when used as a tool in energy efficiency regulation should allow individuals to make informed choices that align with their particular housing aspirations. Within Australia, the existing approaches to meeting societal goals, expressed through the Energy Efficiency provisions in the National Construction Code (NCC), are intended to meet the perceived needs of a standardised population. This causes an incongruity when used to assess dwellings designed to meet alternative needs.

To investigate these issues this research studied the preferences and behaviour of occupants within two distinct forms of housing; dwellings incorporating earth construction elements in a cool temperate climate and naturally ventilated dwellings in a hot humid climate. A review of the literature provided anecdotal evidence indicating that these occupants have alternative performance expectations of their dwellings which are not currently being met by existing thermal performance assessment methods. The research was conducted through national surveys to confirm that the cohorts' attitudes, behaviours and preferences were distinguishable from those of the broader population. These surveys were followed by a longitudinal comfort study of 40 households from these cohorts; 20 in Melbourne and 20 in Darwin. The comfort study was complimented by the analysis of long-term household energy use records, an exploration of dwelling operation in relation to thermal conditions and, importantly, an assessment of the individuals' environmental attitudes.

Results of the national surveys confirmed that occupants of the two forms of atypical housing are identifiable cohorts whose perception and operation of their dwelling is different when compared to those of the broader population. These trends were similarly reflected across the 40 case study households. Notably, the type of fuels used and the operation of heating and/ or cooling appliances were dissimilar to typical houses in the same locations. This was seen in the considerably lower average energy consumption of the two case study cohorts when compared to the figures for households generally in those areas. Rather than choosing to

control the internal temperature by using heating and/or cooling appliances the occupants demonstrated a range of means of adapting to and modifying their thermal environment across a wide range of conditions. Their acceptance and preference for diversity within their thermal environment was further revealed through acceptable thermal sensation votes cast outside of the range of the adaptive comfort model. This illustrates the disadvantage imposed upon occupants when standard methods of design assessment are applied. The occupants displayed significantly higher levels of environmental concern than the broader population, likely motivating their preferences and behaviour in relation to the operation of their dwellings. Despite the uniqueness of the two cohorts (e.g. construction characteristics of the houses, climate and use of heating and/or cooling) the relationships between prevailing outdoor conditions and the occupants' subjective response to internal conditions were similar, as were their overall levels of environmental concern.

Based on the collected data, this research offers an alternative process by which to judge the potential thermal performance of new dwellings of these typologies. The method developed is aimed at reducing energy use by demonstrating that an acceptable level of comfort is achieved without heating and/or cooling. Whilst the applicability of the proposed method is confined to the types of houses presently studied, it is expected that its application could be broadened to other forms of housing, where occupants demonstrate comparable levels of environmental concern.

This research is the first in Australia of residential buildings that combines both the use of traditional thermal comfort and post occupancy evaluation methods with a measure from environmental psychology to provide contextual information about the actual operation and performance of two distinct forms of housing. Importantly, this research supports broadening the boundaries of thermal comfort parameters in situations where occupants have access to a wide range of adaptive opportunities. The implications of these findings are theorised in the proposal of alternative building performance assessment methodology in the Australian context. On an international scale, this work offers an exciting pathway towards the creation of less energy intensive built environments, not just through the rationalisation of technical systems, but also through consideration of how individuals' thermal preferences may be informed by their value system.

Statement of originality

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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Associated publications

Daniel, L., Williamson, T., Soebarto, V., & Chen, D. (2015) A model for the cooling effect of air movement, in Crawford, R H., & Stephan, A. (Eds) *49th International Conference of the Architectural Science Association (ANZAScA),* Victoria, Australia, 2-4 December 2015, Melbourne: The University of Melbourne.

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Chapter 1. Introduction

1.1 Overview

Residential thermal performance assessment is an important means in understanding the future performance of a design or the actual performance of an existing dwelling. This understanding is vital in the creation of a more sustainable built environment, a goal expressed by countries around the world. The behaviour and preference of intended and actual building users is critical in determining how the building will be used and what can be judged as acceptable thermal performance. Therefore it is of utmost importance that any form of thermal performance assessment purposely respond to the behaviours and preferences of occupants to enable them to make informed choices about performance that align with their specific housing aspirations.

In Australia, Energy Efficiency performance provisions were introduced to the National Construction Code (NCC) in 2003 (ABCB, 2015), in order to reduce the emission of greenhouse gases associated with energy use in residential buildings. Within Australian homes, 41% of household energy consumption is attributable to the operation of space heating and/or cooling appliances (DEWHA, 2008). The Energy Efficiency provisions require certain characteristics of the building envelop (i.e. floor, walls, glazing and roof) aimed at enabling the efficient use of these heating and/or cooling appliances. Within the methods to demonstrate compliance with the performance provisions, assumptions about how the dwelling will be used are based on standardised occupant behaviour and preferences (NatHERS, 2014). This causes a gap between the predicted and actual performance of dwellings that are designed and operated in a manner that is different to the standardised assumptions (Daniel et al, 2015a). In many of these cases, the occupants' behaviours and preferences are motivated by a more holistic approach to housing performance and conservation of natural resources.

In order to accurately reflect the performance of these dwellings, the assessment methods should respond in some manner, not just to a rationalisation of the building envelop performance, but also to the interrelated socio-cultural issues informing user behaviour and preferences (Stevenson & Leaman, 2010). Stevenson & Leaman (2010) argue that such an approach to housing design and performance assessment would offer a more long-term solution to a sustainable built environment than housing designed only to meet standardised needs:

> *"User behaviour cannot be used as an excuse by designers for performance deficits or unintended consequences, but must be understood and influenced appropriately." (Stevenson & Leaman, 2010)*

Therefore, this research will investigate the preferences of occupants living in dwellings of atypical constructions to determine how the thermal performance of these types of houses can be appropriately assessed. The following section will introduce the current state of residential regulatory thermal performance assessment and relevant research within the Australian context.

1.2 A study of occupants of atypical housing in Australia

In Australia, the majority of housing is built by project home builders; for example, in the 2014/2015 financial year the largest 100 building companies claimed 42% of the market share for new detached housing (HIA, 2015). Climatically appropriate design is not the predominant aim in this housing market with minimal variation in form and construction across a wide range of climates (see Figure 1.1). The NCC Energy Efficiency provisions are largely aimed at ensuring this mass market housing meets minimum thermal performance requirements.

Houses designed for specific climates and occupants that require little or no heating and/or cooling to maintain acceptable thermal conditions represent a minority of new home starts. Often these dwellings incorporate a diverse range of design and construction techniques that are not found in the typical mass market house designs. In this thesis, this type of housing is referred to as 'atypical'. It is this minority of housing where many occupants are facing barriers in achieving compliance with current Energy Efficiency performance provisions (Williamson et al, 2010). In Australia 20.5% of households do not have any form of heating and 26.9% do not have cooling (ABS, 2014), however underpinning the Energy Efficiency provisions is the assumption that all houses will have some form of heating and/or cooling appliances that may operate in all main living areas day and night. The current provisions are inequitable for those wishing to build atypical forms of housing that use little or no artificial heating and/or cooling.

Figure 1.1. Predominant housing stock in Australia: generic design, unresponsive to local climate and context, left image Darwin, Northern Territory and right image Adelaide, South Australia

Building or buying a house of atypical construction can be considered conspicuous ‘environmental’ *under*-consumption, where some aspect of the occupant’s value system is displayed through the choices they make about built form, design and construction (Mazar & Zhong, 2010). A well-established example of this is dwellings incorporating earth construction walls (pise, adobe and compressed earth blocks). Occupants of this type of dwelling have previously been linked to higher levels of environmental concern and energy-saving behaviours (Casey & Scott 2006; Daniel & Williamson 2011); as well, there is considerable anecdotal evidence that occupants of earth buildings value a low-impact lifestyle (Dethier 1981; Easton 1996; Rael 2009). A second, but almost more intrinsic, example is dwellings that are designed to be naturally ventilated, particularly in hot humid climates. While the form of these buildings is not as easy to define as that of earth buildings, these dwellings offer a similar expression of an individual’s choice to ‘experience the climate’ and not to rely on artificial cooling for comfort. The capacity for reduced energy consumption of this type of household is not only intuitive but also firmly supported by the literature (Cândido et al. 2010; Gill et al. 2010). Whilst these forms of housing are remarkably different in terms of construction characteristics, local climate and use of heating and/or cooling, they have both faced similar barriers in attaining building certification due to the current Energy Efficiency provisions of the NCC.

The term ‘thermal maverick’ has been used in this thesis to describe households or occupants who choose to live in atypical dwellings that do not necessarily have extensive heating or cooling. It refers not only to their expectation and perception of the thermal environment, but also to the thermoregulatory behaviours embraced that sit outside of current standardised assumptions. It is suggested that the study of 'thermal mavericks' could demonstrate that such a universal approach to thermal performance assessment is not only inappropriate but undesirable in some forms of housing (Hitching, 2009);

> *"It might therefore be better to study the 'thermal mavericks' in terms of those with unusual techniques for handling temperature or particular ideas about whether they are happy to stay within buildings. ... To do so would underscore the diversity of approaches people still take when they organize their warmth. It would also throw fresh light upon the ease with which thermal convention can be subverted. Perhaps most importantly it could help make the strongest case against the further spread of ambient standards by showing how some people can detest the monotony of being cooped up within precisely controlled bodies of air." (Hitchings, 2009, p92)*

In Australia, the relationship between regulatory performance assessment of housing and the influence of individuals' environmental attitudes on behaviour, expectation and preferences has not yet been adequately addressed. A gap between the predicted, measured and perceived thermal performance of five houses that used little or no heating and/or cooling was established by Williamson et al (2010). Similarly, Kordjamshidi (2011) demonstrated that the main method to show compliance with the Energy Efficiency provisions is not appropriate for the assessment of naturally ventilated house designs. Kordjamshidi (2011) subsequently proposed an alternative method to assess naturally ventilated dwellings using comfort criteria; while such a method may address the issue, it has not been incorporated into the regulatory framework.

In other research, the behaviour and thermal comfort of occupants in 70 households across Sydney, Adelaide and Brisbane were investigated as part of a larger study of household adaptation to increasing occurrence of heatwave events (Saman et al, 2013). The monitoring period was limited to summer conditions in line with the aims of the study, and the recommendations primarily focused on the use of air conditioning to achieve comfort conditions. Importantly, the report also recommended that an adaptive model be adopted for air conditioning design guides and standards, instead of current static thermostat settings. Whilst an adaptive model for thermal comfort is likely to be the most appropriate method for assessing residential thermal environments, it has not been extensively tested in Australian conditions.

Several studies have sought to understand the relationship between an individuals' socio-cultural context or environmental attitude and their thermoregulatory behaviour, forgiveness factor or household utility use (Healey & Webster-Mannison, 2012; Deuble & de Dear, 2012; O'Callaghan et al, 2012). Healey & Webster-Mannison (2012) reported on the importance of cultural and contextual factors on comfort-related adaptions, while Deuble & de Dear (2012) established a link between pro-environmental attitudes and the 'forgiveness factor'. In another study, O'Callaghan et al. (2012) demonstrated a correlation between pro-environmental attitudes and lower energy use. Whilst none of these studies share the same aims as this research, the findings from all three support further investigation of the connection between environmental concern and occupants' behaviour and preferences. There is a clear gap in the current knowledge of the impact of occupants' environmental attitudes on their behaviour, expectations and perceptions in relation to the thermal performance of their home. By addressing this concern within the context of regulatory building performance assessment in Australia, a more equitable solution for the demonstration of compliance with the Energy Efficiency provisions for atypical housing may be achieved.

1.3 Research hypothesis

The hypothesis underpinning this research project is that occupants of atypical dwellings have higher levels of environmental concern than the general population and that, by modifying their behaviour, expectations and perceptions relating to the thermal performance of their dwelling, the amount of energy use associated with heating and/or cooling the home is minimised.

1.4 Aim of the thesis

This research aims to contribute to knowledge of the thermoregulatory behaviours, expectations, and preferences of occupants' in houses of atypical construction and how the thermal performance of these buildings should be *meaningfully* assessed.

Therefore the objectives of this research are;

1. To discuss the current state of thermal performance and energy efficiency assessment for residential construction in Australia;

2. To gather data on the behaviour, preferences and attitudes of occupants living in dwellings incorporating earth construction components in a cool temperate climate and naturally ventilated dwellings in a hot humid climate;
3. To analyse the data and draw conclusions to reveal and describe trends in the behaviour, preferences and attitudes of these occupants and whether these trends are alternative when compared to those of the general population and standardised assumption used in regulatory performance assessment; and
4. To develop an alternative performance assessment method for dwellings of atypical construction capable of adequately responding to the behaviour, preferences and attitudes of these occupants.

1.5 Methodological approach

This research is informed by an inclusive systems approach to building design and performance (Williamson et al, 2003). As such it borrows methods from several different disciplines; however, the presentation and discussion of the results will be based in the language and understandings of thermal comfort and building science research. The thermal performance of residential buildings remains the focus of the research, and it is what frames the discussions of housing aspirations, socio-cultural context and environmental concern.

A pragmatic approach guides the choice of a mixed methodological research plan (Robson, 2011). The methods are derived from established forms of inquiry used by previous studies within the field. The qualitative data will be used to describe the context in which the quantitative data exist and to contribute to a deeper level of comprehension of the behaviours, preferences and attitudes of the studied cohorts. Five primary methods were used: literature review, national survey, in-depth case study, longitudinal thermal comfort survey and environmental attitudes survey.

The investigation of these occupants as 'thermal mavericks' is underpinned by the merit of extreme case analysis (Flyvberg, 2004; Gerring, 2007);

> *"A typical or extreme cases often reveal more information because they activate more actors and more basic mechanisms in the situation studied... it is often more important to clarify the deeper causes behind a given problem and its consequences than to describe the symptoms of the problem and how frequently they occur" (Flyvberg, 2004, p425)*

The application of extreme case analysis to the current framework of residential building performance assessment in Australia will assist in understanding the extremes of thermal experience and thermoregulatory behaviour in dwellings. Whilst there is scope to address the research hypothesis through the investigation of a representative sample of typical housing in Australia, the use of extreme case analysis techniques limits the scope of the study and in doing so encourages a more rigorous exploration of the occupant preferences and thermal performance of residential buildings.

The research will focus on the occupants of dwellings incorporating earth wall construction in a cool temperate climate (Melbourne), and solely or partially naturally ventilated dwellings in a hot humid climate (Darwin). The methods respond directly to objectives 2 to 4 outlined in section 1.4 and are summarised below (see Table 1.1).

Table 1.1. Summary of methodological steps

	Objective 2.
2. (a)	Survey households from a nationwide sample of atypical dwellings
2. (b)	Measure the thermal environments, record building construction information and energy use of a sample of atypical constructions in two distinctive climates
2. (c)	Record occupant perceptions and behaviours in relation to the thermal environment
2. (d)	Survey the occupants in regard to their environmental attitude
	Objective 3.
3. (a)	Describe the characteristics and operation of two examples of dwellings of atypical construction
3. (b)	Investigate the relationship between the thermal environments of the case study houses and their energy consumption for heating and cooling
3. (c)	Compare collected thermal comfort information with current thermal comfort standards
3. (d)	Compare the level of environmental concern of the occupants in the case study houses to standard population
3. (e)	Examine the relationship between environmental concern and thermal comfort
	Objective 4.
4. (a)	Propose a residential thermal performance assessment method based on comfort criteria
4. (b)	Investigate the implications of such a proposal

The literature review seeks to demonstrate that current building performance regulation does not meet the needs of some forms of housing in Australia. The national survey attempts to define the housing characteristics of two examples of this housing (i.e. demographic, construction and dwelling operation in relation to heating and/or cooling appliance use) to investigate whether the two cohorts are indeed distinct from the general population. The in-depth case study of households of the two atypical housing typologies seeks to understand the occupants' behaviour in relation to thermoregulatory practices within the home and how this impacts on energy use and the indoor thermal environment. A longitudinal comfort study of the same households explores the occupants' thermal preferences in their home. The environmental attitudes inventory compares the level of environmental concern of the same occupants with that of two samples that represent the general population. The findings are then used to formulate an alternative assessment methodology that can be used to demonstrate compliance with the Energy Efficiency provisions for designs of these two types of housing.

1.6 Organisation of the thesis

This thesis is divided into nine chapters; Introduction, Literature review, Research methodology, National survey, In-depth case studies, Thermal mavericks: comfort and preference, Environmental attitudes, Design assessment methodology and Conclusions. Chapter Two (*Literature review*) provides the context and establishes the relevance of the two forms of atypical housing chosen as the focus of the research. Chapter Three (*Research methodology*) gives detailed information about the methods employed in the investigation. Chapters Four to Seven present the results of the four primary areas of inquiry. Chapter Four (*Results: national surveys*) explores whether the attitudes, behaviours and preferences of two samples of occupants of atypical houses are distinguishable from those of the general population. Chapter Five (*Results: in-depth case studies*) illustrates in greater detail the behaviour, expectations and perceptions relating to building thermal performance of a sample of 20 households from each form of atypical housing. Chapter Six (*Results: thermal mavericks: comfort and preference*) describes the thermal comfort and preferences of these same households for a full year. Chapter Seven (*Results: environmental attitudes*) compares the environmental attitudes of the occupants from the same case study households with two samples of the general population. Chapter Eight (*A proposal for design assessment methodology using comfort criteria*) presents an alternative method by which the thermal performance of these two forms of atypical housing can be judged by drawing on the findings from the previous four chapters. Chapter Nine (*Conclusions*) concludes the thesis by highlighting the contribution of the research to the understanding of occupant preferences in residential building performance assessment.

Chapter 2. Literature review

2.1 Introduction

In the formation of a less energy intensive built environment there is a need to understand the likely future performance of a building (Williamson, 2010; Foxell & Cooper, 2015). A vast international field of research contributes to this understanding from the perspective of many different disciplines, such as medicine and physiology (Roaf et al, 2010), engineering and architecture (Chappells & Shove, 2005), environmental psychology and social-science (de Dear, 2004; Healey & Webster-Mannison, 2012). Much of this research has contributed to the development international and regional standards for building thermal performance for example: ISO EN 7730 (2005), CEN EN 15251 (2007) and ASHRAE 55 (2013). However, inherent to many of these standards is the assumption of universality; that 'good' thermal performance can mean the same thing to all users (Stevenson & Leaman, 2010). Often, because of this, occupants are designed out of the equation, continuing the perception that it is the building fabric that is responsible for energy use, rather than the actions of the occupants (Williamson et al, 2003; Janda, 2011).

In Australia, the framework for the regulatory performance assessment of residential buildings is designed to meet the perceived needs of a standardised user creating a disparity between the predicted future performance of a house design and actual energy consumption (Williamson et al, 2006; Clune et al, 2012).

> *"Claims of accuracy can lead to a spurious impression of legitimacy, as in the 'accurate' prediction of some aspects of a building's environmental performance being used to legitimate its design when other aspects that are predicted with far less accuracy, or simply ignored, may collectively be far more significant." (Williamson et al, 2003, p70)*

The need to recognise and account for the behaviours, expectations and perceptions of occupants in residential building performance assessment is clear (Zou & Yang, 2014; Daniel et al, 2015a; Ioannou & Itard, 2015; Yan et al, 2015). Taking an inclusive systems based approach may be more successful in understanding the interrelated issues of building performance that contribute to energy consumption within the home rather than a simple rationalisation of the building envelope (Williamson et al, 2003).

Current trends in the literature support an approach to thermal performance assessment that incorporates both technical (building fabric and systems) and social (occupant behaviour, expectations and preference) perspectives; however, barriers to implementation of responsive assessment methods in the Australian context are revealed. Within thermal comfort research, investigating the influence of social and cultural factors on an individual's subjective response to thermal conditions is becoming an area of increasing interest (Roaf et al, 2010). Similarly, across several disciplines, researchers have demonstrated a link between occupants' environmental concern and energy use in buildings (O'Callaghan et al, 2012; Sapci & Considine, 2014). However, the technological approach of the current building performance assessment framework in Australia may limit opportunities for application of the findings to a rationalisation of the current assessment methodologies.

This review of literature will seek to provide a context for the research presented in the thesis, while also demonstrating the contribution and significance of the findings presented in later chapters. The first section explores the historical and current research activities concerning the thermal performance of housing in Australia. The second section examines international thermal comfort research and how existing models may relate to residential thermal environments. The third section will investigate the role of environmental concern in motivating occupant behaviour and preferences. Finally, the fourth section introduces the two forms of atypical housing in Australia that will be basis for exploration of the issues described above. The chapter will conclude with a summary of the opportunities to contribute to gaps in the existing knowledge of occupant behaviour and thermal performance in residential buildings.

2.2 Design of houses for thermal performance in Australia

Whilst it is argued that the thermal performance of buildings cannot be separated from the social and cultural context in which the occupants operate the buildings (Gill et al, 2010; Stevenson & Leaman, 2010), current regulatory thermal preference assessment methods in Australia seek to negate the influence of user behaviour. This can be seen in the aim of producing house designs that are appropriate for a wider range of occupants. Whilst this may be suitable for the majority of housing stock, it leaves little room for those occupants who express alternative needs when designing and building their homes. Arguably, these occupants and/or architects, in their consideration, of the social and cultural context in which the house will be operating, as well as the climate, are creating more regionally relevant housing (Harris & Welke, 1981) that has the capacity for (greater) sustainability.

2.2.1 A search for relevant housing: research and design guidelines

It is useful to broadly group the history of residential building performance research within Australia by the approach of those working within the field(s). The early research into building performance was largely driven by concern for the health and work efficiency of European immigrants in the northern hot humid climates (Cilento, 1925; Douglas, 1940; Macpherson, 1956; Wyndham, 1963; Ryan, 2014). Due to the researchers' background in medicine and physiology the 'problem' was defined in terms of [work] efficiency of occupants. In a review of this period of building research, Ryan (2014) comments;

> *"the 'plight of the housewife' became cause for housing reform"*
> *(Ryan, 2014, p6)*

This work mainly contributed to defining or demonstrating 'the problem' of appropriate housing design, as opposed to offering design advice. For example; in 1956, Macpherson made a particularly scathing report on the *Environmental Problems in Tropical Australia.* Whilst this report was mainly focused on general health and conditions of work, issues of the suitability of existing housing were also covered. This report typifies the key limitation in the research of this time; that it was based on a Eurocentric view of housing and lifestyle;

> *"It [researchers' approach] also demonstrates the engrained belief that housing in the tropics was principally a technical question of climate design, not a socio-cultural one of lifestyle." (Ryan, 2014, p9)*

Given the grounding of this research in physiology, just a single thermal comfort metric was used by which to judge the adequacy of conditions within the houses. The use of this metric limited the understanding of housing to simply a technical one and failed to account for the complex social and cultural context of the occupants. Using a comfort temperature (even if slightly modified to account for acclimatisation) to assess the housing, Macpherson concluded that it was not possible to live in the tropics without air-conditioning;

> *"It is hoped that, in the near future, widespread use will be made of air conditioning in the home" (Macpherson, 1956, p35)*

McPherson does note, however, that the open, ventilated design of existing building stock would be poorly suited to the use of air conditioning.

Whilst much of the early building performance research in Australia was engaged with the challenge of providing suitable housing for the tropics, after World War II, appropriate design for the cooler temperate climates was also investigated. Some of the research of this period concentrated on proposing design guidelines or solutions based on broad climatic classifications (Phillips, 1948; Drysdale, 1952; Marshall, 1955). These guidelines were based in scientific enquiry, however many authors acknowledged the different needs of occupants and stated that houses must be designed accordingly;

> *"Since the attitude of the occupant of a house to his or her thermal environment must be regarded as the true reflection of the adequacy of construction … for the climate concerned, temperatures occurring indoors, and their relation to desirable levels, are of paramount importance as design factors." (Drysdale, 1952, p2)*

and …

> *"Individual differences in the tolerance of heat are very great, and private buildings can be designed for individual tastes and tolerances." (Marshall, 1958, p23)*

This concern for the preferences of individual occupants was extended to include broader social and cultural values in a review of Queensland housing (Summer, 1974);

> *"When the personal, social and cultural values of the inhabitants are in harmony with the combination of physical, visual and aesthetics properties of a particular structure, then is attains a satisfactory level of habitability." (Summer, 1974, p59)*

This is a considerable change in approach compared to the early thermal comfort based work in the tropics. Interestingly, despite the early work, Drysdale (1952) and Marshall (1955) still referred to 'comfort' temperatures that had not been tested for Australian conditions (ASHVE, 1943; Bedford, 1954; Chrenko, 1956; Olgyay, nd).

Concurrent to the release of these guidelines and studies, targeted experimental work was carried out by two main research organisations; the Commonwealth Experimental Building

Station (CEBS) and the Division of Building Research (DBR) at the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (Drysdale, 1947; 1948a; 1948b; 1950; Macfarlane, 1958; Weston, 1959; Ballantyne, 1975). This period was typified by somewhat disparate studies addressing various concerns of the time. It is noted, however that the findings of these studies were not widely disseminated amongst architects or builders (Williamson, 2013).

In the early 1970s the motivation for housing research and design shifted from achieving adequate indoor conditions to the conservation of energy through passive design techniques (Williamson, 2013). The 'solar house' was largely promoted as a solution for the temperate climates (Mollison, 1979; Den-Ouden, 1980; Williamson et al, 2003; McGee, 2013). During this period it is noted that the 'problem' was once more viewed from a technical perspective and that little consideration was given to the needs or behaviour of occupants;

> *"People are strangely absent from this image. They are assumed either as keen participants whose aims are identical to those expressed in the design advice or they are 'designed' out of participation because they cannot be trusted." (Williamson et al, 2003, p72)*

This largely remains the framework in which current building research is conducted within Australia, however the discussion of performance is now centred on efficiency rather than sufficiency since the introduction of mandatory minimum thermal performance provisions for housing in 2003. The focus on this 'one size fits all' model is clearly demonstrated in the majority of building stock across Australia, where the same basic designs are used across considerably different climates. For example, in 2012 the Department of Climate Change and Energy Efficiency (DCCEE) commissioned two reports to investigate least cost pathways for new houses to meet increased regulatory building performance requirements. The investigation by Sustainability House (2012a; 2012b) conducted simulations of 20 typical house designs in eight different climate zones across Australia. The upgrade pathways involved little modification to the overall designs, in line with the major builders' current approach to satisfying the minimum performance requirements. This indicates that for the majority of new homes built in Australia, the focus is on meeting these minimum performance requirements, rather than tailoring the designs to meet any specific thermal requirements of the occupants.

Despite the rich history of building performance research within Australia, two key deficiencies are noted. The first is a lack of interest from the majority of the building sector to account for the social and cultural context of housing, and how this context may inform the occupants' operation of the building as demonstrated above (Williamson et al, 2010). The second is the absence of a thermal comfort standard based on data from residential buildings within Australia, even though significant work has been done in this area by Australian researchers (Macfarlane, 1958; Hindmarsh & MacPherson, 1962; Wyndham, 1963; Auliciems, 1977; Ballantyne et al, 1977; Auliciems & de Dear, 1986; Williamson et al, 1990; Saman et al, 2013). Of the field studies conducted in residential environments, Williamson et al (1990) found that the ISO EN 7730 (1984) standard could not be used to predict the thermal preferences of occupants in air conditioned and naturally ventilated houses in Darwin, while Saman et al (2013) observed that the ASHRAE 55 (2013) adaptive model adequately describes the thermal comfort of occupants in Adelaide Brisbane and Sydney houses during summer conditions. To date, there are no explicit links between the findings of these studies and current policy relating to thermal performance requirements of housing in Australia.

2.2.2 Standards and regulations: the National Construction Code

The Volume Two of the National Construction Code (NCC) (formerly the Building Code of Australia) incorporates provisions for the design of energy efficient Class 1 detached residential buildings (ABCB, 2015). Note that the full Code can be freely accessed online (URL provided in the reference list). The Code is a national standard, however is administered by the States and Territories, resulting in some variations in the application of the standard across Australia. The Energy Efficiency provisions were introduced to Volume Two of the NCC in 2003 through an agreement between the Council of Australia Governments (COAG). The provisions are aimed at addressing perceived market failures within the residential building sector related to the implementation of the Carbon Pollution Reduction Scheme (CPRS) (ABCB, 2009). All COAG agreements require the completion of a Regulatory Impact Statement (RIS) to determine the possible economic impact and regulatory outcomes of the resultant policy (COAG, 2004). The weakness of the Final Regulation Impact Statement for residential buildings is that the economic implications are based on simulations of residential buildings that use standardised occupancy information (ABCB, 2009). Therefore, the true economic consequences of the Energy Efficiency provisions for occupants wishing to operate their home in a different manner remain unqualified.

The objective of the Energy Efficiency performance provisions is to *"reduce greenhouse gas emissions"* (Australian Building Codes Board, 2015, section O2.6). This is further clarified by a functional statement;

> *"To reduce greenhouse gas emissions, to the degree necessary-*
>
> *(a) A building, including its domestic services, is to be capable of efficiently using energy; and*
>
> *(b) A building's domestic services for heating are to obtain their energy from-*
>
> *(i) A low greenhouse gas intensity source; or*
>
> *(ii) An on-site renewable energy source; or*
>
> *(iii) Another process as reclaimed energy."*

Which is again further clarified;

> *"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 …"*

The key aspect of these introductory statements to note is that the efficient use of energy for artificial heating and cooling is the sole way to achieve the performance provision objective. Therefore discussion of the thermal performance of dwellings in Australia, in a regulatory context anyway, remains confined to the efficient use of energy for heating and/or cooling, and not a reduction in energy consumption or an improvement in thermal comfort per se. Note that consideration of the appliance/equipment does not form part of the assessment, nor is there any requirement to install heating and/or cooling appliances in the home once built.

Within the Code there are two overarching methods to demonstrate the compliance of a house design with the Energy Efficiency performance provisions; proposal of an alternative solution (i.e. Verification-using-a-reference-building) or a deemed-to-satisfy approach. The alternative solution method is seldom used for the majority of housing stock because it is labour and knowledge intensive. The deemed-to-satisfy approach is more widely used, giving two options to demonstrate compliance; Option 1 Energy Rating and Option 2 Elemental Provisions. The energy rating option requires the dwelling design to achieve 6.0 Stars (with some State and Territory variation) using thermal simulation software within the framework of the Nationwide House Energy Rating Scheme (NatHERS). Option 2 specifies minimum total R-values for building components as well as glazing and ventilation requirements. This option is favoured by architects and design professionals as it does not require knowledge of thermal simulation software. Currently the energy rating (NatHERS) method to demonstrate compliance with the Energy Efficiency provisions is the primary form of assessment used in most States and Territories (Dong et al, 2014; NatHERS, 2015).

The NCC specifies eight different zones that broadly encapsulate variations in climate across Australia, see Figure 2.1. The performance requirements of the Energy Efficiency provisions vary according to these zones.

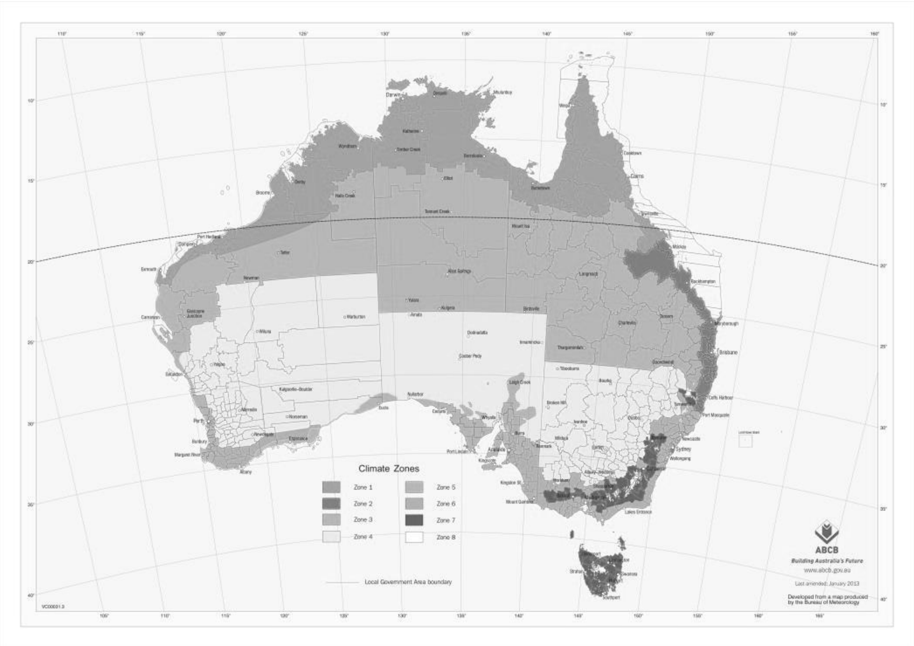

Figure 2.1. NCC Australia Wide Climate Zone Map (ABCB, 2014)

Nationwide House Energy Rating Scheme

NatHERS was developed in the 1990s as a response to Australia's signing of the United Nations (UN) Framework Convention on Climate Change in 1992 and the resulting National Greenhouse Response Strategy (Williamson, 1997). Based on the voluntary Glass, Mass, Insulation (GMI) Rating Scheme and the CSIRO *Chenath* simulation engine, NatHERS was not intended for mandatory use, but rather, as a design tool to assist the public and building industry (Williamson, 1997). NatHERS was adopted as the framework for the thermal simulation compliance assessment process when the Energy Efficiency provisions were introduced to the NCC in 2003.

The NatHERS simulation software, *Australian Government Endorsed calculation engine* second generation *AccuRate*, simulates the thermal performance of the building envelope and, based on predicted heating and cooling loads, produces a star rating from 0-10. A 10 star rating infers that the dwelling will require almost no additional heating and cooling to maintain the prescribed 'comfort range'. Whilst these comfort range settings are not specifically based on a standardised adaptive model (e.g. ASHRAE 55, 2013 or CEN EN 15251, 2007), they are based on an understanding that acceptable conditions vary somewhat with the climate. In warm and hot conditions, an allowance is made for the positive effects of air movement provided by natural ventilation or ceiling fans in the determination of whether or not cooling is needed (Szokolay, 2000; Chen, 2011).

Input required for simulation includes detailed information about location, construction, layout, shading, glazing and ventilation, while the NatHERS framework prescribes non-variable data such as occupancy profiles, casual heat loads and appliance use (see Table 2.1). Changes made to any of the input can result in a critical variation in the star rating realised and ultimately whether or not compliance with the Energy Efficiency performance requirements is satisfied.

Table 2.1. NatHERS fixed occupancy and user assumptions, note: Sensible and latent heat gains based on 160m^2 dwelling with 2 adults, 2 children, 80m^2 for living, 80m^2 for bedroom, an algorithm to adjust these occupancy variables are based on the floor area allocated to living space

User variable	**NatHERS regulatory setting**	
Heating and cooling energy loads	Heating and cooling load potential during all occupancy hours, all days of the year	
Rooms conditioned	All habitable rooms	
Thermostat settings	Heating	Minimum 20ºC in living areas between 7AM–12AM
		Minimum 18ºC in bedroom between 7AM-9AM & 4PM-12AM, minimum 15ºC in bedrooms between 12AM-7AM
	Cooling	Ranges from 22.5-28ºC during hours of occupancy based on climatic zone
Hours of occupancy	Living areas 7AM-12AM	
	Bedrooms 4PM-9AM	
Sensible and latent heat gains	Living areas with kitchen	8740W/day sensible* 2950W/day latent*
	Living areas	4590W/day sensible* 1365W/day latent*
	Bedrooms	2200W/day sensible* 900W/day latent*

Throughout the development of *AccuRate*, validation studies have sought to test the adequacy of the core computational engine to model the thermal performance of the building. The original iteration of the simulation engine, *Cheetah*, was included in a substantial international validation study completed in 1992 (Lomas et al, 1997). The study assessed the predicted temperatures of 25 dynamic thermal simulation programs against measured temperatures from three constructed test cells and demonstrated a general level of comparability between *Cheetah*, the other simulation programs and the measured data. Following the progression of *Cheetah* to *Chenath*, inter-program (inter-modal) and empirical validation exercises (using International Energy Agency (IEA) methodologies) were completed to test the enhancements of the tool (Delsante, 1995a; 1995b). Whilst minor discrepancies were reported, it was concluded that the evolution from *Cheetah* to *Chenath* did not result in the corruption of the original engine and that the findings *"should lead to increased confidence in its use."* (Delsante, 1995a). In 2004, a subsequent inter-program validation of the *AccuRate* simulation engine was completed, again using the International Energy Agency Building Energy Simulation Test and Diagnostic Method (IEA BESTEST). Results similarly indicated a good agreement with the reference programs and only produced minor over estimation of heating and cooling demands due to the temperature calculation and control algorithms (Delsante, 2004).

Issues or concerns with the current scheme

Internationally, house energy rating schemes (HERS) employing thermal performance simulation have been developed in an attempt to mitigate the amount of energy consumed in the building sector during the operation phase of the building (Lombard et al, 1999; Perez-Lombard et al, 2009; Scalco et al, 2012; Koo et al, 2014). However, despite the inherent and regulatory goals of HERS, substantial failings in their effectiveness in reducing energy consumption have been noted. These include; the take back effect (Sunikka-Blank & Galvin, 2012), accuracy of simulation tools (Stein & Meire, 2000; Williamson et al, 2001), appropriateness for passive architectural designs (Kordjamshidi, 2011; Williamson et al, 2010), reporting of results (Fabi et al, 2011; Lee et al, 2011) and standardisation of user behaviour (Murphy et al, 2011; Hoes et al; 2011). Within a regulatory context as is the case in Australia, these failings become increasingly important as the HERS outcome can ultimately affect whether a house design attains building approval certification.

NatHERS in Australia, as the most publically conspicuous method to demonstrate compliance with the NCC Energy Efficiency performance provisions has similarly attracted such criticisms. Specific issues that encompass both the overarching performance provisions and the NatHERS framework include; a lack of understanding and/or interest by associated professionals and general public (Pitt & Sherry, 2014), perception of efficacy (Ambrose et al, 2013; Pitt & Sherry, 2010; Sustainability House, 2012a; 2012b), poor perception of simulation tools (Daniel et al, 2015a; Williamson, 2010; Thomas, 2010), shortage of funding (Morrissey & Horne, 2011) and a fundamental flaw in the manner in which occupants are perceived (Williamson et al, 2010; Williamson, 2013; Pitt & Sherry, 2014). These issues culminate in a gap often seen between the predicted performance of a design and the actual performance of built dwellings (Williamson et al, 2010; Ambrose et al, 2013; Daniel et al, 2015a). This is noted in a technical assessment of the NCC Energy Efficiency performance provisions by Pitt and Sherry (2010);

> *"Unfortunately it is equally the case that poorly designed, constructed, commissioned and/or operated buildings – which may nevertheless demonstrate minimal compliance with the BCA – often*

> *struggle to deliver occupant comfort despite relatively high energy consumption and capital costs, let alone achieving their intended efficiency goals." (Pitt & Sherry, 2010, p18)*

The crucial role of occupants in the operation of the dwelling is again evident in this excerpt. Despite the vast amounts of literature demonstrating the importance of occupant behaviour in building performance (Stevenson & Leaman, 2010; Janda, 2011; Zaraket et al, 2015; Martinaitis et al, 2015; Ioannou & Itard, 2015), the NatHERS protocols adopt just a single user profile (see Table 2.1). The fixed or generic user profile is explained on the NatHERS website by the following statement;

> *"Every house is used in a unique way every day of every year and therefore it would be impossible to assess a building according to its actual use. To allow houses to be compared fairly a standard occupancy pattern is applied to represent a reasonable expectation of how a room (or space) is used (its function)." (NatHERS, 2014)*

Recent research (Daniel et al, 2015a) has demonstrated how this static model of occupancy disadvantages those seeking building approval that will operate their dwelling in a different manner. Furthermore, within a broader context, the current assumptions do not even represent a 'typical' Australia household (ABS, 2011; Ren et al, 2013).

At a fundamental level, the current provisions fail to take into account the wider housing aspirations of different types of occupants. For example, houses in Australia are becoming larger, this reflects the broader population's aspirations, but it also reduces the potential outcome of any energy efficiency policy (Clune et al 2012; Pitt & Sherry, 2014). At the other end of the scale are occupants who have different aspirations that motivate the design and their operation of the dwelling, often resulting in homes that have lower energy consumption (Williamson et al, 2010; Daniel & Williamson, 2011).

These issues clearly demonstrate an important aspect of building performance assessment that requires further thought. This is increasingly echoed in the field of building science research (Stevenson & Leaman, 2010). Similarly, in a discussion of the history of building science research in Australia, Williamson (2013) concludes that;

> *"Perhaps now it is time to move on and realize that the reality of the thermal performance of a building in use cannot be prescribed by the*

> *application of a purely positivist science with the occupants as relatively neutral participants." (Williamson, 2013, p 206)*

It is evident that whilst technical solutions of the building envelope are necessary, they are not sufficient to achieve a comprehensive reduction of greenhouse gas emissions from the residential sector (Janda, 2011) and further consideration must be given to the social and cultural contexts in which these houses are designed and operated.

Direction of assessment: current propositions

It is widely acknowledged that improvement is needed within both the Energy Efficiency performance provisions and the methods by which the compliance of house designs can be demonstrated. There is also evidence that indicates that Australia's building performance regulation (currently in the form of Energy Efficiency provisions) is at a very low standard compared with international counterparts (Hayles et al, 2006; Pitt & Sherry, 2010; 2014; Morrissey & Horne, 2011; Morrisey et al, 2013; Moore et al, 2014). Whilst many of these studies argue the need for market intervention and broader policy approaches, it is likely that simulation using the NatHERS framework, with only minor refinements, will remain one of the primary approaches to design compliance assessment in the foreseeable future (SOG-EE, 2012; NatHERS, 2015).

As such, much of the current work within this field focuses on improvements to this process within the current paradigm, including; consideration of embodied energy within the assessment process (Morrisey & Horne, 2011; Stephan et al, 2012; Stephan & Crawford, 2014; Crawford 2014), improvements to weather data and climate files used in simulation (Wang et al, 2010; Chen et al, 2012) and the inclusion of additional modules in *AccuRate* (e.g. lighting and water assessment) (Ren et al, 2011; 2013). What is important to note about these studies is that all of the proposals continue to be founded on the underlying assumption that houses must always be mechanically conditioned. There is a mentality that artificially heated and/or cooled buildings are the norm and that natural ventilation or bioclimatic designs are unusual or second rate (Nicol & Wilson, 2011). A notable exception to this school of thought is exemplified in the work done by Kordjamshidi (2011; 2013), who found that the NatHERS assessment method discriminates against houses designed to be free-running (naturally ventilated). This work proposes the use of a comfort metric for thermal performance, as well as greater flexibility in the manner in which occupancy related variables are modelled.

However, the work has not yet influenced current practices, likely because the proposal sits outside of the current assessment paradigm.

2.3 International standards for thermal environments

International thermal comfort standards originated from heating, cooling and ventilation engineers in an attempt to define the conditions that equipment needed to provide. Within this context it was appropriate to view thermal comfort as largely a physiological phenomenon. Increasingly, standardised thermal comfort models are being used to assess thermal environments and therefore make some kind of judgement about the thermal performance of a building. The three often cited international standards for thermal conditions are ISO EN 7730 (2005), CEN EN 15251 (2007) and ASHRAE 55 (2013). The use of these standards to assess the indoor thermal environments of buildings has precipitated an interest in the impact of other factors (e.g. social and cultural) on thermal comfort. An emerging theme in the discussion of thermal comfort research, in a situation where there is a need to reduce reliance on mechanical heating and/or cooling, is the appropriateness or otherwise of current models to account for these influences in the assessment of thermal performance. The following section will briefly describe the development of the relevant thermal comfort standards and examine recent research that supports further investigation of thermal comfort in context.

2.3.1 Thermal comfort

Thermal comfort has been defined as; *“that condition of mind which expresses satisfaction with the thermal environment”* (ASHRAE, 2013, p3). Thermal comfort research was largely initiated by the need for specifying design temperatures associated with the provision of mechanical heating, ventilation and air conditioning (HVAC) systems within buildings (Cooper, 1998; Shove, 2003). Various methodologies for the calculation of human thermal comfort have been proposed since the early 1900s; however a key publication in this field was by Fanger (1970). In this text Fanger proposes the thermal sensation index, Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD) index for the thermal quality assessment of existing indoor climates. The original PMV/PPD equations were based on steady-state climate chamber studies of college age subjects and accounted for the influence of six environmental and personal stimuli: air temperature, radiant temperature, air speed, humidity, metabolic rate and clothing insulation. Importantly, underlying these models is an expectation that a ‘neutral’ thermal sensation vote equates to ‘comfort’ or optimum thermal conditions in all cases for all subjects (Gagge et al, 1967; Fanger, 1970).

The PMV/ PPD indices were included in the ISO 7730 standard in 1984 and the ASHRAE 55 standard in 1991. Fanger's work remained the accepted thermal comfort standard throughout the later part of the twentieth century (Roaf et al, 2010). In the late 1970s and early 1980s a number of researchers argued that the PMV model did not correlate well with the neutral temperatures reported by occupants in naturally ventilated buildings (Humphreys, 1978; Auliciems, 1981). It was thought that occupants in naturally ventilated buildings had more opportunity to adapt to the local climate, therefore influencing their subjective response to indoor conditions. This was confirmed by Humphreys who found that the neutral temperature of occupants in naturally ventilated buildings was closely linked with prevailing outdoor temperature (Humphreys, 1978). This approach to thermal comfort acknowledges the ability of occupants to adapt to a wide range of indoor thermal environments when there is an explicit connection with external conditions (Auliciems, 1981). Importantly, the adaptive model attributes greater responsibility to occupants to be active and interact with the building to achieve personal thermal comfort.

In 1998 de Dear and Brager formalised this concept into an adaptive model of thermal comfort that was based on approximately 21,000 field observations from predominantly non-residential buildings (Brager & de Dear, 1998; de Dear & Brager, 1998; 2001). Three areas of thermal adaption influencing thermal perception were cited: behavioural adjustment, physiological adaption and psychological adaption (Fountain et al, 1996). The authors recognised that the existing PMV model adequately accounted for the limited adaptive opportunity in HVAC buildings and therefore presented the adaptive comfort model as complementary to the established PMV model; appropriate for the design and assessment of naturally ventilated thermal environments.

The adaptive comfort model was included in the ASHRAE 55 standard in 2004, while a European counterpart, CEN EN 15251, was released in 2007 (CEN EN, 2007). The ASHRAE 55 adaptive comfort model is currently the focus of a substantial amount research within this field and is frequently updated to reflect new advances (Cândido et al, 2011), such as: calculation of the prevailing mean outdoor air temperature and accounting for the benefits of elevated air speeds in warm conditions (de Dear, 2011a). This focus highlights the prominence of mixed mode and naturally ventilated buildings that are designed to reduce reliance on mechanical heating and cooling.

Developing in parallel with the PMV/PPD and adaptive models of thermal comfort was the standard effective temperature (SET) model (Gagge et al, 1986). This model is based on a two-node heat balance model of the human body and seeks to determine particular combinations of physical (environmental) conditions that produce equal physiological strain (Fountain & Huizenga, 1995). Originating from early work by Houghten & Yagloglou (1923a), this model has undergone several iterations; effective temperature (ET) (Houghten & Yagloglou, 1923b), corrected effective temperature (CET) (ASHVE, 1932), resultant temperature (RT) (Missénard, 1959), new effective temperature (ET*) (Gagge et al, 1971; 1974; Rohles et al, 1975). It is now predominantly used in conjunction with the analytical comfort zone method (PMV) to calculate the cooling effect of elevated airspeeds in ASHRAE 55-2013 (Fountain & Huizenga, 1995).

The PMV and adaptive models remain the most widely used in both international standards and thermal comfort research. Whilst these models are well tested and accepted for use in air conditioned commercial buildings (e.g. offices), for which they were largely designed, there seems little consensus in the application of thermal comfort models in residential buildings. The PMV and adaptive models are the most commonly referenced in studies of existing residential thermal environments (Yang et al, 2013; Luo et al, 2014; Jamaludin et al, 2014; Nematchoua et al, 2014; Dhaka et al, 2015; Udaykumar et al, 2015), however in the analysis of predicted indoor environments, a wider range of measures are used such as cooling/heating degree hours (Kordjamshidi, 2011; Scalco et al, 2012) and Givoni’s model (Attia & Carlucci, 2015). It likely that an adaptive model of thermal comfort may be most useful in the assessment of thermal conditions in residential buildings due to the wide range of adaptive opportunities available to most occupants within their own homes (Peeters et al, 2009; Saman et al, 2013; Pacheco & Lamberts, 2013). Interestingly, when the thermal comfort votes of residential occupants have been compared with the ASHRAE adaptive model, the slope of the relationship between the prevailing mean outdoor temperature and reported acceptable indoor temperatures is generally steeper than that of the adaptive model (Williamson et al, 2010 ; Yang et el, 2013; De Vecchi et al, 2015; Dhaka et al, 2015). This may indicate that these occupants have a higher level of adaption to their thermal conditions, which would support broadening the upper and lower comfort parameters in residential indoor environments. It is clear, however, that the current adaptive model needs further testing to confirm its appropriateness for residential buildings (Luo et al, 2014).

Shifting focus of thermal comfort research

From recent thermal comfort research two key themes emerge that are of particular relevance to this thesis; that neutrality does not necessarily equate to comfort and the importance of the subjects' social and cultural context.

The formation of thermal comfort models has traditionally been based on the understanding that an individuals' neutral temperature equates to comfort (Fanger, 1970). This reflects the origin of thermal comfort research in engineering and physiology. In the practical application of thermal comfort models, it is not necessarily neutrality (or lack thereof) that determines whether or not an individual deems their thermal environment acceptable. The relevance of the individual's judgement is that their preference is likely to motivate operation of available controls (e.g. mechanical heating and/or cooling, windows, fans). This, of course, has a direct impact on energy use, so is vital in the consideration of the thermal performance assessment of buildings. In 2004 Humphreys & Nicol demonstrated that the neutral point on the ASHRAE 7-point sensation scale does not necessarily equate to thermal comfort. This has also been confirmed by Humphreys & Hancock (2007), Li et al (2010) and Tweed et al (2014) amongst others.

In 2009 de Dear furthered this discussion by (re)introducing the concept of alliesthesia (Cabanac, 1971; 1981; Attia & Engle, 1981; 1982; Attia, 1984; de Dear, 2009). Alliesthesia has been defined as *"the perception of external stimulus as pleasant or unpleasant depending upon internal stimuli"* (Medical Dictionary, 2009) and is summarised in the context of thermal experience by de Dear;

> *"The simple concept of alliesthesia can now be summarized: any external or environmental stimulus that has the prospect of restoring the regulated variable within the milieu interieur to its set-point will be perceived as pleasant (positive alliesthesia), while any environmental stimulus that will further displace the error between the regulated variable and its set-point will be perceived as distinctly unpleasant, or even noxious in more extreme cases (negative alliesthesia). Alliesthesia leads us to seek pleasant stimuli and avoid unpleasant ones" (de Dear, 2011b, p110).*

Alliesthesia is offered as the 'fundamental theoretical underpinnings' to the adaptive model; demonstrating how a set of thermal conditions can be perceived so differently by occupants in

HVAC buildings compared to those in naturally ventilated buildings (Cândido et al, 2010; de Dear, 2011b; Parkinson et al, 2015; Parkinson & de Dear, 2015). The concept is gaining purchase within the field of thermal comfort research and is increasingly referenced in contemporary studies (Tweed & Dixon, 2012; Zhang et al, 2015).The hypothesis of alliesthesia coupled with Humphreys & Nicol's (2004) findings show that variation in indoor thermal environments is highly desirable where occupants have some level of control or adaptive opportunity. This has clear benefits in the provision of thermally acceptable environments without heavy reliance on mechanical heating and/or cooling in residential buildings.

The second theme currently prominent in thermal comfort research is inquiry into the influence of an individual's social and cultural context on their expectations and perceptions of the thermal environment (Howell & Stramler, 1981; Chappells & Shove, 2005; Roaf, et al 2010; Nicol et al 2012). It is widely acknowledged that social and cultural factors appreciably influence thermal perception and expectation. For example, Heschong (1979) writes extensively about the virtues of contextual and varied thermal environments, and dissuades the idea that thermal comfort can mean the same thing to different individuals. Similarly, Humphreys (1995) explores these ideas using J R R Tolkin's Hobbits as an example of how individuals' location, cultural and experiences can influence their sense of thermal comfort. Further, Chappells & Shove suggest that *"[thermal] comfort is a highly negotiable social-cultural construct"* (2005, p32). While only a limited number of studies have addressed the influence of social and cultural factors specifically, there is increasing evidence to show that expectations and preferences of thermal comfort can vary depending on the particular context. This is particularly notable in field studies; for example, Williamson et al (1990), Strengers & Maller (2011) and Healey & Webster-Mannison (2012) all comment on a wide range of contextual factors (e.g. broader lifestyle preference, social practices, notions of productivity) that influence how the occupants studied responded to thermal conditions. Furthermore, studies have examined these issues in the context of outdoor urban spaces (Knez & Thorsson, 2008; Aljawabra & Nikolopoulou, 2010; Kenawy & El Kadi, 2012). Findings from these studies revealed that factors such as an individual's previous thermal experience, socio-economic background (Aljawabra & Nikolopoulou, 2010) and nationality (Knez & Thorsson, 2008) influenced their perception and preference of thermal conditions. Consequently, thermal comfort standards that deal only with the physiological response to thermal stimuli may not be adequate in describing an individual's thermal preference. These sources clearly demonstrate the importance of social and cultural factors on occupants' expectations and perceptions of thermal environments; this in turn informs decision making about the use of heating and/or cooling appliances, and other thermoregulatory techniques. Again, this is of particular relevance in housing where occupants are directly responsible for energy use. This area of research is in the early stages of investigation with researchers highlighting the value of further studies (Hitchings, 2009; Strengers & Maller, 2011; Yang et al, 2014).

2.4 Environmental concern

An area of expanding activity within several overlapping fields of research is examination of the impact of occupants' values and attitudes on their behaviour, performance expectations, thermal perception, and uptake of environmental systems or technology. These aspects of building performance and operation may be motivated by the occupant's level of environmental concern (Mazar & Zhong 2010; Gatersleben et al, 2010). In environmental psychology research often a distinction is made between eco (or enviro) centric and anthropocentric attitudes towards the environment (Thompson & Barton, 1994; Milfont & Duckitt, 2006; Casey & Scott, 2006). Ecocentric attitudes acknowledge the intrinsic value of the natural environment, while anthropocentric environmental attitudes place value in the environment because of its benefit to humans. These attitudes can inform and motivate behaviour;

> *"Understandings and beliefs about environmental change have to be seen as intermeshing within a wider set of understandings and beliefs, and it is this inter-relationship that enables the prediction of pro-environmental behaviour" (Gatersleben et al, 2010, p38).*

This values/attitudes and behaviour relationship is also subject to other factors such as; the individual's perceived importance and influence of their actions (Poortinga et al, 2004; Ohler & Billger, 2014) and socio-demographic factors (i.e., income, gender, age, education) (Gatersleben et al, 2010; Bond, 2011; Martinsson et al, 2011; Wilson et al, 2013; Tranter, 2014; Lange et al, 2014; Sargisson & McLean 2015). The existence of multiple pressures on the value/attitude and behaviour connection indicates that context dependant assessment is necessary to provide a holistic understanding of an individual's motivation in their operation of their home. To this end, various theoretical models to assess the relationship between environmental attitudes *inter alia* and energy saving behaviours within housing have been suggested (Stragier et al, 2012; Wang et al, 2014), however they remain largely untested.

2.4.1 Pro-environmental attitudes and energy saving behaviours

A study in The Netherlands found that intrinsic worldviews correlate with pro-environmental attitudes and behaviours (Hedlund-de Witt et al, 2014), demonstrating that it is an individual's innate understandings of the world that motivate the formation of attitudes and beliefs. In Australia, it has been established that there is a strong association between environmental attitudes and energy saving behaviours (Casey & Scott, 2006; Gadenne et al, 2011).

This association has been investigated in the context of office buildings in the UK (Lakeriduo et al, 2012), Canada (McGunn & Gifford, 2012) and Australia (Dueble & de Dear, 2012). All three studies used the New Ecological Paradigm (NEP) (Dunlap et al, 2000) to assess environmental concern. Whilst *energy saving* behaviours were not specifically addressed because of the lack of controls generally available to office workers, related variables were; such as, forgiveness factor (Deuble & de Dear, 2012), air temperature (Lakeridou, 2012) and pro-environmental behaviour (McGunn & Gifford, 2012). All studies found a positive association between environmental concern and the specific variable measured.

Within the housing sector, several studies have sought to understand the connection between environmental attitude and willingness to pay for or adopt 'green housing attributes' and energy efficient technology (Hostetler & Noiseux, 2010, Yau, 2012; Ameli & Brandt, 2015; Long et al, 2015; Ramos et al, 2015). Pro-environmental attitudes were found to be a likely indicator of participation in an energy retrofit scheme (Long et al, 2015) and adoption of energy efficient technology (Ameli & Brandt, 2015). In Hong Kong, a strong association was found between environmental attitude and willingness to pay for green housing attributes (Yau, 2012).

This sentiment is similarly upheld by the majority of research into environmental concern and energy saving behaviours or energy use within homes. Studies in China (Wang et al, 2014), Canada (Scott et al, 2001) and the UK (Brandon & Lewis, 1999) found that energy saving behaviours were strongly influenced by environmental attitudes (Wang et al, 2014; Scott et al, 2001) and that education assisted the development of energy conserving behaviours in occupants with positive environmental attitudes (Bradon & Lewis, 1999). Research conducted in Australia (O'Callaghan et al, 2012) and the US (Sapci & Considine, 2014) found a positive relationship between environmental concern and actual water and energy consumption within the home. At a more detailed level, Lillemo et al (2013) revealed that environmental attitude motivated Norwegian householders' choice of heating appliance; those with higher levels of environmental concern were more likely to invest in heating systems with a perceived environmental benefit. A range of tools were used in these studies including the NEP scale and Environmental Attitudes Inventory (EAI) (Milfont & Duckitt, 2010). However, all of these studies clearly indicate the importance of environmental concern in determining the operation of dwellings in relation energy use and thermal performance.

2.5 Examination of key themes within the Australia context

The above review of relevant literature reveals an opportunity to address three key themes within the context of residential design and performance assessment in Australia; the impact of socio-cultural context of dwelling design, operation and performance, the appropriateness of the application of international thermal comfort standards for housing, and the relevance of environmental concern in expectations and perceptions of dwelling performance.

Two distinct forms of housing that present as useful case studies, by which to examine the above issues in further detail are; earth houses in cool temperate climates and naturally ventilated dwellings in hot humid climates. Whilst these forms of housing are remarkably different in terms of construction characteristics, local climate and use of heating and/or cooling, they both similarly embody the tension between the existing regulatory paradigm and housing that has been developed over-time to respond to particular climatic and socio-cultural needs.

2.5.1 Earth buildings

Unfired earth construction techniques were introduced to Australia from Europe and the Americas in the late 1700s (Coombe, 1979). As construction methods were refined Australia became widely recognised as proficient in this form of building (Williams-Ellis et al, 1947). Rammed earth and mud brick walls are the primary forms of earth construction utilised in contemporary architecture. Since 2003 there has been a decline in new earth builds as design incorporating earth wall have struggled to demonstrate compliance with minimum thermal performance standards (Building Commission of Victoria, 2007).

Both the elemental approach and the energy rating approach have presented barriers in the compliance assessment of earth building designs; the earth walls often do not satisfy the R-value requirements in the cool temperate climate zones of southern Australia (Dong et al, 2014), whilst low energy ratings are not seen to reflect the perception of ‘good’ thermal performance (Daniel et al, 2015a). The challenge with the elemental approach is relatively straight forward; traditional methods of earth wall construction generally do not include a separate layer of thermal insulation and therefore are not seen to provide adequate protection from outdoor conditions (Dong et al, 2014). The issue of the performance gap noted when using the energy rating method is more complex. Responding to concerns that the simulation engine could not adequately model massive construction and, in particular, account for thermal lag; predicted data from *AccuRate* were compared with measured data from a mud brick house (Delsante, 2006). The study found that there was no significant discrepancy between *AccuRate* simulation results and measured data. Importantly, the author suggests that any discrepancies may be attributable to the difference between behaviour and occupant assumptions included within the program and actual occupant perceptions. Similarly, a 2009 study of houses incorporating rammed earth walls concluded that lower energy bills were not directly attributable to the use of rammed earth wall construction but instead the occupants' perceptions that influence behaviour related to energy use (Soebarto, 2009). Notably, the uninsulated rammed earth houses were on average approximately 5°C cooler in winter than the insulated rammed earth house, yet the occupants were satisfied with thermal performance and their energy use was approximately 50% of the average energy use per person in the region (Soebarto, 2009). These studies confirmed that the performance gap was likely attributable to inappropriate assumptions about the users incorporated into the simulation model, rather than any fault with the actual simulation engine (Daniel et al, 2015a).

In cool temperate climates, the use of thermally massive wall construction (i.e. earth walls) is likely to result in cooler indoor conditions than those that may be found in comparable dwellings that include a separate layer of thermal insulation in the walls (Dong et al, 2014). According to the way in which thermal performance is currently assessed, this is judged as unacceptable. However, it is likely that, in addition to modifying their expectations of performance, the occupants within these houses have adapted to the cooler conditions experienced.

Throughout the history of earth building it is acknowledged that this form of housing satisfies particular needs of the occupants which may be considered alternative when compared with those of the general population. In Australia small communities of earth house owner/builders have formed, often reflecting an attitude towards the natural environment rather than employing earth purely as a tectonic building material (Rael, 2009; Daniel & Williamson, 2011). The choice to live in an earth building is indicative of a broader approach to housing, community and the environment;

> *"families who build their own homes in earth each year are … ignored because they do not consume according to the norms of industrial production." (Dethier, 1981, p12)*

In the examination of one these communities, (Casey, 2005) found that the occupants have higher levels of ecocentric concern and pro-environmental behaviour than that of a broader Australian sample (Casey & Scott, 2006).

2.5.2 Naturally ventilated buildings

Dwellings designed to capture and maximise the benefits of natural ventilation were born out of necessity in the hot humid climates of northern Australia. This was typified in Darwin where early European housing was informed by a wide range of building traditions; from Indigenous structures to Chinese, Malay and Japanese construction techniques (Harris & Welke, 1981). Despite the variety of influences much of the housing stock responded in a similar manner to climatic conditions, with large eaves, well shaded walls, lightweight materials, raised floors and minimal glazing in windows (Harris & Welke, 1981). These design features were epitomised in the government houses constructed for Commonwealth employees in Darwin in the 1950s and are similarly echoed in the well-known 'Queenslander' house (Summer, 1974; Saini, 1983). A significant shift in the design of housing in Darwin occurred in the late 1970s after cyclone Tracy destroyed over 50% of housing stock in 1974 (Walker, 2010). House design moved to on ground masonry construction, with smaller windows and compartmentalised rooms (Harris & Welke, 1981). This also coincided with a greater up take of air conditioning systems.

Even though resurgence in the aspiration for naturally ventilated dwellings was noted in the early 1980s in Darwin (Harris & Welke, 1981), almost all (96.3%) houses in the Northern Territory have air conditioning appliances installed (ABS, 2014). Whilst this may be attributable to changing lifestyle aspirations of the majority of the population, the Energy Efficiency provisions are also proving to be barriers in the construction of contemporary naturally ventilated houses (Williamson et al, 2010; Kordjamshidi, 2011). The energy rating method operates under the assumption that all houses must be (heated and/or) cooled. Fundamentally, the design of a naturally ventilated building is different to the design of one that will be artificially cooled and therefore cannot legitimately be tested in the same manner (Kordjamshidi, 2011). The inappropriateness of the energy rating method to assess the design of a naturally ventilated dwelling is highlighted in (Williamson et al, 2010) who found that;

> *"because of the porous nature of the building envelope of this house, the current NatHERS software cannot provide a sensible evaluation of the building and it thus receives zero Stars." (Williamson et al, 2010, p525).*

A variation in the application of the Energy Efficiency provisions in the Territory attempts to compensate for this; new house designs require a lower Star rating than the national requirements with additional allowances for outdoor living spaces with ceiling fans. The primary concern remains that the provisions do not encourage naturally ventilated design that is appropriate for the climactic conditions, but instead promotes the use of artificial cooling to achieve comfort. Despite the barriers presented by the Energy Efficiency provisions, the capacity for reduced energy consumption of naturally ventilated buildings is not only inherent but also firmly supported by the literature (Cândido, et al 2010; Gill, et al 2010; Taleb, 2015).Whilst the form of naturally ventilated dwellings can be quite varied, they stand as an expression of an individual's choice to 'experience the climate' not to rely on artificial cooling for comfort (Heschong, 1979).

2.6 Summary

Increasingly, evidence based pathways are being sought in the discussion of regulating for residential building thermal performance in Australia (Pitt & Sherry, 2010; Newton & Tucker, 2011);

> *"evidence-based roadmaps are being increasingly sought that are capable of informing governments, industries and consumers"*

and

> *"It is clear that policy cannot be based exclusively on technical/engineering evidence while ignoring the evidence of occupants' behaviour." (Newton & Tucker, 2011, p35 & 48)*

Gaps within the existing knowledge of the interaction between occupant behaviour and building performance can be summarised;

- The influence of occupant preferences on energy consumption attributable the use (or otherwise) of mechanical heating and/or cooling within the home is not fully understood;

- Existing models of thermal comfort have not been tested in residential thermal environments in Australia; and
- The role of environmental concern in motivating occupant's preferences is not an area that has been fully explored in this context.

The literature demonstrates a need to investigate the impact of occupant preferences in the thermal performance of residential buildings, contributing to an evidence based pathway to (more) sustainable housing in Australia.

Chapter 3. Research methodology

3.1 Introduction

This research investigates the occupants of two distinct forms of housing in two very different climates: dwellings incorporating earth construction elements with high levels of thermal mass in a cool temperate climate and naturally ventilated houses in a hot humid climate. The occupants of these types of dwellings are likely to represent definable cohorts with similar housing needs and aspirations as demonstrated by the literature in Chapter 2. Four main means of inquiry were used to address the research objectives: (1) a national survey of occupants, (2) in-depth case study of 40 households, (3) longitudinal thermal comfort survey of the 40 households, and (4) a survey of the environmental concern of the 40 households and a sample taken from the general population.

The methodological approach of this investigation borrows from multiple disciplines; however, the discussion of methods and results will be framed within the understandings and language of thermal comfort research.

Low Risk Human Research Ethics Approval was granted by The University of Adelaide Research Branch: Office of Research Ethics, Compliance and Integrity on the 22nd of August 2012 (approval number: HP-2012-063). See Appendix A for approval letter.

Portions of this chapter were previously published and have been quoted directly from the following sources (Daniel & Williamson, 2011; Daniel et al, 2012; 2013; 2014a; 2014b; 2015a; 2015b). Permission has been granted by all co-authors to quote published material without rephrasing.

3.2 National surveys

From 2011 to 2014 national surveys of the occupants of the two examples of atypical housing were undertaken. The surveys targeted dwellings incorporating earth construction walls, and both light weight and heavyweight naturally ventilated dwellings. The survey of earth buildings did not restrict the location of the respondents, while the survey of the naturally ventilated houses sought respondents specifically from hot humid climates.

The survey questions were adapted from a previously established questionnaire model originating from a study of energy efficient houses in Australia (Williamson et al, 1989) and modified to be appropriate for the target cohorts (see Appendix B). The survey of earth building households was primarily conducted from 2011 to 2013, while the survey of naturally ventilated households was conducted from 2012 to 2014.

The two surveys were distributed in both hardcopy and online formats in order to collect as many responses as possible by catering to participants' preferred method of response. The paper-based questionnaire package that was circulated included: a) a cover letter with rubric regarding the research project and intended outcomes; b) the questionnaire; c) a contact information sheet separate from the questionnaire; and d) a reply paid envelope. Online versions of the survey were made available through the *Survey Monkey* platform. The online questionnaires were essentially the same as the hard copy questionnaires, both were expected to take 15 minutes to complete.

Hard copies of the earth building survey were distributed by the following organisations: *Earth Building Association Australia*, *Nillumbik Mudbrick Association* and *Aldinga Arts Eco Village*, while the URL for the online version was made available on their web pages in 2011. The naturally ventilated building survey was primarily promoted online by a sustainable building interest group in Darwin, *CoolMOB.* The URL of a University of Adelaide landing page was made available on their website from December 2012 to August 2014. A small number (less than 50) of hardcopy surveys were also distributed by the group; the online platform being their preferred method of distribution. The use of the interest/industry organisations in the distribution of the questionnaires assisted in accessing the target audiences; however is recognised that by doing so select groups of respondents are defined.

The completed hardcopy questionnaires were collected and entered into the manual response option on the *Survey Monkey* website. The data was downloaded and analysed in Microsoft Excel file format. Results are presented in Chapter 4.

3.3 In-depth individual dwelling case studies

Forty households (20 of each form of housing) were selected for detailed case study. The earth dwellings were located within the Nillumbik Shire, Victoria and the naturally ventilated dwellings within or close to Darwin, Northern Territory (see Figure 3.1 to Figure 3.3). These two locations were chosen because of the large proportion of the two forms of housing in these areas and because of the distinct climates. Recruitment was via a third-party and written consent was attained from the occupants before direct contact was made with the households in adherence with The University of Adelaide's ethics policy. Therefore, the selection of the households was largely based on who answered first and whether or not the occupants would be leaving the house unoccupied for any significant amount of time during the monitoring period (if they were they would be excluded from the study). The target number of dwellings for each cohort was determined by the timeframe available to install the monitoring equipment.

Three methods of recruitment were used; however the primary form of recruitment was via the initial national surveys. Respondents to the initial surveys were given an opportunity to nominate their interest in participating in further research. An information package was distributed to those interested that were located within the geographical boundaries of the two case study areas (i.e. Nillumbik Shire and Darwin). The information package included an information sheet (see Appendix C), description of the monitoring equipment, consent form, contact form, complaints form and reply paid envelop. If the respondent did not return the consent form no further contact was made. A secondary method of recruitment utilised interest and industry groups to distribute hardcopies of the information package. Lastly, a short article was published in a local Nillumbik Shire paper, *the Diamond Valley Leader*, in mid-January 2013 to promote the research and provide the researcher's contact details for any interested households. Consent forms were obtained from all households before an initial visit by the researcher. Building selection criteria is given in Table 3.1. The results from this investigation are presented in Chapter 5.

Figure 3.1. Location of Darwin and Melbourne (Nillumbik Shire) in Australia

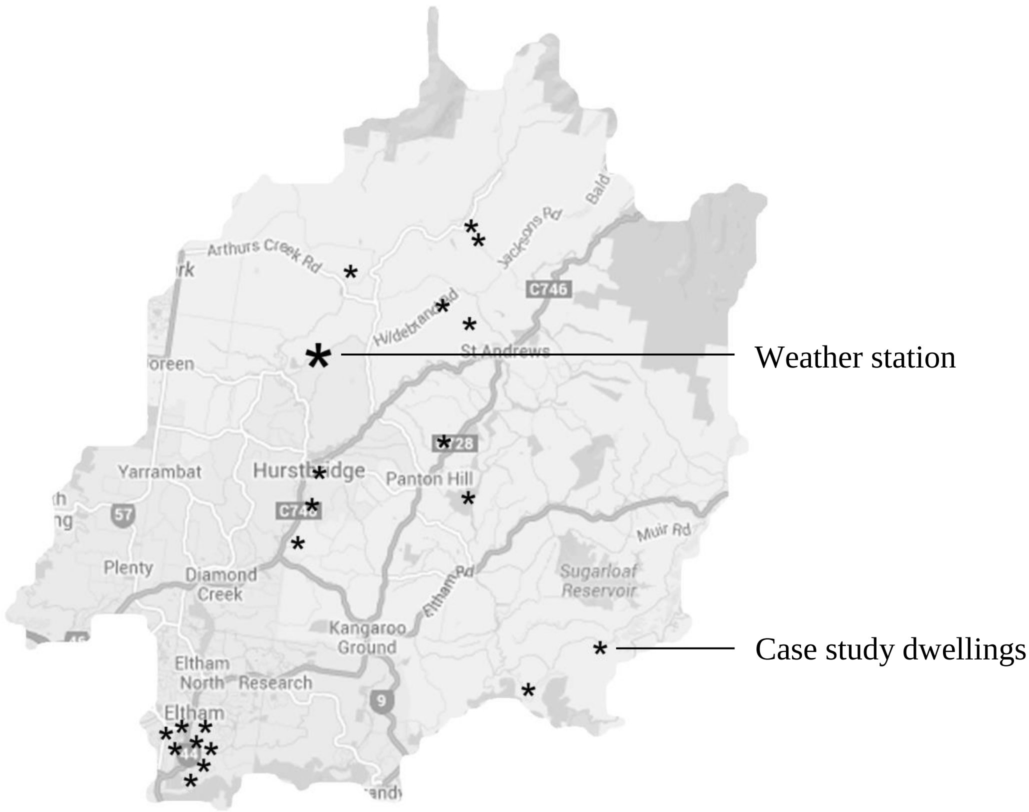

Figure 3.2. Location of the earth construction case study dwellings and weather station in Nillumbik Shire

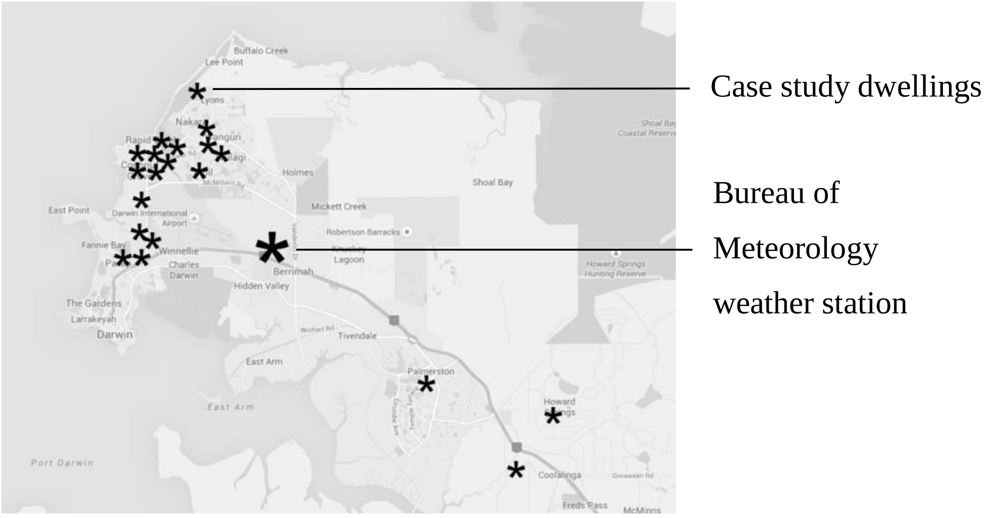

Figure 3.3. Location of the naturally ventilated case study dwellings and weather station, Darwin

Table 3.1. Selection criteria for case study households, note: 'Pre-Tracy' refers to the lightweight government built houses that were predominant in Darwin before the cyclone at the end of 1974

Selection criteria	Melbourne households	Darwin households
Location	All households located in Nillumbik Shire	<25km from Darwin
Age of house	1950 onwards	Pre-Tracy government houses onwards
Number of occupants	1+ occupants	1+ occupants
Age of occupants	25 years or older (participating in interview and comfort survey)	25 years or older (participating in interview and comfort survey)
Period of occupancy	2 years or more of consistent continuous occupancy including holidays	2 years or more of consistent continuous occupancy including holidays
Access to construction plans	Construction in some form	House plan in some form
Access to energy records	For the last 2-3 years or at least for the study period	For the last 2-3 years or at least for the study period
Typology	Detached	Detached or semi-detached
Construction	>50% earth construction external wall	House operated primarily as naturally ventilated

3.3.1 Semi-structured interview

A semi-structured interview was conducted with at least one member from all of the households, with questions aimed at gathering information about dwelling characteristics, and heating and/or cooling practices (Appendix D). A series of structured questions were asked however occupants were encouraged to elaborate on issues that they felt were important. The researcher recorded answers on a paper-based copy of the questionnaire whilst the interview was conducted. The responses were then coded and entered into an Excel spreadsheet and analysed using Excel software. All interviews were recorded using a USB audio recorder or the Voice Memo Application on the Apple iPhone. The interviews are used to provide a context for the information about dwelling operation.

House plans of varying levels of detail were obtained from the majority of the participating households and are presented in Appendix E.

3.3.2 Energy use records

The long term energy use of the households was ascertained through the collection of billing records and estimations of alternative fuels (e.g. wood, LPG gas). The records were primarily in the form of accounts from the electricity and gas retailers; however, those households with wood burning stoves or fires were asked to estimate their wood consumption in tonnes per annum. Similarly, households that used LPG gas were asked to estimate how many bottles were consumed per annum. The energy use data were then entered into an Excel spreadsheet and aggregated to provide average daily energy consumption for each household in kilowatt hours (kWh).

3.3.3 Meteorological measurements and data

The following climate statistics are sourced from the Bureau of Meteorology (BOM) website (2015). The weather stations were chosen for their proximity to the greatest proportion of case study dwellings.

Climate classification

The Nillumbik Shire is located north-east of Melbourne, Victoria and has the Köppen climate classification ‘Csb’, Mediterranean climate, dry warm summer, mild winter. The climate has four distinct seasons. Average annual rainfall recorded at the closest BOM weather station, Viewbank (Station number 086068, latitude 37.74 ºS, longitude 145.10 ºE), is 659.5mm. The rainfall is fairly evenly distributed throughout the year with the wettest months being November and December, and the driest January and March. Mean daily maximum temperatures range from 14.0 ºC in July (winter) to 27.8 ºC in January (summer), while mean daily minimum temperatures range from 6.0 ºC in July to 14.7 ºC in February. Humidity remains moderate throughout the year ranging from a mean 9am relative humidity of 86% in winter to a mean 3pm relative humidity of 43% in summer (BOM, 2015).

Darwin is located in the Northern Territory, Australia and 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; however the local Aboriginal Peoples identify up to seven distinct seasons. The weather during the build-up is characterised by high humidity and hot temperatures but little or no rainfall. It is generally perceived as a fairly uncomfortable season. Average annual rainfall recorded at the closest BOM weather station, Darwin Airport (Station number 014015, 12.42 ºS, longitude 130.89 ºE), is 1730.5mm. The monsoon period through January, February and March is when the majority of rainfall is received. The driest period is through June, July and August where very low amounts of rainfall are received (1.8mm, 1.2mm and 4.9mm respectively). Mean daily maximum temperatures have a narrow range from 30.5 ºC in June and July (the dry) to 33.3 ºC in October and November (the build-up/the wet), while mean daily minimum temperatures have a similarly narrow range from 19.3 ºC in July to 25.3 ºC 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, 2015).

Concurrent outdoor meteorological measurements

Outdoor meteorological measurements for Nillumbik Shire and Darwin were obtained from two sources: a HOBO U30 weather station installed in Nillumbik Shire (see Figure 3.2) and from the BOM climate data service. The weather station was located on a north-western facing slope exposed to the sky with no shading from surrounding trees (see Figure 3.4) to measure and record air temperature, relatively humidity, barometric pressure, solar radiation, and wind speed and direction at 30 minute intervals. For both locations, hourly weather data (precipitation, air temperature, dew point, relative humidity, wind speed, direction and gust, and barometric pressure) was sourced from the closest BOM weather stations to the respective case study areas (Viewbank Station and Darwin Airport Station), covering the monitoring period as well as the three previous years. The measurements from the weather station at Nillumbik Shire were used to describe the climate in which the Melbourne houses are located (see Figure 3.2), while the Darwin Airport Station BOM data were used for the Darwin climate (see Figure 3.3).

3.3.4 Measurement of indoor thermal environment

The indoor thermal environments of the case study households were monitored for a period of 11-12 months from March 2013 to March 2014 for the Melbourne households and from June 2013 to May 2014 for the Darwin households. Installation of the monitoring equipment for the Melbourne households took nine days from the 13th to the 21st of March 2013. Installation in the Darwin households also took nine days from the 5th to the 13th of June 2013. The primary loggers were placed in the household's most used living area and the secondary loggers were either placed in a secondary living area or main bedroom. Loggers were located away from heat sources, out of direct sunlight and, where possible, in a central location within the room at approximately 1.1m above floor level (ASHRAE, 2013).

Equipment

The indoor environmental conditions were measured using HOBO data loggers; the U12-013 model was the primary logger used (60 in total), while 20 H08-003-02 were used to enable the installation of two loggers in each house. In the Melbourne houses one U12-13 measured and recorded air temperature, relative humidity and globe temperature at 30 minute intervals. The second logger, the H08-003-02, recorded air temperature and relative humidity at hourly intervals (decreased sampling due to data storage capacity of the logger). Globe temperature was measured using the widely accepted technique of inserting an external temperature sensor inserted into a 38mm diameter matt black plastic sphere (Humphreys, 1977). In the Darwin households two U12-13 loggers recorded air temperature, relative humidity and globe temperature at 30 minute intervals. The logger located in the main living area of the Darwin households had an anemometer sensor included to record and measure air directional speed, also at 30 minute intervals. No known longitudinal field surveys in Australia have monitored air movement before due to the fragility, expense, accuracy and power consumption of the devices. A prototype system connecting an AccuSense F900 anemometer to a HOBO U12-013 data logger was developed in early 2013 (Daniel et al, 2014a) for this study (see Figure 3.5 and Appendix I for full description of the system). The open source hardware and software platform, Arduino, was used to regulate power flow to the anemometer sensor. It was not deemed necessary to measure air movement in the Melbourne houses due to low indoor air speeds (mean airspeed ranged from 0.05m/s to 0.23m/s during equipment installation) and relatively small influence on the occupants' thermal comfort within these conditions (Nicol et al, 2012; ASHRAE, 2013). The product details, including range and accuracy, for all of the measurement equipment used in the fieldwork are presented in Table 3.2 below.

Table 3.2. Equipment schedule

Qnty	Type	Model	Location	Range	Accuracy
60	HOBO logger Temp/RH + 2EXT	U12-013	20 Melbourne, 40 Darwin	-20°C to 70°C 5% to 95%	±0.35°C from 0°C to 50°C ±2.5% from 10% to 90%
20	HOBO Temp/RH loggers	H08-003-02	Melbourne	-20°C to 70°C 25% to 95%	na ±5%
20	AccuSense anemometer	T-DCI-F900-L-P	Darwin	0.05 to 10m/s	±5% of reading
60	HOBO ext temp sensor	TMC6-HD	20 Melbourne, 40 Darwin	-40°C to 50°C	±0.25°C
1	HOBO U30 Weather station	U30-NRC-000-05-S100	Melbourne	na	na
	HOBO U30 battery charger	AC-U30-EU		na	na
	Solar panel	Solar-SW		na	na
	Wind speed and direction sensor	S-WSET-A		0 to 45 m/s 0 to 355 degrees	±1.1m/s or ±4% of reading ±5 degrees
	Mounting arm for wind sensor	M-C AA		na	na
	Temp/RH sensor	S-THB-M002		-40°C to 75°C 0% to 100%	±0.21°C ±2.5%
	Radiation shield	Rs3		na	na
	Pyranometer sensor	S-LIB-M003			
	Mounting bracket for radiation sensor	M-LBB		na	na
	Level for radiation sensor mounting	M-LAA		na	na
	Barometric pressure sensor	S-BPB-CM50		660 to 1070 mbar	±3.0 mbar
	Tripod	M-TPB-KIT		na	na
1	Thermal anemometer	ThermoAir3	na	0.015 to 5m/s	±0.2% of full scale

Figure 3.4. HOBO U30 weather station, Nillumbik Shire

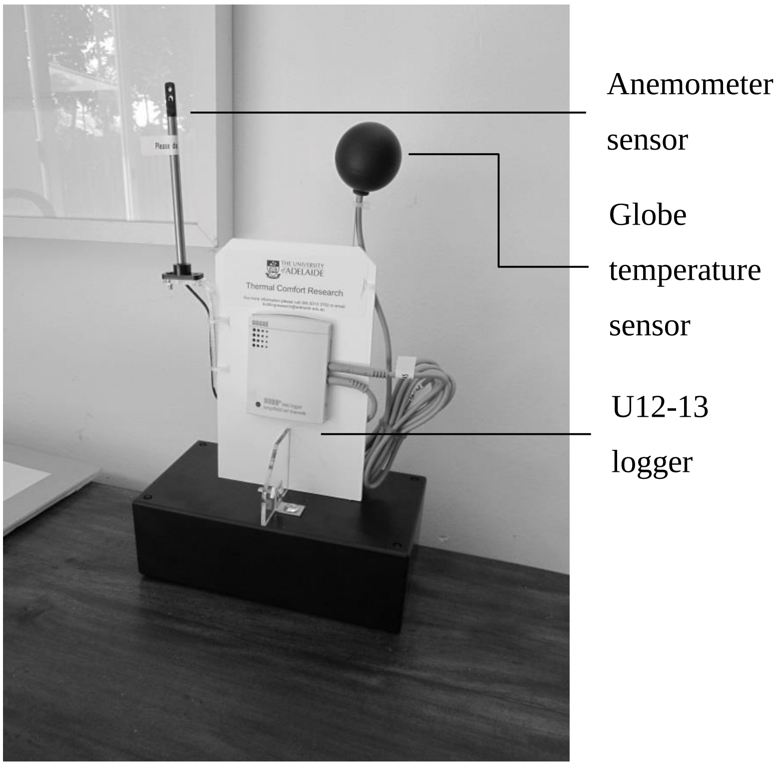

Figure 3.5. Anemometer system and HOBO U12-13 logger, Darwin

3.4 Thermal comfort survey

A paper based comfort vote survey in booklet form was distributed to all households. Occupants 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; thermal sensation vote (TSV) 1=Cold to 7=Hot (ASHRAE, 2013); thermal preference vote (TPV) 1=Cooler, 2=No change, 3=Warmer (McIntyre, 1982) and; thermal comfort vote (TCV) 1=Very uncomfortable to 6=Very comfortable (Brager et al, 1993; Luo et al 2014). The survey also asked the respondents to report their general clothing level, activity over the previous fifteen minutes, 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). The respondents were instructed to complete the survey within the rooms that the loggers were situated. Refer to Appendix F for full survey. The occupants completed the surveys with initial enthusiasm, however some survey fatigue occurred toward the end of the 12 month period. Some Darwin households also noted that they reduced the frequency of survey responses because they were always recording the same answers.

At the mid-point and the end of the monitoring periods, the hardcopy comfort vote booklets were collected and manually entered into Microsoft Excel spreadsheets. The logger readouts from each household were converted from *.dtf or *.HOBO to Excel files. Data points were filtered to readings on every hour. The comfort votes were entered to the closest corresponding hourly measurements. Where there were two votes recorded at the same time the second vote was entered to the next hourly measurement. Votes recorded where the environmental measurements were missing (air temperature, relative humidity and globe temperature) were entered to the corresponding time and date but discarded for analysis purposes.

Analysis was primarily conducted using Microsoft Excel and IBM SPSS Statistics 20. The outdoor running weighted seven-day mean temperature was used as the primary descriptor of outdoor conditions. Throughout the majority of the analysis Equation 3.1 (ASHRAE, 2013) was used to calculate this temperature, except for where comparisons were made with the EN 15251 standard when the equation specified by the standard was used (CEN Standard EN 15251, 2007). Results are presented in Chapter 6.

$$T_{rm} = 0.34T_{od-1} + 0.23T_{od-2} + 0.16T_{od-3} + 0.11T_{od-4} + 0.08T_{od-5} + 0.05T_{od-6} + 0.03T_{od-7} \quad (3.1)$$

Where: T_{od} = the daily outdoor mean air temperature

3.5 Environmental Attitudes Inventory survey

The Environmental Attitudes Inventory (EAI) survey developed by Milfont and Duckitt (2006; 2010) was chosen to assess environmental concern of the occupants of the case study households with a sample of the general population. This tool has previously been used by O'Callaghan et al (2012) within a study of occupancy assessment and building performance. The authors of the model and others (Sutton & Gyuris, 2015) claim that this tool addresses deficiencies within the more commonly used New Ecological Paradigm (NEP) scale (Dunlap et al, 2000; Deuble & de Dear, 2012). It also offered a brief version of the tool, EAI-24 (Milfont & Duckitt, 2007), which was desirable to minimise survey fatigue within the cohort of respondents (see Appendix G).

The EAI tool judges a respondent's level of environmental concern based on 12 attitudinal scales (see Table 3.3). The tool requires respondents to indicate their extent of agreement or disagreement with 24 statements (referred to as items) on a 7-point Likert scale. The scores given define two higher-order factors of environmental attitude; 'preservation' and 'utilisation' (Milfont and Duckitt 2006). Seven of the 12 scales contribute to an overall preservation score, while five contribute to an utilisation score. The preservation dimension broadly reflects biocentric (ecocentric) concern (conservation and protection), while the utilisation dimension reflects anthropocentric concern (utilisation of natural resources) (Milfont and Duckitt 2010).

Surveys were manually coded and entered into a Microsoft Excel spreadsheet. Mean scores were calculated for each item, which were then used to calculate the mean scores for each first and second order factors. Two control groups from a general population sample (for the corresponding locations; north-eastern suburbs of Melbourne, n=113, and Darwin area, n=36) were sourced using a commercial data collection agency. This agency sourced respondents from their panel database in the requested locations. The survey was administered online and, except for subsequent demographic questions, was identical to that conducted with the case study households. Results of the EAI survey are presented in Chapter 7.

Table 3.3. Twelve attitudinal scales for use in EAI survey (Milfont & Duckitt, 2007)

Scale label	Preservation	Utilisation
01 Enjoyment of nature	*	
02 Support for interventionist conservation policy	*	
03 Environmental movement activism	*	
04 Conservation motivated by anthropocentric concern		*
05 Confidence in science and technology		*
06 Environmental threat	*	
07 Altering nature		*
08 Personal conservation behaviour	*	
09 Human dominance over nature		*
10 Human utilisation of nature		*
11 Ecocentric concern	*	
12 Support for population growth	*	

Chapter 4. Results: national surveys

4.1 Introduction

Two initial surveys of broad populations of the two study groups were conducted in order to gather information about demographics, housing typology, and heating and/or cooling practices. The key aim of these surveys was to gauge whether or not occupants living in the two different forms of atypical housing can be identified as defined cohorts with alternative preferences and behaviours when compared to the general population.

Portions of this chapter were previously published and have been quoted directly from the following sources (Daniel & Williamson, 2011; Daniel et al, 2015a). Permission has been granted by all co-authors to quote published material without rephrasing. Since the initial collection of responses in 2011, subsequent responses have been collected and the findings as a whole are reported below.

The following chapter includes the results of the two surveys and a summary of the key findings.

4.2 Overview

A total of 176 responses to the earth building survey were collected and 102 to the naturally ventilated houses survey. The percentage of responses for each State and Territory are presented in Figure 4.1. The largest proportion of responses to the earth construction survey originated from Victoria, while almost all of the responses to the naturally ventilated dwelling survey came from the Northern Territory. This is likely due to the use of industry interest groups based in those locations, as well as the natural distribution of the two forms of housing. Due to the high proportions of responses originating from Victoria and the Northern Territory respectively, trends in the results will be compared to Australian Bureau of Statistics (ABS) data from these locations, as well as the national averages.

4.2.1 Demographics and occupancy

The surveyed households from both cohorts had a higher occupancy rate than the national figure of 2.6 persons per dwellings, as well as the figures for Victoria (2.6) and the Northern Territory (2.7), (ABS, 2013). The earth construction cohort had an occupancy rate of 2.8

persons per dwelling (SD 1.3), while the naturally ventilated cohort had an average occupancy rate of 3.1 persons per household (SD 1.3). On average the households within the earth construction cohort had lived in their current home for 14.9 years (SD 11.1 years) and the households within the naturally ventilated cohort for 11.1 years (SD 9.0 years). The age of occupants in the earth construction cohort is skewed towards the ‘50-59 year old’ and the ‘60 years old and over’ brackets, indicating mainly established households. This is similarly reflected by the average number of years respondents had lived in their current house. The distribution of the ages of the occupants within the naturally ventilated households is more normal (see Figure 4.2).

4.2.2 Age, dwelling type and location

The highest proportion of survey respondents from both cohorts lived in separate houses; 97.7% of the earth construction cohort and 91.1% of the naturally ventilated cohort (see Figure 4.3). Nationally, only 77.5% of households live in separate houses (ABS, 2011).

Most of the houses in both cohorts were estimated to be between 20 – 39 years old (see Figure 4.4). The proportion of newer houses was higher for the earth construction cohort than the naturally ventilated cohort.

The earth constructed dwellings were located in a range of settings; rural bushland (32.1%), inner town (26.7%) and rural countryside (21.5%), (see Figure 4.5). A high proportion of earth construction cohort respondents also nominated “Other” (21.1%), all of which described some kind of suburban block in a bushland or natural settings. This setting is typical of Nillumbik Shire north-east of Melbourne, Victoria that has a long history of earth building. The dwellings from the naturally ventilated cohort were primarily located in suburban settings (66.6%), rural bushland was the second most nominated location (14.7%). Of the six responses to “Other”, all described semi-rural settings with neighbours in relatively close proximity.

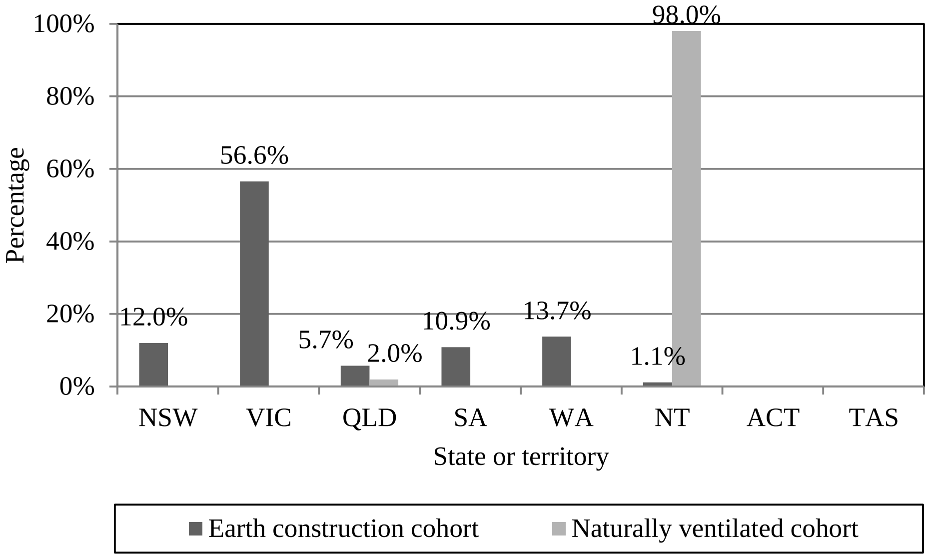

Figure 4.1. Distribution of responses from each State and Territory

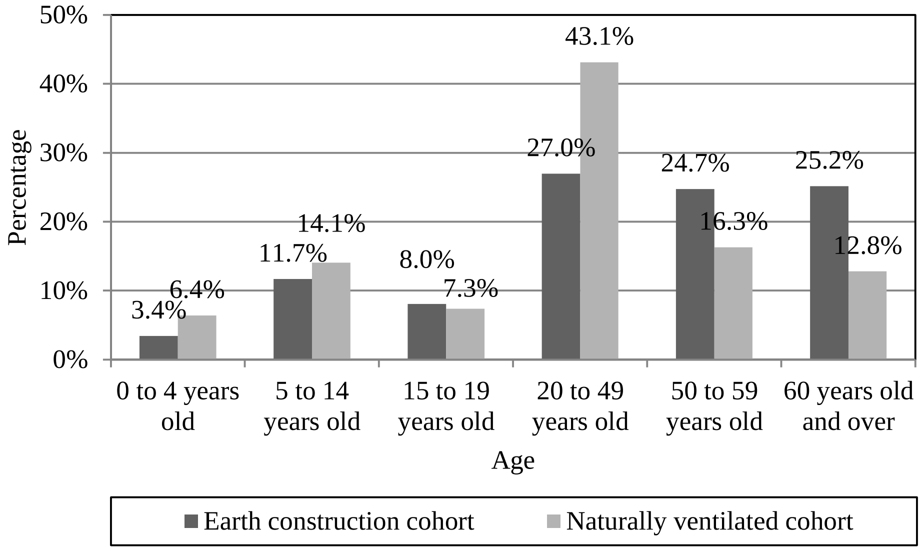

Figure 4.2. Distribution of age brackets of members of the surveyed households

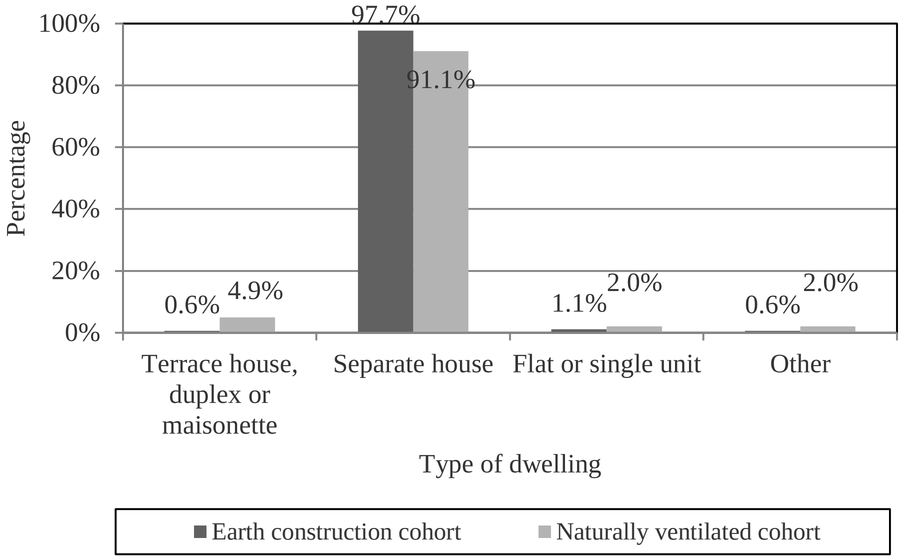

Figure 4.3. Type of dwelling

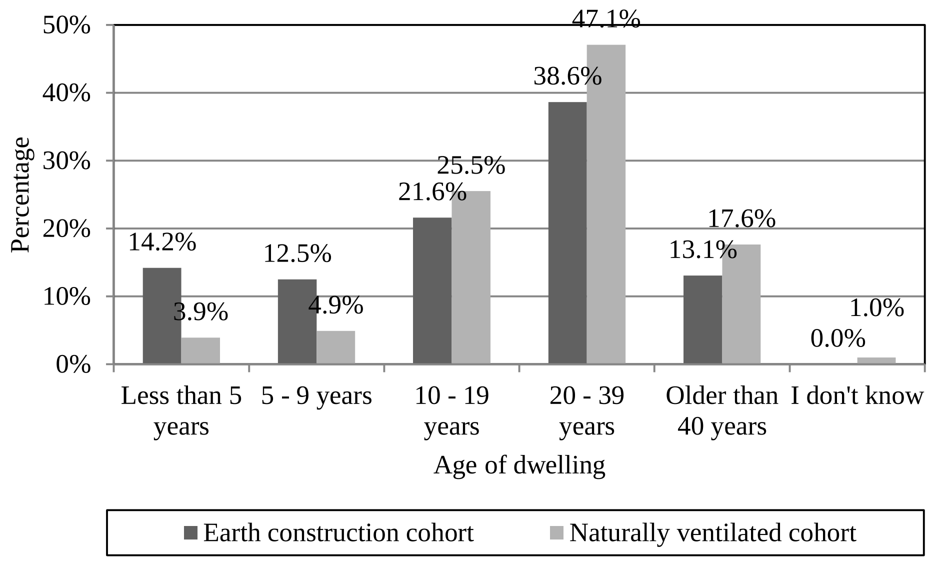

Figure 4.4. Age of dwellings

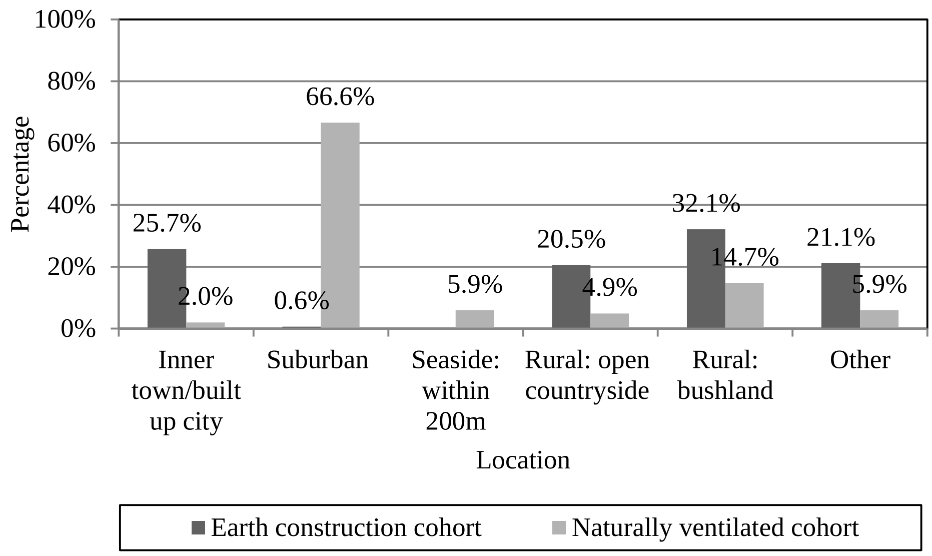

Figure 4.5. Location of dwellings

4.2.3 Choosing to live dwellings of atypical construction

Respondents to both surveys were asked to indicate reasons for choosing to live either in an earth constructed dwelling or a naturally ventilated dwelling. The answers presented to the respondents were modified for each cohort to reflect perceived qualities of the respective dwelling types. The earth building survey largely reflected the owner builder nature of dwellings incorporating earth construction components, while the naturally ventilated survey recorded sentiments around lifestyle and environmental impact. Respondents were given the option to nominate multiple choice answers as well as express their own reasons by selecting “Other”.

A large proportion of the earth construction cohort claimed that “Appearance” was important when choosing their home, followed by “Natural/renewable material” and “Low energy impact” (see Figure 4.6). Of the responses to “Other”, 13 cited the perceived thermal or acoustic performance of earth walls, 10 described "the feel" or some kind of connection to earth walls, four were due to involvement in the earth construction industry, three cited the perceived embodied energy benefits, three cited (low) maintenance of earth walls, three generally referred to aspects of sustainability and appropriateness for the environment, three were due to development overlays and one simply stated that the choice was due to the convenience of the particular property.

The reason nominated by the highest proportion of naturally ventilated cohort respondents was “Lifestyle” followed by “Low energy” and “Environmental impact” (see Figure 4.7). Of the responses to “Other”, five respondents commented on aspects of comfort, aesthetics and climatically appropriate design, four indicated availability of housing stock, two were philosophically opposed to air-conditioning and two claimed that “All of the above” were appropriate reasons.

The responses from both cohorts, as well as the reasons given in the “Other” section, broadly indicate an awareness of environmental issues when considering house choice. Whilst cost was nominated a reason by both cohorts, the proportions of respondents citing it were relatively low compared to other reasons.

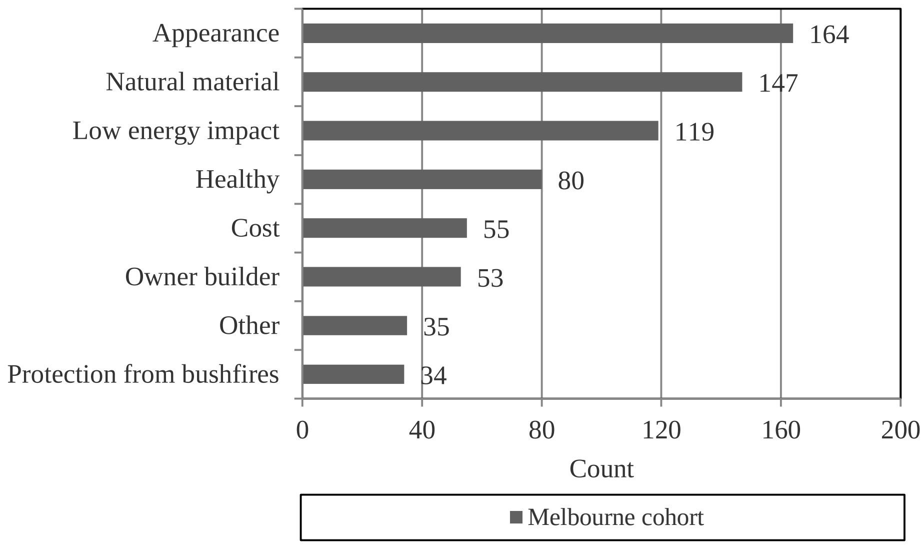

Figure 4.6. Reasons given for choosing to live in a dwelling incorporating earth construction

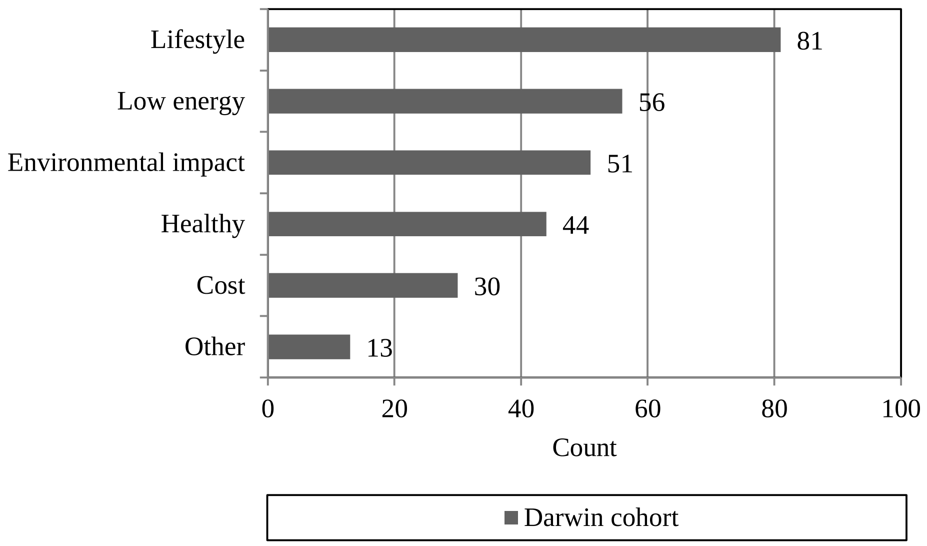

Figure 4.7. Reasons given for choosing to live in a naturally ventilated dwelling

4.2.4 Climate and comfort

Overall both cohorts responded positively on a 7-point Likert scale (1= “Dislike very much”, 7= “Like very much”) when asked about their perception of the climate in which they lived (see Table 4.1). Note that the Likert scale has been reversed for consistency of reporting. The average rating given by the earth building cohort was 6.0 (SD 1.0) and 5.7 (SD 1.4) by the naturally ventilated cohort. When asked to elaborate on their perceptions of climate, the earth construction cohort expressed 80 positive comments (e.g. mild conditions, seasonal variation and specific features of the micro-climate), 44 comments that cited both positive and negative aspects of the climate (e.g. seasonality, periods of extreme temperature – both hot and cold, and bushfire risk) and 12 negative comments (e.g. extreme temperatures – mostly heat related). Many respondents’ comments reflected their perception of the performance of their house in particular weather events rather than the climate itself. A common theme throughout the comments was an appreciation for the variation in seasons;

> *“[The climate] enables us to experience an extreme variety of seasons.” (Anonymous respondent, 2011)*

> *“There are four definite seasons. The summers are short but hot. The springs and autumns are glorious. The winters are longer and cold but with sunny days.” (Anonymous respondent, 2011)*

> *"Contrasting climates of Victoria, cold winters, hot summers, beautiful autumn and spring days... the house copes quite well in all conditions." (Anonymous respondent, 2011)*

In the explanation of their perceptions of climate, 45 of the respondents to the naturally ventilated national survey highlighted positive aspects of the climate (e.g. outdoor living, lifestyle, and constant warmth), 23 cited both positive and negative aspects of the climate (e.g. climate generally acceptable except for the build-up period and humidity) and eight expressed negative comments (e.g. restriction of movements due to climate - specifically humidity). A notable theme of the positive comments was the ability to experience the climate and surrounding natural environment; expressed in the following explanations;

> *"We live in Darwin in an urban area but are exposed to a huge variety of wildlife and climatic experiences. Living in an open house is an adventure. Last night a storm came through. It starts with flashes of intense light followed by rolling thunder, then the wind drives in before a curtain of heavy rain. Depending upon the direction, it's a race to close the louvres before we're inundated - the change is palpable, refreshing and incredibly energising." (Anonymous respondent, 2014)*

> *"We like to live in the weather and experience our climate fully." (Anonymous respondent, 2014)*

> *"90% of the time the tropical design and tropical living provides a pleasant and comfortable way to enjoy the climate. If the house was not 'tropical' i.e. built to 'southern energy efficient standards' i.e. close everything up and crank up the AC- not only would it be very expensive and energy inefficient but it would also be impossible to get any enjoyment from the tropical climate." (Anonymous respondent, 2014)*

In order to investigate acclimatisation to hot humid climates, respondents of the naturally ventilated survey were also asked about the length of time they had resided in this climate. A majority (79.4%) of the respondents had lived in a hot humid climate for more than 5 years. Of those that had lived in a hot humid climate for five years or less; nine were from Victoria, four from the Australian Capital Territory, two from Queensland, two from Western Australia, one from Tasmania and one from overseas (England). There did not appear to be a correlation between the numbers of years to respondents had resided in a hot humid climate and their perception of it.

When asked about their perception of thermal comfort in particular times of the day and season on a 7-point Likert scale (1= “Very uncomfortable”, 7= “Very comfortable”) (see Table 4.2 and 4.3), both cohorts again responded positively with average ratings of 5.6 for the earth construction cohort and 5.3 for the naturally ventilated cohort. Of the scores given for a particular time of day and season, the build-up during the daytime was the lowest, indicating uncomfortable conditions. All of the scores for other times of the day and seasons were broadly positive.

Table 4.1. Perception of the climate in which the respondents are located (1= “Dislike very much”, 7= “Like very much”)

Cohort	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Earth construction	0.6%	0.6%	1.1%	5.6%	15.0%	39.4%	37.8%
Naturally ventilated	1.0%	3.1%	6.2%	11.3%	8.2%	39.2%	30.9%

Table 4.2. Perception of thermal comfort in different seasons within dwellings incorporating earth construction components (1= “Very uncomfortable”, 7= “Very comfortable”)

Season	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Winter during the nighttime	2.8%	7.8%	6.1%	10.0%	13.9%	31.7%	27.8%
Winter during the daytime	5.0%	2.8%	5.6%	3.9%	9.4%	32.2%	41.1%
Summer during the nighttime	5.6%	1.7%	2.2%	7.8%	12.2%	35.6%	35.0%
Summer during the daytime	3.9%	2.8%	1.1%	6.1%	16.1%	36.7%	33.3%

Table 4.3. Perception of thermal comfort in different seasons within naturally ventilated houses in a hot humid climate (1= "Very uncomfortable", 7= "Very comfortable")

Season	1	2	3	4	5	6	7
The build up during the daytime	8.2%	20.0%	25.9%	21.2%	16.5%	5.9%	2.4%
The build-up during the nighttime	4.7%	11.6%	18.6%	18.6%	14.0%	23.3%	9.3%
The wet season during the daytime	4.7%	4.7%	7.1%	20.0%	18.8%	27.1%	17.6%
The wet season during the nighttime	4.5%	3.4%	0.0%	17.0%	17.0%	26.1%	31.8%
The hot and dry season during the daytime	5.7%	3.4%	3.4%	16.1%	17.2%	26.4%	27.6%
The hot and dry season during the nighttime	5.7%	1.1%	1.1%	8.0%	11.4%	25.0%	47.7%
The cool and dry season during the daytime	3.3%	0.0%	0.0%	3.3%	2.2%	18.5%	72.8%
The cool and dry season during the nighttime	3.3%	0.0%	0.0%	5.4%	1.1%	17.4%	72.8%

4.3 Construction

The configuration of the dwellings (i.e. number of floor levels) was relatively evenly distributed between single storey and two storeys for both cohorts (see Figure 4.8).

The main type of flooring in the earth construction houses was concrete slab on ground (54.6%) followed by timber flooring (22.3%) (Figure 4.9). The use of earth as a flooring material within these dwellings (5.5%) is also notable as it highlights non-standard construction practices. Of the responses to "Other" 18 indicated brick flooring, two some kind of non-standard masonry flooring, two reported some kind of non-standard timber flooring, and two a combination of masonry and timber materials.

The main types of flooring found in the naturally ventilated houses were timber flooring more than 500mm above ground level (38.6%) and concrete slab on ground (36.6%) (Figure 4.10).

The timber flooring is likely representative of the traditional ‘highset" or elevated housing, while the concrete slab on ground would likely be found in more contemporary blockwork and brick housing. Of the responses to “Other” five indicated concrete flooring downstairs and timber flooring upstairs, three indicated a variation of timber flooring, two a variation of concrete or masonry flooring and one replied “suspended fridge panels”.

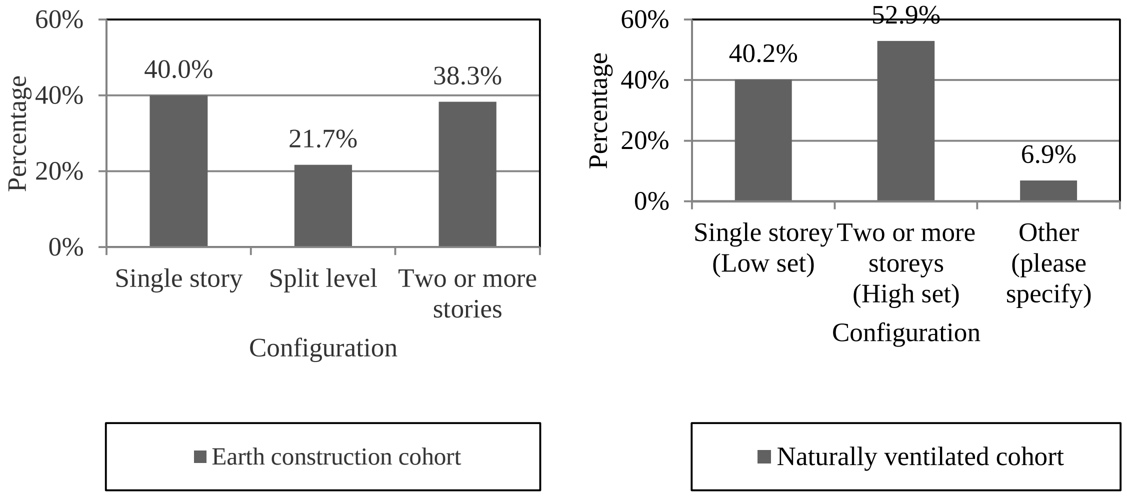

Figure 4.8. Configuration of dwellings

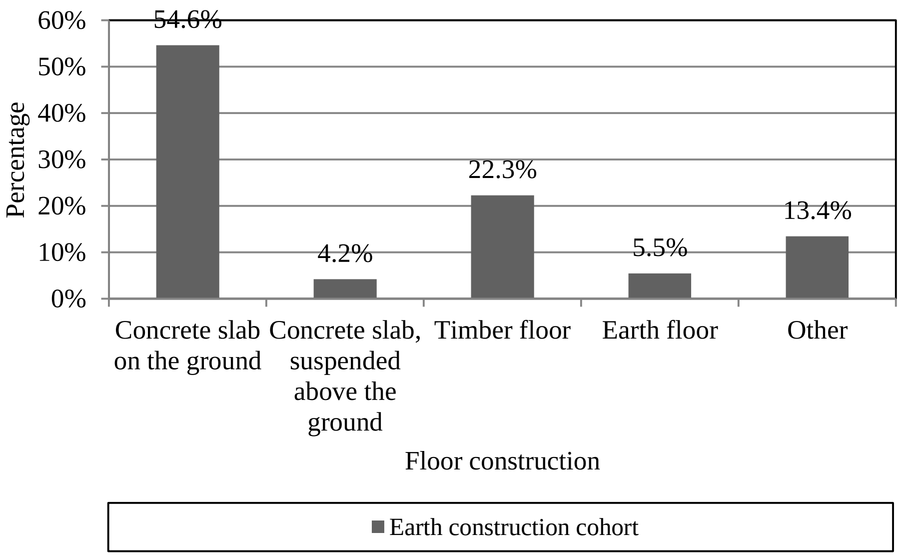

Figure 4.9. Flooring type in the earth construction dwellings

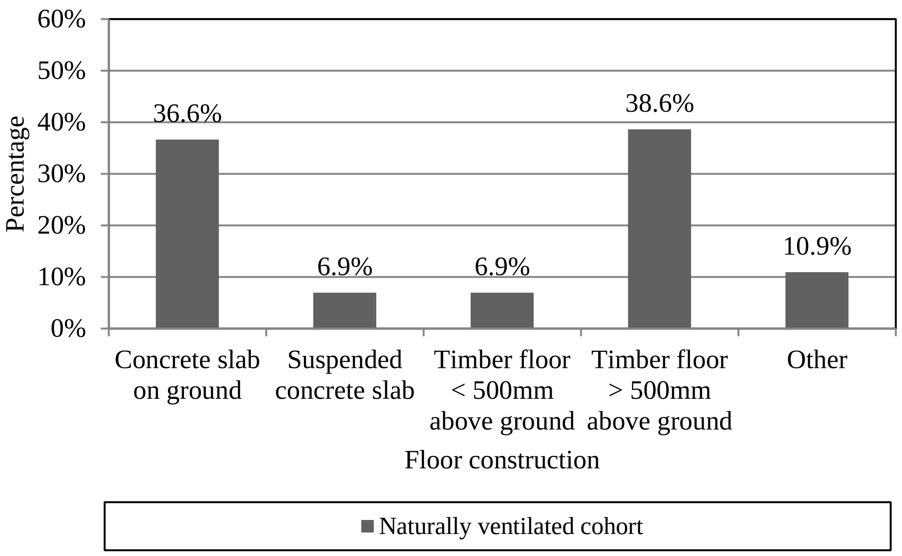

Figure 4.10. Flooring types in the naturally ventilated dwellings

4.3.1 Earth wall construction

Mud brick and rammed earth were the two main types of earth walling used, which most houses employed for both internal and external walls (see Figure 4.11). Other types of earth walling include pressed bricks (4.5%) and in-situ stabilised earth (two responses) and wattle and daub (1 response). The majority (74.9%) of respondents did not report any issues or concerns regarding the use of earth walling in their homes. Of those that did, the issues mainly related to specific construction techniques; e.g. the walls had not been sealed internally, causing dust, and the exterior of the earth wall not been sufficiently protected from the weather resulting in rising damp. Of the responses to “Other” seven voiced concerns regarding insects and pests, five relating to the perception of poor construction practices and two regarding the thermal performance of the earth walls (e.g. high thermal mass, low insulation).

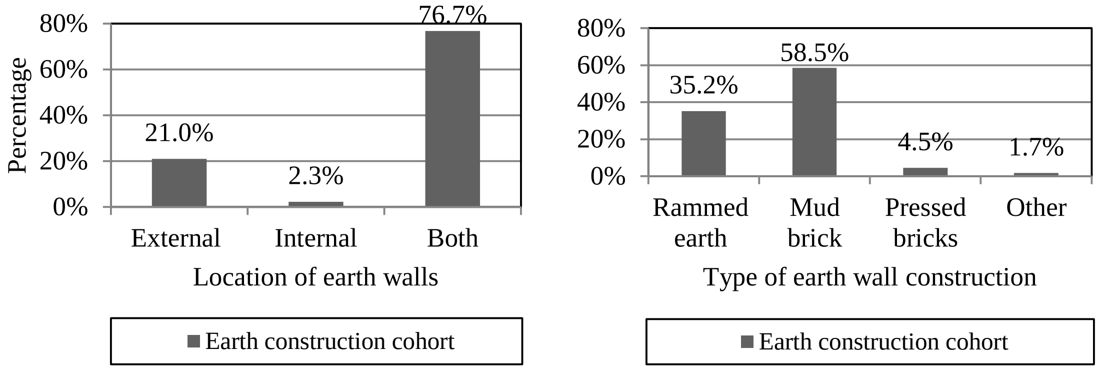

Figure 4.11. Earth wall configuration and type of construction

4.3.2 Naturally ventilated dwellings

The naturally ventilated houses were predominantly of lightweight construction (e.g. timber or steel frame with lightweight cladding). All of the responses to "Other" wall material indicated some form of brick or blockwork. In 30.0% of the homes, the walls in the living areas were 60 to 80% openable to allow for natural ventilation, while in 31.2% of homes the bedroom walls were 20 to 40% openable (see Table 4.4). For both the living areas (84.0%) and bedrooms (80.6%), the majority of respondents had between 20 and 80% openable external wall area.

The roofs of the naturally ventilated houses were predominantly pitched (typically 20-35°) with flat ceilings and attic space (68.3%) (Figure 4.12 and Figure 4.13), again consistent with typical forms of tropical housing. The responses to "Other" ceiling/roof type indicated a variation or combination of raked and flat ceilings.

A high proportion (87.4%) of respondents reported to have issues or concerns about living in a naturally ventilated house when queried (see Figure 4.14). The most nominated concerns were mould, noise, unwanted insects or wildlife and dust or smoke. Of the response to "Other", three indicated concerns relating to the ingress of extreme weather and one commented on the negative effect of the humidity on the lifespan of electronic goods.

Table 4.4. Percentage of external wall openable for ventilation in the living areas and bedrooms

Rooms	< 20 % openable	20 – 40 % openable	40 – 60 % openable	60 – 80 % openable	> 80 % openable
Living areas	6.0%	25.0%	29.0%	30.0%	10.0%
Bedrooms	11.8%	31.2%	29.0%	20.4%	7.5%

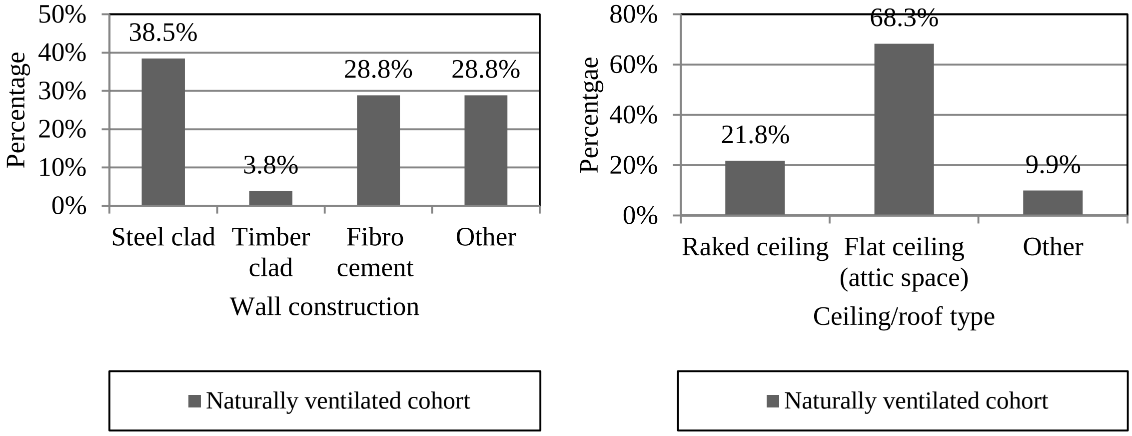

Figure 4.12. Wall type and ceiling configuration in the naturally ventilated dwellings

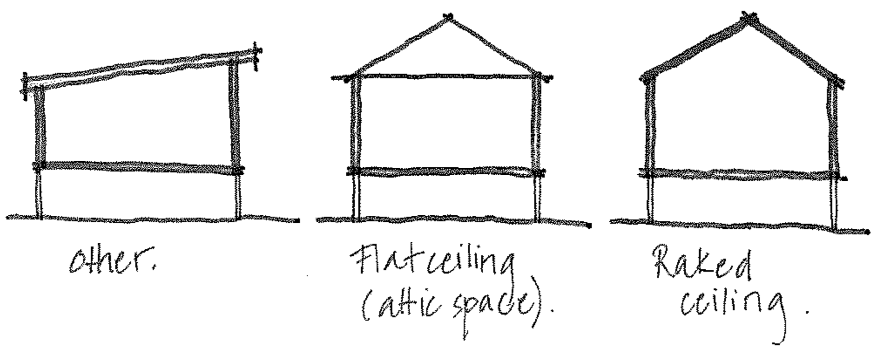

Figure 4.13. Roof and ceiling configurations

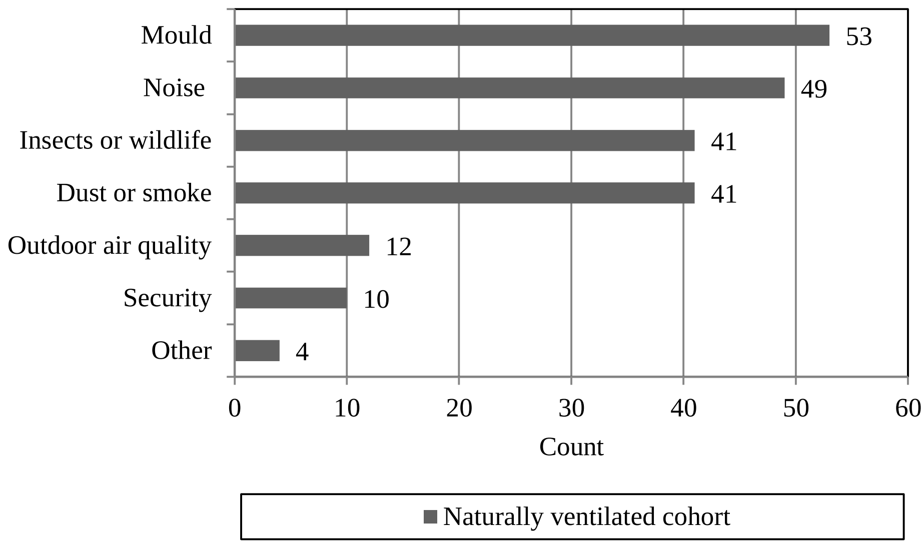

Figure 4.14. Issues or concerns with naturally ventilated houses

4.3.3 Insulation

Both cohorts displayed quite different trends in terms of adding insulation within the walls and roof/ceilings when compared to the State and Territory figures. Only 5.7% of the earth construction cohort reported to have additional insulation in their external walls compared to 26.3% of overall housing in Victoria (ABS, 2011), (Table 4.5 and 4.6). This is largely indicative of the traditional earth wall construction methods employed, where the walls are often solid and load bearing and a separate layer of thermal insulation is not incorporated. Conversely, a higher proportion (32.7%) of the naturally ventilated cohort reported to have insulation in their walls than the Territory average (6.9%). The proportion of dwellings from both cohorts that had roof/ceiling insulation was much higher than that of either Victoria or the Northern Territory respectively. Of the earth construction cohort 94.9% had some kind of roof/ceiling insulation as did 63.0% of the naturally ventilated cohort (see Table 4.6). Of the responses to “Other” from the earth construction cohort two indicated that their roofs were insulated with straw, one with a product that they referred to as ‘active insulation’ with no further explanation and one described wooden panels as insulation. Of the responses to “Other” from the naturally ventilated cohort one indicated ‘fridge panels’ and the other indicated recycled paper insulation.

Table 4.5. Roof/ceiling insulation type in both cohorts of dwellings, note: 'bulk insulation' refers to batt/blanket insulation

Cohort	None	Don't know	Bulk insulation	Reflective Foil	Both bulk insulation and reflective foil	Other method
Earth construction cohort	3.4%	1.7%	25.6%	13.1%	54.0%	2.3%
Naturally ventilated cohort	21.0%	16.0%	19.0%	31.0%	11.0%	2.0%

Table 4.6. Insulation within walls and roofs/ceilings (ABS, 2011), note: "Other" includes floor insulation and "Don't know"

Cohort	Walls	Roof/ceiling	Other
Victoria	26.3%	74.6%	3.3%
Northern Territory	6.9%	41.7%	1.8%
Australia	17.5%	67.5%	2.1%

4.3.4 Modification and operation for thermal performance

The following section was aimed at understanding the extent and manner in which the respondents from both cohorts engage with and operate their homes for thermal performance.

Of the earth construction cohort, 59.7% of respondents reported to have made some kind of changes to improve the thermal performance of their home as shown in Figure 4.15. Planting vegetation for shading and installing a built-in heater were the most frequently nominated changes, followed by, installing insulation to the ceiling or roof, installing ceiling fans and adding a verandah or pergola for shading. The majority of the primary responses can be considered as passive measures to improve the thermal performance of the dwelling, indicating awareness of low impact measures to regulate internal conditions amongst this cohort. Of the responses to "Other changes" 16 respondents reported to have installed additional internal or external shading, seven had made changes to increase natural ventilation or increase the airtightness of the dwelling, six had made changes to improve the glazing (low-e, double glazing etc.), three had added north facing glazing to increase passive solar performance and two had made changes to the vegetation surrounding the house (i.e., plant lawn around the house to reduce ground temperature and reflectance).

Similarly, 55.6% of the naturally ventilated dwelling cohort had made some kind of changes to improve the thermal comfort of their home, while 37.4% had completed more general renovations. Most changes were the addition of rooms, followed by adding a verandah or pergola, installing roof/ceiling insulation and installing ceiling fans (see Figure 4.16). Of the reported other changes, 11 had made modifications to improve ventilation (wind driven attic ventilation devices, modifying windows and doors), eight had increased shading to the house with vegetation or shade structures, seven had made modifications to the roof (reflective paint, lining the underside) and three had installed solar panels.

Consistent with the earlier finding that respondents from both cohorts overall responded positively to their respective climates, the majority of respondents had an outdoor area that they regularly used for entertaining and relaxing; 87.4% of the earth construction cohort and 95.0% of the naturally ventilated cohort. These spaces were generally protected from weather (sun, rain and wind) and most of the respondents from the naturally ventilated cohort also reported to have ceiling fans in their outdoor areas (see Figure 4.17).

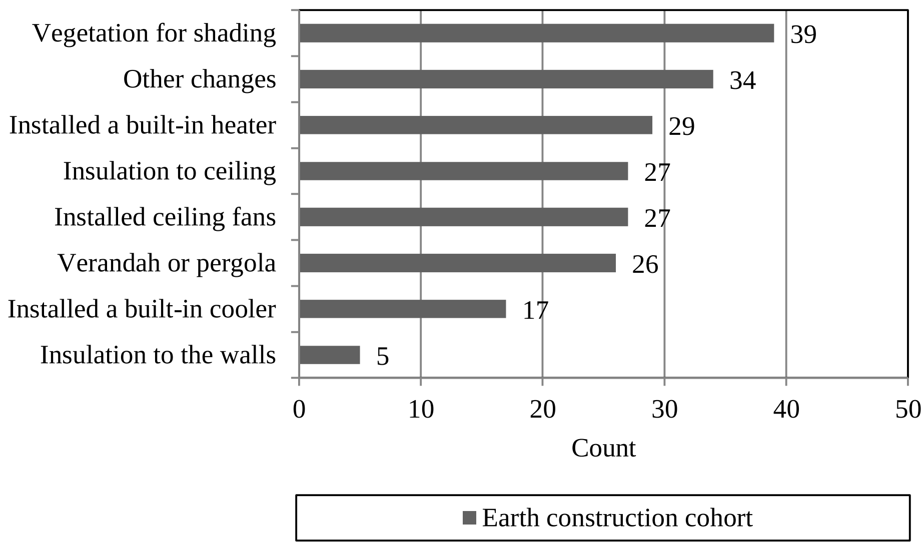

Figure 4.15. Modifications made to improve thermal comfort in the earth construction dwellings

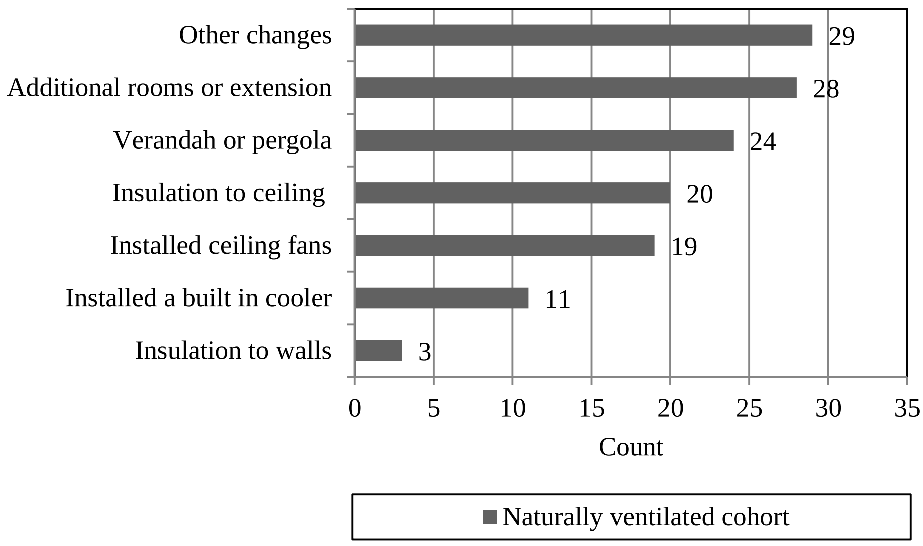

Figure 4.16. Modifications made to improve thermal comfort in the naturally ventilated dwellings

The majority of earth construction cohort respondents (80.1%) had some form of internal window covering, while the majority of naturally ventilated respondents did not (62.9%), (see Figure 4.18). Of the responses to "Other" from the earth construction cohort 11 described some form of timber covering, 10 nominated roman blinds or a variation of roman blinds, three stated roller blinds and three 'honeycomb' blinds. Responses to "Other" for the naturally ventilated dwellings were primarily some kind of light timber blind, while two indicated an alternative fabric covering and one indicated a metal louvre blind. External window shading for both cohorts was primarily provided by the eaves of the dwellings, a verandah or pergola, or vegetation rather than a specific operable shading device (see Figure 4.19). The types or presence of internal window coverings in the houses of both cohorts are consistent with typical response to climatic design in both locations; the earth houses typically have substantial internal window coverings to control heat flow in both summer and winter, while the naturally ventilated cohorts generally have minimal internal window coverings as the benefits of natural ventilation are prioritised over providing an additional thermal barrier. It is interesting that both cohorts reported similar types of external window shading, whilst shading the walls of the building is a common design technique in tropical climates, it may not be as suitable for heating driven climates such as those where many earth buildings are located (Marshall, 1955).

Both cohorts generally reported that their windows let in enough light; the earth construction cohort gave an average rating of 3.7 in summer and 4.3 in winter on a 7-point Likert scale (1= “Too much”, 7= “Not enough”), while the naturally ventilated cohort gave an average rating of 3.9 on the same scale (only an overall rating was sought from this cohort).

Management of shading devices and windows to moderate indoor environmental conditions was demonstrated by the earth construction cohort through the operation of internal window shading at specific times of the day (see Table 4.7) and ventilated to improve air quality. The majority of respondents had positive perceptions of the air freshness and humidity levels within their homes. Of the 111 comments recorded in the section regarding fresh/stale air within the home, 90 were positive, demonstrating awareness of natural ventilation and citing aspects of the home such as high ceilings, natural materials, location and operation of windows and doors as reasons for good air quality. Of the neutral or negative comments given in response to this section most attributed poor air quality to insufficient sealing of the building or lack of windows in particular rooms. Comments regarding the humidity level within the homes were again generally positive and that any concerns regarding indoor humidity were related to the current outdoor weather conditions. These comments indicate that the indoor conditions in many of these dwellings are closely coupled with outdoor weather conditions because of the ventilation strategies employed by the occupants.

This information was not sought from the naturally ventilated cohort because internal conditions are even more closely aligned with outdoor weather due to the ventilated nature of the buildings; however practices relating to the operation of the home for natural ventilated are described in section 4.6.

Table 4.7. Management of thermal conditions within the earth construction dwellings

Action	Yes	No
In hot weather do you keep some windows and doors open during the day?	44.4%	55.6%
On hot nights do you open most of your windows?	86.0%	14.0%
During hot days do you close your indoor window coverings?	75.4%	24.6%
On cold nights do you close your indoor window coverings?	80.7%	19.3%

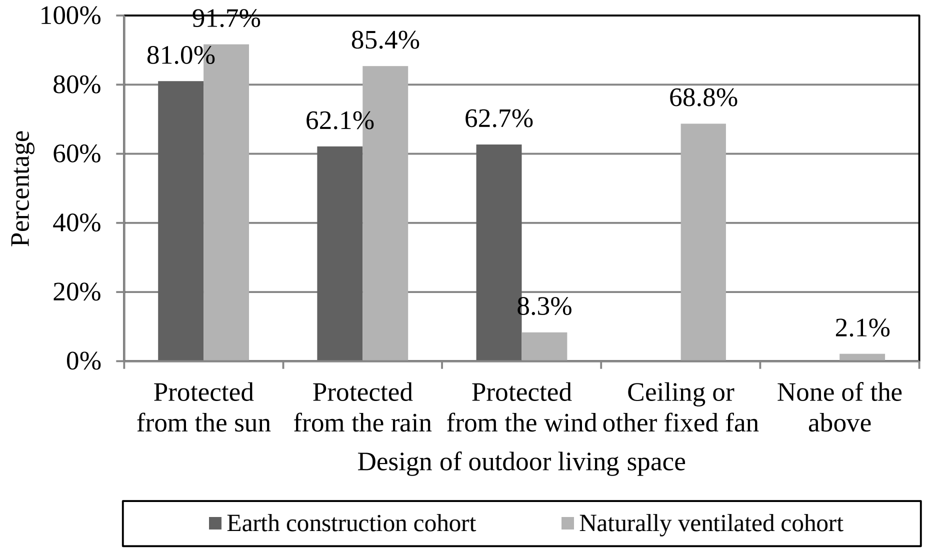

Figure 4.17. Features of both cohorts' outdoor living spaces

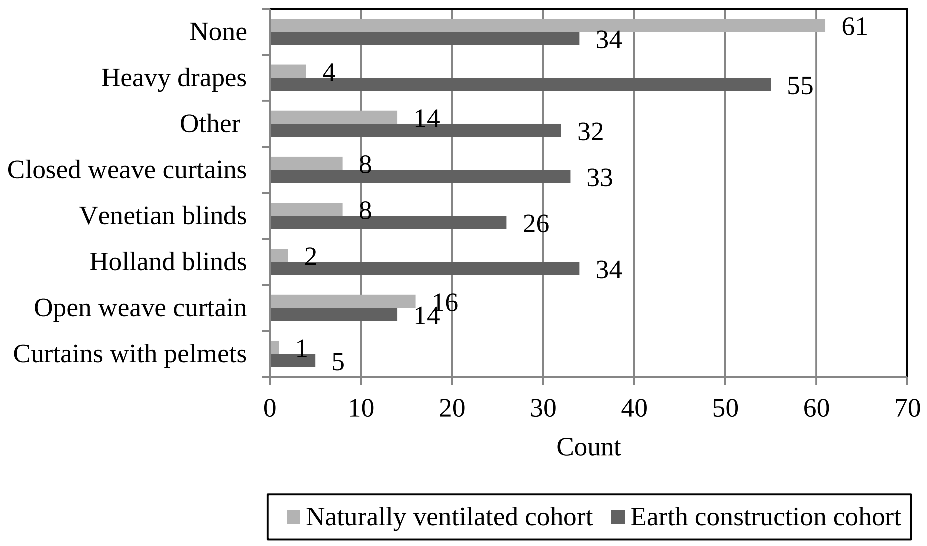

Figure 4.18. Type of indoor window covering of both cohorts

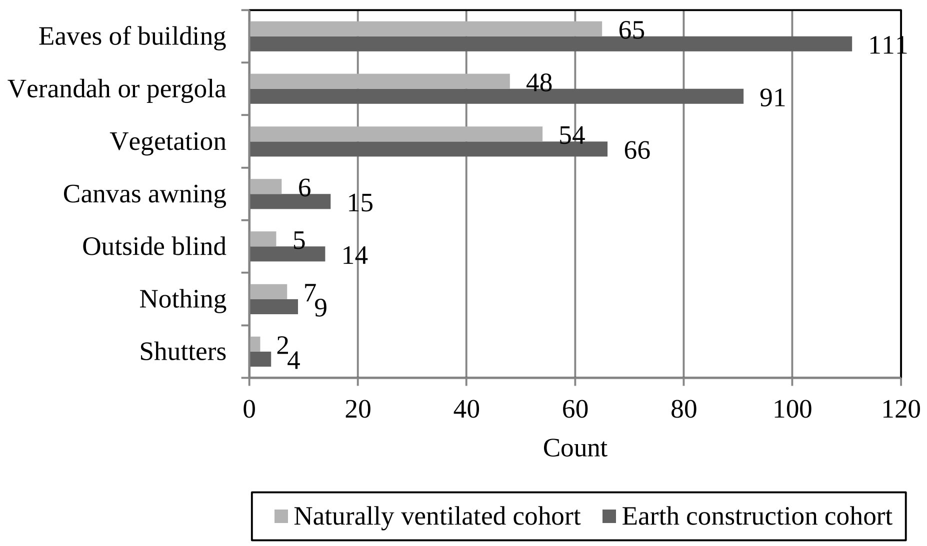

Figure 4.19. Type of outdoor window shading for both cohorts

4.4 Earth construction cohort: heating

Almost the entire earth construction cohort (97.8%) had some form of heating appliance in their home. This figure aligns with both that of Victorian households overall (99.8%) and that of Australian holds more broadly (98.7%), (ABS, 2011). Of the 4 respondents who did not have heating, only one thought that there may be a future need to install one; however, the three other respondents stated that they did not perceive a need to install heating citing mild weather conditions and appropriate house design. The most common heating appliance used in these households was a slow combustion stove (98), followed by an open fire (60), and gas space heaters (45) (see Figure 4.20 and Figure 4.21). This choice is remarkably different to that of Victorian and overall Australian households, where the main heating appliances are gas space heaters (see Table 4.8). Of the responses to “Other”, 26 indicated hydronic in-floor heating, one indicated an oil heater, one indicated a wall panel heater and one described an air transfer system. The choice of alternative heating appliances (i.e. slow combustion stoves and open fires) of the occupants of earth buildings is indicative of the underlying approach to lifestyle and housing taken by many of these households. Slow combustion stoves and open fires are perceived as having lower environmental impact than more widely used appliances (e.g. gas space heaters).

The livings areas and kitchen were identified as the most commonly heated rooms, while fewer respondents heated bedrooms, studies and bathrooms (see Figure 4.22). In the comments section many respondents sought to clarify their heater use; some cited open plan layout as a reason for heating multiple rooms, some demonstrated use of zoning to minimise heater use and some qualified their heater use by stating time frames and thermostat settings. Heating appliances were generally used in the evenings until bedtime, while many of those reporting to use them all of the time had in-floor hydronic heating that was controlled by a thermostat (see Figure 4.23). Again, respondents clarified their heater use; 31 in terms of time (i.e., only for 4-5 hours, only on weekends), and 26 clarified their heater usage in terms of specific thermal conditions (i.e., particularly cold mornings, thermostat controlled heating). Heating use is calculated as heating days per annum, i.e. the number of days heating appliances were used. The average approximated days heating was used per annum for the cohort was 108 (SD 53.7), ranging from just five to 250. This figure was similar to that of other Victorian households but understandably higher than overall Australian households due to the range of climates represented by the national figures (see Table 4.9). Occupants were generally satisfied with their heating with an average rating of 5.7 on a 7-point Likert scale (1= "Very dissatisfied", 7= "Very satisfied").

Table 4.8. Proportion of types of heating appliances used in Victoria and Australia wide (ABS, 2011)

Cohort	**Electric (incl. floor slab)**	**Gas**	**Reverse cycle**	**Wood**	**Other**
Victoria	9.7%	68.7%	11.6%	8.7%	1.7%
Australia	15.0%	38.0%	31.6%	12.7%	2.8%

Table 4.9. Proportion of heating days for earth construction cohort, Victoria and Australia (ABS, 2011)

Cohort	**Less than 1 month**	**1 month to less than 3 months**	**3 months to less than 6 months**	**6 months or more**	**Did not know**
Earth construction	8.2%	16.5%	60.6%	14.7%	0.0%
Victoria	6.1%	19.4%	51.3%	19.4%	3.8%
Australia	13.5%	32.1%	40.7%	9.7%	3.9%

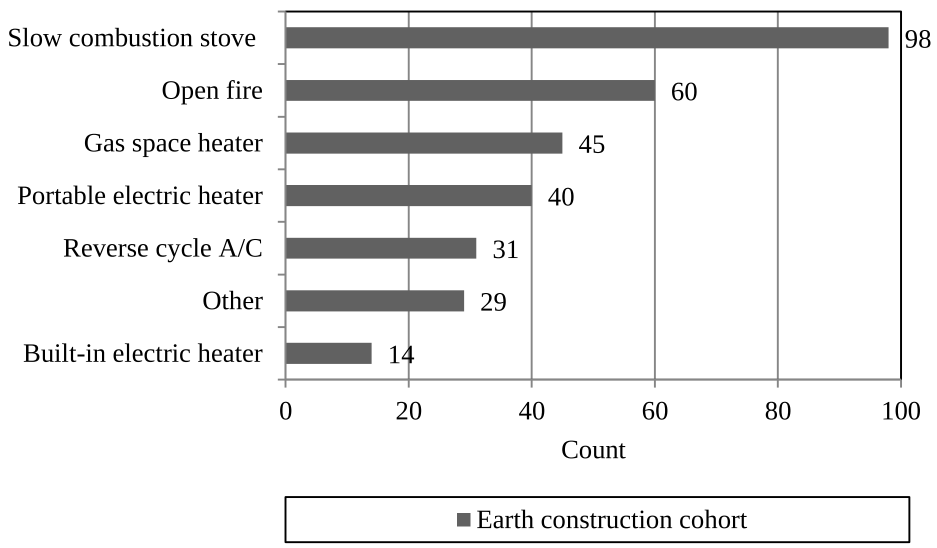

Figure 4.20. Type of heating appliances present in the earth dwellings

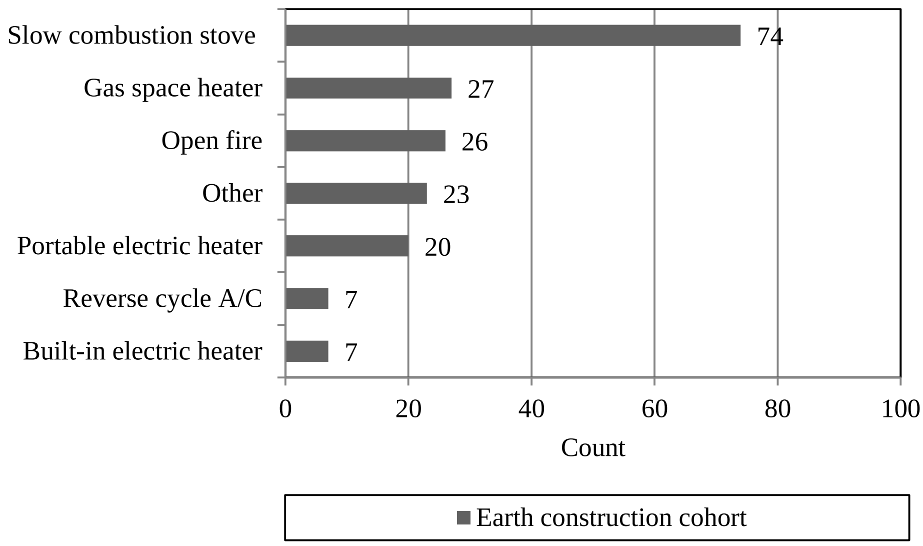

Figure 4.21. Main heating appliances used in the earth dwellings

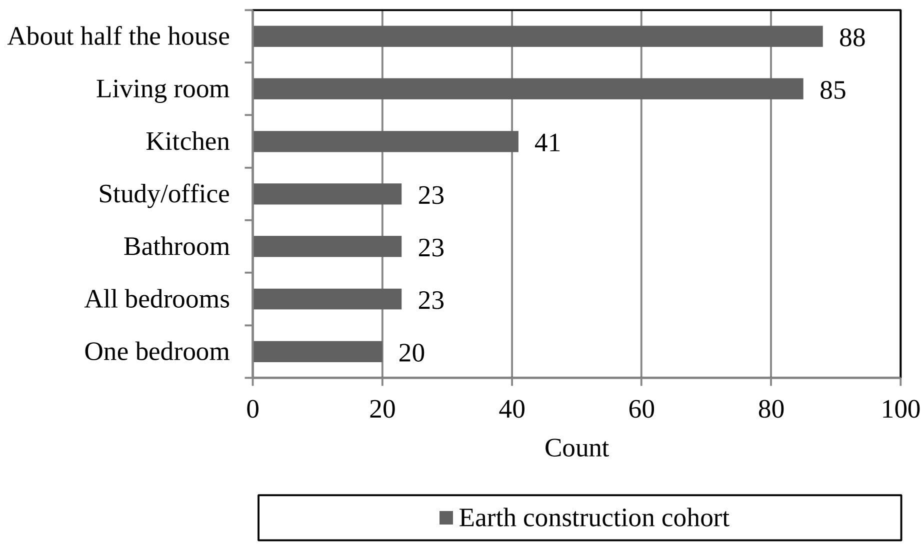

Figure 4.22. Rooms heated in earth construction dwellings

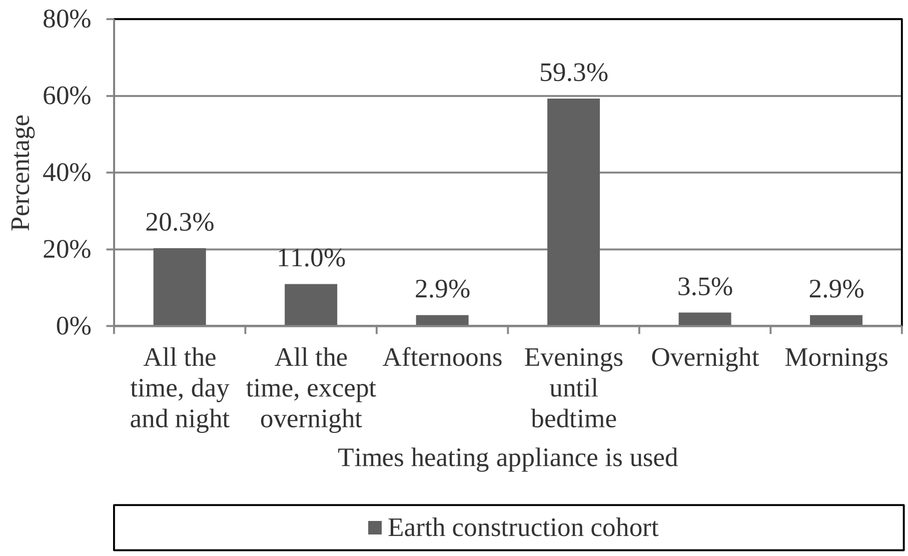

Figure 4.23. Times of the day that heating appliances are used in cold weather

4.5 Earth construction cohort: cooling

Whilst 76.1% of the respondents had some kind of fan for cooling in their home (see Figure 4.24), only 33.5% had an air conditioning appliance. This is lower than the Victorian average of 75.5% of households with cooling appliances or the national average of 73.1% (ABS, 2011). Of those that did not have an air-conditioning appliance 99 did not perceive a future need to install one, while 18 did. Respondents were invited to give further explanation of their choice; 37 of those that did not see a need gave reasons relating to the acceptable or good performance of their home, 20 stated that it is simply not warranted or not required and four were opposed on philosophical grounds. Of the respondents that did see a need to install a cooler seven specifically mentioned the poor performance of upper level rooms, five gave reasons relating to extended periods of hot weather or heatwaves and a changing climate, and two cited aging and health as a reason. The most common cooling appliance was a reverse cycle air-conditioning unit, which was also the most common appliance in Victorian and Australian households more broadly (see Figure 4.24 and Table 4.10). Of the three responses to “Other”, two cited passive natural ventilation as a ‘cooling appliance’, while one indicated an old air-conditioning unit but gave no further information.

Cooling, where installed, was mostly used in the living areas during the afternoons and evenings in hot weather (see Figure 4.25 and Figure 4.26). In the comments section some respondents clarified their cooler use; 11 mentioning specific thermal conditions and nine citing specific times of the day or hours of operation. From the explanatory comments associated with the questions relating to use of cooling appliances it is clear that some the respondents have taken the meaning of cooling to include fans and natural ventilation as well as the conventional understanding of mechanical cooling appliances. Cooling use is calculated as cooling days per annum, i.e. the number of days the cooling appliance is used. For this cohort the average cooling days per annum was 28.7 (SD 28.0), ranging from 1 to 120, with usage substantially lower to that of other Victorian and Australian households (see Table 4.11). Occupants were generally satisfied with their air-conditioning appliances with an average rating of 5.4 on a 7-point Likert scale (1= "Very dissatisfied", 7= "Very satisfied").

Table 4.10. Types of cooling appliances used in Victorian and Australian households (ABS, 2011)

Cohort	Reverse cycle/heat pump	Refrigerated (cools only)	Evaporative	Other
Victoria	43.7%	26.1%	29.7%	0.5%
Australia	62.1%	18.9%	18.4%	0.6%

Table 4.11. Proportion of cooling days for earth construction cohort, Victoria and Australia (ABS, 2011)

Cohort	Less than 1 month	1 month to less than 3 months	3 months to less than 6 months	6 months or more	Did not know
Earth construction	60.7%	29.5%	9.8%	0.0%	0.0%
Victoria	33.8%	44.8%	17.3%	1.3%	2.6%
Australia	22.9%	42.3%	27.7%	5.0%	2.1%

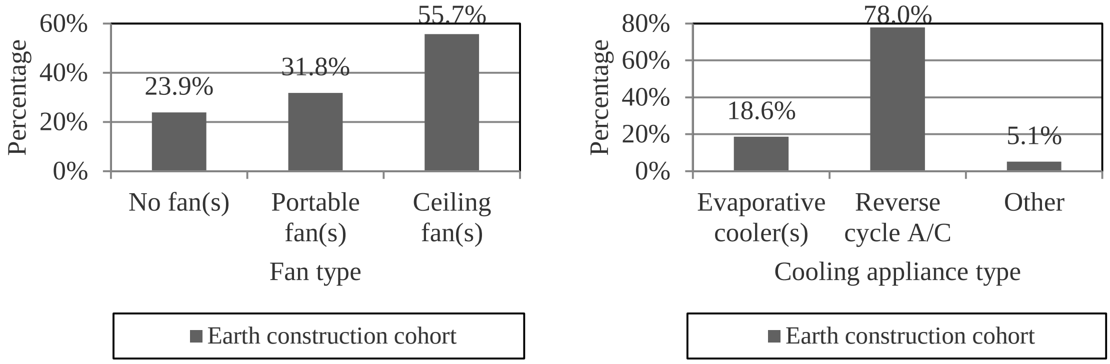

Figure 4.24. Types of fans and cooling appliances in earth construction dwellings

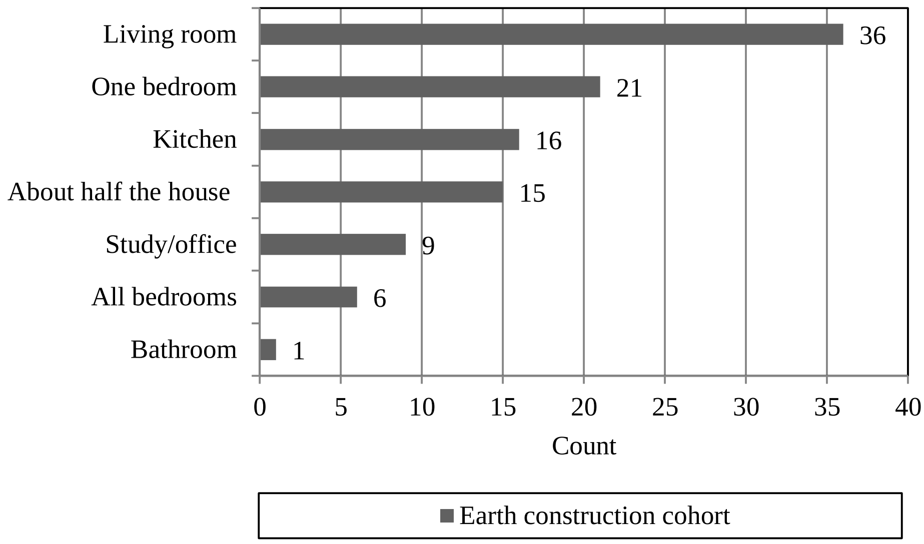

Figure 4.25. Rooms cooled in earth construction dwellings

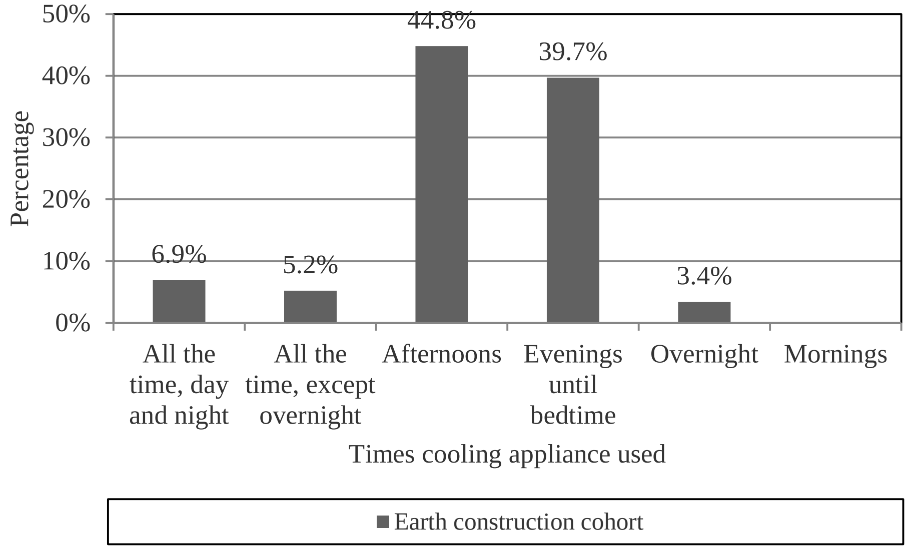

Figure 4.26. Times of the day that cooling appliances are used in hot weather

4.6 Naturally ventilated cohort: cooling

The majority (75.3%) of this cohort reported that their whole house was designed specifically to be naturally ventilated (see Figure 4.27), and that it was operated in this manner for most of the year (see Table 4.12 and Table 4.13). In the comments section many respondents actually noted that they either could not close their windows (only flyscreen/mesh – no glass) or would only do so if there was heavy rain. Generally, most respondents reported that open doors and windows provided adequate ventilation throughout the year; however, in the build-up the effectiveness of the openings for ventilation decreased (see Table 4.14).

4.6.1 Fans

Almost all of the respondents had ceiling fans in their house (99.0%), while 18.6% also had portable fans. The fixed fans were primarily located in the living areas, the bedrooms and the kitchen. Many (20) respondents also reported to have fixed fans in their outdoor living areas, while few reported them in other rooms; 1 in the laundry, 1 in a walk-in-robe and 1 in the hallway. Interestingly, in this section numerous respondents noted that the fans were also operated to reduce mould growth and not just for cooling purposes. Fans were used throughout the year during both the daytime and nighttime (see Table 4.15).

Table 4.12. Proportion of time that rooms are naturally ventilated

< 20 % of the time	20 – 40 % of the time	40 – 60 % of the time	60 – 80 % of the time	> 80 % of the time
2.1%	6.2%	10.3%	4.1%	77.3%

Table 4.13. Proportion of respondents who operate their homes as naturally ventilated during the different seasons and times of day

Time of day	Build-up	Wet season	Hot and dry season	Cool and dry season
Daytime	90.6%	93.8%	91.7%	90.6%
Nighttime	83.3%	87.5%	87.5%	79.2%

Table 4.14. Perception of air flow within the naturally ventilated houses when windows and doors are open (1= "Too much", 4= "About right" and "7= "Too Stagnant")

Season	1	2	3	4	5	6	7
The build up	0.0%	1.1%	3.2%	58.1%	29.0%	8.6%	0.0%
The wet season	1.1%	2.1%	7.4%	73.7%	12.6%	3.2%	0.0%
The hot and dry season	0.0%	1.1%	4.2%	80.0%	12.6%	1.1%	1.1%
The cool and dry season	1.1%	8.5%	11.7%	75.5%	2.1%	1.1%	0.0%

Table 4.15. Proportion of respondents who operate fans during the different seasons and times of day

Time of day	Build-up	Wet season	Hot and dry season	Cool and dry season
Daytime	98.9%	92.6%	83.0%	44.7%
Nighttime	99.0%	91.7%	79.2%	31.3%

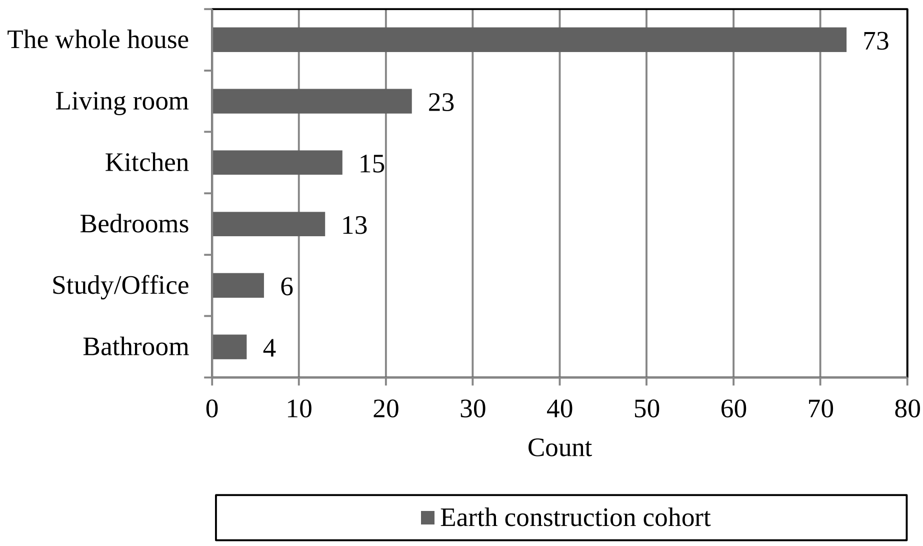

Figure 4.27. Rooms that were designed to be naturally ventilated

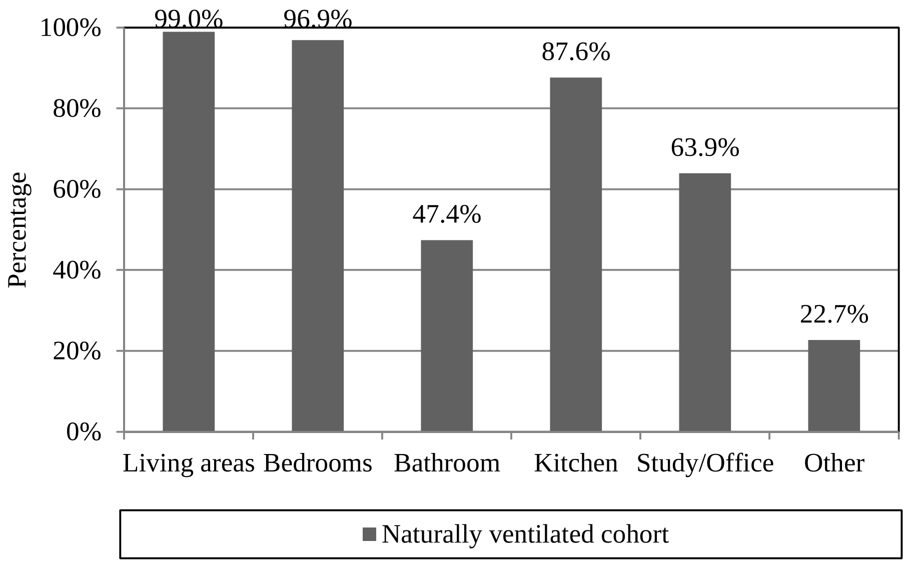

Figure 4.28. Location of fixed ceilings fans

4.6.2 Air conditioning

Of the naturally ventilated cohort 28.9% of respondents did not have an air-conditioner, while a further 10.3% said they had one but it was never used. This proportion of households with air-conditioning is considerably smaller than the average for the Territory, 93.9%, as well as the national average, 73.1% (ABS, 2011). The bulk of the respondents without air-conditioning (18) did not think there would be a need to install one, generally citing the adequate thermal performance of their house. Of those who did think there may be a need to install air-conditioning 4 cited health concerns (particularly related to increasing age), 3 to assist with sleeping, 1 to prevent mould, 1 if they had to sell the dwelling and 1 if a temperature increase associated with climate change occurred.

The predominant type of cooling appliance was a split-system air-conditioner (93.6%); aligned with the trend in both the Territory and Australia wide (see Table 4.16). Air-conditioning was mostly used in bedrooms in the afternoons and overnight (see Figure 4.29 and Figure 4.30). In the comments section associated with Figure 4.30, respondents clarified their use of air-conditioning; nine giving sleep as a reason, seven saying that is was rarely used, three saying that it was only used in the build-up, three for when they have visitors, two respondents noted that their school-age children used air-conditioning while studying and one when their daughter wanted to ice a cake!

The average approximation of cooling days per annum by the occupants was 88.7 (SD 83.8), considerably lower than the average usage in the Northern Territory (see Table 4.17). Again 23 respondents chose to clarify the times at which they use coolers, most specifying a time limit (1-2 hours) or in certain situations such as young children needing to sleep, visitor comfort, shift work, and very hot afternoons. Occupants were generally satisfied with their air-conditioning appliance with an average rating of 5.5 on a 7-point Likert scale (1= “Very dissatisfied”, 7= “Very satisfied”).

Table 4.16. Types of cooling appliances used in the Northern Territory and Australian households (ABS, 2011), note: figures for “Evaporative” and “Other” in the Northern Territory not published by the ABS

Cohort	Reverse cycle/heat pump	Refrigerated (cools only)	Evaporative	Other
Northern Territory	7.2%	78.7%	NA	NA
Australia	62.1%	18.9%	18.4%	0.6%

Table 4.17. Proportion of cooling days for naturally ventilated cohort, the Northern Territory and Australia (ABS, 2011)

Cohort	Less than 1 month	1 month to less than 3 months	3 months to less than 6 months	6 months or more	Did not know
Naturally ventilated	28.6%	23.2%	35.7%	12.5%	0.0%
Northern Territory	6.5%	10.3%	25.0%	56.4%	1.9%
Australia	22.9%	42.3%	27.7%	5.0%	2.1%

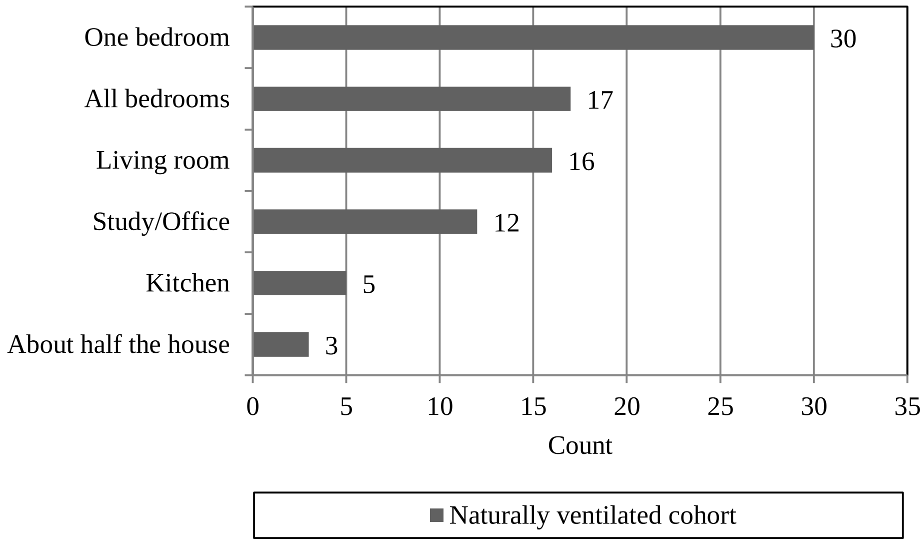

Figure 4.29. Rooms where air-conditioning is operated

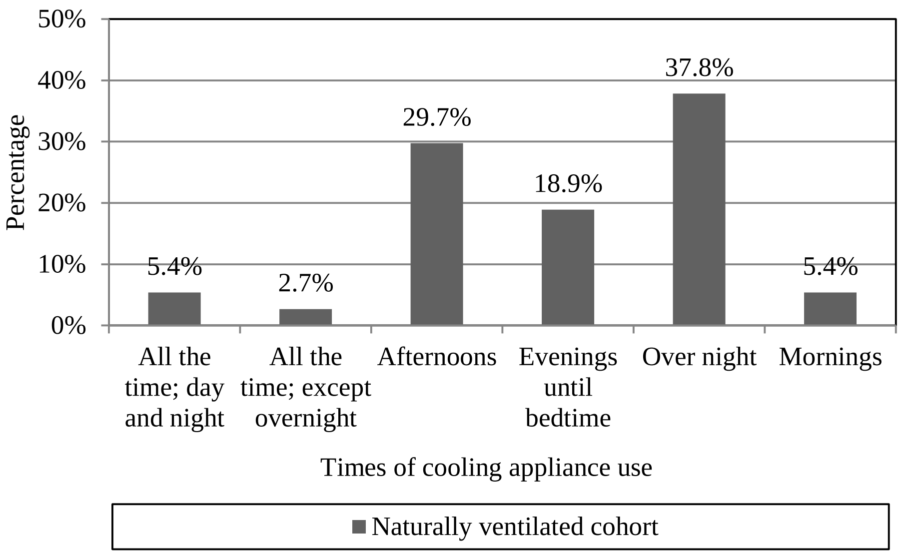

Figure 4.30. Times of the day that the air-conditioning is operated

4.7 Summary

The results from the two national surveys demonstrate trends in the perceptions of housing and climate, the expectations of performance, and the behaviours to adjust thermal environments of occupants living in earth buildings in Victoria and those living in natural ventilated dwellings in the Northern Territory.

Inquiry into the dwelling characteristics of the two surveyed cohorts confirms that the design and construction of both the earth buildings and naturally ventilated buildings does not emulate building practices within the majority of new housing stock in Australia. The respondents predominantly lived in older separate dwellings on suburban or semi-rural blocks with larger households than the national average. The non-standard and possibly poor construction practices in some earth buildings were particularly highlighted when respondents were queried about the wall and floor construction of their dwellings. These constructions issues are likely to be partly due to the, now outdated, trend of earth construction as an owner builder form of housing. The design of the naturally ventilated dwellings largely reflects traditional forms of housing in tropical climates such as raised floors, lightweight walls and lourved windows. The non-standard construction practices of both forms of housing are similarly demonstrated through the incorporation of insulation. The earth buildings had a lower presence of wall insulation than the national average, confirming that added insulation is not standard in current earth wall buildings practices. Conversely, a higher proportion of the naturally ventilated houses had wall insulation when compared to housing more broadly in the Northern Territory. Both cohorts had higher rates of ceiling insulation than the national average.

Throughout the survey responses, both cohorts demonstrated an awareness of environmental issues in relation to the design and operation of their homes. When choosing their homes, the respondents indicated that the low energy requirements and environmental impact of the particular forms of housing were important considerations, as well as the dwelling's appearance, contribution to lifestyle and perceived health benefits. Their awareness of the natural environment was similarly reinforced when respondents were queried about their perception of the outdoor climate. For many of the respondents the ability to connect with the outdoors was a very important aspect of the design of the house. This was also embodied in the extensive presence and use of outdoor living spaces across the both cohorts and climates. Generally, the perception of comfort within the home was positive, although the respondents from the hot humid climates cited the build-up season as uncomfortable. Finally, many respondents demonstrated that they actively operate their dwelling through the use shading devices, natural ventilation and other techniques to improve the thermal conditions without resorting to the use heating and/or cooling appliances.

When heating and/or cooling appliances were used within the surveyed homes the operation of these appliances was notably different to that of typical households across Australia. Within the earth dwellings, open fires or slow combustion stoves were the predominant forms of heating used. Wood burning heaters are not commonly used in Australia so their extensive presence in earth dwellings confirms that the operation of these dwellings is quite different to that of typical homes. Similarly, earth building occupants mainly heated only the living spaces within the house and not all rooms. Few households from either cohort had air conditioning appliances. Interestingly, some of the earth building respondents extended their understanding of air conditioning to natural ventilation, revealing a very different attitude toward the performance of their homes. Notably, in the naturally ventilated households air conditioning was primarily used for social reasons or for sleeping and studying. However, mostly these households simply relied on natural ventilation assisted by ceiling fans for cooling. The responses to questions about heating and cooling from both cohorts revealed a wide range of techniques used by the respondents to adjust and adapt to their thermal environment reinforcing the idea that they have different expectations of the thermal performance of their dwelling.

The results presented in this chapter have demonstrated that the two cohorts of respondents; occupants of dwellings incorporating earth construction components and naturally ventilated dwellings in hot humid climates, can be considered as distinct cohorts with similar aspirations in terms of the construction and operation of their homes. Key themes to emerge from the results are;

- The ways in which respondents from both cohorts manage indoor thermal conditions are alternative when compared to relevant national statistics; and
- The responses to both national surveys demonstrate an awareness of environmental issues in the choice and operation of their homes, as well as a desire for connection with the natural environment.

The construction, operation, thermal performance and energy use of dwellings incorporating earth construction components and naturally ventilated dwellings will be further explored in greater detail in the next chapter.

Chapter 5. Results: in-depth case studies

5.1 Introduction

This chapter describes the dwelling characteristics, heating and cooling practices, energy use, local climate and the indoor thermal environments of the 40 case study households. The dwellings represent two samples of atypically constructed houses in two distinct climates; 20 dwellings incorporating earth construction in a cool temperate climate and 20 naturally ventilated dwellings in a hot humid climate.

The chapter includes a description of the results and a summary of key findings. The main aim of the research presented in this chapter is to examine the heating and/or cooling practices, energy use and indoor thermal environment within the case study households in order to provide a context for the forthcoming results in Chapter 6 and Chapter 7.

The earth houses located in Nillumbik Shire, a north-east suburb of Melbourne, Victoria will now be referred to as the 'Melbourne houses'. The naturally ventilated dwellings located in, or close to, Darwin, Northern Territory will now be referred to as the 'Darwin houses'.

Portions of this chapter were previously published and have been quoted directly from the following sources (Daniel et al, 2014b; 2015b). Permission has been granted by all co-authors to quote published material without rephrasing.

5.2 Semi-structured interview

Nineteen of the 20 Melbourne households participated in the semi-structured interview. The single house that did not was located on the same property as another case study dwelling, where responses to the interview broadly reflected conditions within the other dwelling. All of the Darwin households participated in the interview. Whilst some of these households participated in the national surveys, due to confidentiality requirements the semi-structure interview covered many of the same avenues of inquiry as the national surveys (see Appendix D for interviews questions).

5.2.1 Household and dwelling characteristics

The average occupancy rate for the Melbourne cohort was 2.3 persons per dwelling (SD 0.8); while for the Darwin cohort it was higher at 2.9 persons per dwelling (SD 1.4). The distribution of the ages of the family members indicates that the Melbourne households were primarily older couples, while the Darwin households were largely made up of families with young children (see Figure 5.7).

The average age of the Melbourne houses was 32.1 years old (SD 15.4 years old), ranging from eight to 64 years old. Ten of the Darwin houses were pre-cyclone Tracey (1974), while the average age of the other Darwin dwellings was 20.3 years old (SD 12.1 years old), ranging from three to 38 years old. All of the Melbourne participants owned their homes. Two of the Darwin households were renting their homes, while the rest were owned by the participants. The majority of households had lived in their current home for at least three years. For both cohorts the most common setting was suburban with close neighbours, although the block sizes allowed for significant vegetation in many cases (see Figure 5.1 and Figure 5.2). All of the Melbourne dwellings were separate houses, although three had multiple dwellings on the same property that shared electricity/gas/water meters. Eighteen of the 20 Darwin houses were separate houses; one was a unit and one a townhouse.

The majority of the Melbourne houses were single storey, while the majority of the Darwin houses were two storey or ‘high-set’ elevated houses (see Figure 5.6). All of the Melbourne houses incorporated some form of earth wall construction; either using traditional puddled mud bricks or pressed earth blocks (see Figure 5.3 and Figure 5.4). Many also incorporated recycled timber as structural elements within the building (e.g. wharf pylons, railway timbers). Almost all of the Melbourne houses had concrete slab-on-ground or masonry floor construction. All of the single story houses in Darwin, except one, incorporated heavyweight construction (i.e. brick or blockwork walls). The two story or high set houses were predominantly lightweight construction (i.e. stud walls with steel or timber cladding, with some use of heavyweight materials in the construction of the ground floor walls (see Figure 5.5). Floors of the single story houses were predominantly slab-on ground construction, while upper floors often incorporated some form of timber construction.

Figure 5.1. Typical setting of Melbourne houses; semi-suburban bushland

Figure 5.2. Typical setting of Darwin houses; highly vegetated suburban blocks

Figure 5.3. Post and beam construction with mud brick infill predominantly used in Melbourne houses

Figure 5.4. More contemporary examples of earth construction; left house built in 2001 & right house built in 2010, Melbourne

Figure 5.5. Left image, an example of heavyweight construction & right image, an example of light weight construction, Darwin

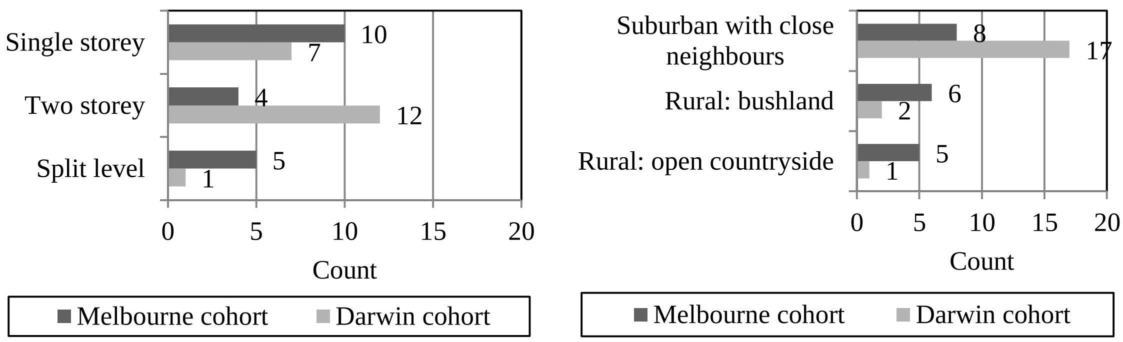

Figure 5.6. Dwelling configuration and setting

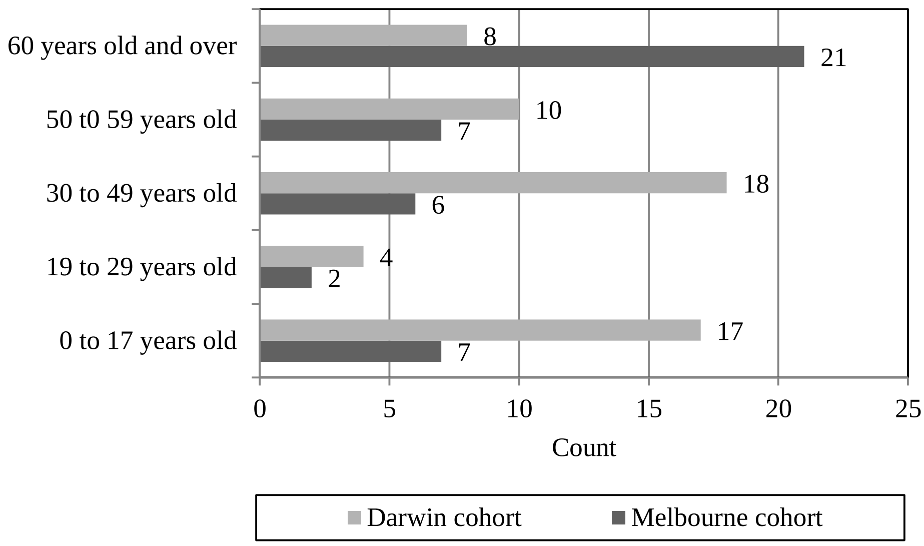

Figure 5.7. Distribution of age brackets of members of the case study households

5.2.2 Choosing to live in a dwelling of atypical construction

When asked about the reasons behind their choice of housing, many of the Melbourne cohort nominated "Other" and referred to the "Feel" of the dwelling or earth walls (42.1%). This represented 29.6% of responses to "Other" so has been given its own category in (see Figure 5.9). The second highest reason nominated was "Appearance" (26.3%). Of the additional responses to "Other", however, five claimed that it was not necessarily due to the earth construction, citing other reasons such as convenience, land or layout. In this section four also said that they had some kind of history or connection with earth houses, three stated that it was fashionable to buy an earth houses at the time, three cited thermal or bushfire performance, whilst one mentioned the perceived lifestyle of living in an earth house.

Only a few of the Darwin cohort cited "Cost" (10.0%) or "Low energy impact" (10.0%) as reasons for choosing to live in a naturally ventilated home; most nominated other reasons. Eight of the participants were opposed to air-conditioning or did not desire to live in an air-conditioned environment, seven participants said that they had previously lived in naturally ventilated houses in the same climate and five cited climatically appropriate design.

Generally, the Melbourne cohort did not have any major concerns regarding the use of earth construction walls within their home. Only six had concerns including increased dust, dampness or moisture from the walls and unwanted pests/insects attracted to the walls. A greater proportion of the Darwin cohort (11) had concerns attributable to natural ventilation (see Figure 5.8), primarily regarding the ingress of dust, insects and noise.

Interestingly, only four of the Melbourne households had previously lived in a dwelling incorporating earth construction; however, all but two claimed that if they had the opportunity to build or buy another house, they would choose earth construction. Conversely, most of the Darwin cohort (15) had previously lived in naturally ventilated houses. For three of the households this question was not applicable because they had lived in different climates where naturally ventilated houses were not necessarily appropriate. All of the Darwin households claimed, many emphatically, that they would choose to live in a naturally ventilated house in the future.

When queried about whether or not the occupants had any intentions to make the home more energy efficient both cohorts demonstrated an awareness of passive design principles. Twelve of the Melbourne cohort and 16 of the Darwin cohort reported that aspects of energy efficient design or the opportunity to make the house more energy efficient encouraged them to choose their dwelling. The Melbourne cohort cited orientation for passive solar gains, northern oriented glazing, the perceived beneficial thermal performance qualities of the earth walls and zoning encumbrances as key passive design principles. The Darwin cohort nominated cross ventilation, aspects of the perceived suitability of the envelop construction for the climate and orientation as key principles. Fourteen households from each cohort had modified their dwelling to use energy or water more efficiently. The most common additions to the Melbourne houses were rainwater tanks, solar hot water heaters and photovoltaic (PV) panels. The modifications made by the Darwin households include the addition of solar hot water heaters and photovoltaic (PV) panels, increased shading of the dwelling walls and roof (see Figure 5.10), changes to the roof fabric (insulation, vents, reflective foil), and more efficient pool pumps and lighting. There was a general satisfaction with the impact of the above changes; however some did perceive the need for further improvement.

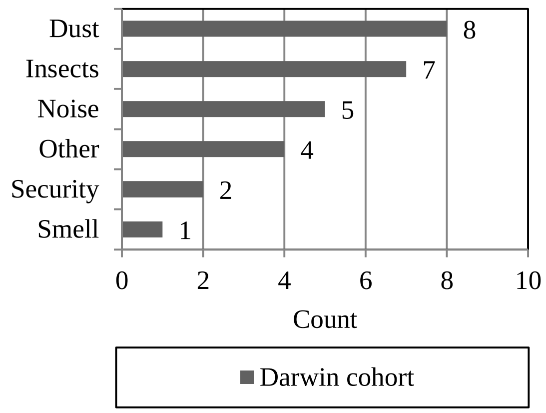

Figure 5.8. Concerns of the Darwin cohort about living in a naturally ventilated house

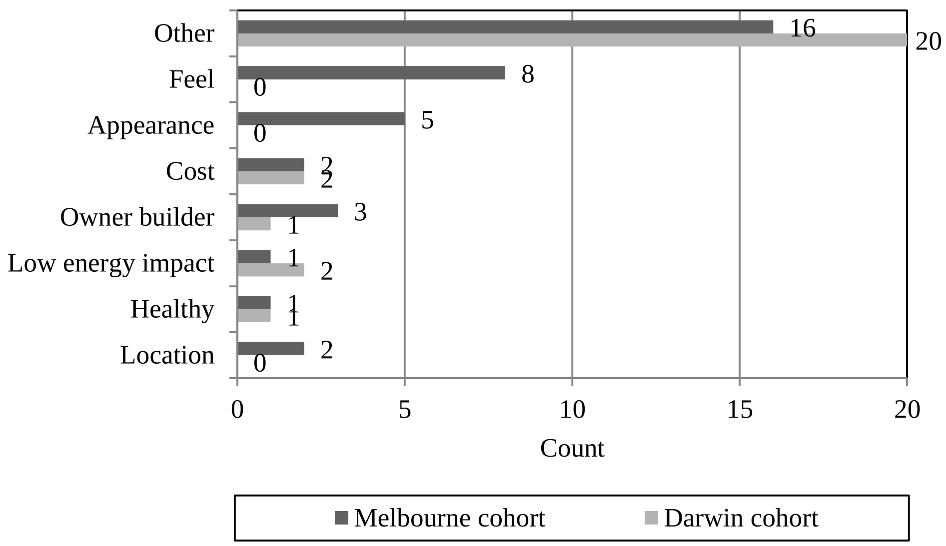

Figure 5.9. Reasons given for choosing their respective types of housing

Figure 5.10. Verandah and deck extension to standard government housing, Darwin

5.2.3 Perception of climate

When asked about their perception of the climate in which they lived the households generally responded positively with the Melbourne cohort giving an average rating of 5.8 (SD 1.6) on a 7-point Likert scale (1= "Dislike very much" and 7= "Like very much") and the Darwin cohort giving an average rating of 6.4 (SD 1.3). Despite the positive response from the Melbourne cohort, many were concerned about increasing periods of hot weather and bushfires. The Darwin cohort expressed far fewer concerns with only two participants commenting on discomfort in the build-up. Table 5.1 and Table 5.2 give the average rating for the perception of thermal conditions during different times of the day and year for each cohort respectively. The largely positive response from the Melbourne households was reflected by their comments, with many simply claiming to adjust their conditions until they were comfortable. Again, the discomfort experienced in the build-up within the Darwin houses is reflected in Table 5.2. Despite these concerns, all of the Darwin households had some form of outdoor living space which was often used more than indoor living spaces (see Figure 5.11). In fact, 14 of the 20 interviews were conducted outside, clearly demonstrating the occupants' preference and acceptance of the local climate.

The perceptions of climate and comfort in the home of the case study cohorts are similar to those expressed by the respondents to the two national surveys (see section 4.2.4). This is useful in further confirming that the thermal experiences of these occupants are not necessarily specific to the particular households in this case study but are equally shared by other occupants of these two forms of housing.

Figure 5.11. Outdoor living spaces, Darwin

Table 5.1. Perception of thermal comfort in different seasons of the Melbourne households (1= "Very uncomfortable" and 7= "Very comfortable")

Season	**Average rating (SD)**
Winter during the daytime	6.2 (1.3)
Winter during the nighttime	6.4 (1.3)
Summer during the daytime	6.2 (1.1)
Summer during the nighttime	6.2 (1.2)

Table 5.2. Perception of thermal comfort in different seasons of the Darwin households (1= "Very uncomfortable" and 7= "Very comfortable")

Season	Average rating (SD)
The build up during the daytime	2.9 (1.4)
The build-up during the nighttime	3.3 (1.2)
The wet season during the daytime	5.1 (1.4)
The wet season during the nighttime	5.2 (1.5)
The hot and dry season during the daytime	5.4 (1.4)
The hot and dry season during the nighttime	6.2 (1.0)
The cool and dry season during the daytime	6.7 (0.6)
The cool and dry season during the nighttime	7.0 (0.2)

5.2.4 Melbourne cohort: heating and cooling

The Melbourne cohort's response to cold conditions within their homes was primarily to change clothes or to turn a heating appliance on (see Figure 5.12). Of the responses to "Other", two either consumed warm beverages or food, or used their oven for cooking to warm the kitchen, one used a blanket and one suggested that they simply acclimatise to the cool conditions.

The entire Melbourne cohort had some kind of space heating in their homes. Gas space heaters and slow combustion stoves were the most common (see Figure 5.13), while responses to "Other" include three oil heaters, one hydronic in floor system and one wall furnace heater. Of the heaters present, gas space heaters (9 households) and slow combustion stoves (8 households) were the main heaters used. Heating was primarily used in the living areas in the afternoons and evenings until bedtime (see Figure 5.14 and Figure 5.15). On average, the households estimated that they use their heaters for 136 days of the year (SD 60.5) and were generally satisfied with their main heating appliance, giving an average rating of 6.2 (SD 1.7) on a 7-point Likert scale (1= "Very dissatisfied" and 7= "Very satisfied").

Thirteen of the Melbourne households had either portable fans or ceiling fans for cooling, while 11 had some kind of cooling appliance (see Figure 5.17). Of those that did not have cooling, only two households perceived a future need to install an air-conditioner, citing the increasing likelihood of heatwaves. Air-conditioning was primarily installed in the living areas and in the main bedroom, and used in the afternoons and evenings until bedtime (see Figure 5.18). In this section and throughout the interview when discussing hot weather, many of the participants commented that air-conditioning was only needed, when conditions in the house became uncomfortable only after prolonged periods of hot weather. The average estimation of days per year that air-conditioning was used was 12.9 cooling days per annum (SD 9.7), ranging from just 1 to 30. All of the households with air-conditioning were satisfied with its performance.

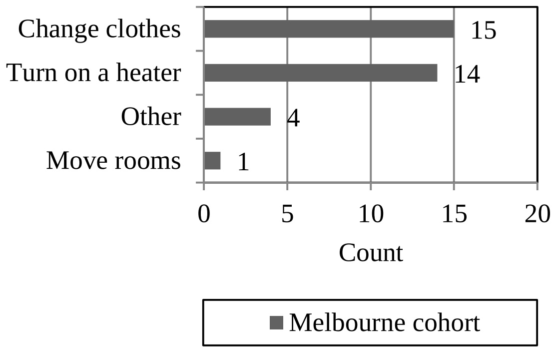

Figure 5.12. Common responses to cold conditions within the Melbourne households

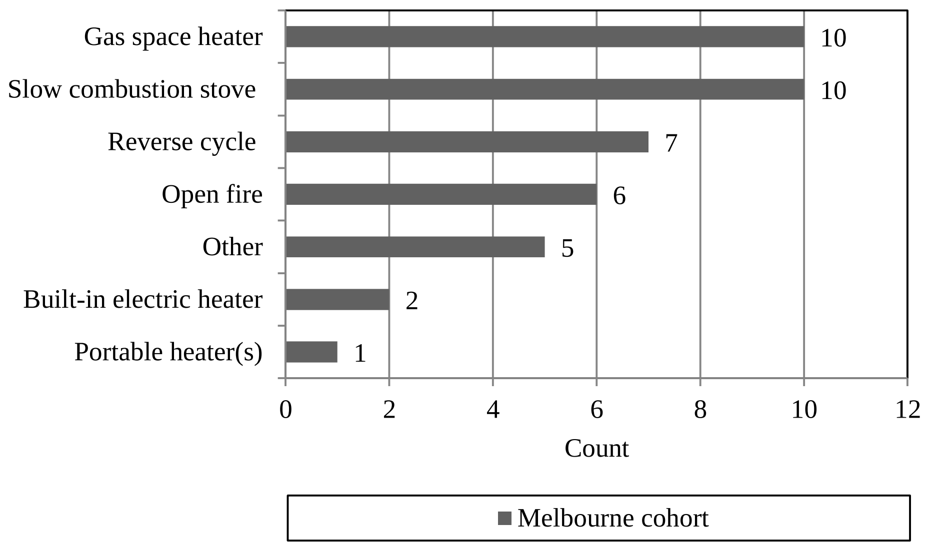

Figure 5.13. Types of heating appliances in the Melbourne households

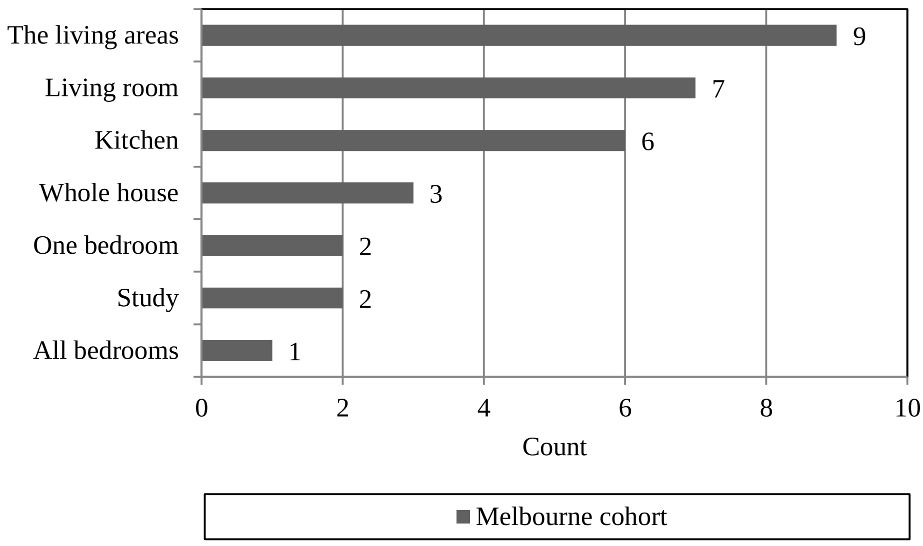

Figure 5.14. Rooms heated in cold weather

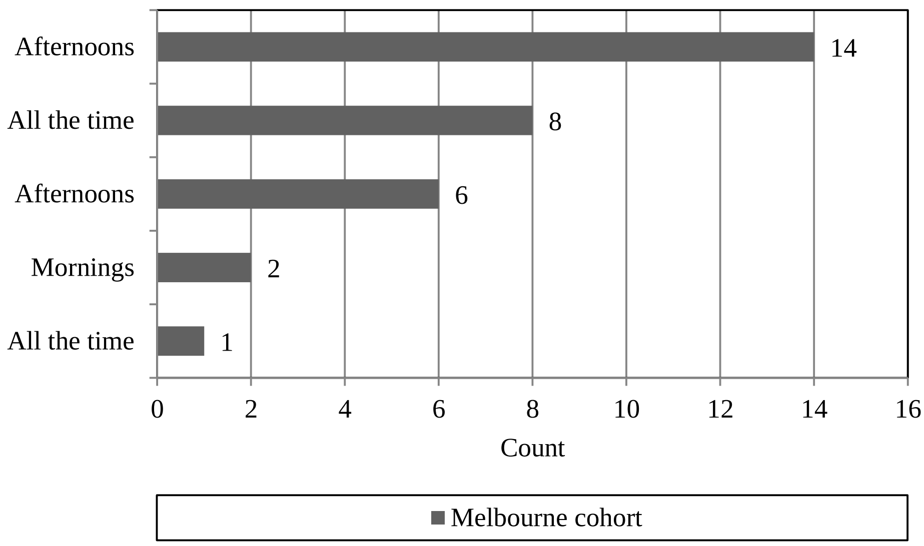

Figure 5.15. Times of the day and night heating used in cold weather

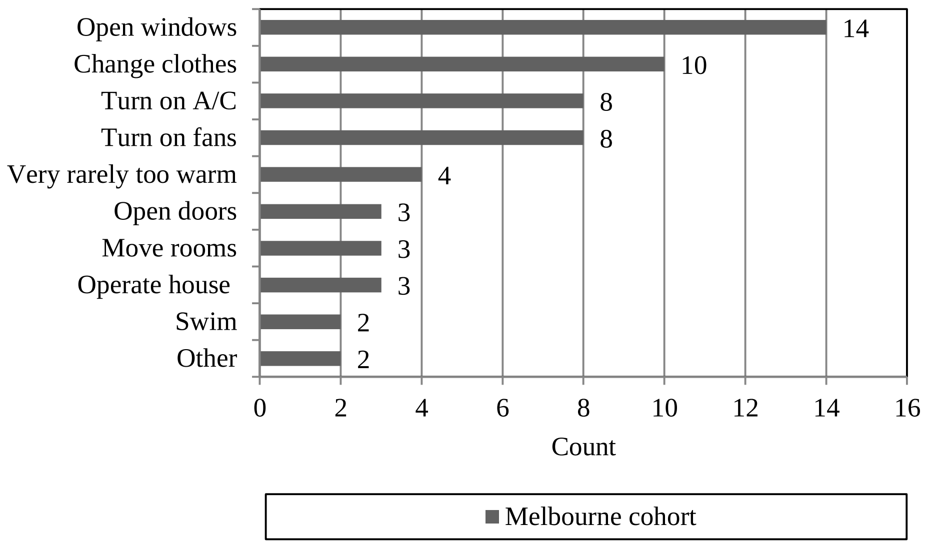

Figure 5.16. Common responses to hot conditions within the Melbourne households

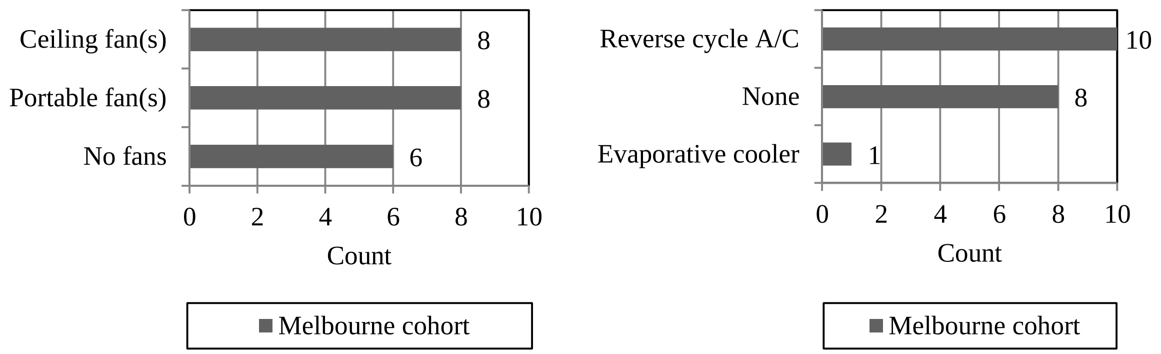

Figure 5.17. Fan and cooling appliance type in Melbourne households

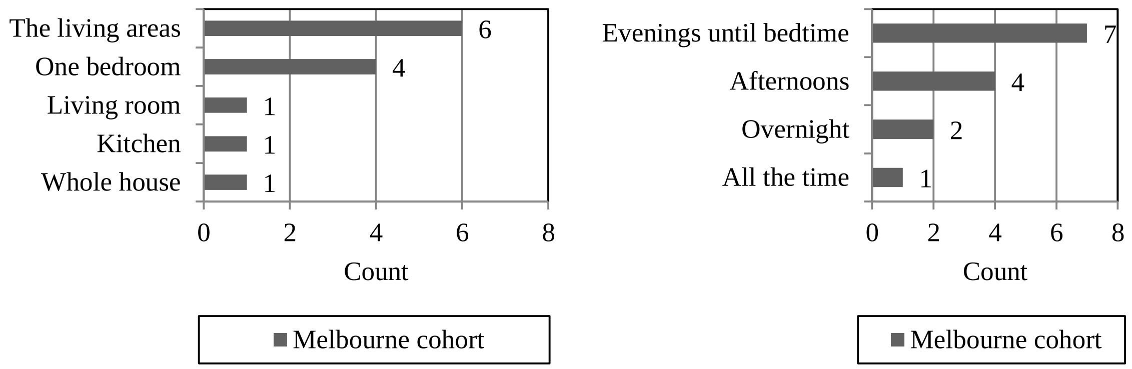

Figure 5.18. Rooms air-conditioned and times of day air-conditioning used in the Melbourne households

5.2.5 Darwin cohort: cooling

The occupants of the Darwin households had many different ways to deal with hot conditions (see Figure 5.20), including taking a swim (13) and turning on the fans (12). The number of households who nominated “Turning on A/C” (4) was relatively small. Other methods given include; resting in the coolest part of the house (5), wetting clothes or skin (3), leaving the house during hottest conditions (2), staying hydrated (2), accepting the hot conditions (1), and modifying behaviour so they do not become too hot (1). During the interviews, one of the occupants claimed that, in Darwin, it is necessary to have either an air conditioner or a swimming pool. Nine of the houses had swimming pools, which were frequently used to lower body temperature during the hottest parts of the day. It was noted that on average the pool pumps had a power capacity between 1000-1500W. These behaviours share similarities with those reported by occupants in Adelaide and Sydney houses in response to warm or hot conditions (Saman et al, 2013). Many of the strategies are the same, though the orders in which they are prioritised are quite different. Opening windows and doors was one of the first strategies nominated by the Adelaide and Sydney cohorts; however, this option was barely considered by the Darwin cohort. This is indicative of the continuous manner in which the Darwin cohort naturally ventilate their dwellings. Almost all (16) of the households reported that opening their windows and doors allowed for sufficient natural ventilation.

All of the Darwin households had either portable fans or ceiling fans within their homes. Additionally most also had some kind of air-conditioning appliance (see Figure 5.21). Of the responses to “Other”, one nominated a dehumidifying appliance, and one a portable inverter air-conditioner. None of the households without air-conditioning perceived a need to install one; instead four of the comments offered alternative methods to cool down, one stating that their house was not designed for air-conditioning (see Figure 5.19) and one saying that they would have already done so if they perceived a need.

Whilst air conditioning was not frequently used within the homes those that did operate them used it in the bedroom(s) in the afternoons and evenings when conditions where uncomfortable (see Figure 5.22). These households sought to clarify their operation of air conditioning by specifying a time limit or time frame (6), usage in certain seasons (5), or specific social circumstances e.g. visitors (3), displaying a general reticence towards its use. The average estimation of days per year that air-conditioning was used was 81.1 cooling days per annum (SD 88.9), ranging from 2 to 240. All of the households were satisfied with the performance of their air-conditioning.

Figure 5.19. Elevated verandah, deep shade, Darwin

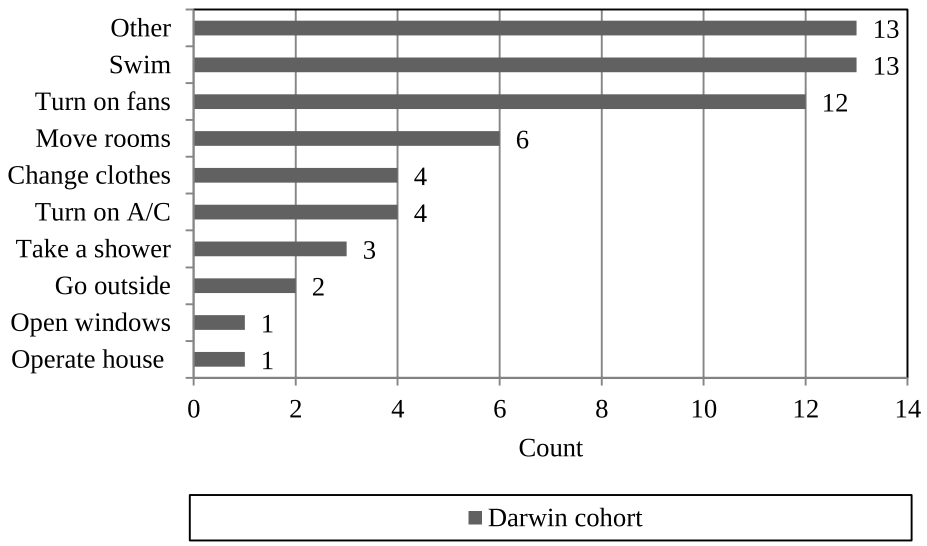

Figure 5.20. Common responses to hot conditions within the Darwin households

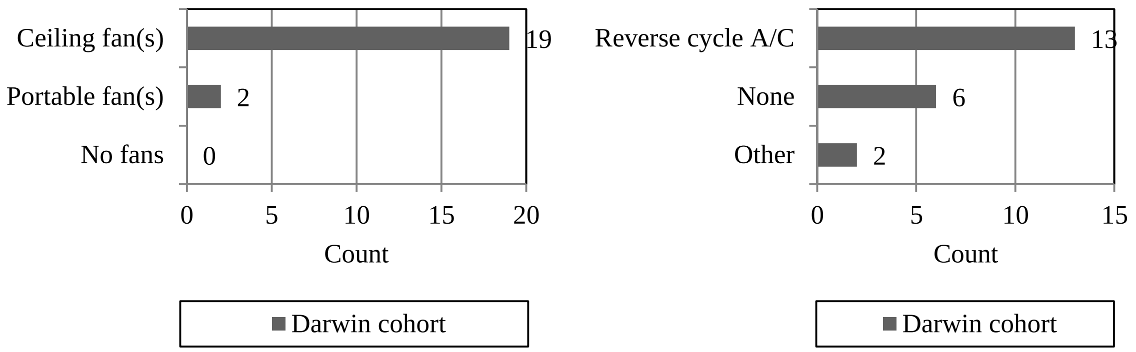

Figure 5.21. Fan and cooling appliance type in Darwin households

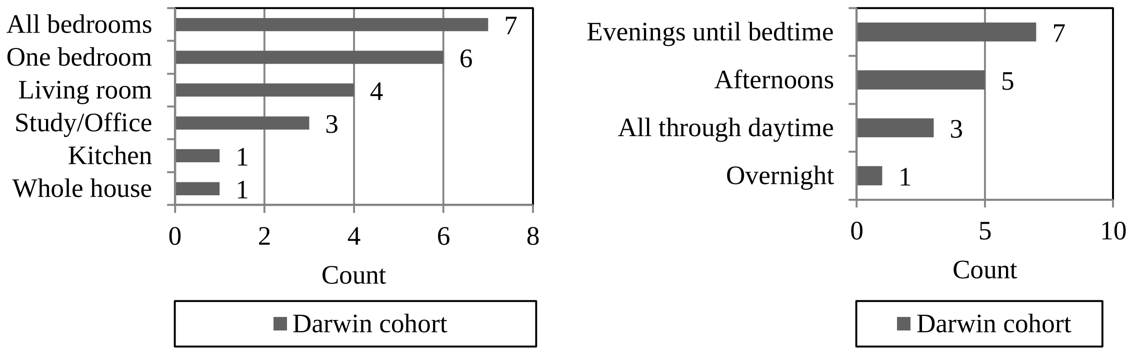

Figure 5.22. Rooms air-conditioned and times of day air-conditioning used in the Darwin households

5.3 Energy use

The long term energy use of the households was ascertained through the collection of billing records and estimations of alternative fuels (e.g. wood, LPG gas). The records generally covered the three to four years preceding the monitoring period (2009 – 2013). In the Melbourne households four primary fuel types were used; electricity, mains gas, wood and liquefied petroleum gas (LPG). In the Darwin houses, electricity was the only form of primary energy used. Electricity from photovoltaic (PV) panels was used in five households in both cohorts, however only billing data from the electricity companies was available, therefore electricity use for these households is confined to what was imported from the grid.

The average daily electricity consumption of the Melbourne households (17.7 kWh) was lower than the average for Nillumbik Shire (24.2 kWh) (State Government of Victoria, 2013). The lower electricity consumption of the Melbourne houses may be indicative of the limited use of air conditioning within the homes, suggesting adequate thermal performance in warm to hot conditions. The average daily gas consumption, however, was comparable at 125.9 MJ for the case study houses and 127.2 MJ for the Shire. Neither wood nor LPG consumption figures were reported for the Nillumbik Shire. In order to roughly compare overall energy consumption of the case studies households with the average for the Shire, the figures for the different fuels types used in the Melbourne households were converted to kWh/day. A conversion factor of 3.6 was used for the mains gas and LPG figures, as well as the gas consumption figure for the Shire. The estimated figures used to convert wood (kg) to kWh were: energy content of wood 18 MJ/kg, moisture content 10% (Zanuncio et al, 2013), and efficiency of the combustion stove 70% (YourHome, 2013). The average total aggregated daily energy consumption of the case study households was 50.5 kWh, lower than the average total aggregated daily energy consumption of the Shire, 59.5 kWh. The majority of energy consumption occurred in the Melbourne households over the winter and shoulder seasons, indicating that additional heating was required by the occupants. It is important to note that three of the households had multiple dwellings on the same metre and at least four had extensive out buildings (sheds etc.) that distort the total energy use figures for those households. It is likely that the actual energy use for the dwellings studied, excluding any other houses or buildings on the same metre, is lower than reported.

The average daily energy use of the Darwin households was 14.3 kWh. Detailed energy consumption figures were not available for the broader Darwin population, however an aggregated figure for electricity consumption of 24.4 kWh for the Northern Territory was quoted on the utility service provider’s website in 2011 (Power and Water Corporation, 2011). The average daily electricity consumption for the Darwin case study households is considerably less than this figure. Electricity consumption remained fairly stable year round with only slight peaks in the build-up and wet season. Some of the occupants noted in the interviews that they needed to operate their pool pumps more regularly to prevent the growth of algae.

Table 5.3. Average daily energy usage for the Melbourne households, note: 'na' denotes that records were not available, whereas '-' denotes that the fuel type is not used within the dwelling, average consumption based on available data

Dwelling ID	Electricity kWh/day	Gas MJ/day	Wood kg/day	LPG MJ/day	Total kWh/day
1	24.4	-	4.1	12.1	40.5
2	na	na	na	na	na
3	8.9	80.1	-	-	31.2
4	4.1	137.2	-	-	42.3
5	5.9	-	1.8	18.0	16.5
6	23.2	83.1	-	-	46.2
7	18.8	-	11.0	-	52.9
8	19.5	109.5	-	-	49.9
9	8.0	251.5	-	-	77.9
10	23.9	-	14.8	6.0	71.6
11	56.6	-	11.0	-	90.7
12	11.8	-	3.6	36.1	33.0
13	4.9	-	-	12.0	8.2
14	7.1	132.9	8.2	-	69.6
15	8.3	128.8	2.7	-	52.6
16	15.6	83.8	-	-	38.9
17	32.2	-	16.4	-	83.3
18	50.1	-	2.7	-	58.7
19	10.1	143.8	2.7	-	58.6
20	2.6	-	6.8	24.2	30.6
Average	**17.7**	**125.9**	**7.2**	**18.1**	**50.2 (SD 21.4)**

Table 5.4. Average daily energy usage for the Darwin households, note: 'na' denotes that records were not available, average consumption based on available data

Dwelling ID	Electricity kWh/day
21	19.1
22	7.1
23	11.6
24	8.1
25	11.2
26	10.0
27	19.6
28	11.5
29	31.5
30	9.8
31	7.9
32	13.6
33	12.4
34	14.9
35	25.3
36	15.3
37	na
38	18.0
39	na
40	10.0
Average	**14.3 (SD 6.2)**

5.4 Outdoor thermal conditions

During the monitoring period from March 2013 to March 2014, the outdoor temperatures that the Melbourne households experienced ranged from a minimum of -2.4°C in July 2013 to a maximum of 45.4°C January 2014 (see Table 5.5 and Figure 5.23). The mean monthly temperature was coldest in July (8.3°C) and warmest (21.7°C) in January. The coldest weather coincided with the highest mean monthly humidity (89.3%), while the warmest weather coincided with the lowest mean monthly humidity (56.8%); indicating a cold wet winter season and a hot dry summer season (see Figure 5.24). The range of outdoor temperatures experienced by the Darwin households from June 2013 to May 2014 was much narrower with a minimum of 16.2°C in August 2013 and a maximum of 35.8°C in October 2013 (see Table 5.6 and Figure 5.25). The coolest months of the monitoring period were from June to August

2013 with mean monthly temperatures increasing by 2 to 4°C from September 2013 to April 2014. The mean monthly humidity was lowest in June 2013 (52.8%) and highest in January 2014 (81.6%) (Figure 5.26).

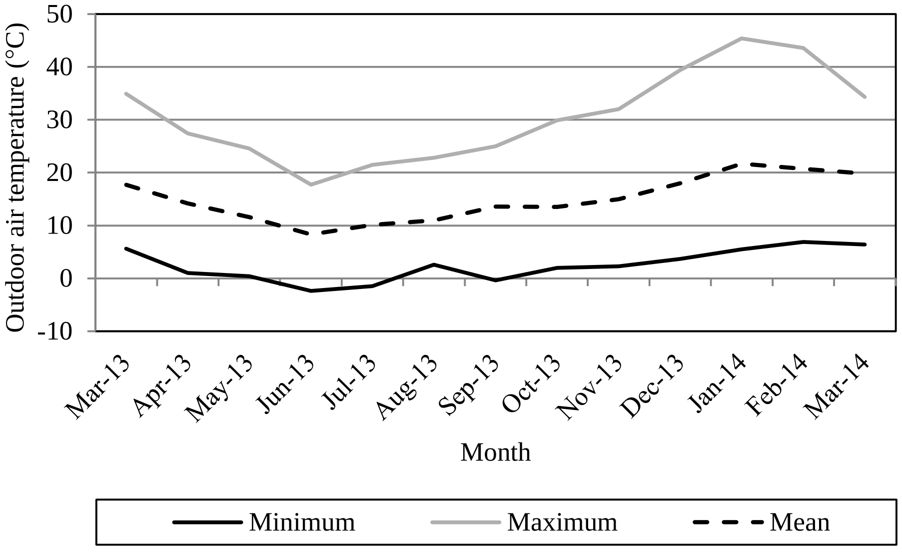

Figure 5.23. Monthly outdoor minimum, maximum and mean temperature from the weather station installed in Nillumbik Shire for the monitoring period

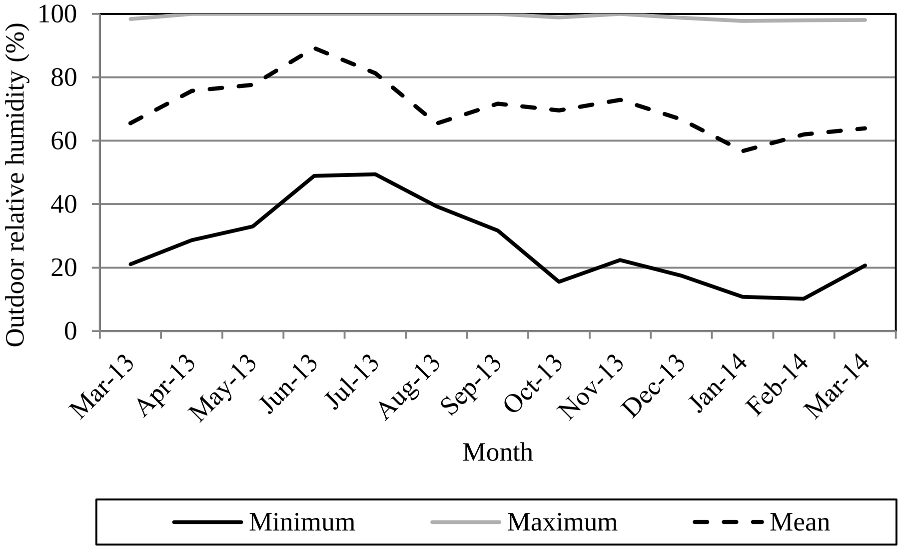

Figure 5.24. Monthly outdoor minimum, maximum and mean relative humidity from the weather station installed in Nillumbik Shire for the monitoring period

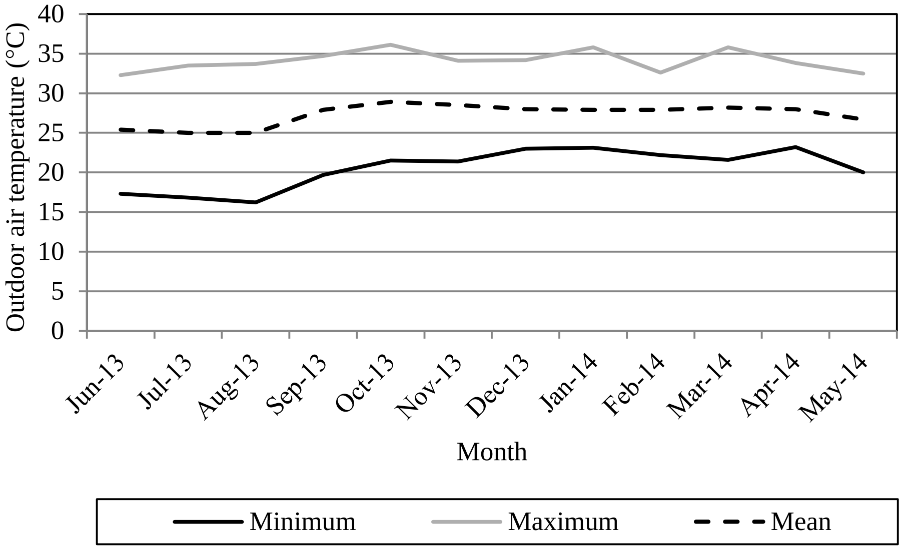

Figure 5.25. Monthly outdoor minimum, maximum and mean temperature from the Darwin Airport weather station 014015 (BOM, 2014) for the monitoring period

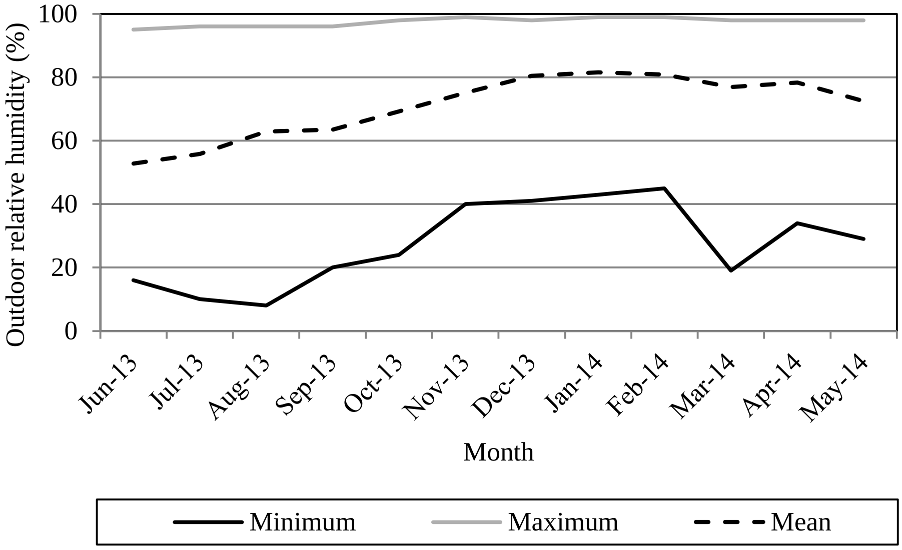

Figure 5.26. Monthly outdoor minimum, maximum and mean relative humidity from the Darwin Airport weather station 014015 (BOM, 2014) for the monitoring period

Table 5.5. Monthly outdoor minimum, maximum and mean temperature and relative humidity from the weather station installed in Nillumbik Shire for the monitoring period

	Mar 13	**Apr 13**	**Ma y 13**	**Jun 13**	**Jul 13**	**Aug 13**	**Sep 13**	**Oct 13**	**Nov 13**	**Dec 13**	**Jan 14**	**Feb 14**	**Mar 14**
T_{min} °C	5.6	1.0	0.4	-2.4	-1.5	2.6	-0.4	2.0	2.3	3.7	5.5	6.9	6.4
T_{max} °C	34.9	27.4	24.6	17.7	21.5	22.8	25.0	29.9	32.0	39.4	45.4	43.6	34.3
T_{mean} °C	17.7	14.2	11.6	8.3	10.1	11.0	13.6	13.5	15.0	18.0	21.7	20.7	19.8
RH_{min} %	21.1	28.6	33.0	48.9	49.4	39.3	31.7	15.5	22.4	17.4	10.8	10.2	20.7
RH_{max} %	98.4	100	100	100	100	100	100	98.9	100	98.8	97.8	98.0	98.1
RH_{mean} %	65.5	75.7	77.7	89.3	81.3	65.4	71.7	69.6	72.9	66.7	56.8	62.0	63.9

Table 5.6. Monthly outdoor minimum, maximum and mean temperature and relative humidity from the Darwin Airport weather station 014015 (BOM, 2014) for the monitoring period

	Jun 13	**Jul 13**	**Aug 13**	**Sep 13**	**Oct 13**	**Nov 13**	**Dec 13**	**Jan 14**	**Feb 14**	**Mar 14**	**Apr 14**	**May 14**
T_{min} °C	17.3	16.8	16.2	19.7	21.5	21.4	23.0	23.1	22.2	21.6	23.2	20.0
T_{max} °C	32.3	33.5	33.7	34.7	36.1	34.1	34.2	35.8	32.6	35.8	33.8	32.5
T_{mean} °C	25.4	25.0	25.0	27.9	28.9	28.5	28.0	27.9	27.9	28.2	28.0	26.7
RH_{min} %	16.0	10.0	8.0	20.0	24.0	40.0	41.0	43.0	45.0	19.0	34.0	29.0
RH_{max} %	95.0	96.0	96.0	96.0	98.0	99.0	98.0	99.0	99.0	98.0	98.0	98.0
RH_{mean} %	52.8	55.8	62.9	63.5	69.2	75.1	80.5	81.6	80.9	76.9	78.3	72.5

5.5 Indoor thermal conditions

In this section the hourly temperature, relative humidity, globe temperature and airspeed measurements from the primary logger in each dwelling have been averaged to provide an overview of conditions experienced within the case study houses (see Table 5.7 and Table 5.8).

5.5.1 Temperature and humidity

The temperatures within the Melbourne houses ranged from 13.3°C in June and July 2013 to 32.4°C in January 2014. The conditions within the homes were coldest in June with a monthly mean of 17.1°C and warmest in January with a monthly mean of 23.5°C. The temperature and humidity measurements presented in Figure 5.27 and Figure 5.28 show that conditions experienced within the houses have a narrower range during the winter season compared to the summer season. This indicates that the occupants use heating indoors during the winter, whilst in summer the conditions are left to 'float' or follow outdoor conditions. This is reflected in Figure 5.29 where the indoor temperature is less coupled with the outdoor temperature, when compared to Figure 5.30 where the indoor temperatures during the summer season more closely follow the outdoor temperature. Despite the use of heating within the Melbourne houses during winter, the conditions are almost completely outside of the ASHRAE comfort zone for conditioned spaces (Figure 5.27). In summer, the conditions are more aligned with the ASHRAE comfort zone, however still tend towards cooler temperatures than expected (Figure 5.28).

In both the winter and summer seasons the indoor temperatures are generally higher than the outdoor temperatures. Indoor humidity was generally stable with monthly means ranging from 46.3% to 55.6%. The earth walls appear to regulate humidity as the outdoor relative humidity is significantly more varied (see Figure 5.31 and Figure 5.32).

The temperature within the Darwin homes during the monitoring period ranged from a minimum of 19.9°C in July 2013 to a maximum of 34.5°C in January 2014. The coolest month was July, with a monthly mean of 26.2°C, while the warmest month was October with a monthly mean of 30.0°C. The lowest monthly mean relative humidity was in June 2013, while the highest in February. The cool, dry conditions in June, July and August and the hot, humid conditions in December, January and February are reflected in Figure 5.33 and Figure 5.34. The temperature and humidity within the homes generally follow the outdoor conditions because the houses are so open to the external climate (see Figure 5.35 to Figure 5.38). Because of this, the conditions within the homes bare little correspondence with the ASHRAE comfort zone (see Figure 5.33 and Figure 5.34), particularly during the wet season when both the temperature and humidity levels are high.

Table 5.7. Monthly indoor minimum, maximum and mean of the average hourly measurements of temperature, globe temperature and relative humidity from all of the Melbourne houses note: the figures for February and March 2014 are representative of two houses only

	Mar 13	**Apr 13**	**May 13**	**Jun 13**	**Jul 13**	**Aug 13**	**Sep 13**	**Oct 13**	**Nov 13**	**Dec 13**	**Jan 14**	**Feb 14**	**Mar 14**
$T_{min\ °C}$	18.0	15.9	15.0	13.3	13.3	14.5	14.5	15.2	15.9	16.9	16.9	17.9	18.7
$T_{max\ °C}$	26.8	22.9	21.7	19.9	20.3	20.3	21.7	23.7	24.7	27.1	32.4	31.7	28.0
$T_{mean\ °C}$	21.4	19.6	18.3	17.1	17.4	17.5	18.6	18.8	19.8	21.4	23.5	23.4	22.6
$Tg_{min\ °C}$	18.0	15.8	14.9	13.3	13.4	14.5	14.4	15.1	15.8	16.8	16.7	17.8	18.2
$Tg_{max\ °C}$	26.9	23.0	21.8	20.2	20.6	20.5	21.8	23.9	24.9	27.1	32.5	32.3	28.4
$Tg_{mean\ °C}$	21.4	19.6	18.3	17.2	17.5	17.6	18.6	18.8	19.8	21.3	23.5	23.3	22.5
$RH_{min\ \%}$	43.2	45.8	43.4	47.1	47.1	45.1	46.6.	36.1	41.0	41.3	29.5	24.1	32.2
$RH_{max\ \%}$	61.1	64.2	61.9	65.1	63.1	60.5	62.6	60.8	61.7	67.0	62.0	61.4	64.5
$RH_{mean\ \%}$	52.8	55.6	52.9	55.1	54.6	53.0	55.0	52.0	54.7	55.0	46.3	47.9	51.5

Table 5.8. Monthly indoor minimum, maximum and mean of the average hourly measurements of temperature, globe temperature, relative humidity and air speed from all of the Darwin houses

	Jun 13	**Jul 13**	**Aug 13**	**Sep 13**	**Oct 13**	**Nov 13**	**Dec 13**	**Jan 14**	**Feb 14**	**Mar 14**	**Apr 14**	**May 14**
$T_{min\ °C}$	20.8	19.9	20.0	23.9	26.3	25.7	26.0	25.8	25.2	25.9	25.7	23.2
$T_{max\ °C}$	30.8	31.8	31.5	32.7	34.2	33.3	33.7	34.5	32.1	33.5	33.2	31.9
$T_{mean\ °C}$	26.5	26.2	26.4	28.9	30.0	29.6	29.2	28.9	28.8	29.5	29.4	28.4
$Tg_{min\ °C}$	20.6	19.6	19.7	23.7	26.1	25.4	25.8	25.6	25.0	25.6	25.5	23.0
$Tg_{max\ °C}$	30.8	31.7	31.6	32.7	34.3	33.2	33.5	34.5	32.0	33.4	33.2	31.8
$Tg_{mean\ °C}$	26.4	26.1	26.2	28.7	29.8	29.5	29.1	28.8	28.7	29.4	29.3	28.2
$RH_{min\ \%}$	25.4	21.0	19.2	30.8	36.6	51.3	57.7	55.7	59.1	31.0	50.8	40.8
$RH_{max\ \%}$	82.1	85.6	84.0	83.5	86.3	90.6	94.1	95.0	93.6	91.0	90.6	87.4
$RH_{mean\ \%}$	54.4	56.7	62.8	64.8	69.7	74.9	79.5	82.1	82.6	76.1	77.0	71.0
$V_{min\ m/s}$	0.18	0.17	0.16	0.16	na	na	0.02	0.14	0.12	0.12	0.12	0.12
$V_{max\ m/s}$	0.33	0.32	0.48	0.75	na	na	0.43	0.68	0.34	0.41	0.26	0.27
$V_{mean\ m/s}$	0.21	0.20	0.20	0.21	na	na	0.20	0.20	0.18	0.16	0.15	0.14

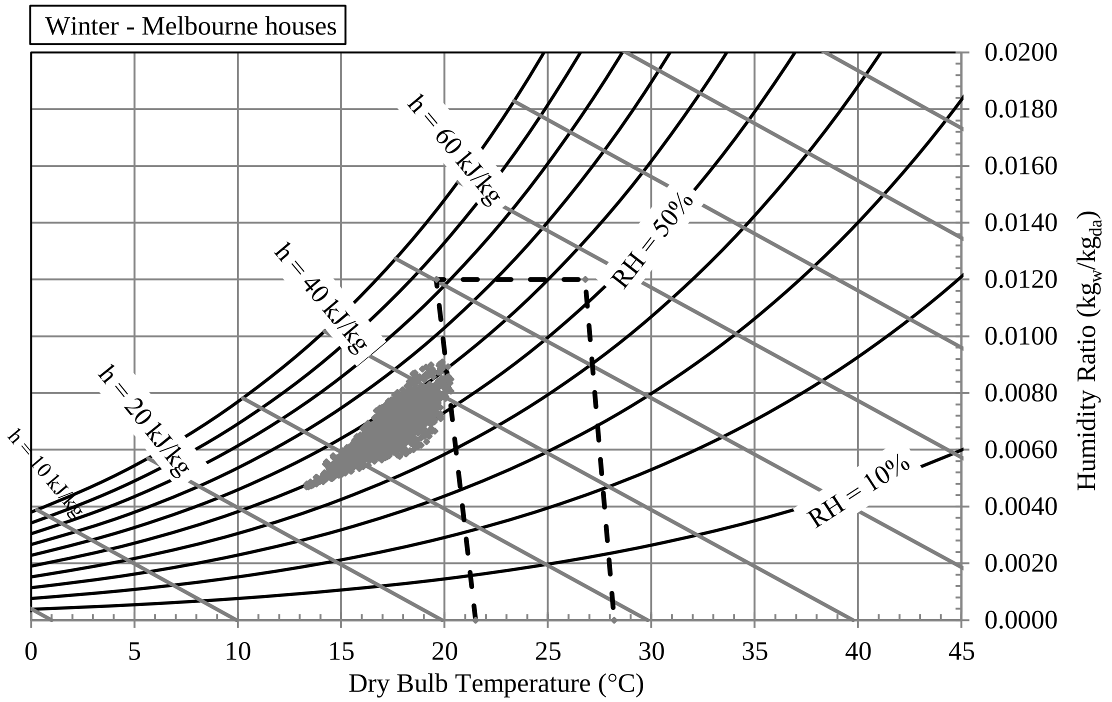

Figure 5.27. Average hourly temperatures and humidity of all Melbourne houses during the winter (June 2013 – August 2013) compared with the ASHRAE acceptable comfort zone for conditioned spaces (0.5 and 1.0 clo zones combined)

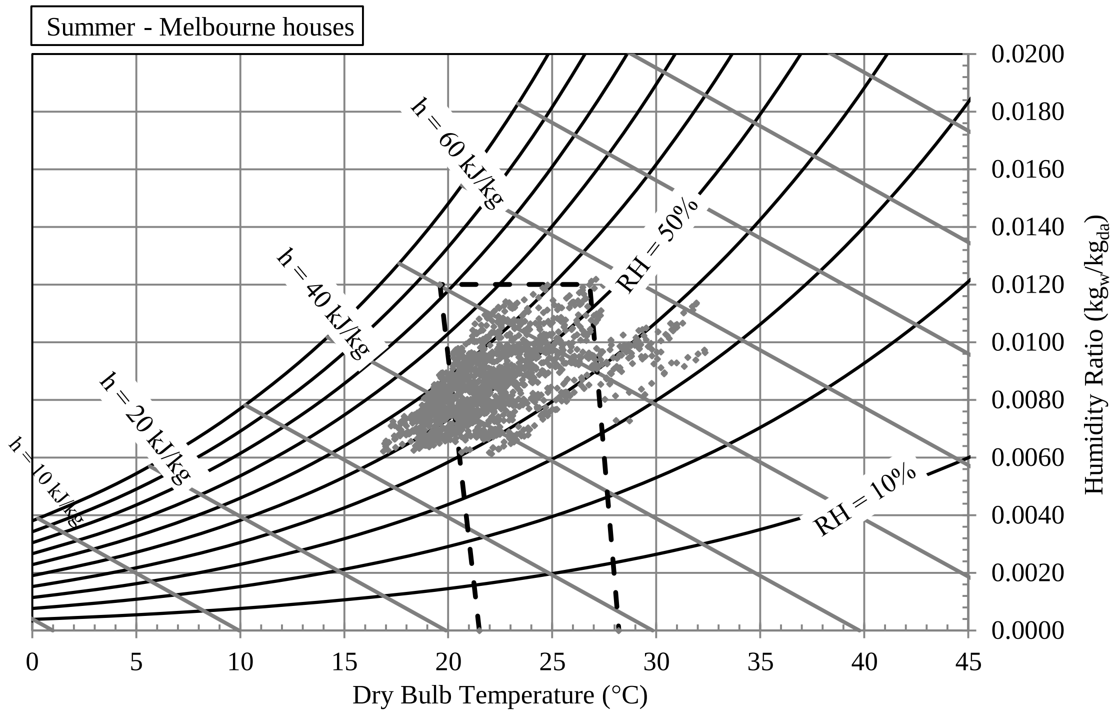

Figure 5.28. Average hourly temperatures and humidity of all Melbourne houses during the summer (December 2013 – January 2014) compared with the ASHRAE acceptable comfort zone for conditioned spaces (0.5 and 1.0 clo zones combined)

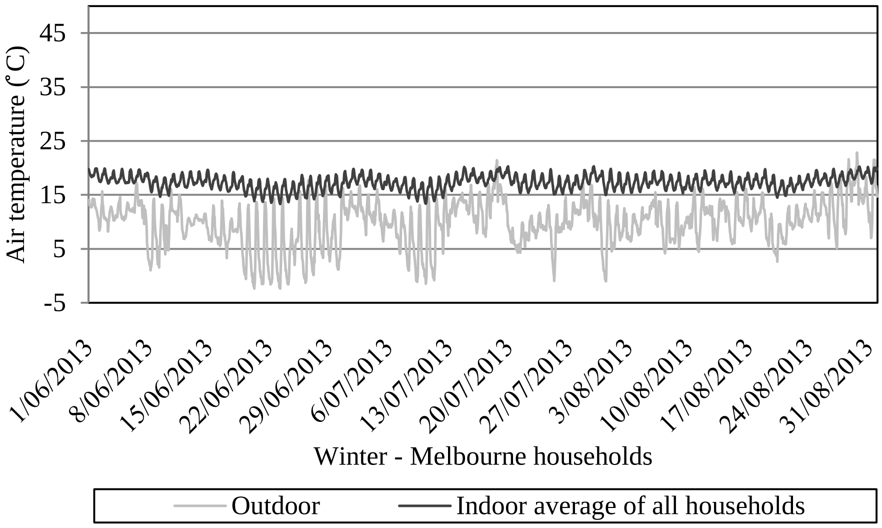

Figure 5.29. Comparison of average indoor and outdoor air temperature in the Melbourne houses during winter

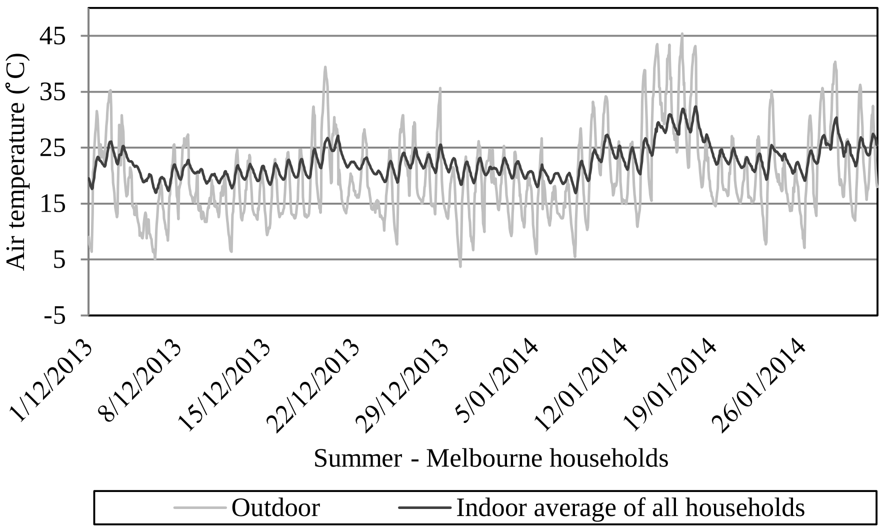

Figure 5.30. Comparison of average indoor and outdoor air temperature in the Melbourne houses during summer

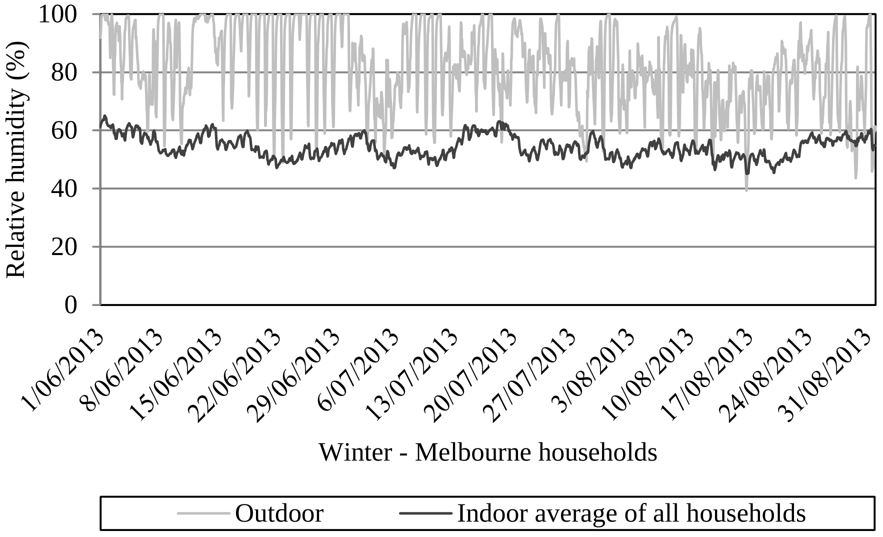

Figure 5.31. Comparison of average indoor and outdoor relative humidity levels in the Melbourne houses during winter

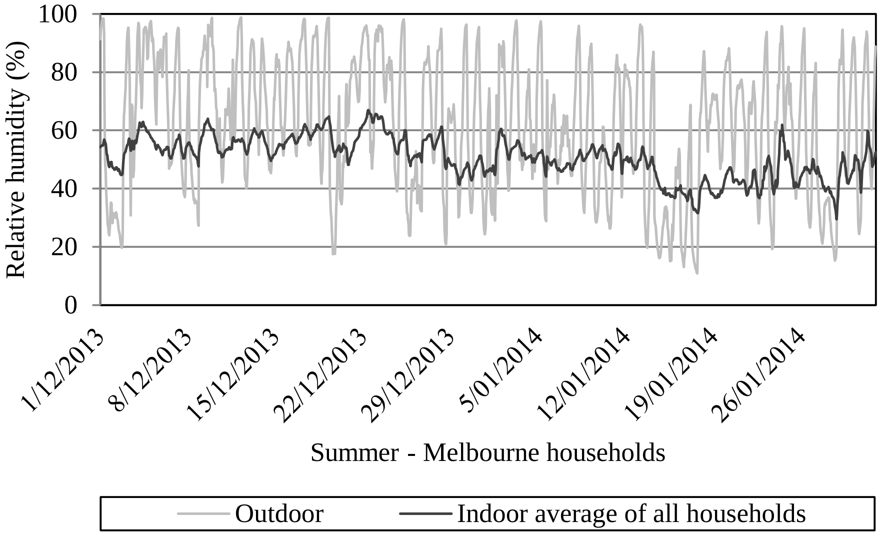

Figure 5.32. Comparison of average indoor and outdoor relative humidity levels in the Melbourne houses during summer

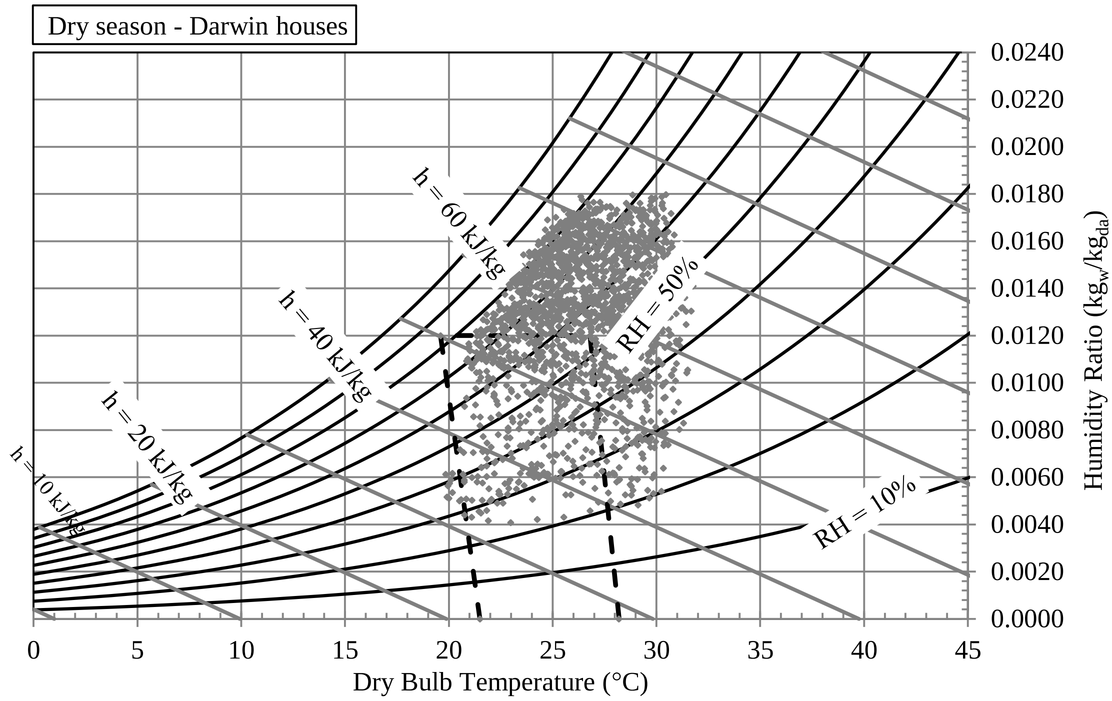

Figure 5.33. Average hourly temperatures and humidity of all Darwin houses during the dry season (June 2013 – August 2013) compared with the ASHRAE acceptable comfort zone for conditioned spaces (0.5 and 1.0 clo zones combined)

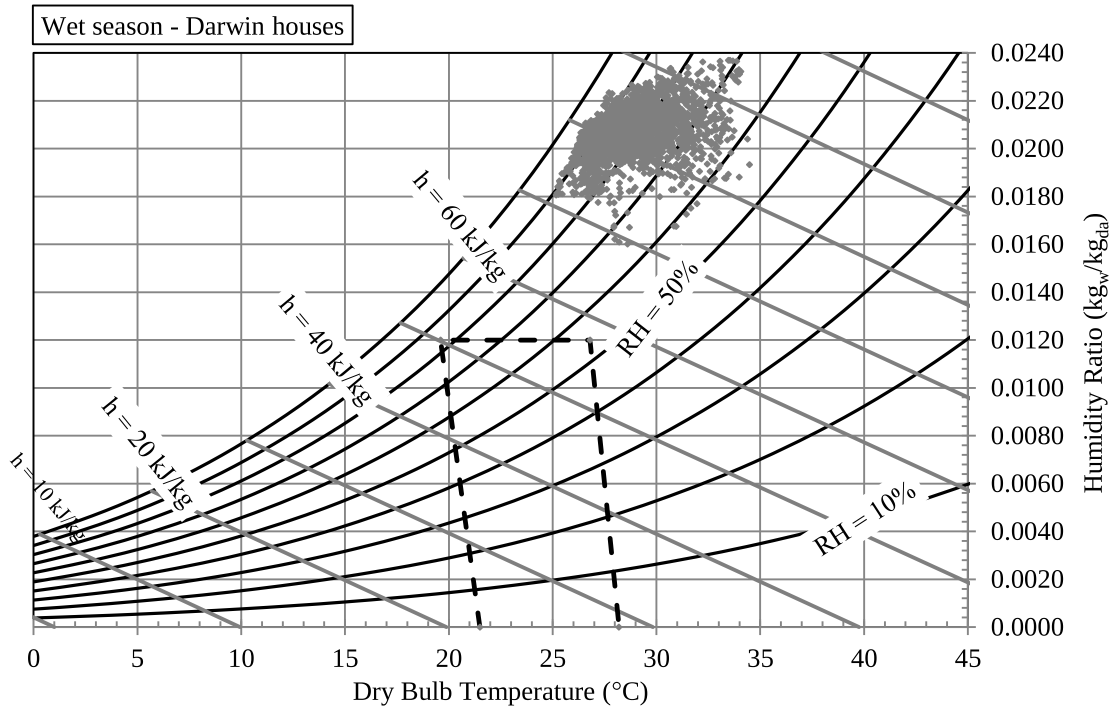

Figure 5.34. Average hourly temperatures and humidity of all Darwin houses during the wet season (December 2013 – February 2014) compared with the ASHRAE acceptable comfort zone for conditioned spaces (0.5 and 1.0 clo zones combined)

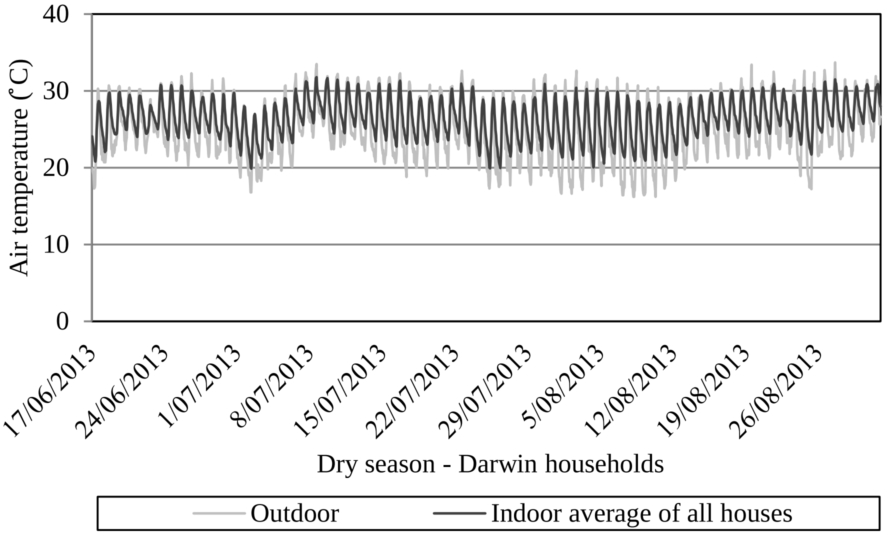

Figure 5.35. Comparison of average indoor and outdoor air temperature in the Darwin houses during the dry season

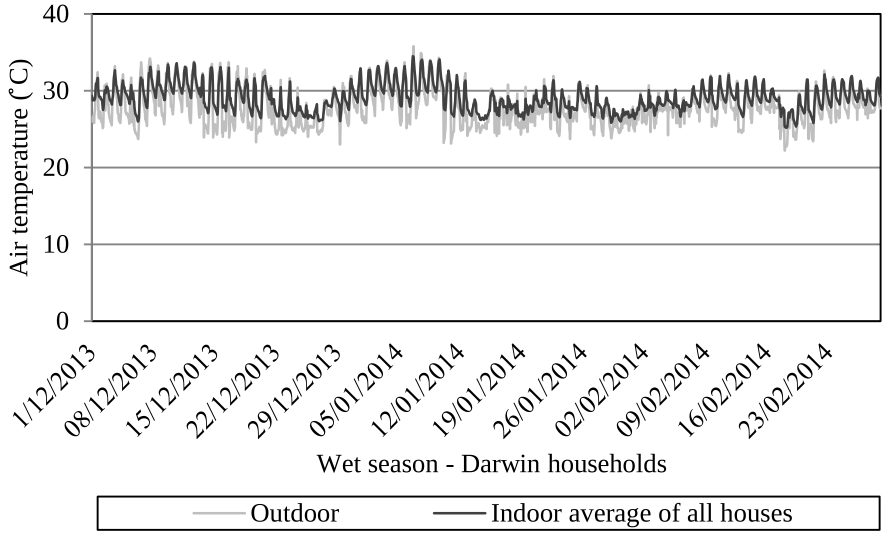

Figure 5.36. Comparison of average indoor and outdoor air temperature in the Darwin houses during the dry season

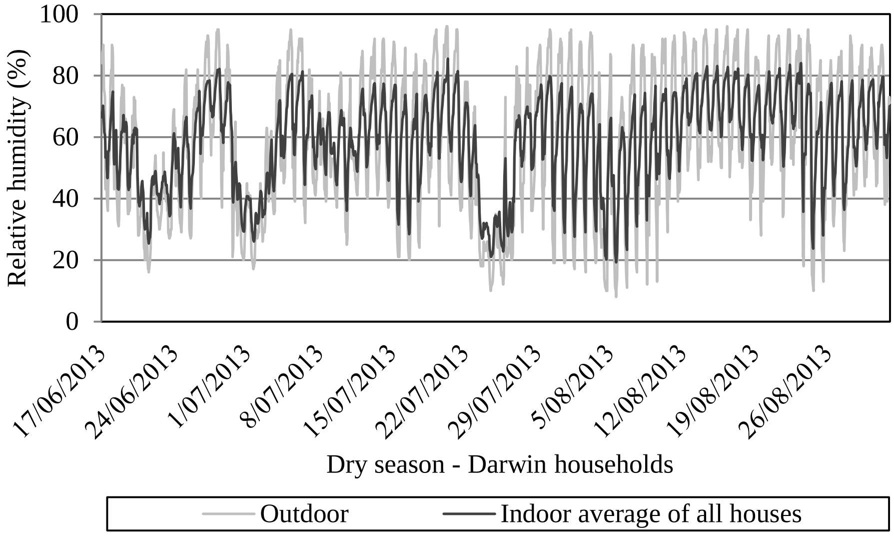

Figure 5.37. Comparison of average indoor and outdoor relative humidity levels in the Darwin houses during the dry season

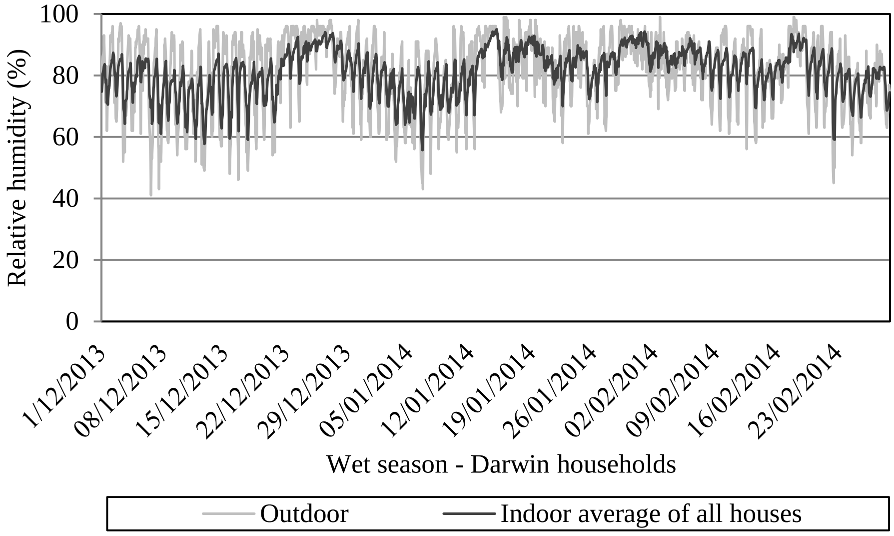

Figure 5.38. Comparison of average indoor and outdoor relative humidity levels in the Darwin houses during the wet season

5.5.2 Air speed

During the first deployment of the experimental air movement loggers all systems failed within 1-2 months. Further investigation revealed that this was likely due to the use of lithium iron disulphide batteries. At the mid-point of the monitoring period the batteries were replaced with standard alkaline batteries which successfully powered the systems for the remaining 5-6 months of monitoring. Despite the system failure, sufficient data were collected. The indoor airspeed recorded within the Darwin houses remained fairly consistent throughout the monitoring period, with a slight increase detectable in the middle of the wet season (see Figure 5.39 and Figure 5.40). The highest airspeed recorded was 9.32m/s in Dwelling 37, however the average highest recording across all Darwin households was just 1.78m/s.

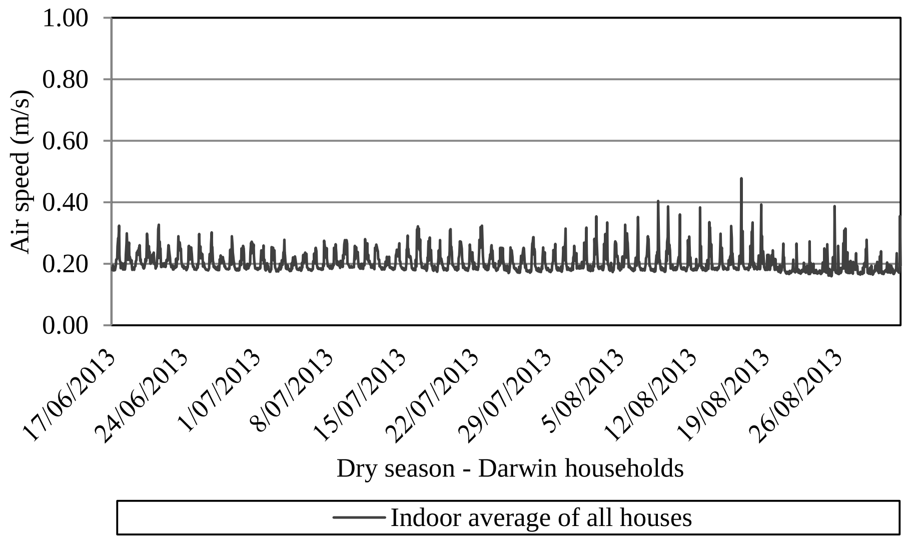

Figure 5.39. Indoor average air speed in the Darwin houses during the dry season

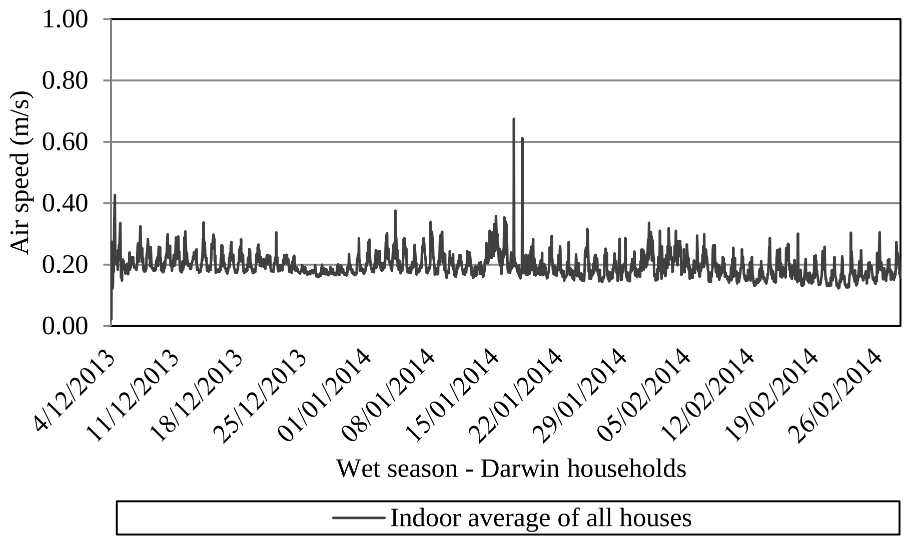

Figure 5.40. Indoor average air speed in the Darwin houses during the wet season

5.6 Summary

The findings from the case studies of the 20 Melbourne and the 20 Darwin households reveal a rich context in which these households, through the operation of their dwelling, including heating or cooling appliances, minimise household energy consumption. The occupants' attitude towards aspects of the design, construction and operation of their homes demonstrated that their dwellings meet their aspirations and needs. It also revealed the occupants' perceptions of the performance of their homes; many recognised that comfort could be achieved, not just through the use of heating and/or cooling, but also by modifying their expectations and behaviours.

The construction of the case study houses broadly reflected trends identified in the national surveys reported in Chapter 4. Again, the importance of a connection to the natural environment was shown through the bushland settings of many of the houses as well as the presence of extensive vegetation on the suburban blocks. The majority of the case study dwellings were separate family homes. Broadly, the Melbourne occupants were older couples with adult children not living at home, whilst the Darwin households mainly consisted of younger families. The majority of houses had more than one occupant. The construction of the Melbourne houses emphasised the owner/builder history of the earth wall construction, with many dwellings also incorporating recycled timbers as structural elements. The Darwin houses mostly reflected traditional design appropriate for tropical climates (i.e. elevated, deep eaves, use of louvres for ventilation); however some of the houses were heavyweight construction with a slab-on-ground. Whilst heavyweight construction is not normally considered appropriate for tropical climates (Harris & Welke, 1981), the occupants of these houses operated them as naturally ventilated and had no major concerns about the thermal performance of their homes. This demonstrates the importance of the occupant's own expectations in the operation and judgement of the thermal performance of the dwelling.

The reasons given by both cohorts regarding their choice of house were not primarily concerned with the thermal performance of the building, rather, indicative of broader attitudes towards housing and lifestyle. The Melbourne occupants cited the 'Feel' and 'Appearance' of the earth walls, suggesting an implicit connection with the dwelling that satisfies the underlying needs of the occupants. The choice of naturally ventilated housing in Darwin was largely driven by an opposition to the use of air conditioning appliances. This demonstrates a much more explicit relationship between the occupants' performance or housing expectations and the design/operation of the dwelling. Both cohorts of occupants expressed overall satisfaction with the thermal conditions experienced within their homes, confirming the appropriateness of these buildings for these particular occupants. Interestingly, many of the Darwin occupants spent considerable time using outdoor living areas, suggesting that, in fact, the thermal conditions within the home are not a priority during a large proportion of the day.

Heating and/or cooling appliances were used judiciously within the Melbourne and Darwin houses. The Melbourne cohort mainly heated the living areas of their homes with gas space heaters or slow combustion stoves in the evenings before bedtime. Cooling appliances were seldom used in the Melbourne houses. When they were it was often in the afternoons and evenings after prolonged periods of hot weather that caused the thermally massive walls to retain excessive heat. All of the Darwin households used ceiling fans to supplement air movement provided through natural ventilation of the home. Interestingly, many of the Darwin households also used air conditioning appliances sparingly in bedrooms in the afternoons and evenings to assist with children's concentration for study as well as sleeping. The use of heating and/or cooling appliances within all dwellings in both locations was complemented by the householders' awareness of other techniques for dealing with internal thermal conditions.

The limited use of heating and/or cooling appliances is reflected in the overall lower energy consumption of the households compared with averages for the same locations. The energy use of the Melbourne households was still unexpectedly high given the careful use of heating within the homes and the overall awareness of the occupants. Further investigation revealed that many of the properties had multiple dwellings or outbuildings connected to the same meter that distorted the consumption figures. Peak energy consumption in the Melbourne households was generally in winter and attributable to heating appliances. Electricity was the only form of primary energy used within the Darwin homes. The consumption was mainly even throughout the year with slightly peaks in the build-up and the wet season. Many of the households noted that swimming pool pumps are run for longer periods during these seasons to prevent the growth of algae so are likely responsible for the peaks in consumption. These results highlight the necessity to incorporate all aspects of energy consumption within the home if building designs are to be assessed on predicted energy consumption.

During the monitoring period, the Melbourne households experienced a cold wet winter season and a hot dry summer season, while the Darwin households experienced a much narrower range of temperatures, consistent with tropical climates. Within the Melbourne houses, conditions in winter were cool, even though temperatures were supplemented by the use of heating appliances. In the shoulder seasons and warmer summer weather, temperatures indoors more closely followed outdoor temperatures. The high thermal mass provided by the earth walls improved summertime performance by keeping temperatures cooler and stable, whilst in winter additional heating was required by the occupants. The conditions in the Darwin households closely followed the outdoor weather patterns throughout the year with little or no artificial cooling used by the occupants.

For much of the time, indoor conditions within both groups of dwellings were outside of the conventional thermal comfort zone for conditioned spaces (ASHRAE, 2013). If the recommendations of the Givoni & Milne (1981) bioclimatic chart are considered, the design and construction of both forms of housing would suggest that they are not appropriate for the climates in which they are located. For example, the high thermal mass in the Melbourne houses means that the strategies for heating suggested by Givoni & Milne (internal gains, passive and active solar, and conventional heating) would not be sufficient to raise the temperatures to the human thermal comfort zone. Similarly, based on the high temperatures and humidity levels experienced with the Darwin houses, air conditioning is the only suitable cooling strategy (Givoni & Milne, 1981). So while the conditions within the case study households can be considered as cool to cold or warm to hot when compared to conventional thermal comfort zones, the occupants still expressed overall satisfaction with the thermal conditions experienced in their homes. Both the thermal environments of the Melbourne houses and those of the Darwin houses are more closely coupled to the outdoor conditions than would be expected in houses of standard construction within the same locations or assumptions made in assessing the thermal performance (e.g. the Nationwide House Energy Rating Scheme). This presents the occupants of the case study dwellings with a greater opportunity for adaptation to the local climate.

The results presented in this chapter provide a detailed understanding of how occupants living in dwellings of earth construction in Melbourne and those living in naturally ventilated houses in Darwin operate their homes and how this contributes to household energy consumption and thermal performance. Key themes to emerge from the results are;

- Behavioural strategies were the main means used to achieve 'comfort' within the case study households, complimented by judicious use of heating and/or cooling appliances;
- Overall, the average energy consumption of the case study households was lower than average figures for the two locations, however the use of heating appliances in the Melbourne households contributed considerably to overall energy consumption;
- The occupants generally expressed satisfaction with the thermal performance of their dwelling, despite the thermal conditions within both cohorts of dwellings been largely outside of commonly referenced thermal comfort zones ; and
- An awareness of environmental issues was reflected in the design, construction and operation of the case study dwellings which was highly responsive to the local climate and context.

The extent to which the contextual factors explored within this chapter relate to the thermal comfort of these occupants will be presented in the next chapter.

Chapter 6. Results: thermal mavericks: comfort and preference

6.1 Introduction

This chapter presents the results of the longitudinal comfort survey of the 40 case study dwellings introduced in the previous chapter. The thermal comfort and preferences of the occupants within these homes are presented and compared with current international thermal comfort standards.

The aim of this chapter is to gauge whether or not the thermal preferences of occupants of the two distinct forms of housing studied can be adequately described by current thermal comfort models (ASHRAE55-2013, EN 15251: 2007). The impact of this is to demonstrate the appropriateness or otherwise of the application of these models in the assessment of the thermal performance of these dwellings.

Portions of this chapter were previously published and have been quoted directly from the following sources (Daniel et al, 2014b; 2015b). Permission has been granted by all co-authors to quote published material without rephrasing.

6.2 Overview of survey responses

The Melbourne households completed a total of 3644 comfort vote surveys (March 2013 – March 2014), while the Darwin households completed a total of 2535 surveys (June 2013 – May 2014). All comfort vote surveys had corresponding indoor climatic measurements.

The following section presents the analysis of the responses to each question. Note that Question 1 of the thermal comfort survey (see Appendix F) corresponds to the ASHRAE 7-point sensation scale (1= “Cold” to 7= “Hot”), Question 2 corresponds to the McIntyre 3-point preference scale (1= “Cooler”, 2= “No change” and 3= “Warmer”), while Question 3 corresponds to a 6-point comfort scale (1= “Very uncomfortable” to 6= “Very comfortable”. The votes cast in response to these scales will now be referred to as ‘Thermal Sensation Votes’ (TSV), ‘Thermal Preference Votes’ (TPV) and ‘Thermal Comfort Votes’ (TCV) respectively. In the analysis of responses, the thermal comfort surveys are often binned, either by indoor operative temperature or by the running weighted mean outdoor temperature. The bins are in 1K increments, for example, the 24°C bin represents temperatures from 23.5°C to 24.49°C. The basic descriptive statistics of the subjects, thermal comfort surveys and indoor environment are presented in Table 6.1, Table 6.2 and Table 6.3.

Table 6.1. Subject demographic information

Cohort	Number of subjects	Female	Male	Median age group	Average number of votes/person
Melbourne	38	23	15	60 +	96
Darwin	56	29	27	30-49	45

Table 6.2. Descriptive statistics of the comfort votes survey responses from the Melbourne cohort, note: the N value varies for some items due to missing responses

Variable	N	Minimum	Maximum	Mean	Std. deviation
Indoor operative temperature °C	3644	7.6	40.7	19.4	3.4
Air velocity (m/s)	-	-	-	-	-
Relative humidity %	3644	21%	80%	54%	7%
Outdoor running mean temperature °C	3644	3.9	31.2	13.4	4.0
Thermal sensation votes	3640	1	7	4.19	1.194
Clothing insulation (clo)	3642	0.35	1.2	0.95	0.27
Metabolic rate (met)	3640	0.8	2.0	1.3	0.4

Table 6.3. Descriptive statistics of the comfort votes survey responses from the Darwin cohort, note: the N value varies for some items due to missing responses

Variable	N	Minimum	Maximum	Mean	Std. deviation
Indoor operative temperature °C	2535	16.3	38.3	28.6	2.8
Air velocity (m/s)	1352	0.00	2.01	0.23	0.12
Relative humidity %	2535	16%	98%	68%	16%
Outdoor running mean temperature °C	2535	19.2	30.5	27.2	1.7
Thermal sensation votes	2528	1	7	4.36	1.074
Clothing insulation (clo)	2531	0.04	1.0	0.33	0.20
Metabolic rate (met)	2529	0.8	2.0	1.3	0.4

6.2.1 Sample size bias

Participants were encouraged to complete the comfort vote survey on a daily basis; however the regularity of which subjects responded varied greatly across the households. As such, the data from both cohorts were examined for potential bias from those that completed significantly more surveys. The mean of the thermal sensation votes (TSV) from each household was plotted against the overall mean TSV and the overall standard deviation of the cohort; see Figure 6.1 and Figure 6.2. All of the household TSV means fell within the overall standard deviation of 0.968 for the Melbourne cohort and 1.034 for the Darwin cohort. Households 1 and 5 were at the edge of the overall standard deviation, perhaps indicating greater and lesser sensitivity to cold conditions respectively. The distribution of the household TSV means for the Darwin cohort is much more uniform, likely due to less variation in the climate and conditions experienced.

The mean indoor temperature when occupants voted 3= “Slightly cool”, 4= “Neutral” or 5= “Slightly warm” for each households was similarly plotted against the cohorts’ neutral temperature, and the overall standard deviation (SD=2.6 for the Melbourne cohort and SD=2.4 for the Darwin cohort), see Figure 6.3 and Figure 6.4. The mean temperatures for one household in each cohort fell outside of the overall standard deviation; households 9 and 28. At the time that votes were recorded in household 9, the indoor environment was often mechanically heated to much higher temperatures than other households in that cohort. Household 28 was one of the few low-set houses within the Darwin cohort with minimal solid external walls (predominantly flyscreens) and no roof cavity, potentially causing warmer conditions than the rest of the cohort and resulting in greater adaption to the local climate.

This investigation indicates that the number of votes completed by each household did not noticeably bias the sample; rather, deviation was due to more extreme indoor environmental conditions. All recorded votes will be used in the subsequent analysis.

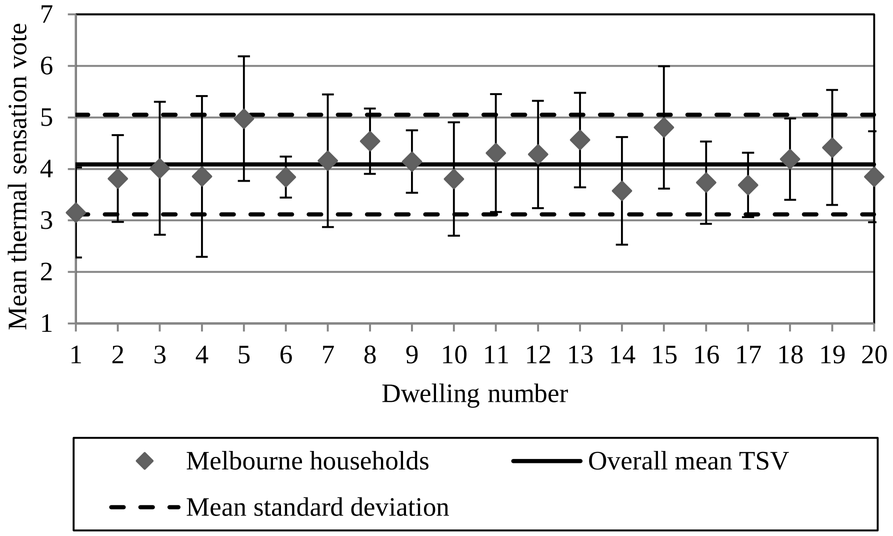

Figure 6.1. Mean and standard deviation of the thermal sensation votes of each household in Melbourne cohort

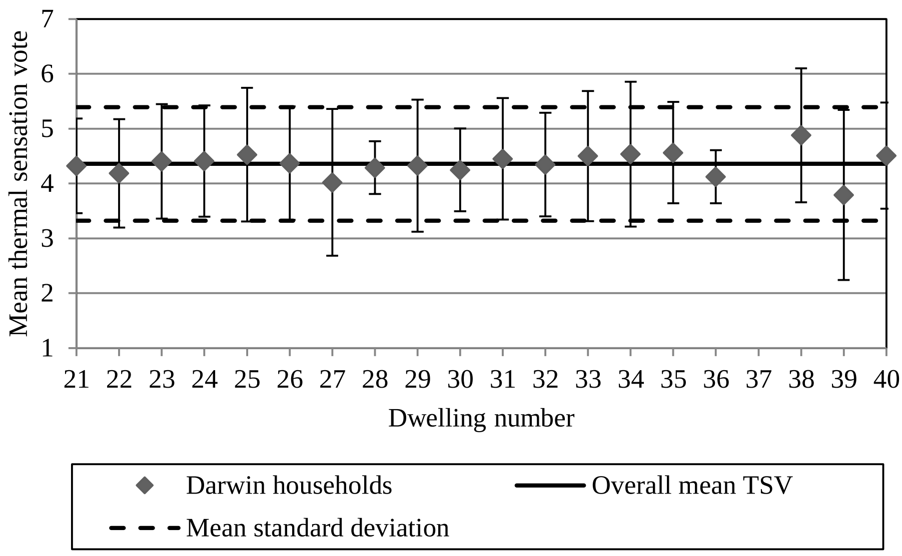

Figure 6.2. Mean and standard deviation of the thermal sensation votes of each household in Darwin cohort

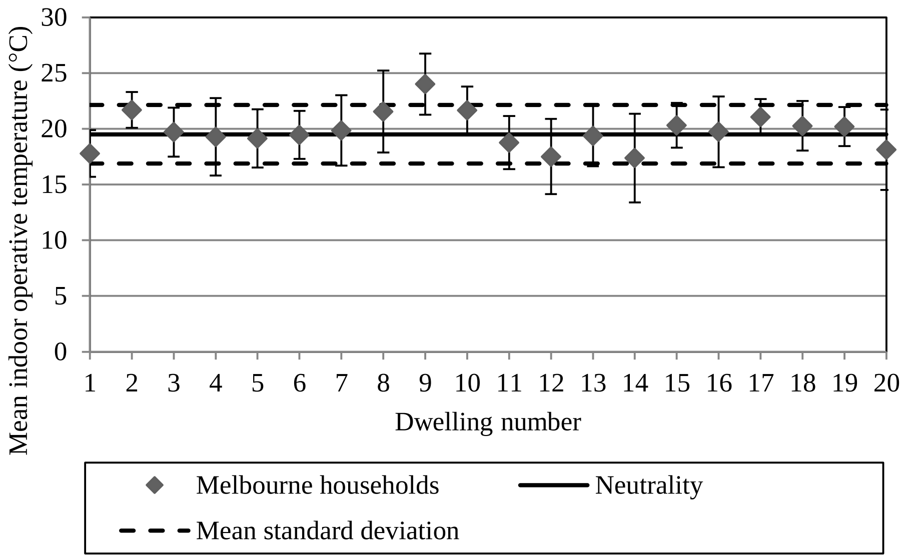

Figure 6.3. Mean and standard deviation of globe temperature when subjects vote 3, 4 or 5 on the thermal sensation scale for each household in Melbourne cohort compared to neutral temperature calculated from the regression equation in Figure 6.6

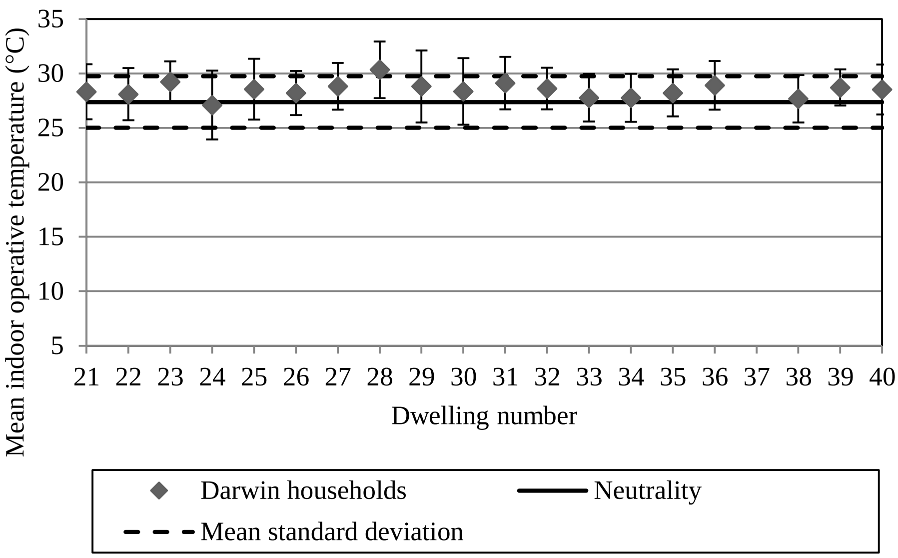

Figure 6.4. Mean and standard deviation of globe temperature when subjects vote 3, 4 or 5 on the thermal sensation scale for each household in Darwin cohort compared to neutral temperature calculated from the regression equation in Figure 6.6

6.2.2 Thermal sensation votes

Of the 3640 TSV responses collected throughout the monitoring period, 75.4% of the Melbourne cohort gave answers at 3= “Slightly cool”, 4= “Neutral” or 5= “Slightly warm” on the 7-point ASHRAE sensation scale, indicating “neutrality” (de Dear & Brager, 1998). The Darwin cohort gave 81.6% of responses within this bracket. For both cohorts, responses were weighted towards 5= “Slightly warm” and 6= “Warm”; the mean TSV for the Melbourne cohort was 4.19 (SD = 1.194), whilst the mean response for the Darwin cohort was 4.36 (SD = 1.074) (see Figure 6.5).

The mean TSV responses from both cohorts achieved high correlation with indoor operative temperature when binned in 1K increments; with R^2=0.92 (p=<0.05) for Melbourne and R^2=0.91(p=<0.05) for Darwin (see Figure 6.6). The temperature for each cohort corresponding to a mean TSV of 4= “Neutral” based on the regression equations from Figure 6.6 are 19.5 °C for the Melbourne cohort and 27.4 °C for the Darwin cohort. Figure 6.7 and Figure 6.8 demonstrate the distribution of TSV responses across the indoor operative temperatures binned in 1K increments.

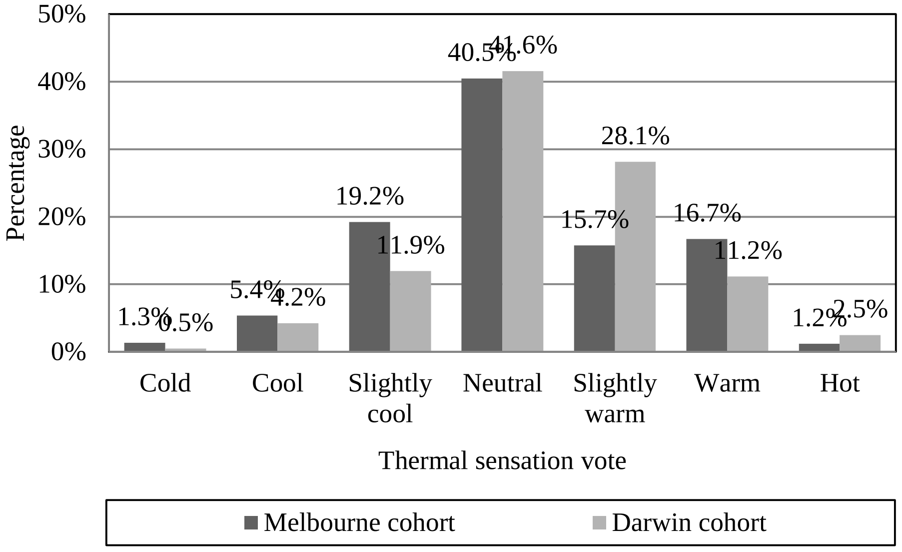

Figure 6.5. Frequency of TSV responses for Melbourne and Darwin cohorts

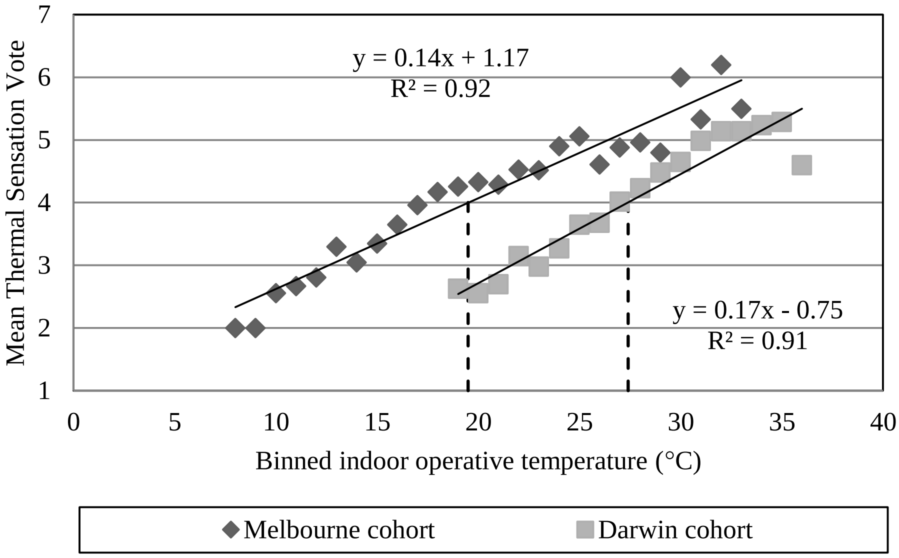

Figure 6.6. Mean TSV of Melbourne and Darwin cohorts at temperatures binned in 1k increments

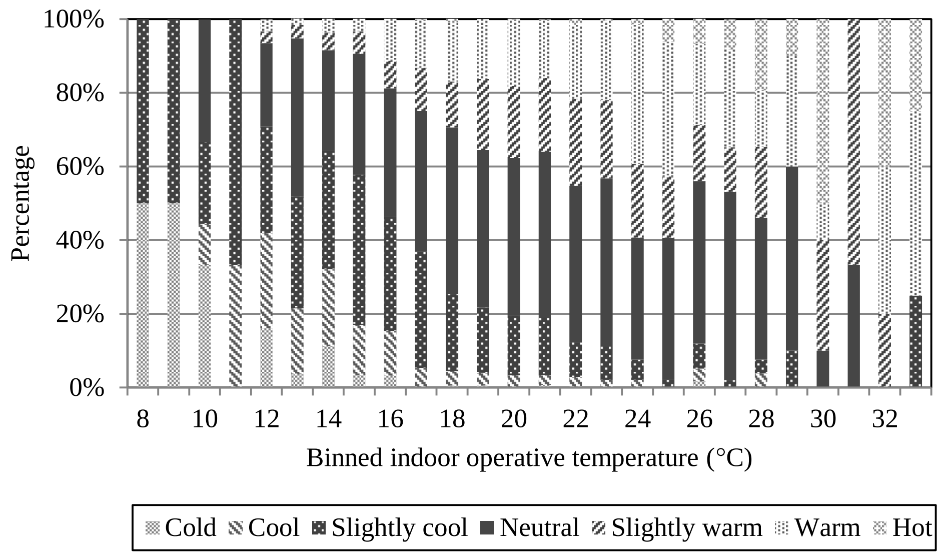

Figure 6.7. Percentage of TSV responses binned by indoor operative temperature for the Melbourne cohort

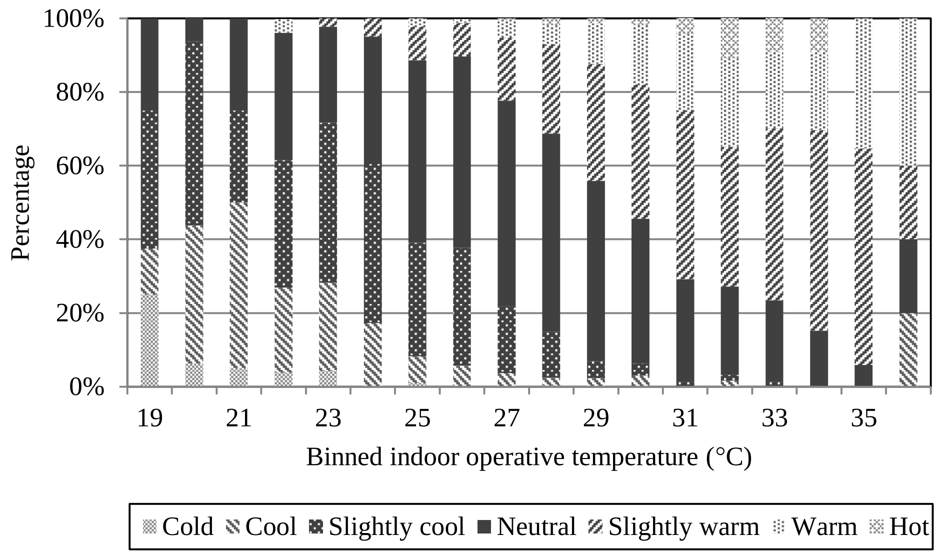

Figure 6.8. Percentage of TSV responses binned by indoor operative temperature for the Darwin cohort

6.2.3 Thermal preference votes

In response to the Thermal preference vote (TPV), the Melbourne cohort nominated 2= “No change” for 76.6% of the votes, and when change was desired it was largely to be 3= “Warmer” (18.6% of the votes). Conversely, the Darwin cohort nominated a similar percentage of votes as 2= “No change” (74.6%); however their preference for change was to be 1= “Cooler” (21.7%), (see Figure 6.9). The mean TPV for the Melbourne cohort was 2.16 (SD = 0.441), whilst the mean response for the Darwin cohort was 1.80 (SD = 0.455). The mean TPV of both cohorts again demonstrated a high correlation, this time negative, with indoor operative temperature when binned in 1K increments; with R^2=0.91 (p=<0.05) for the Melbourne data and R^2=0.95 (p=<0.05) Darwin (see Figure 6.10).

In order to determine the temperature at which the cohorts least desired change, the ‘want change’ preference votes, 1= “Cooler” and 3= “Warmer”, were aggregated so 1= ‘no change’ and 2= ‘change’. The mean of these two numbers was then plotted against the indoor operative temperature binned in 1K increments. This identifies the transition point in which the subjects desire change (see Figure 6.11). The minimum points of the two data series in Figure 6.11 corresponded to 21.7 °C for the Melbourne cohort and 25.3 °C for the Darwin cohort.

Figure 6.12 and Figure 6.13 demonstrate the distribution of TPV responses across the indoor operative temperatures binned in 1K increments.

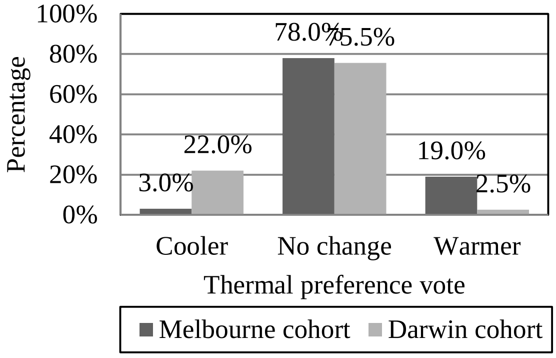

Figure 6.9. Frequency of TPV responses for Melbourne and Darwin cohorts

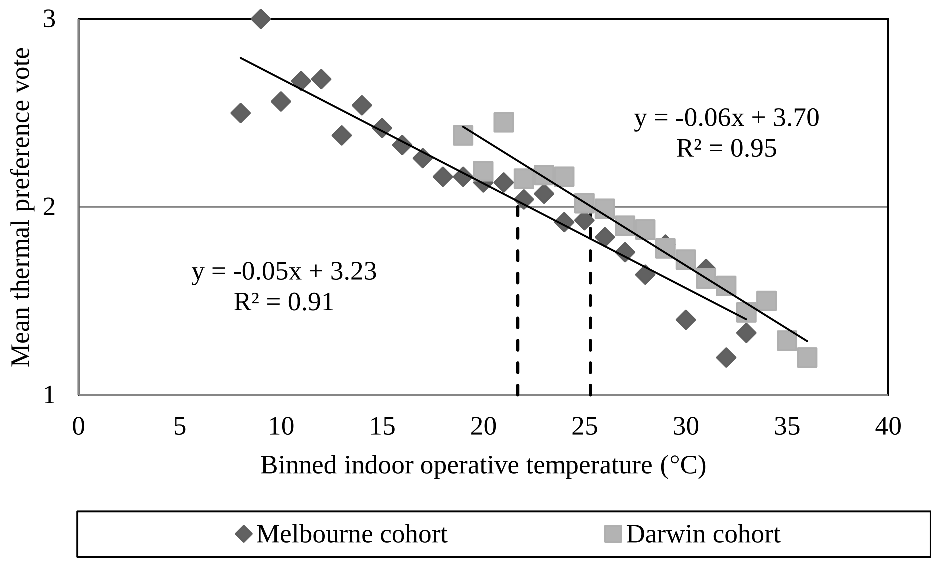

Figure 6.10. Mean TPV of Melbourne and Darwin cohorts at temperatures binned in 1k increments, where 1= "Cooler", 2= "No change" and 3= "Warmer"

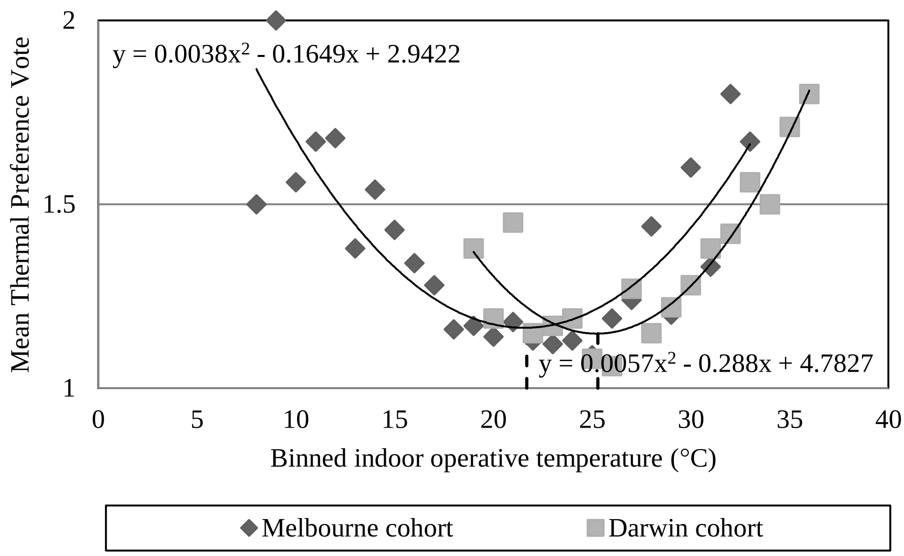

Figure 6.11. Modified mean TPV of Melbourne and Darwin cohorts at temperatures binned in 1k increments, where 1= "No change" and 2= "Change"

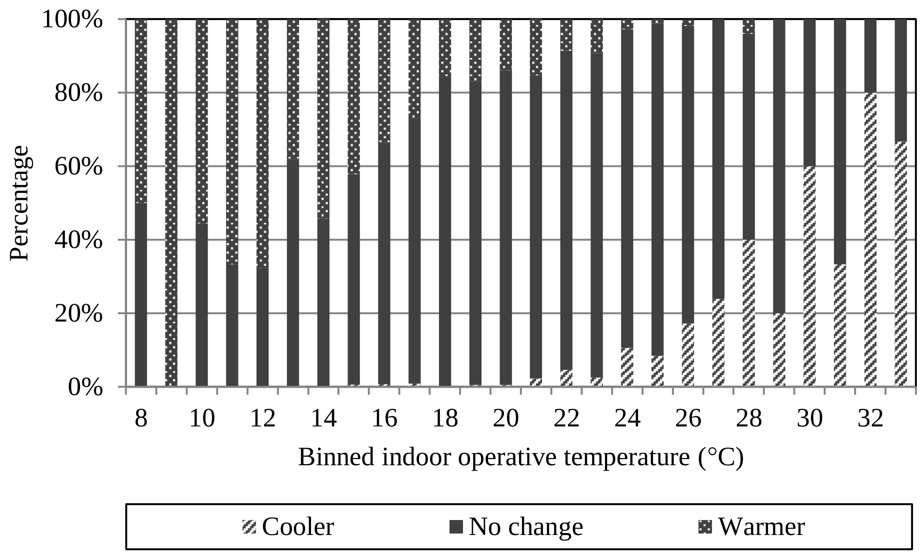

Figure 6.12. Percentage of TPV responses binned by indoor operative temperature for the Melbourne cohort

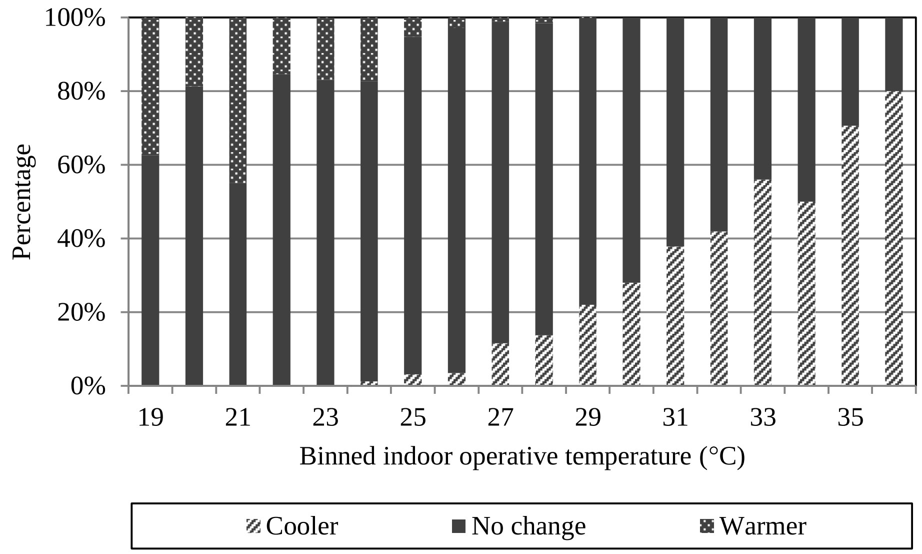

Figure 6.13. Percentage of TPV responses binned by indoor operative temperature for the Darwin cohort

6.2.4 Thermal comfort votes

Responses to the Thermal comfort vote (TCV) were largely positive; 78.2% of the votes recorded by the Melbourne cohort and 77.4% of the votes recorded by the Darwin cohort indicated a ‘comfort’ response, voting either 4= “Slightly comfortable”, 5= “Comfortable” or 6= “Very comfortable” on a 6-point scale (see Figure 6.14). Plotting the mean TCV against binned indoor operative temperature demonstrated a non-linear relationship. When a polynomial trend line was fitted to the data, an R^2=0.78 (p=0.07) for the Melbourne cohort and R^2=0.79 (p=<0.05) for Darwin were achieved (see Figure 6.15). The trend towards discomfort occurring at cooler and warmer temperatures is also reflected in Figure 6.16 and Figure 6.17. The temperature corresponding to the highest mean thermal comfort vote response based on the equations in Figure 6.15 is 22.1 °C for the Melbourne cohort and 24.8 °C for the Darwin cohort.

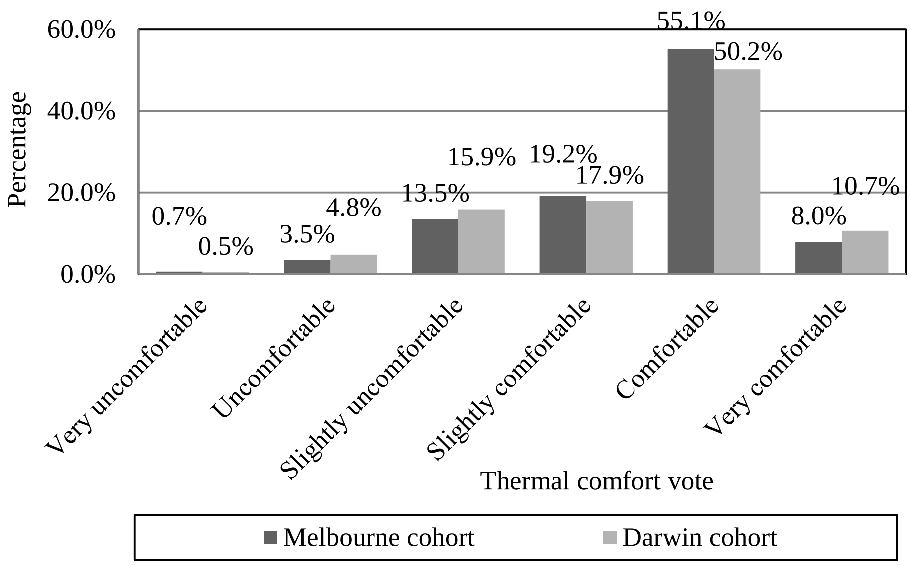

Figure 6.14. Frequency of TCV responses for Melbourne and Darwin cohorts

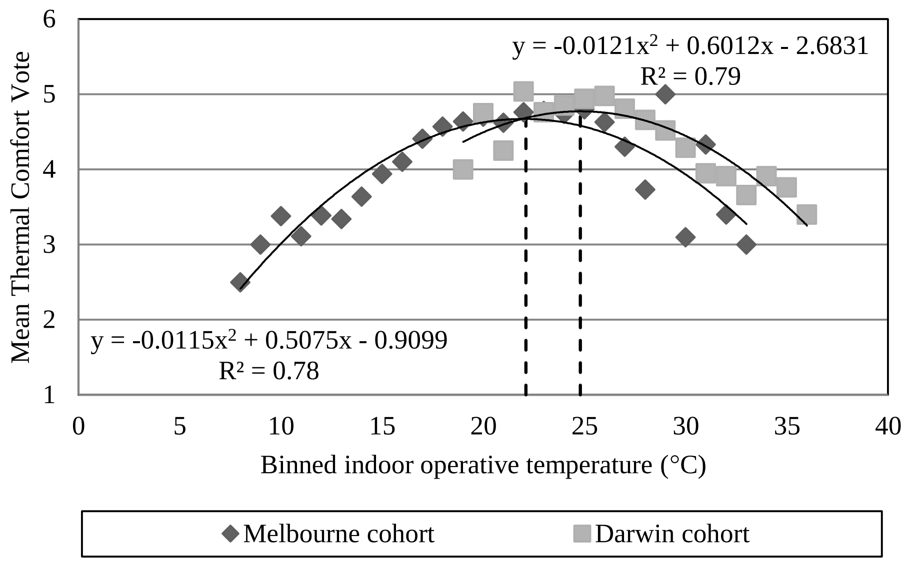

Figure 6.15. Mean TCV of Melbourne and Darwin cohorts at temperatures binned in 1k increments

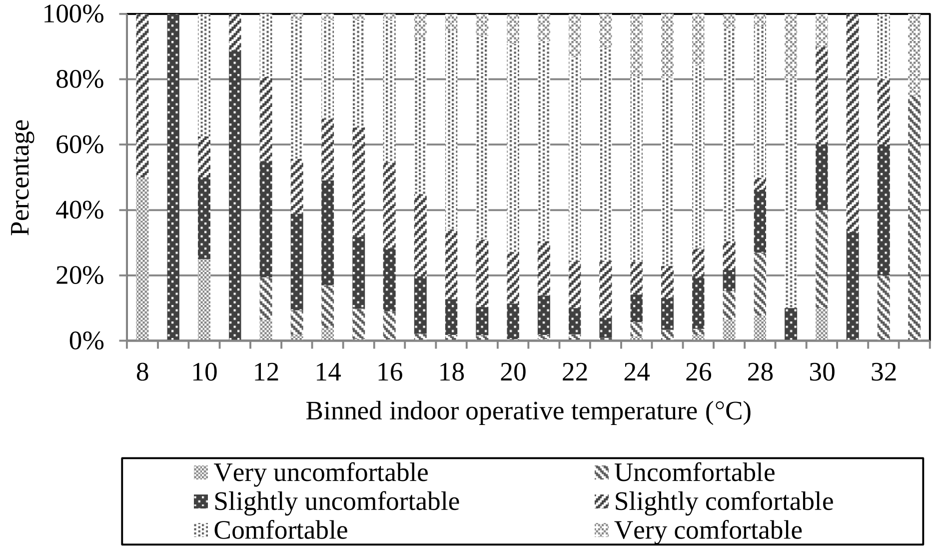

Figure 6.16. Percentage of TCV responses binned by indoor operative temperature for the Melbourne cohort

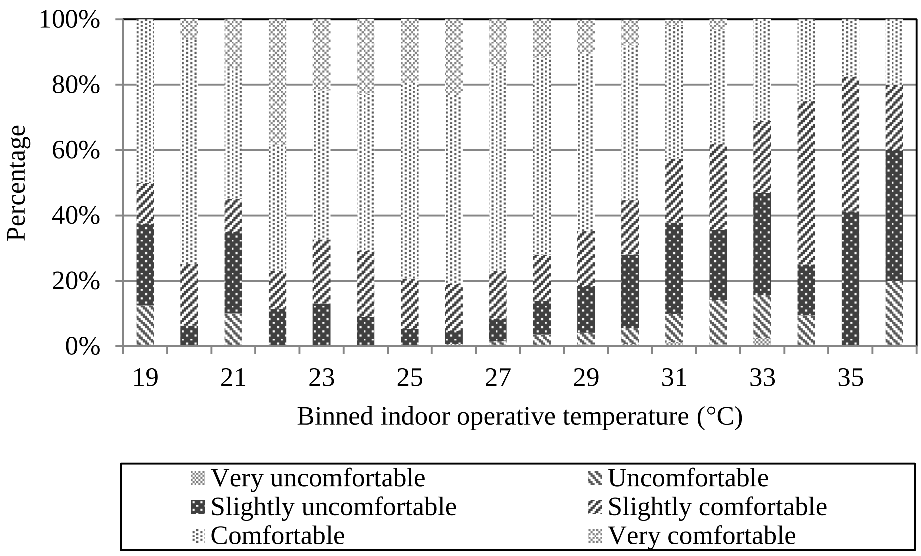

Figure 6.17. Percentage of TCV responses binned by indoor operative temperature for the Darwin cohort

6.2.5 Clothing level

The clothing response options differed between the surveys given to the two cohorts reflecting the type of clothing worn in the two locations; the survey used in the Melbourne households depicted light (0.35 CLO), medium (0.72 CLO), heavy (1.0 CLO) and very heavy (1.2 CLO) ensembles, while the survey given to the Darwin cohort depicted very light (0.04 CLO) light (0.35 CLO), medium (0.72 CLO) and heavy (1.0 CLO) ensembles (see Appendix F). The Melbourne cohort nominated the very heavy ensemble as the most reflective of their dress in 41.6% of the votes, while the Darwin cohort most commonly nominated the light clothing ensemble as representative of their dress (66.1%), (see Figure 6.18). A relationship between mean clothing level and binned indoor operative temperature is apparent with R^2=0.89 (p=<0.05) for the Melbourne cohort and R^2=0.86 (p=<0.05) for the Darwin cohort (see Figure 6.19). Both models exhibit variations that are likely due to a seasonal affect (see Figure 6.20 and Figure 6.21).

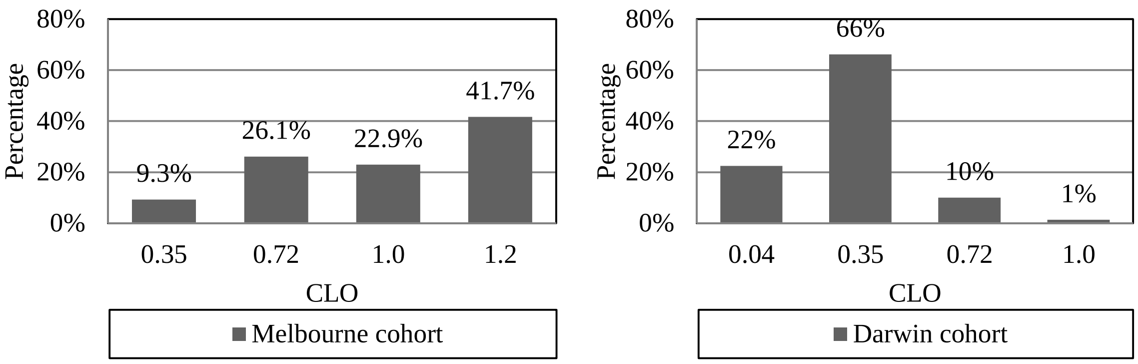

Figure 6.18. Frequency of clothing level response for the Melbourne and Darwin cohorts

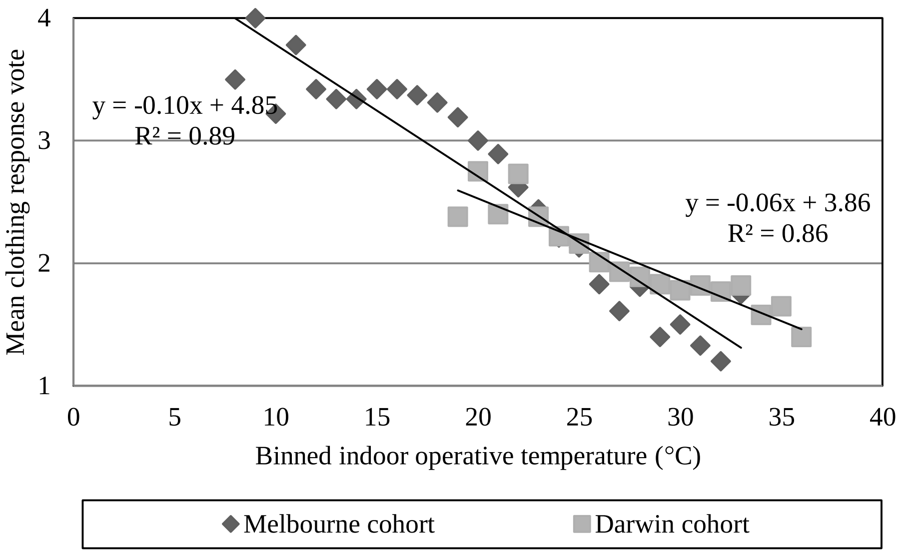

Figure 6.19. Mean clothing level response vote of Melbourne and Darwin cohorts at temperatures binned in 1k increments

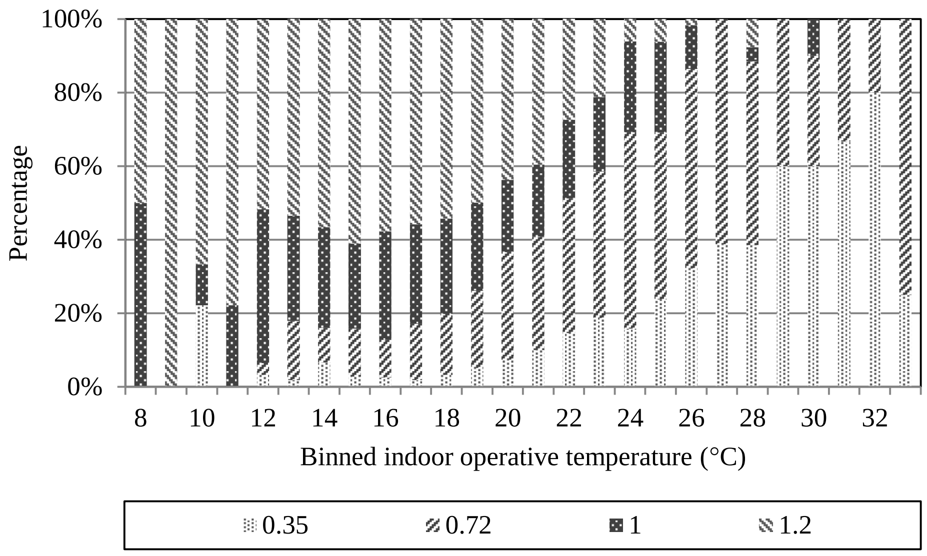

Figure 6.20. Percentage of clothing level binned by indoor operative temperature for the Melbourne cohort

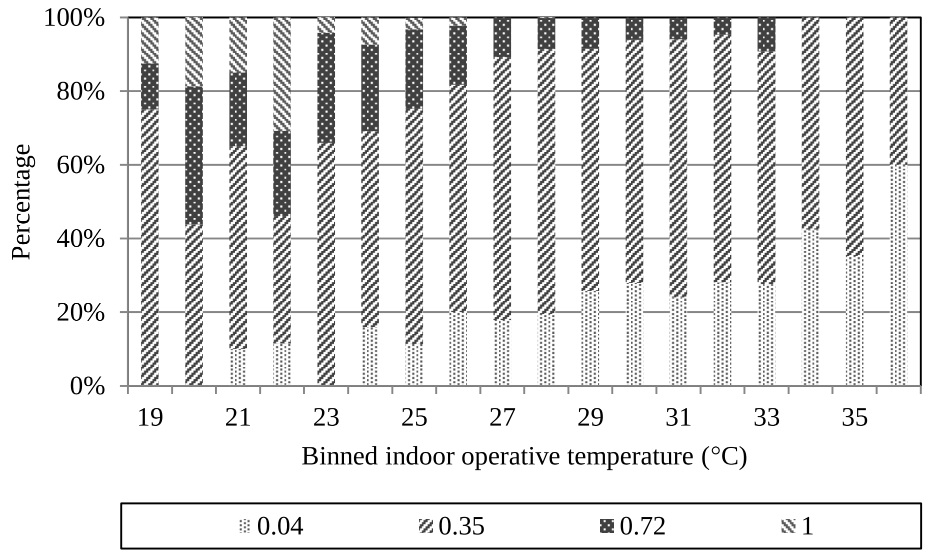

Figure 6.21. Percentage of clothing level binned by indoor operative temperature for the Darwin cohort

6.2.6 Activity level

For both cohorts the most commonly reported activity type was 'sitting, relaxed, reading, watching TV etc', corresponding to an estimated metabolic rate of 1.0 (see Figure 6.22). The reported activity levels of the Melbourne cohort appear to have a slight relationship to the indoor temperature, with activity decreasing as the temperatures increase; this may reflect a strategy to deal with warmer temperatures (see Figure 6.23). The lack of strong relationship (R^2=0.45) may indicate that in residential settings, occupants activities levels are primarily determined by necessary daily tasks, etc. as opposed to specifically responding to current thermal conditions. This is reflected in the reported activity levels of the Darwin cohort to a much greater extent, with a R^2 = 0.04, demonstrating negligible relationship between activity level or metabolic rate and temperature. Similarly, these patterns are also reflected in Figure 6.24 and Figure 6.25.

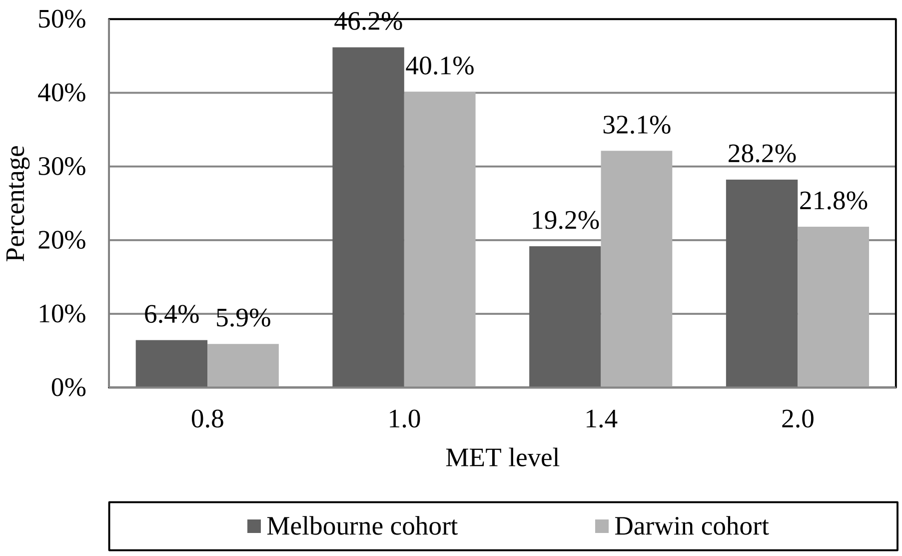

Figure 6.22. Frequency of metabolic rate response for Melbourne and Darwin cohorts

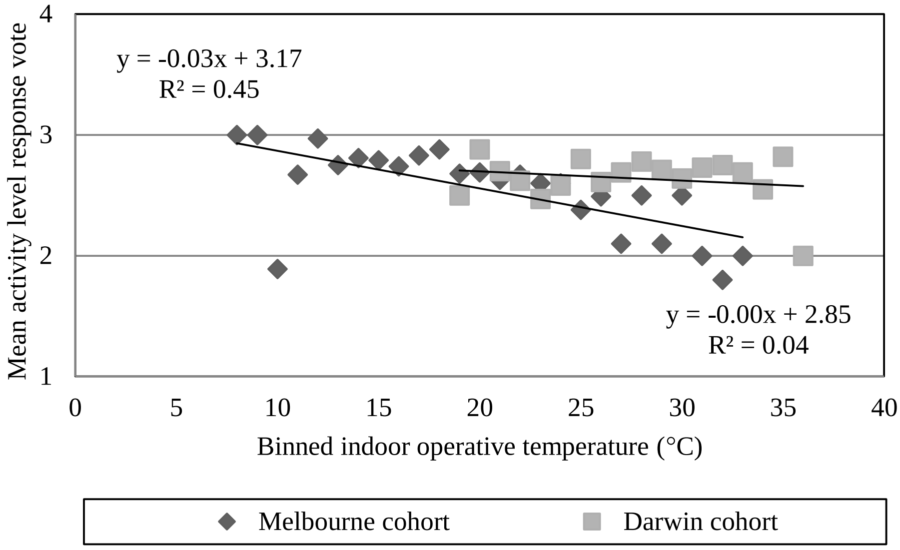

Figure 6.23. Mean activity level response vote of Melbourne and Darwin cohorts at temperatures binned in 1k increments

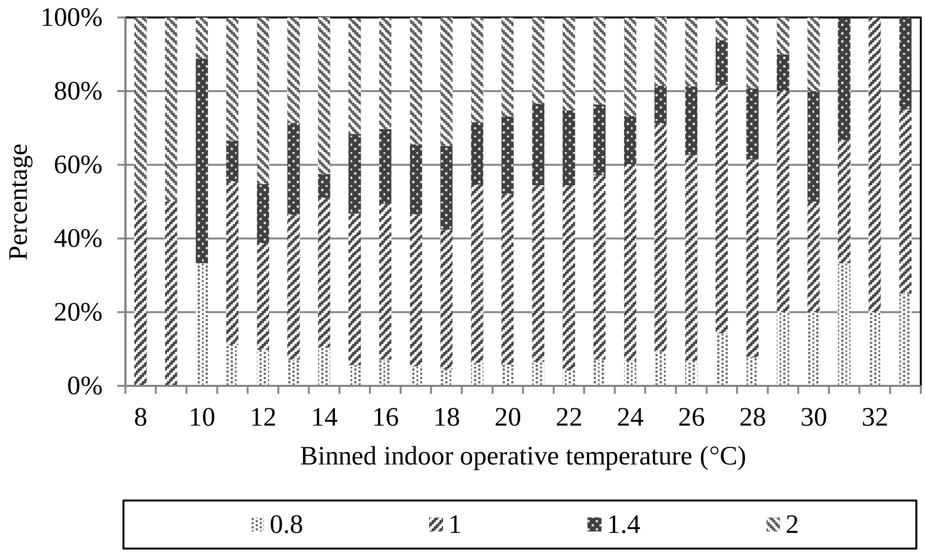

Figure 6.24. Percentage activity level binned by indoor operative temperature for the Melbourne cohort

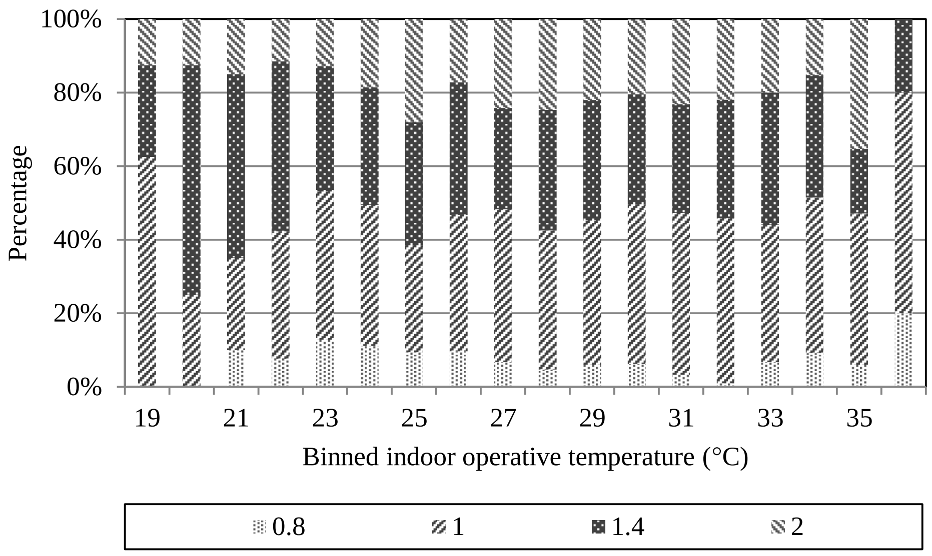

Figure 6.25. Percentage activity level binned by indoor operative temperature for the Darwin cohort

6.2.7 Window, fan and heating and cooling appliance operation

This section examines the use of windows, fans and appliances for heating and cooling within the households. At the time of the majority of the votes recorded by the Melbourne cohort windows (or doors) were not being used for ventilation (77.1%), however intuitively, this is reversed for the Darwin cohort with windows open for 97.6% of the time that votes were recorded (see Figure 6.26). There appears to be a slight relationship between window operation and indoor operative temperature in the Melbourne households (see Figure 6.27), however there is a much greater relationship when window operation is alternatively plotted against the running weighted 7-day outdoor mean air temperature (see Figure 6.28). This indicates that thermal motivation for window operation is much more dependent on outdoor temperature than indoor temperature. There is no indication that temperature influenced window operation within the Darwin households, with the proportion of windows reported open or closed relatively constant despite the indoor or outdoor temperature (see Figure 6.29). Due to the high proportion of time that the Darwin households are naturally ventilated, coupling the indoor temperature to the outdoor temperature, there appears little use examining window operation in comparison with outdoor temperature.

Conversely, there appears to be a strong relationship between reported fan use and indoor operative temperature in both cohorts (see Figure 6.30 and Figure 6.31). The Melbourne cohort only reported using a fan in small percentage of surveys (5.2%); however, the relationship between use and temperature appears remarkably similar to that of the Darwin cohorts who reported a significantly higher percentage of fan use (49.8%), (see Figure 6.26). Over 90% of fan use occurred at or above the 24°C indoor operative temperature bin for the Melbourne cohort, and at or above the 27°C indoor operative temperature bin for the Darwin cohort.

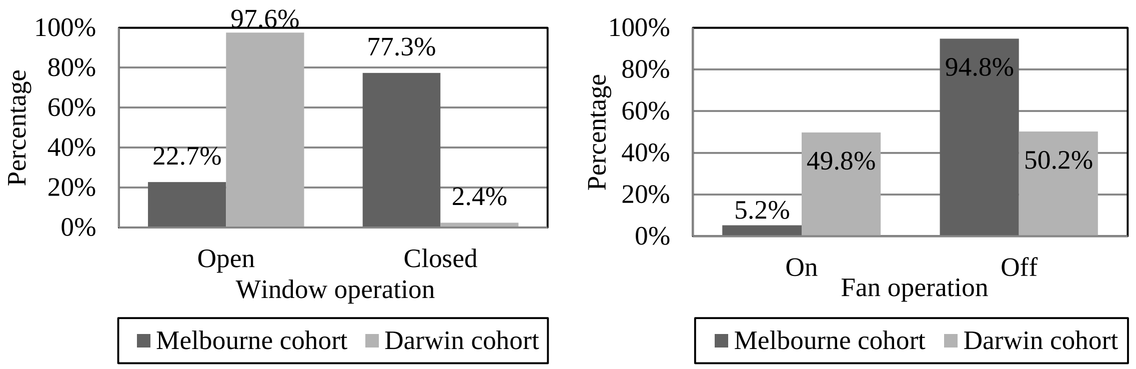

Figure 6.26. Frequency of window and fan operation for Melbourne and Darwin cohorts

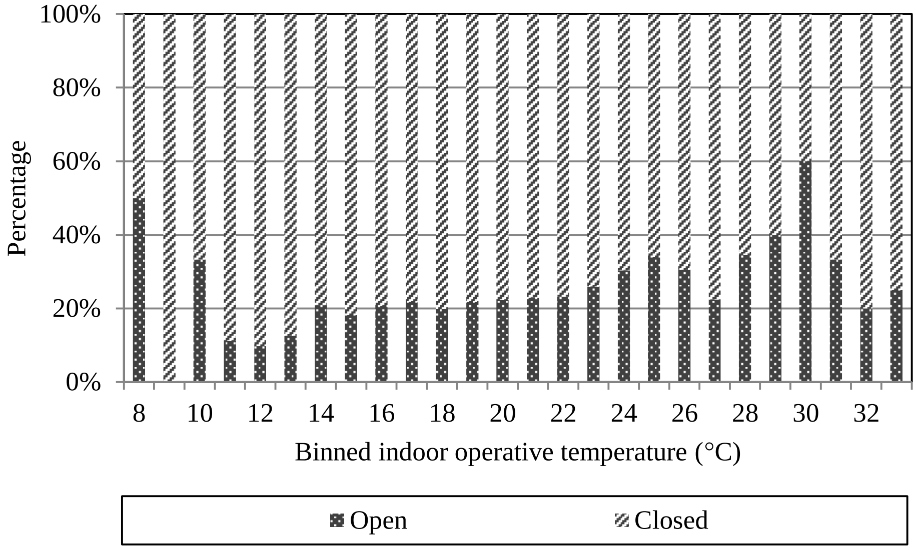

Figure 6.27. Percentage window operation binned by indoor operative temperature for the Melbourne cohort

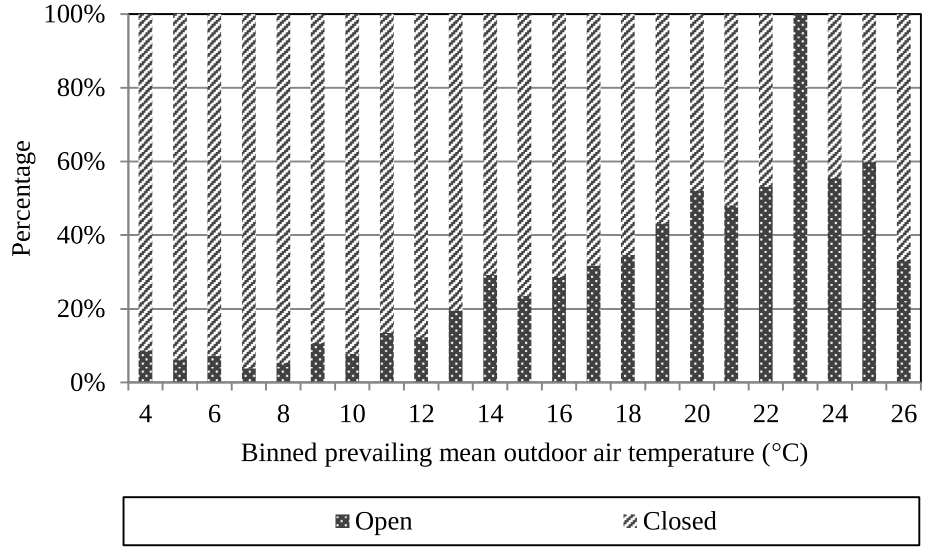

Figure 6.28. Percentage window operation binned by running weighted mean outdoor air temperature for the Melbourne cohort

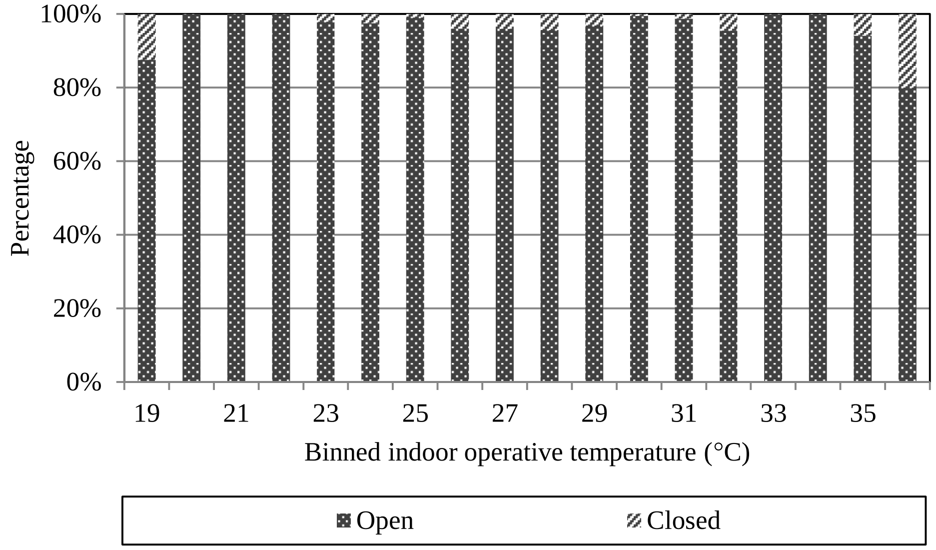

Figure 6.29. Percentage window operation binned by indoor operative temperature for the Darwin cohort

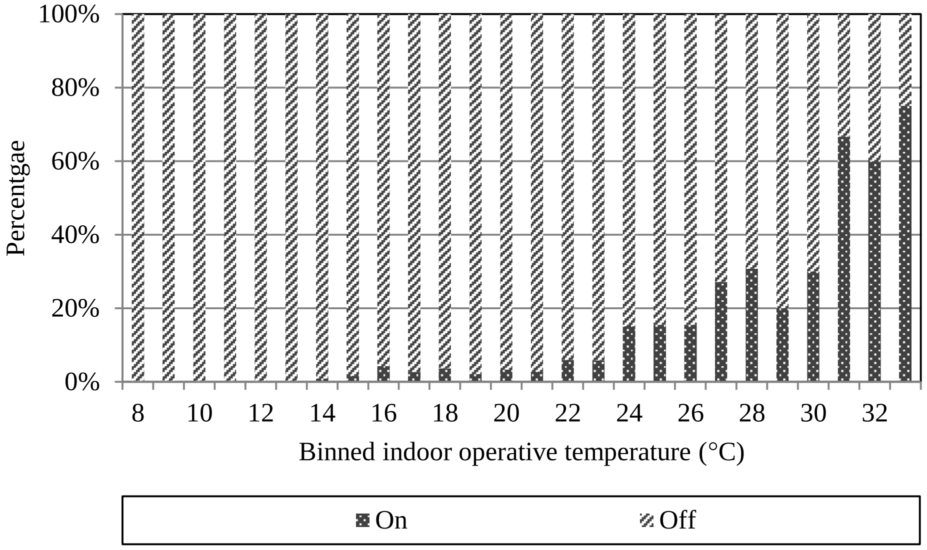

Figure 6.30. Percentage fan operation binned by indoor operative temperature for the Melbourne cohort

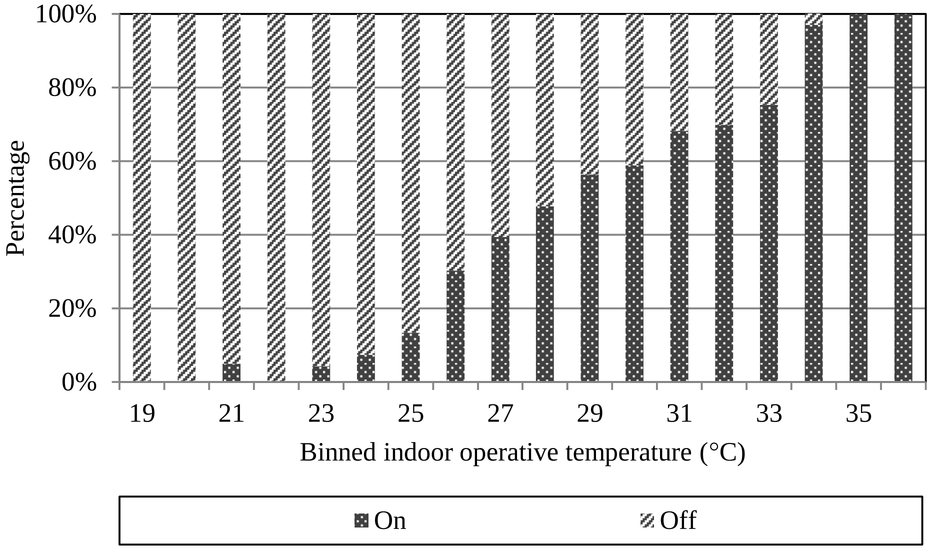

Figure 6.31. Percentage fan operation binned by indoor operative temperature for the Darwin cohort

In examining reported use of heating or cooling appliances at the times that votes were recorded in conjunction with temperature, comparison with indoor temperature appears to indicate a temperature range to which the spaces are conditioned, while comparison with outdoor temperature indicates when the space heating or cooling is likely to be used. Figure 6.33 shows the range of temperatures that the Melbourne cohort heat or cool their houses to is from the 11°C to 30°C bins, with the bulk of the distribution between the 19°C to 29°C bins. If considered in conjunction with the calculated neutral temperature for this cohort (see section 6.4.1), this temperature range supports their preference for neutral or warmer sensation. A clear relationship is apparent when the Melbourne cohort's appliance use is binned by the running weighted 7-day mean outdoor air temperature (see Figure 6.34). The proportion of appliance operation at the time of voting decreases from 65.2% at the 4°C bin to 3.8% at the 21°C bin, suggesting appliance use is primarily for heating rather than cooling. The appliance use at the 22°C and 24°C bins may be indicative of limited cooling appliance use.

Due to the very small proportion of votes (0.08%) recorded whilst cooling appliances were operating within the Darwin households it is unlikely any relationship can be found between temperature, whether indoor, outdoor or prevailing outdoor, and cooling appliance use (see Figure 6.32 and Figure 6.35).

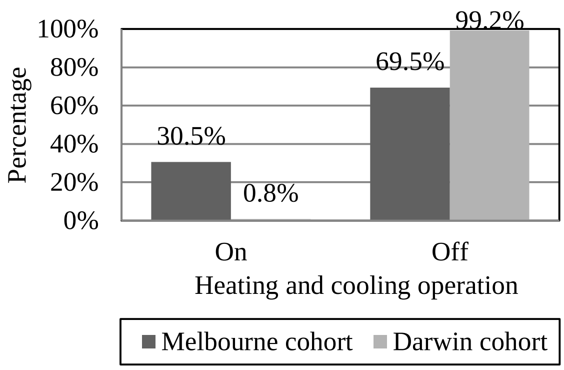

Figure 6.32. Frequency of heating or cooling appliance operation for Melbourne and Darwin cohorts

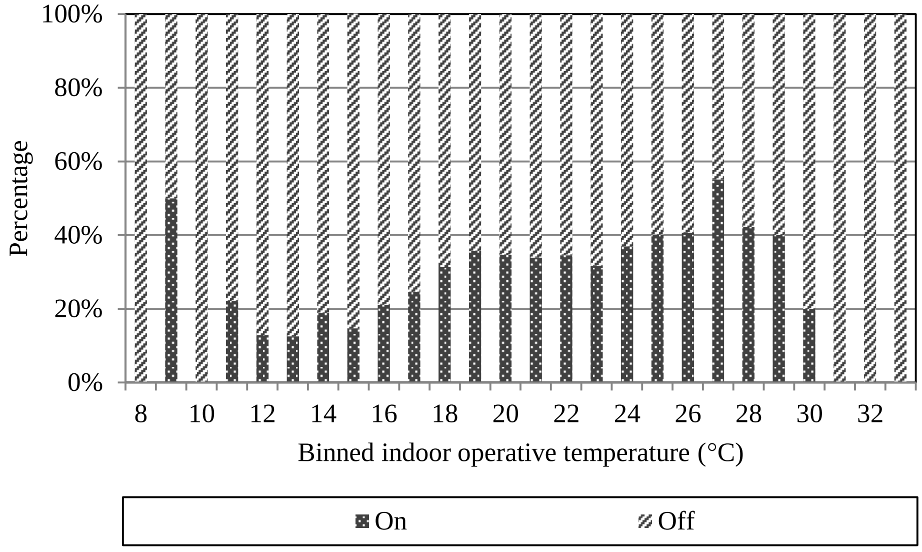

Figure 6.33. Percentage heating or cooling appliance operation binned by indoor operative temperature for the Melbourne cohort

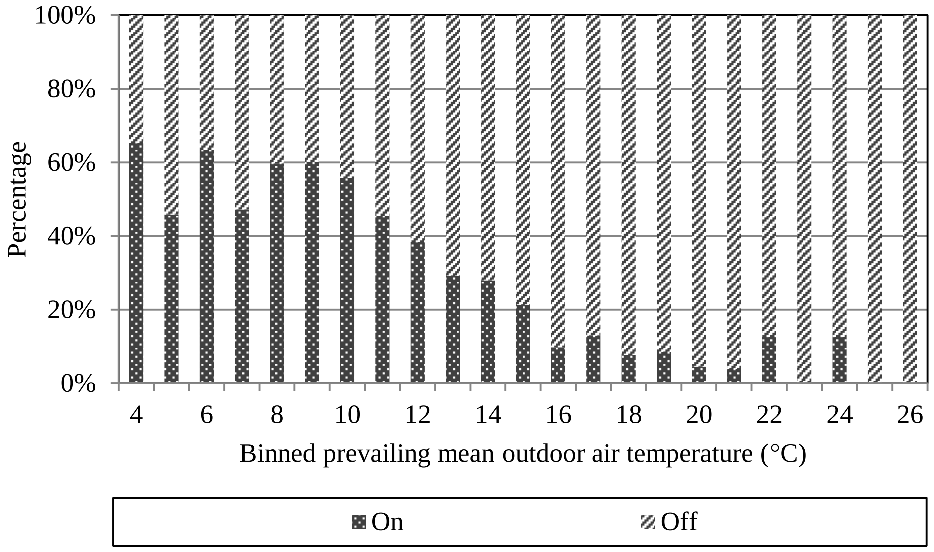

Figure 6.34. Percentage heating or cooling appliance operation binned by running weighted mean outdoor air temperature for the Melbourne cohort

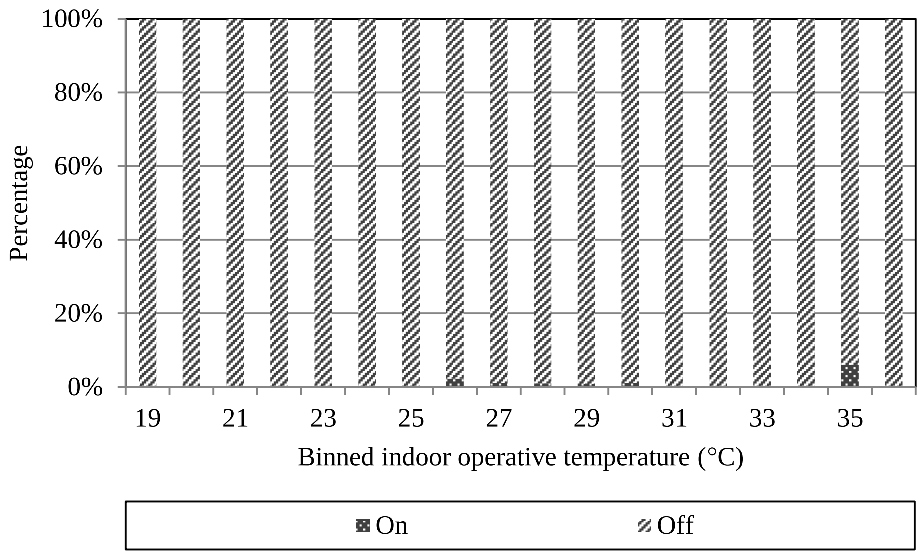

Figure 6.35. Percentage cooling appliance operation binned by indoor operative temperature for the Darwin cohort

6.2.8 Discomfort

Occupants were given the option to indicate a source of discomfort, if not directly related to temperature i.e. draft, stuffiness, dryness or humidity, at the end of the comfort survey. Only 4.2% of the surveys from the Melbourne cohort nominated one of these responses, while a larger proportion (20.6%) from the Darwin cohort nominated a response (see Figure 6.36). Of that proportion the highest cause of discomfort was due to humidity for the Darwin cohort. The results for this part of the survey are likely to reflect the climate in which the two cohorts of dwellings are located, indicating that temperature is the most influential environmental factor on comfort in the Melbourne households, while humidity (and air movement due to convection) is a considerable factor for comfort in the Darwin households.

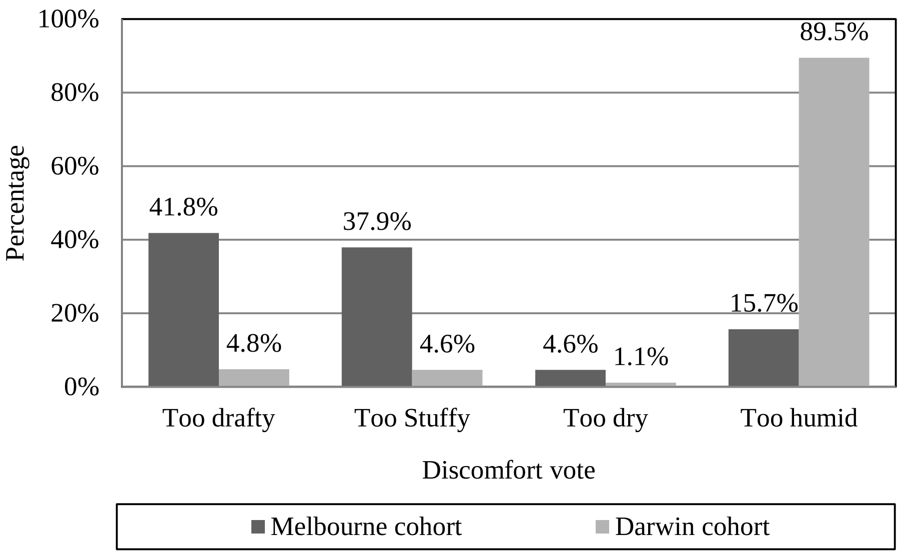

Figure 6.36. Frequency of discomfort for Melbourne and Darwin cohorts

6.3 Cross tabulation

Cross-tabulation of the sensation and preference votes of the Melbourne cohort show that the most common vote was “Neutral” with a preference for “No change” (38.6%), (see Figure 6.37). The subsequent highest percentages of votes recorded by the Melbourne cohort were for “Slightly warm”, “Warm” and “No change” indicating a preference for warmer sensation (29.0%). A proportionally high percentage of votes at “Slightly cool” and “Warmer” (10.1%) similarly support the preference for neutral or warmer sensation.

The cross-tabulation of the sensation and preference votes from Darwin reveal that “Neutral” and “No change” was again the most regularly recorded vote (40.8%), with high percentages also recorded at “Slight cool” (10.9%) and “Slightly warm” (18.4) and “No change” (see Figure 6.38). Noticeable is the percentage of votes recorded at “Slightly warm” with a preference to be “Cooler” (9.6%) when observed in conjunction with the percentage of votes recorded at “Slightly warm” and “No change”; the distribution of votes possibly signifies the limit of preferred conditions.

The cross-tabulation of the sensation and comfort votes from the Melbourne cohort indicate that the highest percentages of comfortable votes are recorded at “neutral” (39.1%), “Slightly warm” (14.6%) and “Warm” (15.3%), again supporting the occupants’ preference for warmer than neutral sensation; similarly echoed by the percentage of “Slightly cool” votes attracting a “Slightly uncomfortable” response (7.6%), (see Figure 6.39).

The sensation and comfort votes recorded by the Darwin cohort were predominantly at "Slightly cool" (11.3%), "Neutral" (40.7%), "Slightly warm" (20.3%) and comfortable. The votes show that the occupants rarely report to being uncomfortable when "Slightly cool", "Cool" and "Cold", rather, discomfort is recorded at "Slightly warm", "Warm" and "Hot", likely also due to humidity levels at these times (see Figure 6.40).

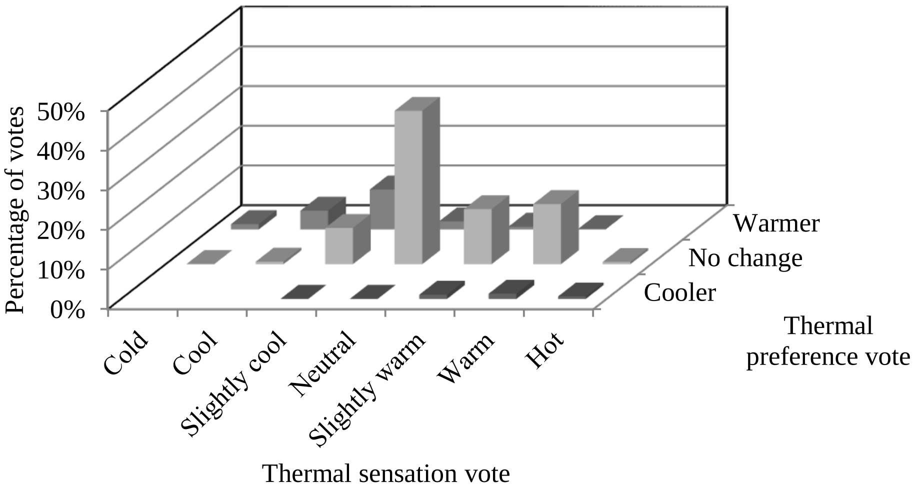

Figure 6.37. Cross tabulation of TSV and TPV of Melbourne cohort

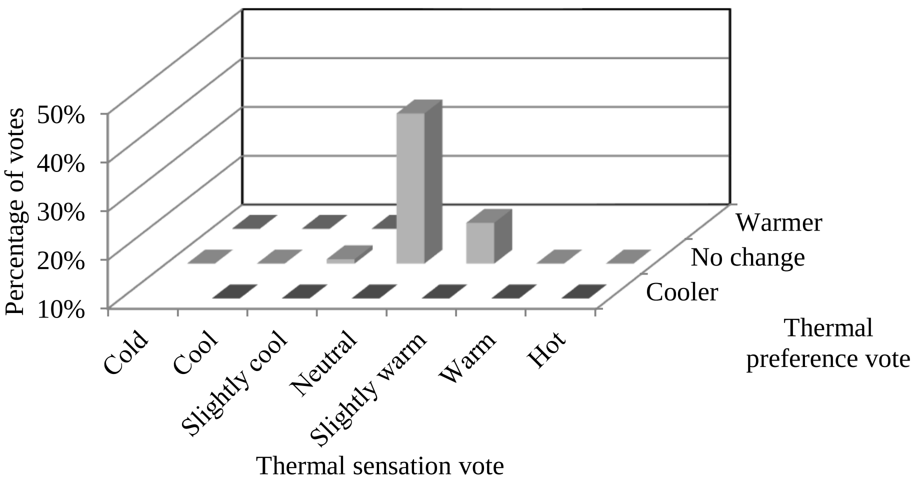

Figure 6.38. Cross tabulation of TSV and TPV of Darwin cohort

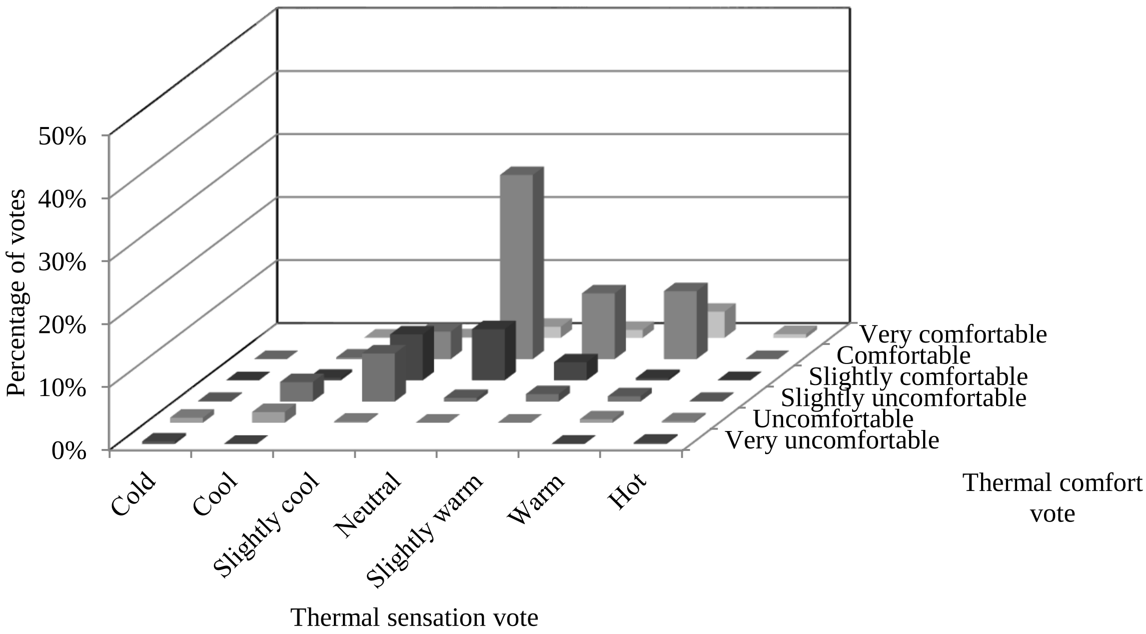

Figure 6.39. Cross tabulation of TSV and TCV of Melbourne cohort

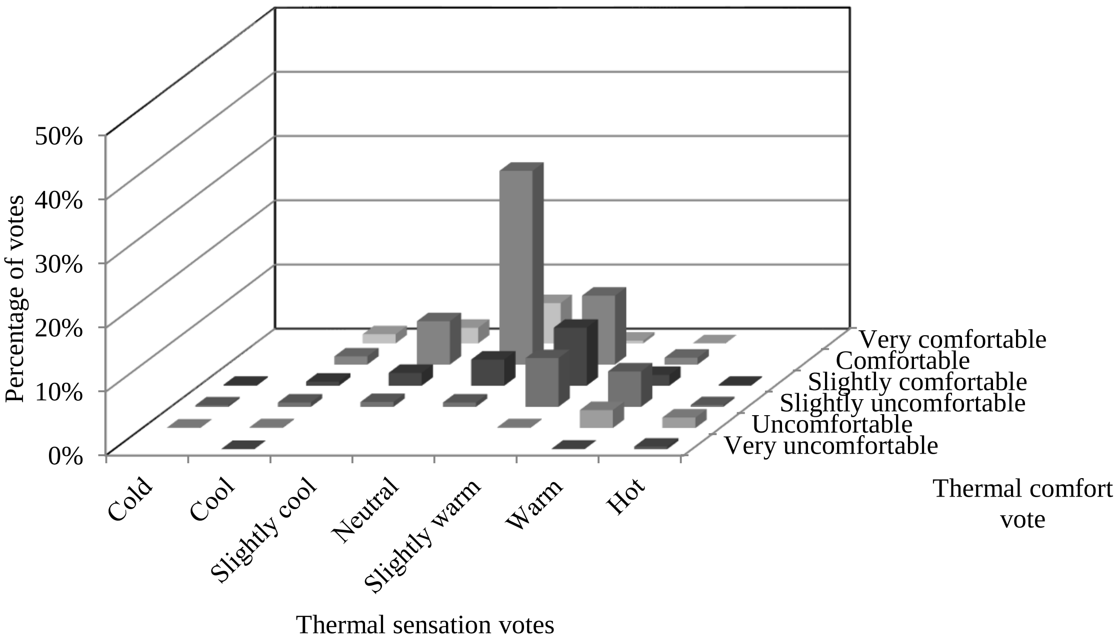

Figure 6.40. Cross tabulation of TSV and TCV of Darwin cohort

Cross-tabulation of the TSV responses and the responses to clothing level suggest a relationship between clothing and sensation in both cohorts. The relatively high proportions of very heavy clothing levels at 5 “Slightly warm” (6.6%) and 6 “Warm” (8.0%) may suggest that clothing is one of the primary thermoregulation techniques used in the Melbourne households (see Figure 6.41). The lower proportion of light clothing at warmer sensations for the Melbourne cohort is likely indicative of the climate; mostly cool to temperate throughout the year. In the Darwin households the relationship between clothing level and sensation appears to be much more intuitive; as sensation increases above 4= “Neutral” to 7= “Hot”, the clothing level decreases from medium to very light ensembles (see Figure 6.42). In Darwin it is likely that there is less appreciable seasonal variation in clothing than in Melbourne; resulting in the more direct correlation between sensation and clothing.

Cross tabulation of the TSV responses and the activity level responses revealed that in both cohorts a majority of the warmer than neutral votes were cast when the occupants reported higher activity levels. The relatively small proportion of cooler than neutral votes where the occupants reported lower activity levels may indicate that the subjects tend to feel cool when not active (see Figure 6.43 and Figure 6.44).

No notable relationships were revealed through the cross tabulation of the TSV responses, and window, fan and appliance operation.

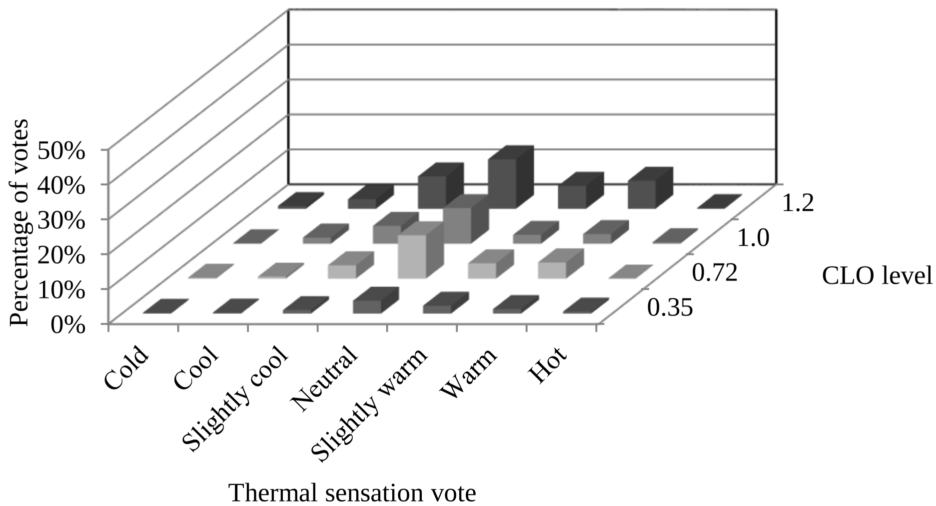

Figure 6.41. Cross tabulation of TSV and CLO level of Melbourne cohort

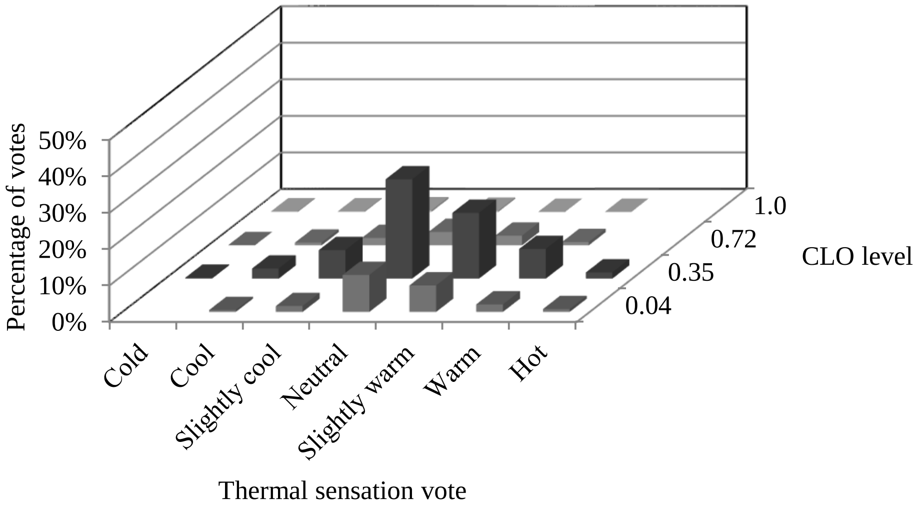

Figure 6.42. Cross tabulation of TSV and CLO level of Darwin cohort

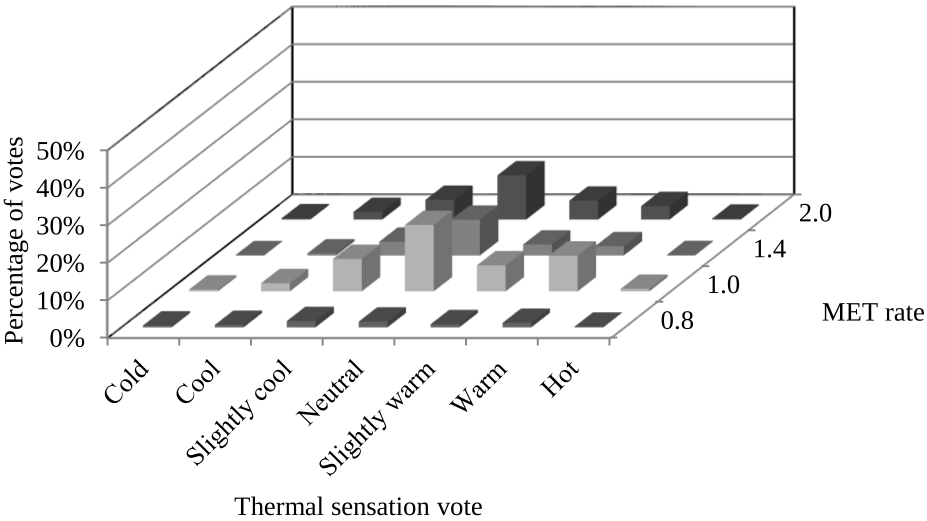

Figure 6.43. Cross tabulation of TSV and MET rate of Melbourne cohort

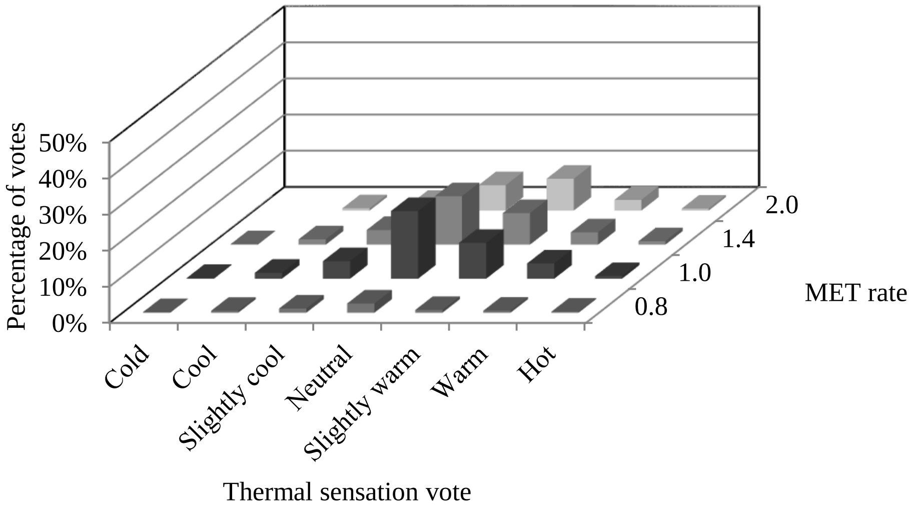

Figure 6.44. Cross tabulation of TSV and MET rate of Darwin cohort

6.4 Comfort temperature

A singular comfort temperature is often used as a straightforward comparison between different subjects' or cohorts' thermal behaviours, however many methods exist to calculate this temperature. This section presents several of these methods of which the results are then compared in section 6.5.4.

6.4.1 Regression analysis

Using liner regression, the temperature for each cohort corresponding to a mean TSV of 4= "Neutral" based on the regression equations from Figure 6.6 are 19.5 °C for the Melbourne cohort and 27.4 °C for the Darwin cohort.

Using quadratic regression (see Figure 6.11and Figure 6.15), the preferred and comfort temperatures are 21.7 °C, 22.1 °C and 25.3 °C, 24.8 °C for the Melbourne and Darwin cohorts respectively.

These methods essentially assume that the temperature increments between each sensation, preference or comfort vote are at equal intervals. The votes are treated as continuous numbers rather than discrete numbers representative of a particular perception. This may be appropriate in the analysis of thermal sensation assessments from studies carried out in climate chambers, however previous research indicates that the temperature increments between the scale descriptors (e.g. “Slightly cool” to “Neutral”) may not be equal in thermal sensation votes collected in field studies (Ballantyne et al, 1977).

6.4.2 Griffiths method

Using the Griffiths Method (Equation 6.1) to predict the comfort temperature and assuming a slope of 0.5/K (Griffiths, 1990; Humphreys et al, 2010; Nicol et al, 2012) the mean comfort temperature for the Melbourne cohort is found to be 19.2 °C (SD 3.3 °C) and the mean comfort temperature for the Darwin cohort is 27.9 °C (SD 2.4 °C).

$$T_c = T_g - (C - 4) / G \qquad (6.1)$$

Where T_c: comfort temperature, T_g: indoor operative temperature, C: thermal sensation vote and G: ‘Griffiths slope’

However, if the actual slope values of the collected data are used to replace G (see Figure 6.6) 0.14 for the Melbourne data and 0.17 for the Darwin data, the mean comfort temperatures are lower at 18.2 °C (SD 7.6 °C) and 26.5 °C (SD 5.2 °C) for the Melbourne and Darwin cohorts respectively. This method also assumes an equal temperature increment between thermal sensation votes.

6.4.3 Probit analysis: Fanger’s method

Probit analysis using the Fanger method (Fanger, 1970) was completed for the Melbourne and Darwin data. The intersecting points of the regression lines for the proportion of cold dissatisfied and warm dissatisfied at each temperature bin for the two cohorts were 17.8 °C and 27.1 °C respectively, see Figure 6.45 and Figure 6.46. The Predicted Percentage Dissatisfied (PPD) curves created for the Melbourne and Darwin data are very shallow when compared to the curves produced in Fanger (1970) (see Figure 6.47 and Figure 6.48). This is because the collected data is from a field study where the internal environments are more varied; therefore, the natural distribution of the thermal comfort votes is not the same as can be produced by climate chamber. This is similarly reflected in Becker & Paciuk’s (2009) findings from a comfort survey of approximately 200 Israeli dwellings. In comparing the collected data to the PPD model, they found that;

> *“discrepancies highlight the role of contextual variables (local climate, expectations, available control) in thermal adaptation in actual settings.” (Beker & Paciuk, 2009, p948)*

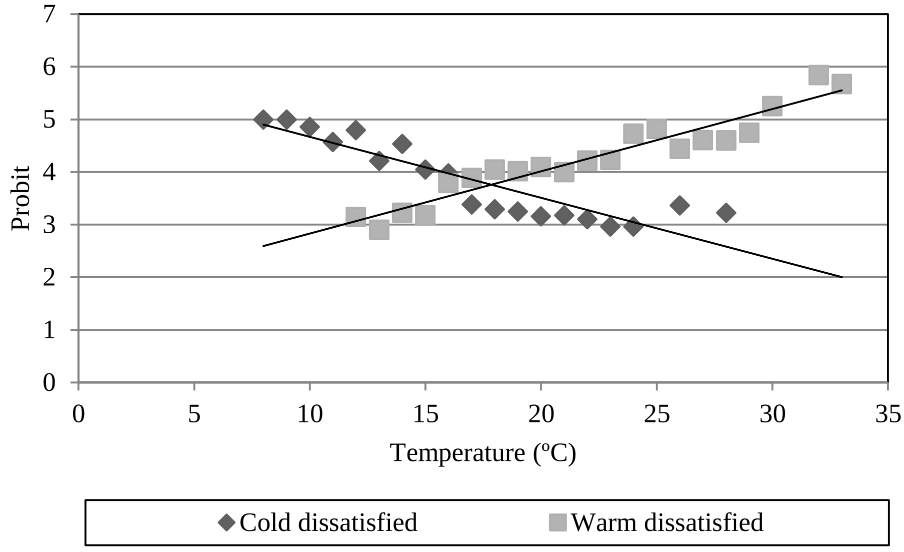

Figure 6.45. Proportion of dissatisfied votes at each binned indoor temperature for the Melbourne cohort

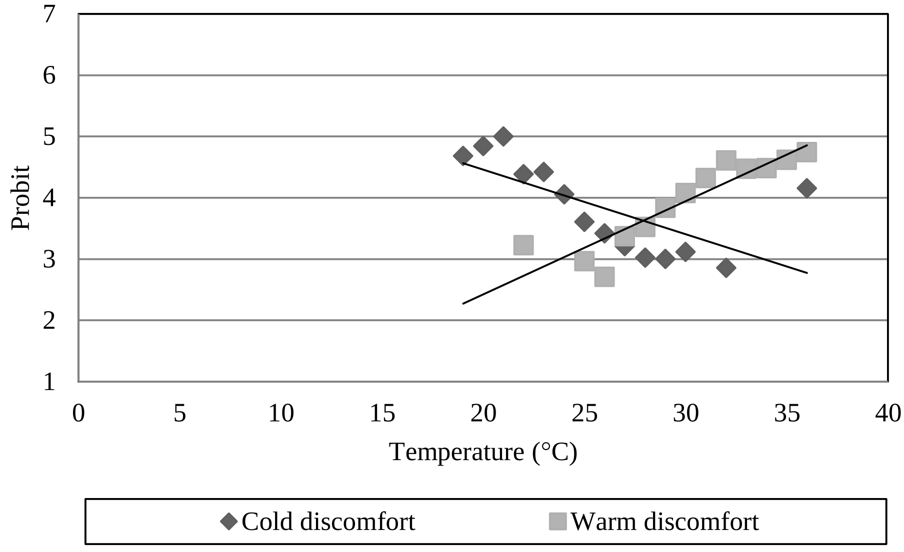

Figure 6.46. Proportion of dissatisfied votes at each binned indoor temperature for the Darwin cohort

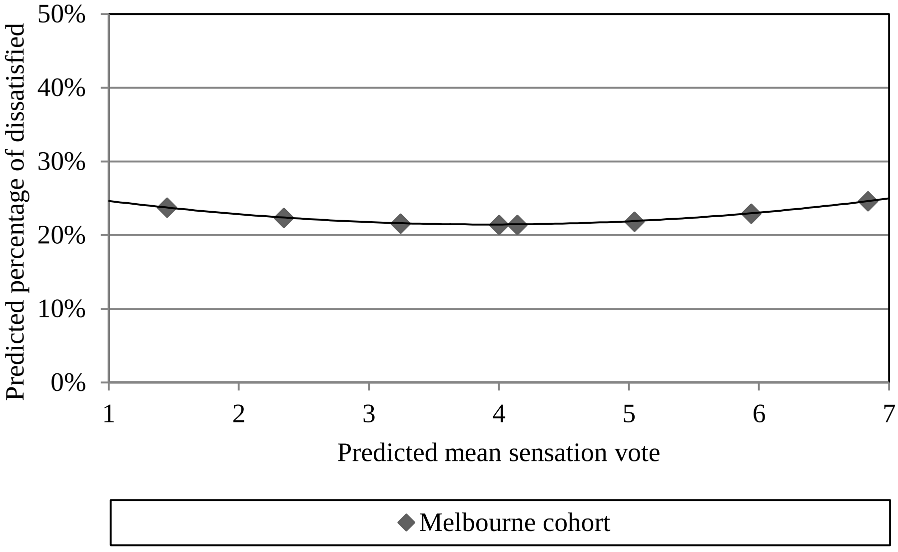

Figure 6.47. Percentage predicted dissatisfied for Melbourne data

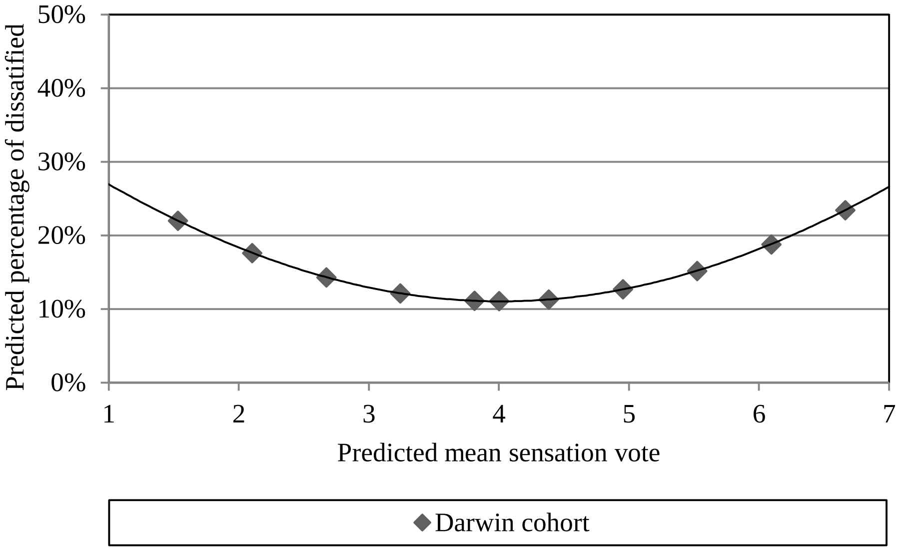

Figure 6.48. Predicted percentage of dissatisfied for Darwin data

6.4.4 Probit analysis: Ballantyne, Hill & Spencer method

An alternative method of probit analysis, used by Ballantyne et al (1977) to determine the preferred temperature of subjects from three different studies, was replicated and used to determine the preferred temperatures of the two case study cohorts (see Figure 6.49 and Figure 6.50). The temperatures corresponding to the maximum percentage of votes between the ≥4 and ≥5 lines were calculated as 18.2 °C for the Melbourne cohort and 26.5 °C for the Darwin cohort, see Figure 6.51 and Figure 6.52.

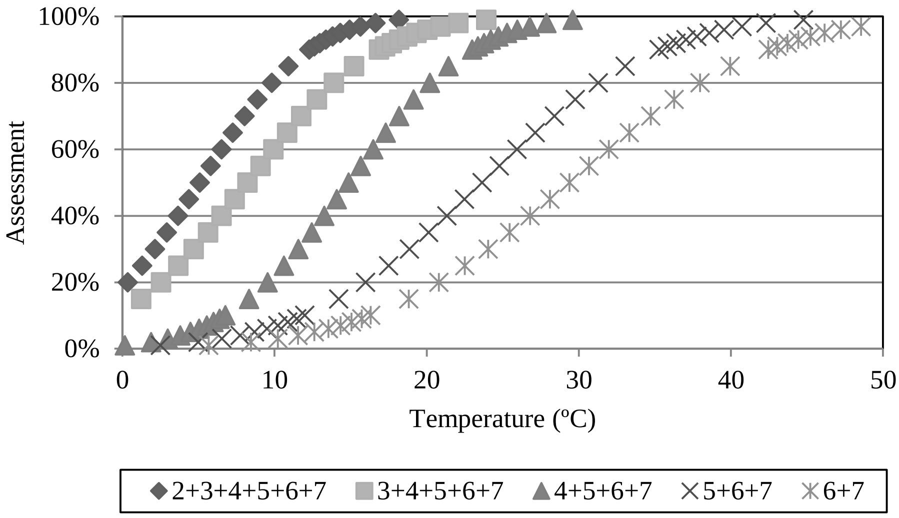

Figure 6.49. Proportion of votes at each 'zone' for Melbourne data

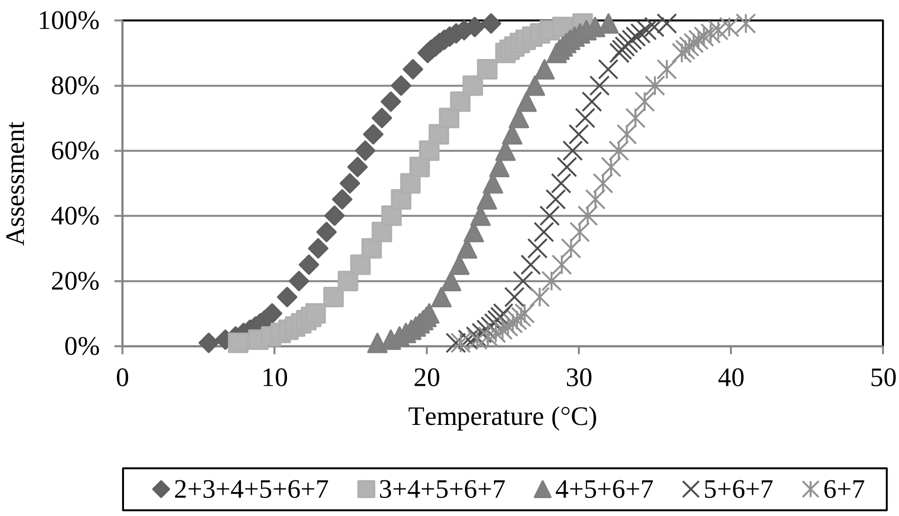

Figure 6.50. Proportion of votes at each 'zone' for Darwin data

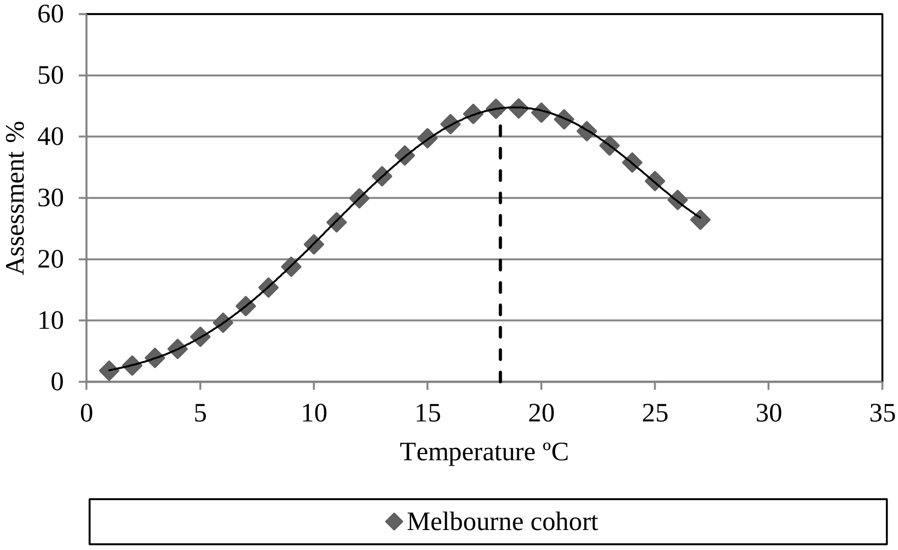

Figure 6.51. Proportion of votes within the neutral zone for Melbourne data

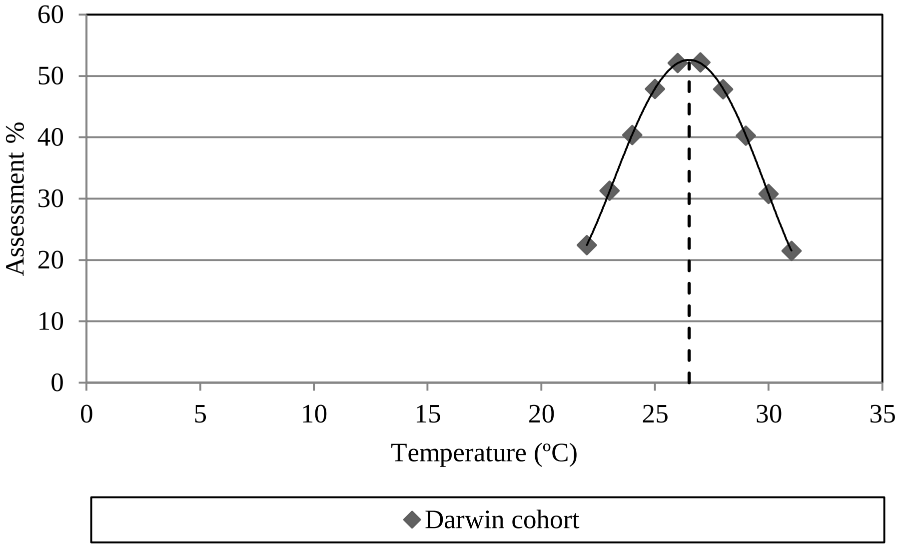

Figure 6.52. Proportion of votes within the neutral zone for Darwin

6.4.5 Neutral, comfort or preferred temperature?

The temperatures calculated above (summarised in Table 6.12) vary by 3.9K for the Melbourne cohort and 3.1K for the Darwin cohort, raising the question of the appropriateness of using a single temperature to describe the thermal comfort of a given cohort of subjects.

Importantly, the neutral temperatures attained using the Griffiths with the actual slope of the collected data corresponds with the preferred temperatures calculated using the Ballantyne et al method of probit analysis within one decimal place. In their original work both Fanger (1970) and Ballantyne et al (1977) used comfort vote data from climate chamber experiments conducted at the Kansas State University (KSU) in the late 1960s (Rohles & Nevins, 1971). To further test the outcome of the Griffiths method and the Ballantyne et al method, the analyses were completed for this KSU data. The calculated neutral and preferred temperatures again corresponded within one decimal place, confirming that it is more valid to use the actual slope of the collected data rather than the assumed slope of 0.5 more commonly used (Humphreys et al, 2010).

Table 6.4. Summary of neutral, comfort and preferred temperatures calculated from thermal sensation votes, note: bold and italic formatting indicates minimum and maximums

Method	Melbourne	Darwin
Linear regression TSVs	19.5 °C	27.4 °C
Quadratic regression TPV	21.7 °C	25.3 °C
Quadratic regression TCV	***22.1 °C***	***24.8 °C***
Griffiths Method (0.5 slope)	19.2 °C	***27.9 °C***
Griffiths Method (actual slope)	18.2 °C	26.5 °C
Probit: Fanger method	***17.8 °C***	27.1 °C
Probit: Ballantyne et al method	18.2 °C	26.5 °C

6.5 Comparison with international thermal comfort standards

In order to evaluate whether or not the measured thermal comfort of the two case study cohorts varies when compared to a ‘typical’ population the collected data was compared with widely used international thermal comfort standards; the Predicted Mean Vote (PMV) index, the Standard Effective Temperature (SET) model, and the ASHRAE and CEN adaptive models.

It is noted that these models are largely based on thermal comfort studies conducted in climate chambers or commercial buildings; therefore their application in residential buildings requires further testing. However, it is thought that an adaptive model of thermal comfort is an appropriate approach for residential buildings due to the wide range of adaptive opportunities available to the occupants (Peeters et al, 2009; Saman et al, 2013).

6.5.1 Predicted mean vote: ASHRAE Analytical Comfort Zone Method

The PMV corresponding to the environmental conditions recorded at the time votes were cast was calculated using the Analytical Comfort Zone Method. The computer program was validated against figures shown in Table G1-1 (ASHRAE 55, 2013). Note that in the calculations the MET and CLO values are estimates only. The data were then binned in 1K increments and the mean calculated PMV compared with the mean TSV cast by the subjects. Whilst the slope from the comparison of the PMV and the Melbourne data has good agreement, the higher *y* intercepts shows that the subjects are likely to cast a neutral vote at lower temperatures than the PMV model (see Figure 6.53). There is little correlation between the mean calculated PMV and mean TSV of the Darwin cohort. The PMV calculations appear to substantially over predict warmth sensation (see Figure 6.54). For example, based on the thermal sensation votes, “Slightly warm” corresponds to 33.2°C, while based on the PMV calculations it corresponds to just 29.3°C. This indicates that the Darwin cohort have a much different perception of warmth than is accounted for in the PMV model.

6.5.2 Standard Effective Temperature (SET) Model

The collected data were similarly compared with SET as used in ASHRAE55-2013, defined by Fountain & Huizenga (1995). The calculated SET temperature was compared with the mean TSV for both cohorts. This revealed that the SET model is a relatively weak predictor for the thermal sensation of the Melbourne subjects (see Figure 6.55). However, it does appear to be significantly more appropriate to describe the thermal sensation of the Darwin subjects (see Figure 6.56). This is likely associated with the effect of humidity and air movement on thermal sensation in hot humid environments. Much of the revision to the formative SET models was focused on improving its accuracy for these particular environmental variables (Auliciems & Szokolay, 2007).

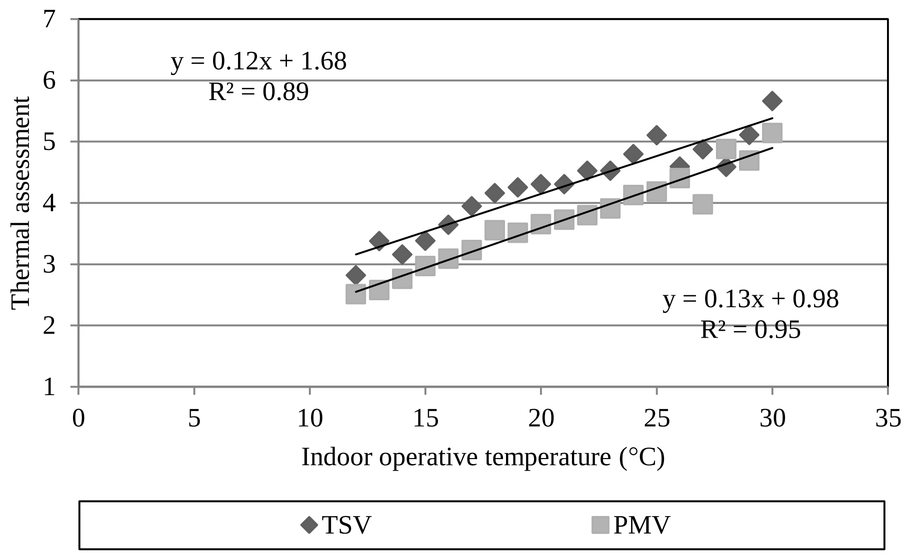

Figure 6.53. Comparison of the mean TSV and mean calculated PMV when binned by indoor operative temperature in 1k intervals for the Melbourne cohort

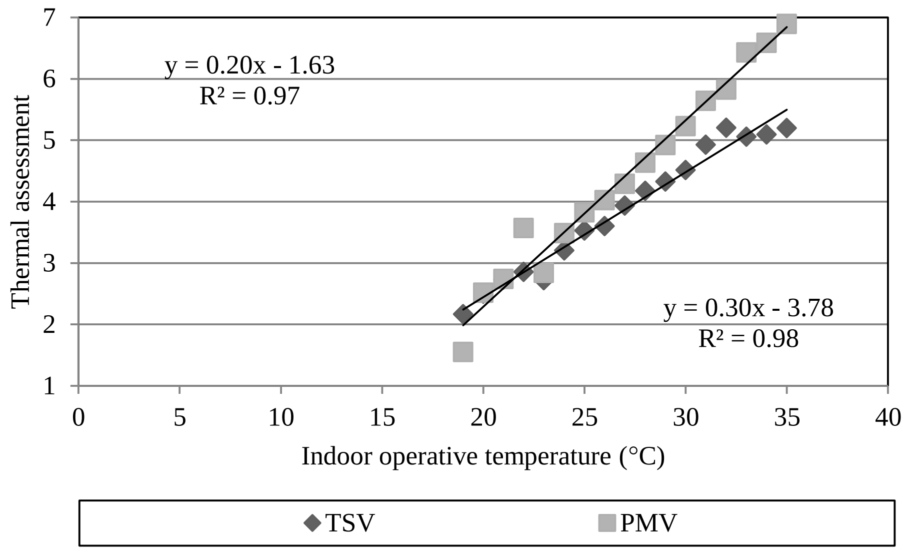

Figure 6.54. Comparison of the mean TSV and mean calculated PMV when binned by indoor operative temperature in 1k intervals for the Darwin cohort

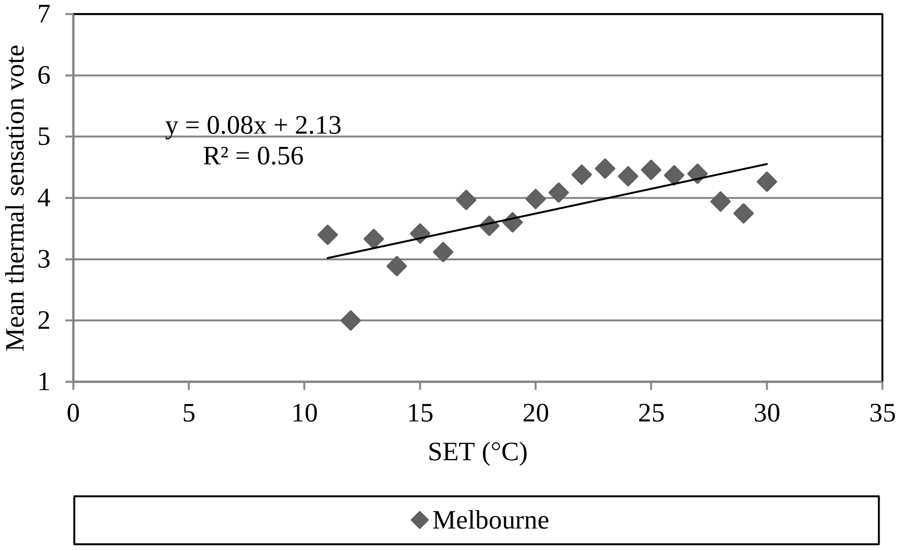

Figure 6.55. Mean TSV when SET binned in 1k increments for the Melbourne cohort

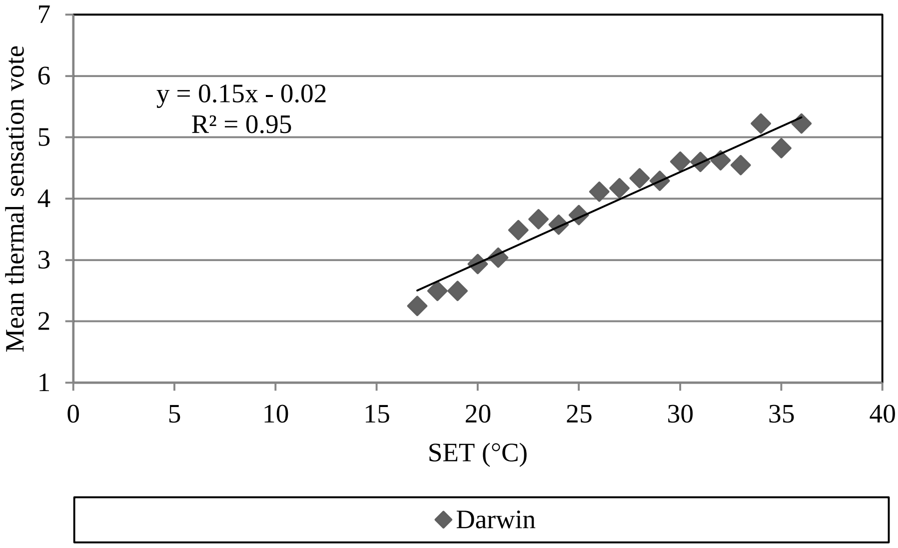

Figure 6.56. Mean TSV when SET binned in 1k increments for the Darwin cohort

6.5.3 ASHRAE 55-2013 Adaptive model

The collected comfort vote surveys from the Melbourne and Darwin cohorts that fall within the parameters for the application of the ASHRAE adaptive model (see section 5.4.1 of ASHRAE55-2013) were plotted against the 80% and 90% upper and lower acceptability limits (see Figure 6.57). Significant proportions of these votes sit outside of the upper and lower limits indicating that the two studied cohorts find a wider range of conditions comfortable than the adaptive model describes (see Table 6.13). Interestingly, the slopes of the two cohorts are very similar (0.62 and 0.68), particularly compared to that of the adaptive model (0.31). Note, to enable straightforward comparison the allowance in extension of the upper boundary of comfort for elevated air speeds has not been taken into consideration.

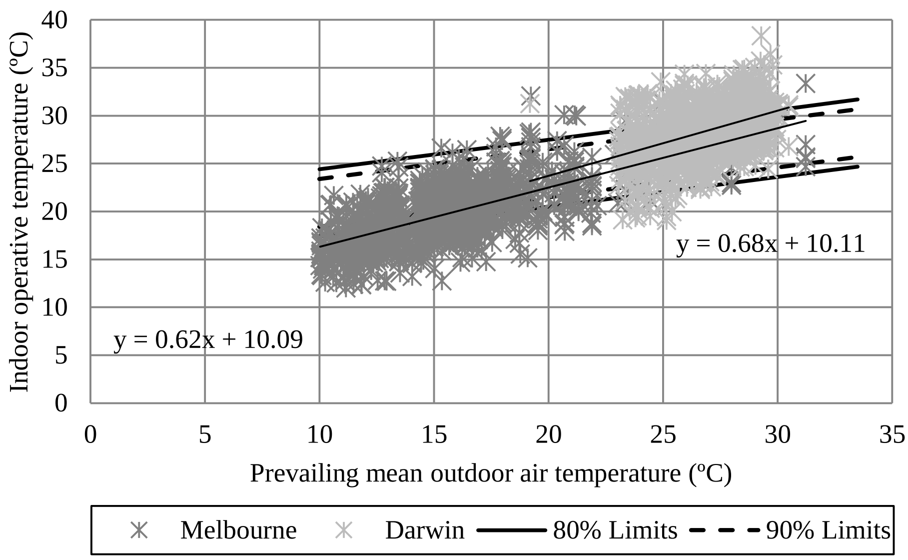

Figure 6.57. Comparison of the 'slightly cool', 'neutral' and 'slightly warm' TSVs from the collected data when parameters are within those described in ASHRAE55-2013 (section 5.4.1) with the acceptable operative temperature ranges for naturally conditioned spaces, where the prevailing mean outdoor air temperature is based on the running weighted 7-day mean

Table 6.5. Percentage of 'slightly cool', 'neutral' and 'slightly warm' TSVs outside of the ASHRAE adaptive upper and lower limits

Cohort	Percentage outside 80% limits		Percentage outside 90% limits	
	Below	Above	Below	Above
Melbourne	42.1%	1.4%	58.1%	2.4%
Darwin	1.8%	30.7%	3.4%	49.1%

To further demonstrate the conditions that the subjects find acceptable, the TPVs of 2= “No change” were similarly plotted against the ASHRAE adaptive upper and lower acceptability limits (see Figure 6.58). No exclusions were made based on CLO, MET or prevailing mean outdoor air temperature as was done in the first comparison. Again, substantial proportions of the conditions were outside of the upper and lower limits (see Table 6.14). The sets of data again also display similarities in both the slope of the trend line and distribution of points. This may indicate that while the thermal conditions experienced by either cohort are remarkably different, their thermal preference could be describe by a singular model.

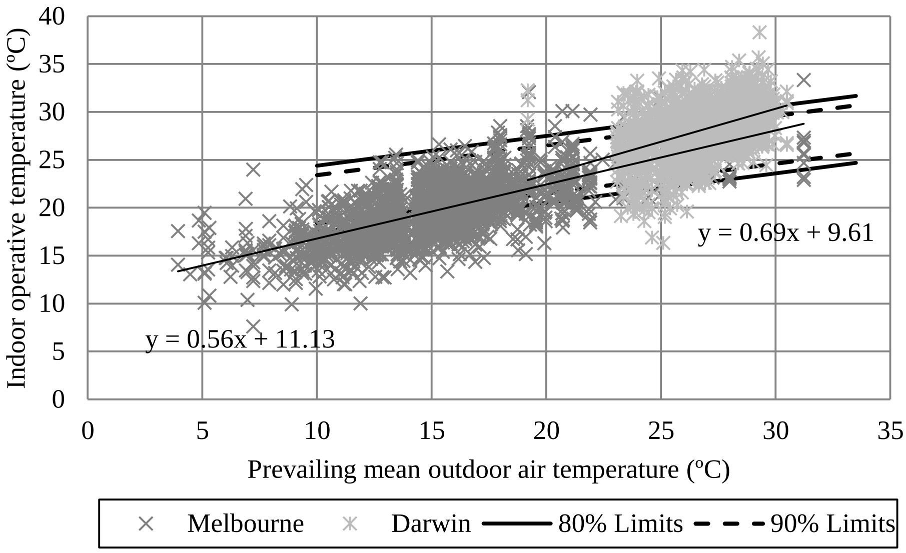

Figure 6.58. Votes where the subjects prefer ‘No change’ and the dwellings are operated as free-running compared with the acceptable operative temperature ranges for naturally conditioned spaces, where the prevailing mean outdoor air temperature is based on the running weighted 7-day mean

Table 6.6. Percentage of votes where the subjects prefer ‘No change’ outside of the ASHRAE adaptive upper and lower limits, note: for the sake of comparison upper and lower limits were assumed to linearly extend below 10 °C

Cohort	**Percentage outside 80% limits**		**Percentage outside 90% limits**	
	Below	Above	Below	Above
Melbourne	40.9%	1.2%	57.3%	2.5%
Darwin	2.2%	27.1	4.3%	45.3%

6.5.4 EN 15251:2007 Adaptive model

A similar comparison was made with the EN 15251: 2007 adaptive model (see Figure 6.59). The Standard specifies four categories of indoor environments/buildings; the two central categories are most relevant to this comparison. Category II is for *"normal level of expectation and should be used for new buildings and renovations"*, whilst category III is for *"an acceptable, moderate level of expectation and may be used for existing buildings"* (CEN, 2007, p13).

The Darwin data appears to be in relatively good agreement with this model (see Table 6.15); however the model remains largely inappropriate for the Melbourne sample. The exclusion of running mean outdoor temperatures below 10 °C and 15 °C for the upper and lower design values respectively, remove over 47% of the Melbourne comfort votes that would otherwise meet the requirements for application of the model. This stringency of this model in cooler conditions is likely due to the extent to which buildings are centrally heated in Europe, which is not reflected in residential buildings in Australia.

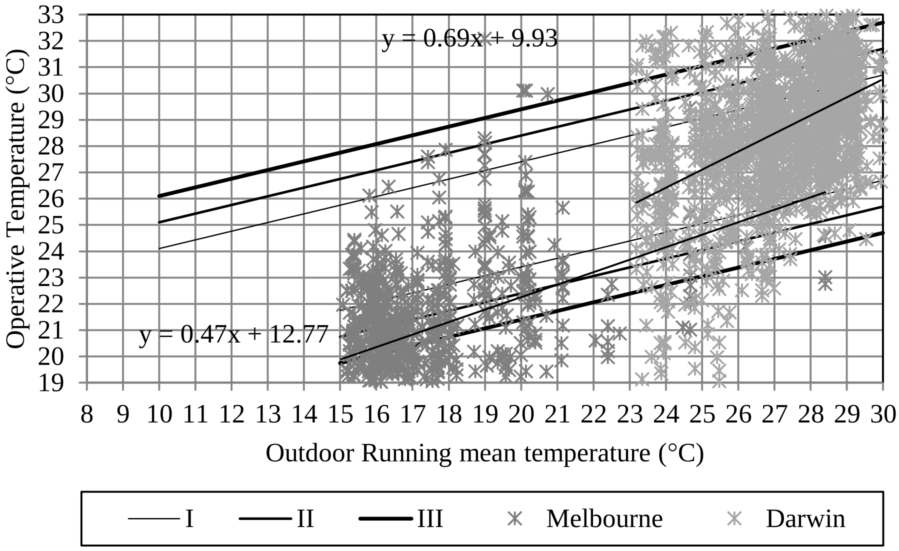

Figure 6.59. Comparison of the 'slightly cool', 'neutral' and 'slightly warm' TSVs from the collected data when parameters are within those described in EN 15251 (2007) with the design values for the indoor operative temperature for buildings without mechanical cooling systems as a function of the exponentially-weighted running mean of the outdoor temperature

Table 6.7. Percentage of 'slightly cool', 'neutral' and 'slightly warm' TSVs outside of the EN 15251 adaptive design values

Cohort	Percentage outside category II		Percentage outside category III	
	Below	Above	Below	Above
Melbourne	60.7%	1.4%	43.2%%	0.7%%
Darwin	6.2%	16.8%	3.5%	8.3%

Again, to demonstrate the extent to which acceptable conditions compare to the EN 15251 adaptive model, the 2= "No change" TPVs were plotted (see Figure 6.60). The large proportion of acceptable votes cast by the Melbourne cohort outside of the design values is clearly visible in both Figure 6.60 and Table 6.16. Whilst this model does appear to be a reasonable description of the Darwin cohorts' thermal comfort, the range of conditions nominated as acceptable by this cohort is wider than the category III design values.

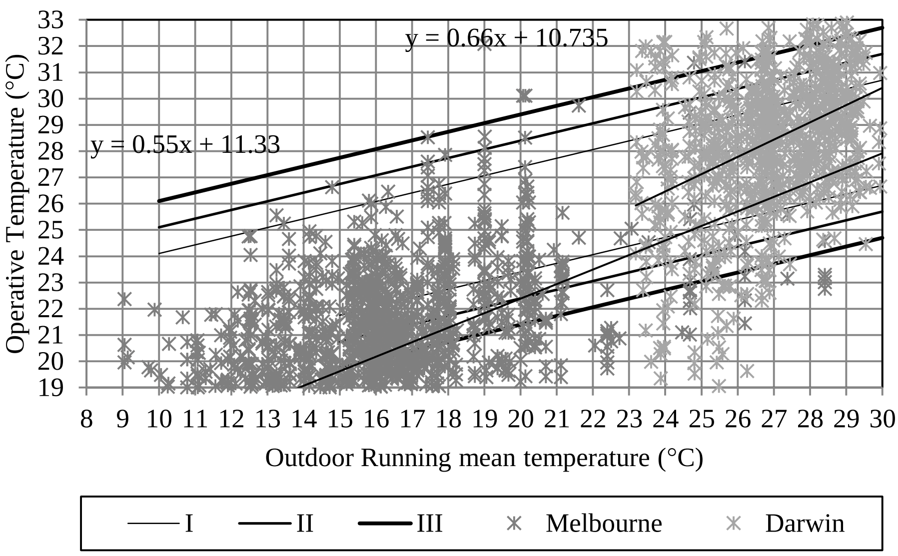

Figure 6.60. Votes where subjects prefer 'No change' and dwellings are operated as free-running compared with the design values for the indoor operative temperature for buildings without mechanical cooling systems as a function of the exponentially-weighted running mean of the outdoor temperature

Table 6.8. Percentage of votes where the subjects prefer 'No change' outside of the EN15251 adaptive design values, note: for the sake of comparison upper and lower limits were assumed to linearly extend below 10 °C and 15 °C respectively

Cohort	**Percentage outside category II**		**Percentage outside category III**	
	Below	Above	Below	Above
Melbourne	68.4%	0.7%	53.9%	0.3%
Darwin	7.5%	13.6%	4.3%	6.0%

6.6 Summary

The results presented in this chapter describe the thermal preferences of the two case study cohorts. In total, 6179 thermal comfort surveys with corresponding indoor climatic measurements were collected. The varying quantity of votes recorded by each household was not found to cause any bias in the sample.

The thermal sensation, preference and comfort votes revealed that the Melbourne cohort generally had a preference for neutral to warmer conditions, while the Darwin cohort rarely reported discomfort at cooler temperatures. The mean thermal sensation vote recorded by the Melbourne cohort was 4.19 and 4.36 recorded by the Darwin cohort. A good relationship was found between the thermal sensation votes and the indoor operative temperature when binned in 1K increments.

Both cohorts actively engaged with their thermal environment through the operation of windows and doors for ventilation, fan use and the use of artificial heating and/or cooling. A clear relationship between the outdoor running weighted mean temperature and window operation by the Melbourne cohort was found. Conversely the Darwin cohort rarely changed the state of their windows (i.e. windows were open almost all of the time) or used cooling appliances so no relationship was able to be detected. Most interestingly, for both cohorts, there was a distinct relationship between fan use and indoor operative temperature. The temperatures at which fan use occurred were also remarkably similar between the two cohorts. The results showed that the Melbourne cohort largely used artificial heating in cooler conditions, and relied on natural ventilation and fan use in warmer conditions, whereas the Darwin cohort generally only adjusted their fan use to suit the conditions.

A range of neutral, comfort and preferred temperatures were attained for each cohort using different methods of calculation. The disparity between the figures achieved, 17.8 °C to 22.1 °C for the Melbourne cohort and 24.8 °C to 27.9 °C for the Darwin cohort, revealed possible ambiguity in describing the thermal comfort of a group of subjects using just a single figure. This indicates that it may not be useful to describe the thermal preference of an individual or cohort using a neutral or comfort temperature. It may be more valuable to describe the range of conditions that occupants find acceptable, particularly as it is on the threshold of this range that occupants are likely to start taking action to modify their thermal environment (e.g. changing clothes, opening windows, using heating and/or cooling appliances). This approach would offer a more inclusive model by which to account for the natural variation in the perception of thermal stimuli across a cohort of occupants. Notably, this comparison also revealed the importance of using the figure of the actual slope of the collected data in the calculation of neutral temperature using the Griffiths method equation.

The collected data were also compared with four widely used models of thermal comfort; the PMV index, the SET model, the ASHRAE adaptive model (2013) and the EN 15251 (2007) adaptive model. Some agreement was found between the Melbourne cohorts' thermal sensation votes and the PMV index, however the PMV over predicted the temperature at which the case study subjects were likely to cast a neutral vote. There was a good correspondence between the Darwin cohorts' thermal sensation vote and the SET model. This may be due to the manner in which this model accounts for humidity and the cooling effect of air movement, which is of great relevance in hot humid climates. The key comparison of the collected data with the ASHRAE adaptive model demonstrated that the subjects from both cohorts found a wider range of conditions acceptable than this model describes as comfortable. It is interesting to note that the distribution of votes is similar to that of a summary of Brazilian thermal comfort field studies where occupants had access to a range of adaptive opportunities (Lamberts et al, 2013). This supports the suggestion that, in residential buildings where occupants have significant influence over their thermal environment, comfort boundaries may be extended. The EN 15251 adaptive model proved to be better fit for the Darwin data, however much less appropriate for the Melbourne sample, despite the model being mainly intended for application for outdoor running mean temperatures below 25 °C. The comparison with international standards revealed that no one model of thermal comfort can adequately describe the thermal preference of both of the case study cohorts.

The results presented above show that the thermal preferences of the two case study cohorts cannot be adequately described by existing international standards for thermal comfort. Key themes to emerge from the results are;

- The operation of windows and heating appliances by the Melbourne cohort was closely linked to prevailing mean outdoor temperature;
- The operation of fans by both cohorts was closely linked to indoor operative temperature (and by extension outdoor temperature in the Darwin households due to the coupled nature of the thermal conditions);
- These thermal maverick occupants expressed acceptance of a wide range of thermal conditions not encompassed by existing widely used thermal comfort models;
- The use of a single temperature to describe the comfort of each cohort was not useful because of the variation possible through the use of different methods of calculation; and
- Rather it may be more useful to describe the extent of conditions that these occupants find acceptable; consistency in the relationships between prevailing mean outdoor temperature and acceptable indoor conditions for both cohorts demonstrates that the thermal preference of the two cohorts may be reflected in a single model.

The extent to which the thermal preferences of the two cohorts may be influenced by their environmental attitude will be explored within the next chapter. Additionally, the development of a model to describe the thermal preference of the two cohorts of subjects will be presented in Chapter 8.

Chapter 7. Results: environmental attitudes

7.1 Introduction

The following chapter presents the results of the Environmental Attitudes Inventory (EAI) survey of both the case study households and a sample of the population from the same locations.

The aim of this investigation is to gauge the cohorts' level of environmental concern and compare it to those of a typical population, testing whether or not the case study cohorts' thermal behaviours and preferences could be influenced by their underlying environmental concern.

Portions of this chapter were previously published and have been quoted directly from the following sources (Daniel et al, 2014b; 2015b). Permission has been granted by all co-authors to quote published material without rephrasing.

7.2 Overview

Thirty-three of the occupants from the Melbourne in-depth case study households and 27 from the Darwin households returned completed EAI surveys. At least one occupant form each household completed the survey. The commercial online panel provider obtained 113 control sample responses from the North-eastern suburbs of Melbourne and 36 from Darwin (see Table 7.1). The availability of control sample respondents corresponded with population size.

The analysis of results is presented at item, first order factor and second order factor levels. The items are the individual statements that contribute to the first order factors. Each first order factor has one standard statement and one reverse statement. The first order factors describe aspects of an individual's attitude that relates to environmental concern (e.g. population growth, environmental degradation, resources consumption etc.). These first order factors, in turn, contribute to two second order factors; preservation and utilisation, which are the overarching measures of environmental attitude of EAI survey.

Table 7.1. Sample size and demographic

Cohort	N	Female	Male	Median age
Melbourne case study	33	17	16	60+
Darwin case study	27	14	13	30 - 49
Melbourne control	112	61	51	50 - 59
Darwin control	36	21	15	30 - 49

7.3 Item analysis

The mean responses given by the case study cohorts to the majority the 24 statements that respondents were asked to nominate their extent of agreement or disagreement with indicated a greater level of environmental concern than the mean responses of the two control samples (see Table 7.2).

The items 1, 4, 6, 7, 12, 20, 17, 24 relating to the first order factors “Enjoyment of Nature”, Environmental Threat”, “Personal Conservation Behaviour” and “Ecocentric Concern” elicited particularly strong agreement from the case study cohorts. Items 9 and 14 belonging to the first order factor “Confidence in Science and Technology”, attracted more impartial responses from both the case study cohorts and the control sample respondents. Generally all items belonging to the utilisation second order factor attracted low scores from the case study cohorts indicating broad disagreement.

Table 7.2. Mean score and standard deviation for each EAI item for the case study cohorts and control samples (1= "Strongly disagree", 7= "Strongly agree), note: (R) reverse coded items, bold and italic formatting indicates highest mean score

Item (reverse coded item)	**Melbourne case study mean score (SD)**	**Darwin case study mean score (SD)**	**Melbourne control mean score (SD)**	**Darwin control mean score (SD)**
1. I really like going on trips into the countryside, for example to forests or fields.	6.2 (1.1)	***6.6 (0.7)***	5.4 (1.3)	5.9 (1.2)
2. I do NOT believe humans were created or evolved to dominate the rest of nature. (R)	2.5 (1.7)	2.1 (1.7)	***4.6 (1.7)***	3.7 (2.2)
3. Protecting the environment is more important than protecting peoples' jobs. (R)	2.8 (1.5)	2.8 (1.5)	***4.3 (1.5)***	3.8 (1.6)
4. Whenever possible, I try to save natural resources.	6.3 (1.0)	***6.5 (0.6)***	5.5 (1.1)	5.8 (0.9)
5. We need to keep rivers and lakes clean in order to protect the environment, and NOT as places for people to enjoy water sports. (R)	2.2 (1.2)	2.4 (1.3)	***5.0 (1.5)***	4.1 (1.9)
6. I think spending time in nature is boring. (R)	***6.6 (0.5)***	***6.6 (1.0)***	2.4 (1.3)	4.4 (2.5)
7. I do not believe that the environment has been severely abused by humans. (R)	5.3 (2.2)	***6.4 (1.0)***	2.7 (1.5)	4.0 (2.1)
8. I would much prefer a garden that is well groomed and ordered to a wild and natural one.	3.3 (1.6)	2.5 (1.2)	***4.2 (1.5)***	3.7 (1.5)
9. Modern science will solve our environmental problems.	***4.1 (1.5)***	3.0 (1.5)	3.8 (1.5)	3.2 (1.3)
10. One of the most important reasons to keep lakes and rivers clean is so that people have a place to enjoy water sports.	2.6 (1.7)	2.3 (1.5)	***3.5 (1.5)***	2.9 (1.5)
11. Protecting peoples' jobs is more important than protecting the environment.	3.0 (1.6)	2.6 (1.3)	***3.7 (1.4)***	3.1 (1.4)
12. Humans are severely abusing the environment.	5.6 (1.9)	***6.0 (1.4)***	5.3 (1.4)	5.4 (1.3)
13. Governments should control the rate at which raw materials are used to ensure that they last as long as possible.	***5.7 (1.7)***	5.6 (1.4)	5.5 (1.2)	5.0 (1.5)
14. Modern science will NOT be able to solve our environmental problems. (R)	3.9 (1.6)	3.2 (1.5)	***4.3 (1.4)***	3.8 (1.4)
15. I would like to join and actively participate in an environmentalist group.	4.8 (1.8)	***5.0 (1.6)***	3.6 (1.5)	3.7 (1.5)
16. A married couple should have as many children as they wish, as long as they can adequately provide for them. (R)	4.4 (1.8)	***5.1 (1.7)***	4.7 (1.7)	4.0 (2.0)

Table 7.2. continued ...

17. It makes me sad to see forests cleared for agriculture.	5.8 (1.6)	***5.9 (1.1)***	5.4 (1.3)	5.4 (1.3)
18. I would NOT get involved in an environmentalist organization. (R)	5.5 (1.9)	***5.9 (1.3)***	4.1 (1.6)	3.8 (1.8)
19. Human beings were created or evolved to dominate the rest of nature.	2.1 (1.5)	1.7 (1.1)	***3.2 (1.6)***	2.6 (1.6)
20. I am NOT the kind of person who makes efforts to conserve natural resources. (R)	5.9 (1.7)	***6.1 (1.6)***	2.7 (1.2)	3.8 (2.0)
21. I am opposed to governments controlling and regulating the way raw materials are used in order to try and make them last longer. (R)	5.1 (1.8)	***5.5 (1.9)***	3.1 (1.5)	3.4 (1.9)
22. Families should be encouraged to limit themselves to two children or less.	4.2 (1.7)	***5.1 (1.8)***	3.4 (1.7)	3.4 (1.9)
23. I'd prefer a garden that is wild and natural to a well groomed and ordered one. (R)	3.3 (1.5)	2.6 (1.3)	3.8 (1.5)	***3.9 (1.7)***
24. It does NOT make me sad to see natural environments destroyed. (R)	6.2 (1.8)	***6.5 (1.1)***	2.3 (1.6)	4.4 (2.4)

7.4 First order factor analysis

Overall, the Darwin case study cohort gave higher mean responses to all of the first order factors contributing to the preservation scale signifying a greater level of environmental concern based on its intrinsic value than the Melbourne cohort or control samples (see Table 7.3). Conversely, the Melbourne control sample gave the highest mean responses to the majority of the first order factors contributing to the utilisation scale, therefore demonstrating that their environmental concern is based on its anthropogenic use. It is again possible to see that the responses given to Scale 05. “Confidence in Science and Technology” are fairly consistent between the two case study cohorts and the control groups (see Table 7.3). Notably, whilst the Darwin cohort had the highest level of environmental concern based on the preservation scale, it also gave the highest mean response to Item 10. “Human Utilisation of Nature”. This may be reflective of the largely outdoor lifestyle enjoyed by many of the case study households.

Table 7.3. Mean scores for the 12 first-order factors for the case study cohorts and control samples, note: bold and italic formatting indicates highest mean score

First-order factor (items contributing to factor)	Melbourne case study mean score	Darwin case study mean score	Melbourne control mean score	Darwin control mean score
First-order factors contributing to the "Preservation" second-order factor				
Scale 01. Enjoyment of Nature (1 & 6)	6.4	***6.6***	3.9	5.1
Scale 02. Support for Interventionist Conservation Policies (13 & 21)	5.4	***5.5***	4.3	4.2
Scale 03. Environmental Movement Activism (15 & 18)	5.2	***5.4***	3.8	3.7
Scale 06. Environmental Threat (7 & 12)	5.4	***6.2***	4.0	4.7
Scale 08. Personal Conservation Behaviour (4 & 20)	6.1	***6.3***	4.1	4.8
Scale 11. Ecocentric Concern (17 & 24)	6.0	***6.2***	3.9	4.9
Scale 12. Support for Population Growth Policies (16 & 22)	4.3	***5.5***	4.4	4.4
First-order factors contributing to the "Utilisation" second-order factor				
Scale 04. Conservation Motivated by Anthropocentric Concern (5 & 10)	2.4	2.4	***4.2***	3.5
Scale 05. Confidence in Science & Technology (9 & 14)	***4.0***	3.1	***4.0***	3.5
Scale 07 Altering Nature (8 & 23)	3.3	2.5	***4.0***	3.8
Scale 09. Human Dominance Over Nature (2 & 19)	2.3	1.9	***3.9***	3.1
Scale 10. Human Utilisation of Nature (3 & 11)	2.9	***4.3***	4.0	3.4

7.5 Second order factor analysis

In order to gain an understanding of the EAI survey results generally, paired-sample t-tests were conducted to compare the mean preservation and utilisation scores of the case study and control groups. The mean preservation scores for both the Melbourne and Darwin case study groups were higher than those of the control samples, indicating a greater level of environmental concern relating to conservation and protection of the environment. On the other hand, the mean utilisation scores of the two case study groups were lower than the mean utilisation scores of the control sample, demonstrating a lower level of anthropocentric concern relating to the utilisation of natural resources (see Table 7.4). Figure 7.1 to Figure 7.3 clearly demonstrate the negative correlation between the preservation and utilisation scales, particularly with the case study cohort sample.

There is a significant difference in the mean preservation scores for the Melbourne case study sample (M=5.6, SD=0.7) and the Melbourne control sample (M=4.0, SD=0.2); t(33.6) = 13.0, p=<0.0001. The utilisation scores for the Melbourne case study group (M=3.0, SD=0.6) when compared to the Melbourne control sample (M=4.0, SD=0.1) are also significantly different; t(32.5) = -9.5, p=<0.05.

Similarly, there is a significant difference in the mean preservation scores for the Darwin case study sample (M=6.0, SD=0.4) and the Darwin control sample (M=4.6, SD=0.4); t(56.2)=13.7, p=<0.0001. The utilisation scores for the Darwin case study group (M=2.8, SD=0.8) when compared to the Darwin control sample (M=3.5, SD=0.2) are again significantly different; t(28.4)=-4.4, p=<0.005.

It is worth noting that these results align with those reported by (O'Callaghan et al, 2012); where the preservation (M=5.88, SD=0.59) and utilisation (M=2.65, SD=0.59) scores for the *Ecovillage* study group (n=39) were higher and lower, respectively, than the preservation (M=4.92, SD=0.62) and utilisation (M=3.35, SD=0.61) scores for the *Observatory* control group (n=36).

Table 7.4. Mean scores for the two second-order factors, preservation and utilisation, for the case study cohorts and control samples, note: bold and italic formatting indicates highest mean score

Second-order factor	Melbourne case study mean score (SD)	Darwin case study mean score (SD)	Melbourne control mean score (SD)	Darwin control mean score (SD)
Preservation	5.6 (0.7)	***6.0 (0.4)***	4.0 (0.2)	4.6 (0.4)
Utilisation	3.0 (0.6)	2.8 (0.8)	***4.0 (0.1)***	3.5 (0.2)

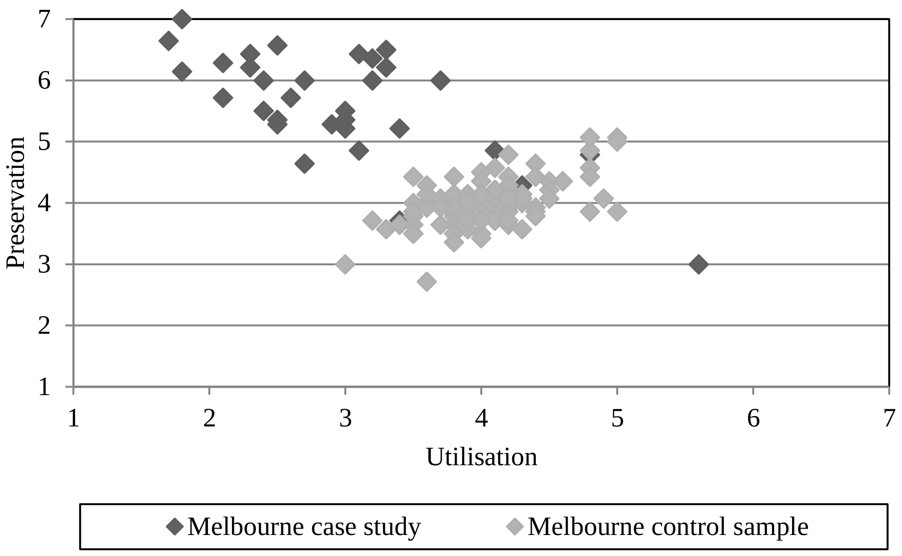

Figure 7.1 EAI survey mean preservation and utilisation scores for individual case study cohort and control group respondents from Melbourne

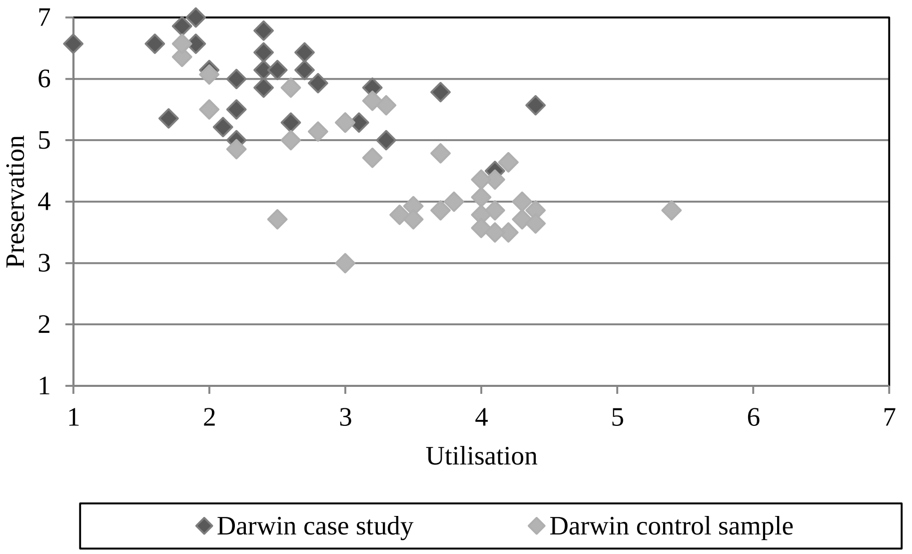

Figure 7.2. EAI survey mean preservation and utilisation scores for individual case study cohort and control group respondents from Darwin

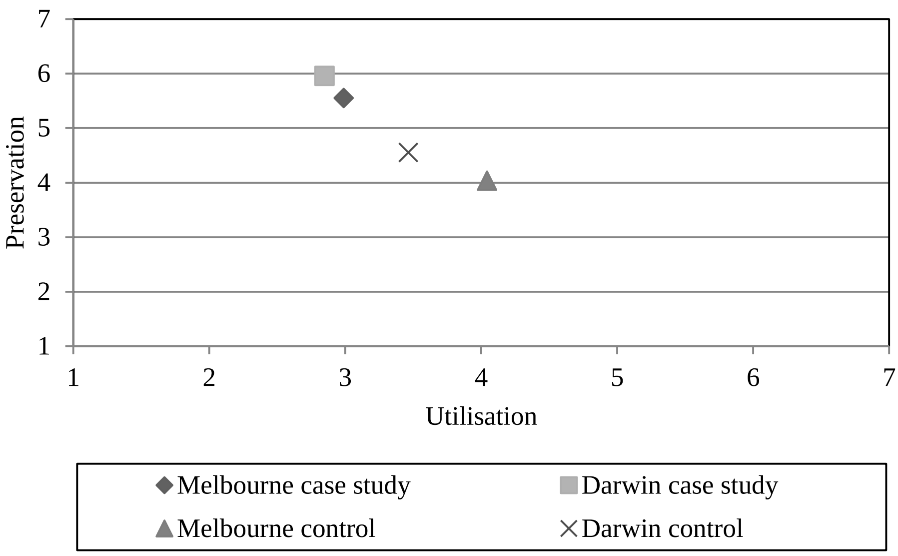

Figure 7.3. EAI survey mean preservation and utilisation scores for the case study and control group samples

7.6 Summary

Overall, the responses to the EAI survey clearly demonstrate that the two case study cohorts have higher levels of environmental concern than the typical population as represented by the two control samples. The strong responses of the case study cohorts to the first order factor Scales 01, 06, 08 and 11 demonstrate that their concern for the environment is largely implicit rather than focused on activism or policy. This aligns with Hedlund-de Witt et al's (2014) finding that linked intrinsic worldviews with the formation of pro-environmental attitudes and behaviours. The relationship also supports the intuitive manner in which the occupants of the case study households have sought to operate their home in a low impact manner as established in the previous chapters.

Whilst an explicit connection cannot be made between the occupants' environmental attitudes and their thermal preferences and behaviour, the results presented above corroborate the housing aspirations, choices and reported behaviours of the occupants these two forms of dwellings. The results support the idea that 'thermal comfort' incorporates a 'value' factor, along with the behavioural, physiological and psychological factors that can influence individuals' adaptation to their thermal environment.

Chapter 8. A proposal for design assessment methodology using comfort criteria

8.1 Introduction

This chapter outlines the proposal of a design assessment methodology using comfort criteria as an indicator of thermal performance. The methodology proposed addresses weaknesses within the current regulatory assessment methods when they are used to assess dwellings of alternative constructions. The proposed design assessment methodology is based on the modification of an existing process with the National Construction Code (NCC) Energy Efficiency provisions (see section 2.2.2 of the Literature Review for an explanation of the structure of the NCC Energy Efficiency provisions and methods for demonstrating compliance with the provisions). As was noted in the literature review, it is unlikely that there will be a radical shift in the manner that the thermal performance of new homes is assessed through the NCC Energy Efficiency performance provisions. Therefore, in order to realistically influence policy, any design assessment methodology must be in some way aligned with the existing process.

The Energy Efficiency provisions include a method of demonstrating the compliance of a proposed design with energy efficiency requirements called ‘Verification using a reference building’ (VURB) (see section V2.6.2.2 of Volume 2 of the NCC, 2015, *note that the full Code can be freely accessed online, URL provided in the reference list*). This method requires the ‘proposed design’ to be modelled in building simulation software capable of calculating heating and cooling loads using prescribed thermostat settings and occupancy profiles. Whilst the Nationwide House Energy Rating Scheme (NatHERS) assumptions are built into *AccuRate*, any suitable software could be used (e.g. Energy Plus, Integrated Environmental Solutions (IES)) that is capable of emulating these assumptions. The proposed model is then tested against a ‘reference building’. The reference building and how it is simulated must be the same as the proposed design in all aspects except for the building fabric, building sealing and air movement, which must comply with the ‘Deemed-to-Satisfy Provisions’ (see Performance Requirement P2.6.2 – Option 2 Elemental Provisions of Volume Two of the NCC, 2015). Compliance is then judged on whether or not the predicted heating and/or cooling loads (MJ/m^2) of the proposed design are lower than those of the reference building. The reference building complies in all respects to the NCC Energy Efficiency elemental approach and therefore complies with certification requirements, i.e. it could be built. It acts as a benchmark of minimum performance requirements by which the performance of the proposed dwelling can be assessed against (ABCB, 2015). Note that the NCC provisions have no requirements that heating and/or cooling appliances be installed in the built dwelling, nor does it deal with appliances in the assessment processes (e.g. coefficient of performance).

The first section of this chapter outlines the development of the assessment methodology and explains how it aligns with the findings presented in Chapters 4 to 7. The second section outlines the formation of models for thermal preference and the cooling effect of air movement based on the collected data to be used in the proposed assessment methodology. The next section demonstrates the validity of the *Australian Government Endorsed calculation engine*, second generation *AccuRate,* in predicting the possible future indoor thermal conditions of dwelling designs. The final section demonstrates the application of this methodology using the designs of four of the case study dwellings; two in Melbourne and two in Darwin. The implications of the inclusion of such an approach in the NCC Energy Efficiency provisions are explored in the summary of the chapter.

Portions of this chapter were previously published and have been quoted directly from the following sources (Daniel et al, 2012; 2013; 2014b; 2015a). Permission has been granted by all co-authors to quote published material without rephrasing.

8.2 Development of design assessment methodology

It is suggested that the existing VURB methodology can be adapted to use comfort criteria as a performance indicator rather than the current energy load indicator. The key attributes, as described in detail further below, of such a modified VURB process would be;

1. Both the proposed design model and the reference building model are simulated as free-running (e.g. no artificial heating and cooling);
2. The predicted internal thermal conditions of the proposed design are assessed against a model of thermal preference developed from the data collected during this research;
3. The predicted internal thermal conditions of the reference building are assessed using the ASHRAE adaptive 80% acceptability limits, as explained below;

4. The upper and lower boundaries of both the proposed comfort model and the adaptive model are based on the 7-day running weight mean outdoor air temperature corresponding to the climate file used for simulation; and
5. Compliance is judged on whether or not the proportion of hours that the predicted internal conditions of the proposed design model were above and/or below the comfort boundaries were less than that of the reference building model.

The above changes seek to provide a more equitable method by which to demonstrate compliance with the NCC Energy Efficiency provisions for dwelling designs that incorporate alternative constructions (summarised in Table 8.1). Justification of these changes is provided below, referring to findings reported in Chapters 4 to 7, as well as relevant literature.

Table 8.1. Comparison of the existing VURB process and the modified VURB process

Steps	Existing VURB process	Adapted VURB process using comfort criteria
1	Model proposed design and simulate to predict heating and cooling energy loads	Model proposed design and simulate in free-running mode to attain predicted hourly internal temperatures Determine proportion of hours that the internal temperatures is outside of the comfort boundaries
2	Modify the model to create compliant reference building and simulate to predict heating and cooling energy loads	Modify the model to create compliant reference building and simulate in free-running mode to attain predicted hourly internal temperatures Determine proportion of hours that the internal temperatures is outside of the comfort boundaries
3	Compare heating and (or) cooling loads to determine compliance of proposed design	Compare proportions of time that internal temperatures are outside of the respective comfort boundaries
4	In climate zones 1 and 2 the cooling load of the proposed design must be ≤ than that of the reference building In climate zones 7 and 8 the heating load of the proposed design must be ≤ than that of the reference building In climate zones 3, 4, 5 and 6 the heating and cooling loads of the proposed design must be ≤ than those of the reference building	In climate zones 1 and 2 the proportion of time that temperatures in the proposed design are above the upper comfort boundary must be ≤ than that of the reference building In climate zones 7 and 8 the proportion of time that temperatures in the proposed design are below the lower comfort boundary must be ≤ than that of the reference building In climate zones 3, 4, 5 and 6 the proportions of time that temperatures in the proposed design are either above or below the comfort boundaries must be ≤ than those of the reference building

Attribute 1: Assessment of thermal conditions

Within the current Energy Rating and VURB compliance assessment methodologies all dwelling designs are simulated in order to predict the heating and/or cooling loads required to maintain ‘comfort’ conditions (note, validation of the simulation tool is examined in Section 8.4). The simulation of heating and/or cooling requires many assumptions to be made about how the occupants may use the dwelling; e.g. hours of occupancy, rooms conditioned, thermostat set-points, timing of appliance use. These fixed assumptions are prescribed by the NatHERS protocols and are outlined in Table 2.1. Importantly, NatHERS requires all habitable rooms to be conditioned during occupied hours. The way in which occupants of earth buildings and naturally ventilated dwellings operate their homes is substantially different to the behaviours reflected by the NatHERS assumptions; therefore, the operation of heating and/or cooling appliances is significantly over estimated (Daniel et al, 2015a). For example, the respondents to the earth building national survey, as well as the occupants of the Melbourne case study dwellings, tended to only heat their main living area during afternoons and evenings, and the majority of these households did not have air conditioning. Where cooling appliances were installed, use was judicious and infrequent; often limited only to periods of prolonged hot weather. In the naturally ventilated dwellings in Darwin, cooling appliances were mainly in bedrooms to assist with sleep. Other reasons for use responded to social factors, such as the presence of guests, which is problematic to capture in any type of thermal performance assessment. These behaviours are similarly reflected in the proportion of instances when heating and/or cooling appliances where used when thermal comfort surveys were recorded within the case study dwellings; the Melbourne households only used heating appliances 29.8% and cooling appliances 0.7% of the times that votes were cast, while in the Darwin households, cooling appliances were used just 0.8% of the times that votes were cast.

The occupants in the Melbourne and Darwin case study households also used a range of techniques to mitigate against an unacceptable thermal environment instead of, or in conjunction with, heating and/or cooling appliances (e.g. change clothes, open windows, turn on fans, move rooms). Other studies of adaptive behaviours in Australian dwellings show that these techniques vary widely with climate and individual households (Williamson et al, 1990; Karol, 2011; Saman et al, 2013). This demonstrates that the range of behaviours relating to the discretionary use of heating and/or cooling appliances in Australian households cannot be sufficiently predicted by temperature alone.

The assessment of thermal comfort conditions addresses a more fundamental level of building performance than the assessment of the potential energy loads from heating and/or cooling appliances. This approach also eliminates the needs for many of the inappropriate assumptions necessary in the simulation of heating and/or cooling.

Attribute 2: Application of thermal preference model in the assessment of the 'proposed building'

The predicted thermal conditions from the proposed design simulation model will be assessed using a thermal preference model developed from the thermal comfort survey data collected in this research, assumed to be representative of these cohorts. The development of a model to describe the thermal preferences of the two case study cohorts was necessary for two reasons; (1) it is no longer useful to aim for a single temperature (i.e. thermostat setting) derived from neutral/comfort temperatures because the dwellings will be simulated without heating and/or cooling appliances; and (2) it is clearly demonstrated in section 6.5 that existing models of thermal comfort do not sufficiently encompass the range of conditions that these occupants find acceptable. Explanation of the development of a model for thermal preference is given in Section 8.3.

Attribute 3: Application of ASHRAE adaptive thermal comfort model in the assessment of the 'reference building'

Within the VURB process, the reference building model essentially represents minimum performance standards of a 'typical' or normal building with which to compare the proposed (atypical) building. Therefore the ASHRAE adaptive 80% acceptability limits have been used to represent conditions that the 'typical' occupant is likely to find comfortable when the building is naturally ventilated. Saman et al (2013) found that the ASHRAE model gives a reasonable indication of acceptable comfort in houses that use heating and cooling in three temperate Australian climates (i.e. Adelaide, Brisbane and Sydney).

Attribute 4: Representation of outdoor climate

The simulations will use the climate files provided within the *AccuRate* software. These are formulated by NatHERS to represent a typical meteorological year. For the assessment of predicted internal conditions both the thermal preference model and the ASHRAE adaptive model use a 7-day running weighted mean temperature to represent outdoor conditions. This is based on the temperature data within the corresponding NatHERS climate file used for simulation. The ASHRAE 55-2013 equation (Equation 3.1) will be used to calculate the 7-day running weighted mean temperature. The development of this equation was support by observations of clothing patterns and outdoor temperatures in Sydney, making it more appropriate for an Australian context than the European based CEN 15251-2007 counterpart. A strong relationship can be observed between the 7-day running weighted mean temperature and acceptable indoor conditions reported by the occupants of the Melbourne and Darwin case study cohorts (Figure 8.1), further supporting the use of this equation. The use of NatHERS climate files assists in integrating the modified VURB process with existing methods to demonstrate compliance with the Energy Efficiency provisions.

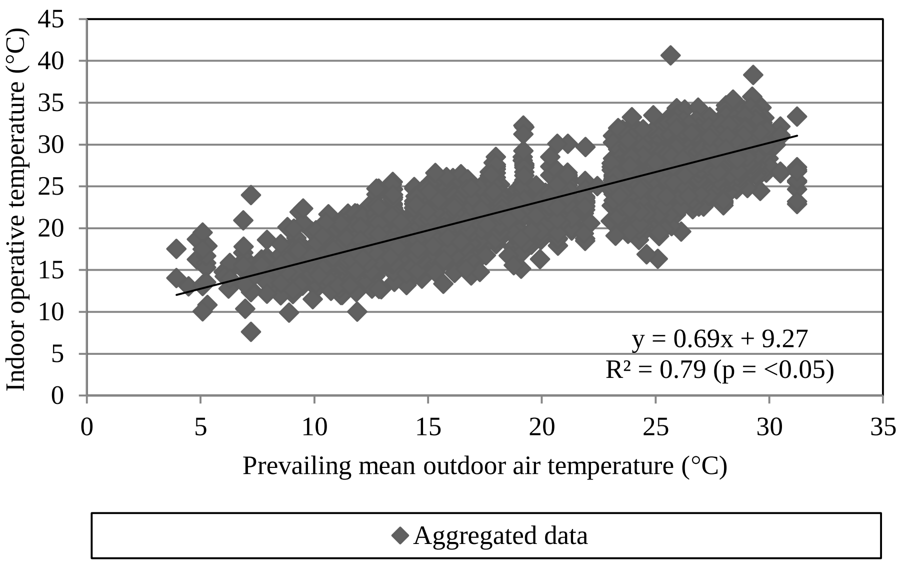

Figure 8.1. Aggregated "No change" votes cast by the Melbourne and Darwin cohorts when no heating and/or cooling appliances were operating

Attribute 5: Determination of compliance

In order to demonstrate compliance with the Energy Efficiency provisions using the modified VURB process, the thermal conditions from the proposed building model must be acceptable for a greater proportion of time than those from the reference building model. This is a simple translation of the requirements from the existing VURB process which compares predicted energy loads instead (see step 4 in Table 8.1). If this requirement is satisfied, then logically, the proposed building offers a more adequate level of thermal performance that aligns with the expectations and preferences of the occupants of the two forms of atypical housing studied.

The simulation software, *AccuRate,* outputs predicted hourly temperatures for each zone (room), for an entire year. All hours are included in the assessment of acceptable conditions to avoid perpetuating standardised assumptions regarding hours of occupancy. Neither the national survey results, nor the in-depth case study results revealed noticeable trends in the times of day that households used certain rooms. Instead, this behaviour seemed largely governed by the individual household's circumstances and daily schedules. Note that in the demonstration of the modified VURB process in section 8.5, the main living area and main bedroom have been assessed, conceivably this process would compare the performance of all habitable rooms if used for regulatory assessment.

8.3 Describing the thermal preference of occupants of atypical forms of housing

In order to make an assessment of the performance of an actual or a simulated thermal environment some judgement must be made on what is an acceptable range of thermal conditions. Currently, both the Predicted Mean Vote (PMV)/Predicted Percentage Dissatisfied (PPD) and the adaptive ASHRAE ranges of thermal comfort are based on the assumption of a relationship between a neutral thermal sensation vote and 'comfort'. This originates from Gagge et al's (1967) finding that the subjective responses of 'comfort' and 'neutral' from one male subject occur at the same temperature, and that discomfort begins to occur at 'slightly cool' or 'slightly warm' (corresponding to ±1 on the -3 to 3 scale, or 3 and 5 on the 1 to 7 scales). Fanger cites Gagge et al's findings in the formulation of the PPD index in Chapter 4 (1970), which is subsequently cited by de Dear & Brager (1998) in the development of the adaptive model upper and lower acceptability limits. The relationship between different sensation and preference scales and 'comfort' (or acceptable conditions) is an ongoing area of work within the field of thermal comfort research (Humphreys & Hancock, 2007; Langevin et al, 2013).

A relationship between a neutral thermal sensation vote and 'comfort' is not apparent in the analysis of the thermal comfort surveys collected from the Melbourne and Darwin cohorts. The temperatures corresponding to 'neutral' (19.5 °C for Melbourne, 27.4 °C for Darwin) and the temperatures corresponding to the highest mean comfort vote response (22.1 °C for Melbourne, 24.8 °C for Darwin) are considerably different; demonstrating a preference for warmer than neutral sensation by the Melbourne cohort and cooler than neutral sensation by the Darwin cohort.

With this consideration in mind the thermal comfort range of the proposed model will be informed by the thermal preferences votes rather than the thermal sensation votes. There are two reasons in choosing to use this scale. The first is that it has been demonstrated in the findings of this research that individuals do not necessarily want to feel 'neutral' (see Figure 8.2 and Figure 8.3); this is also widely supported by the literature (Humphreys & Nicol, 2004; Humphreys & Hancock, 2007; Li et al, 2010; Tweed et al, 2014). Secondly, it is expected that the thermal preference vote more close indicates when an individual is likely to take action to change their thermal environment because it reflects when they desire change (Brager et al, 1993; Williamson et al, 1995). This is particularly relevant in a residential context, as revealed by the case study households, where the occupants utilise a wide range of adaptive responses.

It is important to note that this model has not attempted to distinguish between thermal comfort in living areas and bedrooms. To do so would be beyond the scope of this project. The thermal experience of occupants in bedrooms in cooler climates is primarily influenced by bedding and clothing, rather than the indoor thermal environment (Lui et al, 2014; Wang et al, 2015). Both Liu et al (2014) and Wang et al (2015) found that occupants were quite comfortable sleeping in rooms with relatively low temperatures (15.8°C was cited as the thermal neutral temperature during sleep), as long as the bed temperature was approximately 30°C – 31°C. Studies of sleeping conditions in tropical climates indicate the need for air conditioning to achieve comfort (Tenorio, 2002; Dongmei et al, 2013), and this trend is similarly reflected in the responses from households with air conditioning in the national survey as well as the in-depth case study households. Assisting with sleep was the primary reason given for air conditioning use, however there were also many households that did not use air conditioning during nighttime hours, relying instead on air movement provided by natural ventilation and fans. This is clearly an area that may need further exploration, with the possibility that bedrooms are somehow assessed differently to living areas. When occupants use bedrooms for other purposes than sleeping, it is reasonable to assume that their thermal preference will be adequately represented by the developed thermal preference model.

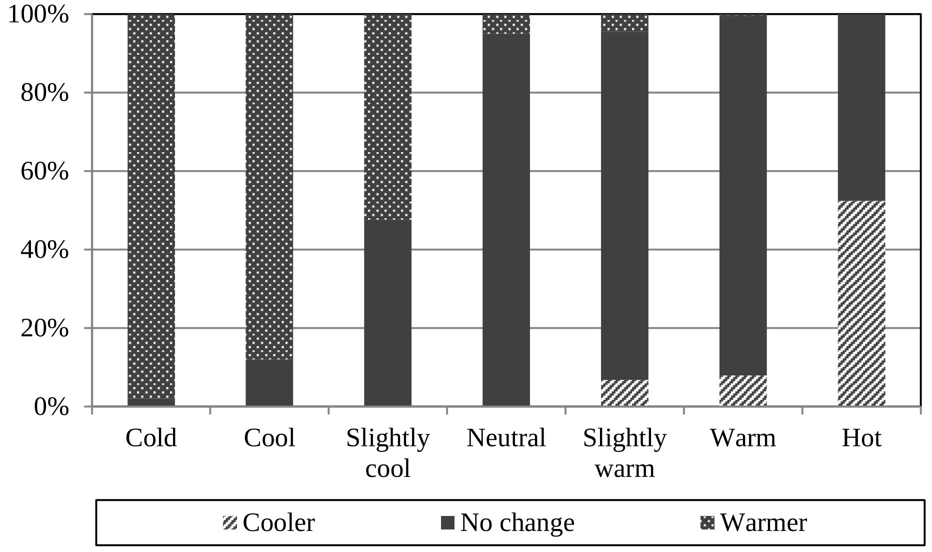

Figure 8.2. Total proportion of thermal preference votes at each thermal sensation vote scale for the Melbourne cohort

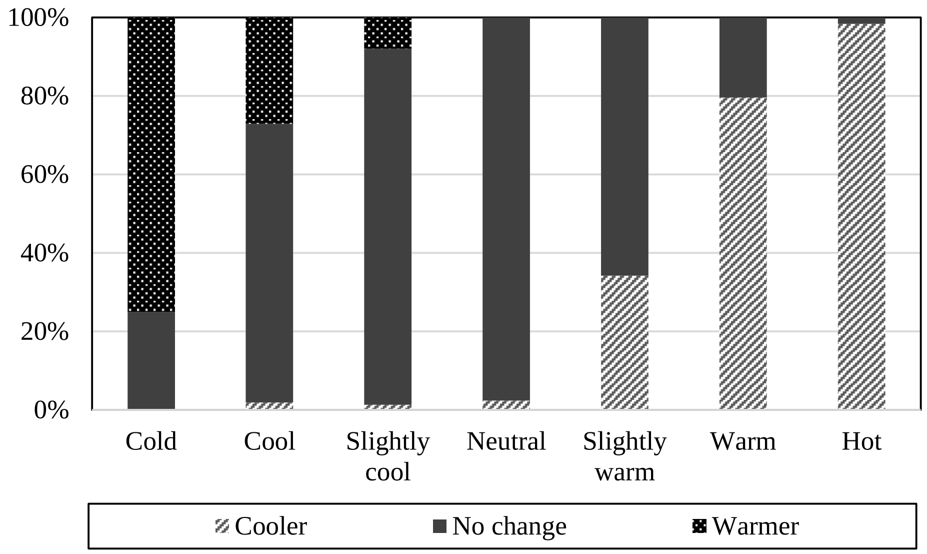

Figure 8.3. Total proportion of thermal preference votes at each thermal sensation vote scale for the Darwin cohort

8.3.1 Proposed model

In order to determine the upper and lower limits of the two cohorts' thermal preference a statistical process was used to calculate the range of 90% of the "No change" votes based on the prevailing outdoor air temperature and measured indoor operative temperature. The thermal preference votes were binned by the running weighted daily mean temperature and filtered to exclude votes that represented the desire for change (i.e. 1= "Cooler" and 3= "Warmer"). Outliers were deleted based on a interquartile range test of the indoor temperatures. The binned data were tested for normal distribution using the Shapiro-Wilk test. An *Excel* function was used to return the inverse of the normal cumulative distributions 0.05 and 0.95 based on the mean and standard deviation of the binned temperatures. This process was completed for both cohorts individually (see Figure 8.4 and Figure 8.5) and then repeated for the aggregated data from both cohorts (see Figure 8.6). The resultant model of thermal preference adopts Equation 8.1 as the lower limit of acceptable conditions and Equation 8.2 as the upper limit of acceptable conditions.

$$\text{Lower limit} = 0.5529t_{pma(out)} + 8.4608 \qquad (8.1)$$

Where: $t_{pma(out)}$ = prevailing mean outdoor air temperature

$$\text{Upper limit} = 0.443t_{pma(out)} + 18.431 \qquad (8.2)$$

Where: $t_{pma(out)}$ = prevailing mean outdoor air temperature

An important distinction to make between this model and the ASHRAE adaptive model is that it only represents conditions where the occupants reported no desire for change and is therefore taken to represent their preferred conditions. Because the thermal preference votes at 1= "Cooler" and 3= "Warmer" were excluded this model does not consider discomfort or non-preferred conditions as such.

The relationship between the proposed thermal preference model and the thermal sensation votes cast by subjects from both cohorts is shown in Figure 8.7, demonstrating the more appropriate 'fit' of this model for the occupants studied (see also section 6.5.3). Again, it is possible to observe the preference for neutral and warmer sensation of the Melbourne cohort, and neutral and cooler sensation of the Darwin cohort in this plot by the slight trend of the bulk of the data points to sit towards the lower and upper boundaries respectively.

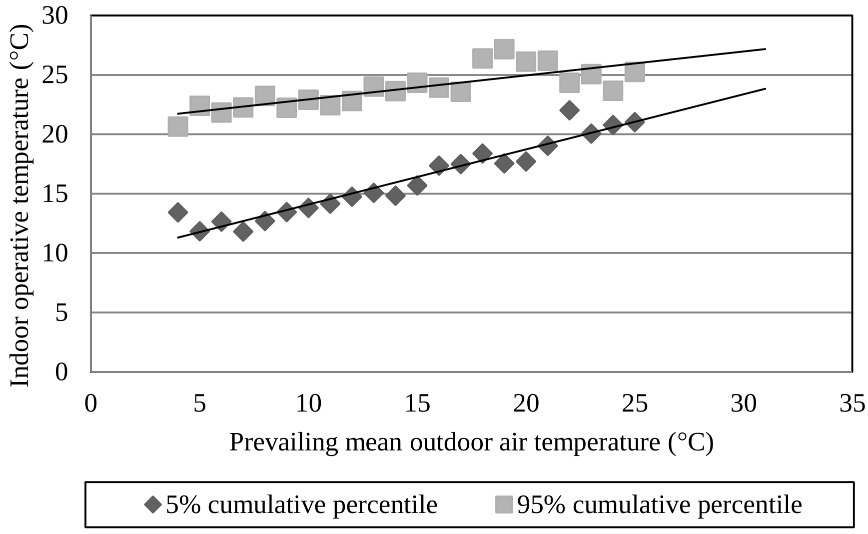

Figure 8.4. 90% percentile preference boundaries for the Melbourne cohort

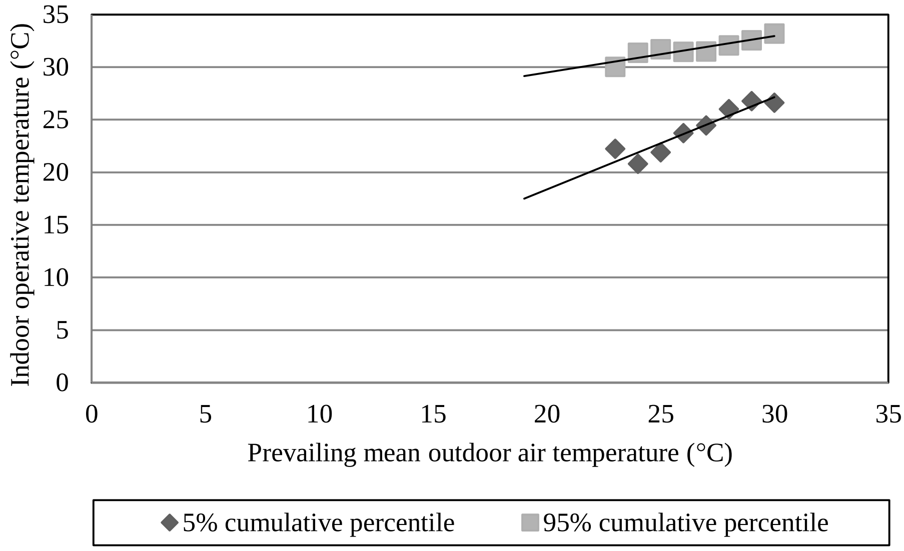

Figure 8.5. 90% percentile preference boundaries for the Darwin cohort

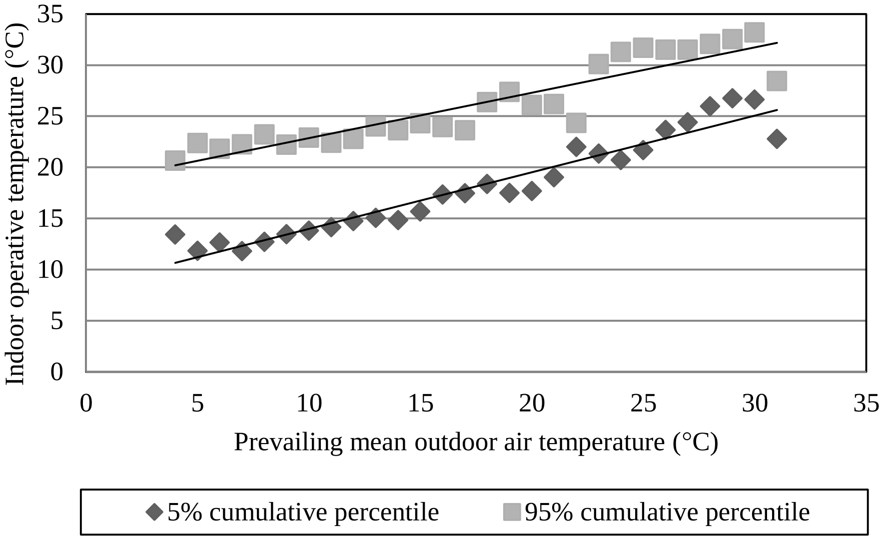

Figure 8.6. 90% percentile preference boundaries for the aggregated data from both cohorts

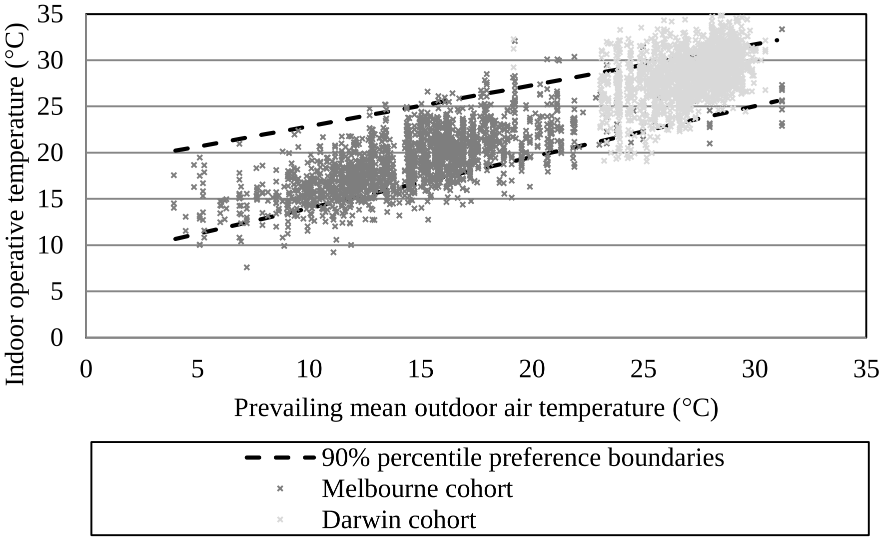

Figure 8.7. Comparison of the "Slightly cool", "Neutral" and "Slightly warm" thermal sensation votes when no heating or cooling appliances were in use with the proposed thermal preference model

8.3.2 Cooling effect of air movement: extension of the proposed model for hot humid climates

Using comfort criteria in the judgement of thermal performance, the cooling effect becomes much more important, particularly in the hot humid climate of Darwin where the houses are specifically design to maximise air movement and ceiling fans are used on a regular basis. The effect of air movement on thermal comfort is inherently difficult to assess, however, in order to attempt to adequately account for the benefits of air movement in the assessment of thermal conditions within the naturally ventilated Darwin houses, a model for the cooling effect of air movement was developed using the collected data.

International thermal comfort standards facilitate some increase in the upper boundary of comfort in warm to hot conditions due to elevated air speeds. 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, for the CEN adaptive model the comfort boundaries are extended for air speeds above 0.2m/s when the indoor operative temperature is above 25°C using a 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.

Within the A*ccuRate* software, 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 8.3 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). The majority of the references used by Szokolay are assessed at RH = 50%. Again, despite the recognition that the cooling affect may diminish with increasing humidity, it is not included in the Szokolay equation.

$$dT = 6v_e - 1.6v_e^2 \tag{8.3}$$

Where: dT = cooling effect (K), v = actual air speed (m/s), v_e = effective air speed = v-0.2m/s

In order to take humidity into account when describing the cooling effect of air movement a model was developed using the thermal comfort survey and environmental measurements data from the Darwin households. A model is proposed for the comfort effect of the form $dT = f(v_e, RH\%)$, in order to identify the parameters of this function the surveys where occupants had elected a 'no change' preference vote were binned into less than 75% RH and greater than 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 (see Figure 8.8 for a diagrammatical explanation of the process).

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 were attained for each of these bins. The temperature corresponding to 0.2m/s was determined using the equations derived from plotting the average temperature and average air speed at each bin. To attain the cooling effect (°K), the temperature at 0.2m/s was subtracted from the average indoor operative temperature for each air speed bin. To get an effective air speed, 0.2m/s was subtracted from the measured average air speed following Szokolay's methodology. The effective air speed was then plotted against the cooling effect; each plot in these cases is constrained to pass through the 0.0 point because by "definition" in the Szokolay method there is no cooling effect at zero effective air speed. The coefficients derived from each humidity bin are presented in Table 8.4.

The coefficient for each humidity group was then plotted against the average humidity for that group (see Figure 8.9). This yields an equation by which the cooling effect of air movement can be calculated (Equation 8.4 and Equation 8.5). The cooling effect for three different humidity levels is compared with Szokolay's function in Figure 8.10.

$$y = 4.86 - 0.029RH \tag{8.4}$$

Where: RH = relative humidity

$$dT = v_e y \tag{8.5}$$

Where: dT = cooling effect (K) as a function of air speed (m/s), v_e = effective velocity

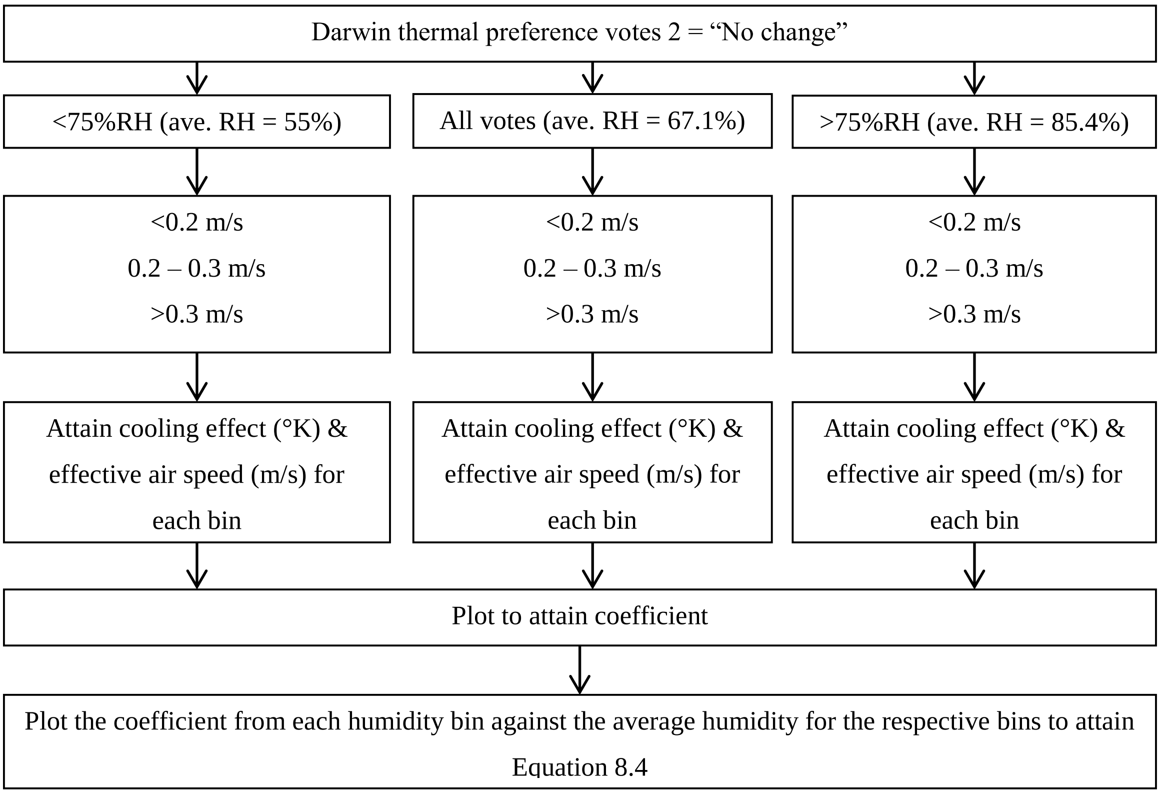

Figure 8.8. Diagram of the process to determine a model for the cooling effect of air movement

Table 8.2. The average humidity and coefficient of cooling effect (°K) vs air speed (m/s) for each humidity bin

Humidity bin	**Average humidity (RH%)**	**Coefficient**
<75RH values	55.0	3.238
All RH values	67.1	2.991
>75RH values	85.4	2.377

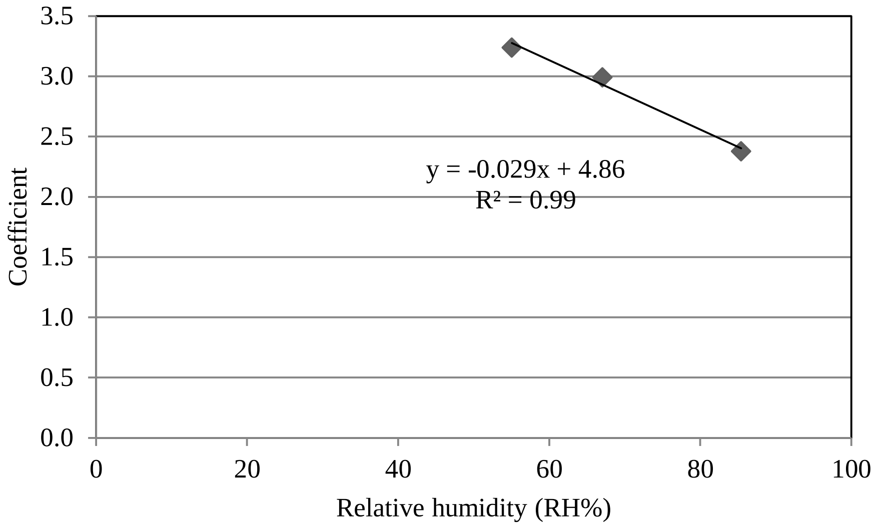

Figure 8.9. Coefficient & relative humidity

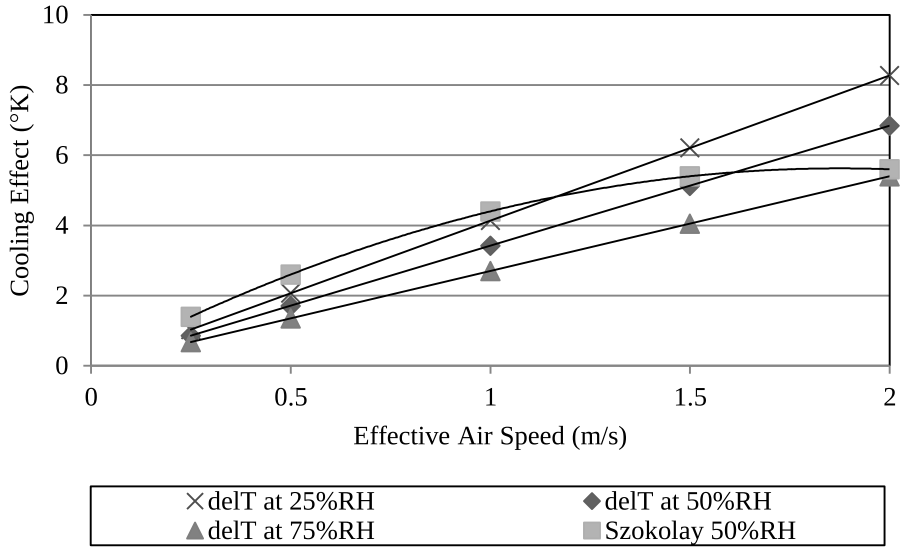

Figure 8.10. Comparison of the calculated cooling effect of air movement with Szokolay's proposed function (Szokolay, 2000, p147)

As demonstrated in Figure 8.10, at higher humidity levels, the cooling effect is reduced. For example, at 50%RH with an effective air speed of 1.0m/s, using the proposed model, the upper boundary of comfort could be raised by 3.4°K, while at 75%RH with the same air speed, it would be raised by only 2.7°K. 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.

Note that this model does not account for turbulence or stratified air movement; however, currently, *AccuRate* only estimates a single figure of air speed for each zone. Therefore, a simplified model for the cooling effect of air movement is sufficient for this application. Currently, other widely used simulation programs such as *Energy Plus* and *IES* do not have the functionality to simply produce such data, instead complex computational fluid dynamic (CFD) modelling would be required (Gu, 2007; IES, 2015). CFD analysis to attain air speed data would likely not be practical in the application of the proposed assessment methods due to time and knowledge requirements.

Simulation output requirements

The standard output from *AccuRate* are predicted heating and/or cooling loads in MJ/m^2 accessed through the user interface, however a *.tem file (essentially a text file) containing hourly predicted internal temperatures and corresponding outdoor temperatures from the climate file can be attained from the program files folder. Whilst the simulation engine does calculate relative humidity and air speed which are included in the calculations of cooling load requirements, these data are not output. Similarly, in the standard version of *AccuRate* in free-running mode the ceiling fan operation algorithm is not called.

In order to attain these data, schedule fan operation and natural ventilation a research version of the *AccuRate* simulation engine was provided by CSIRO. This engine required the supplementary input of a fan on/off temperature and natural ventilation on/off temperatures. The hourly air speed and relative humidity data for each zone were output as a text file.

Simulation of ceiling fan operation and natural ventilation

The temperatures at which ceiling fan operation and natural ventilation occurred were informed by the results of the national survey of occupants living in naturally ventilated homes as well as the results from the thermal comfort survey. The national survey shows that respondents generally run ceiling fans year round, with a small reduction in use over the cooler dry period mid-year. Similarly, the time of day did not consistently dictate fan operation. This is comparable with fan use recorded by occupants of the Darwin case study households in the thermal comfort vote surveys (see Figure 8.11 and Figure 8.12). Therefore, no seasonal or timing restrictions would be placed on fan use. The ceiling fan on/off temperature used for simulation will be 28°C. This corresponds to the temperature at which 50% of the occupants report fan use when recording a thermal comfort vote survey (see Figure 6.31).

The additional air movement provided by the ceiling fans is attained by backward calculation from Equation 8.6 and Equation 8.7 (Dong, 2011). See Appendix H for more detail.

$$dT_{ave} = \text{Minimum}(dT, dT*\text{ZoneCeilingFanNumber}*\text{TargetArea}/\text{ZoneFloorArea}) \tag{8.6}$$

Where: dT = cooling effect attained using Equation 8.3

$$v_e = 2.075-(3.5156 - 0.625dT_{ave})^{0.5} \tag{8.7}$$

Where: v_e = effective air speed = v-0.2m/s

The Darwin case study households were almost always naturally ventilated; therefore the temperatures dictating natural ventilation would be set so that the windows and doors are always open (i.e. minimum threshold temperature lower than any reached in Darwin and maximum threshold temperature higher than any reached).

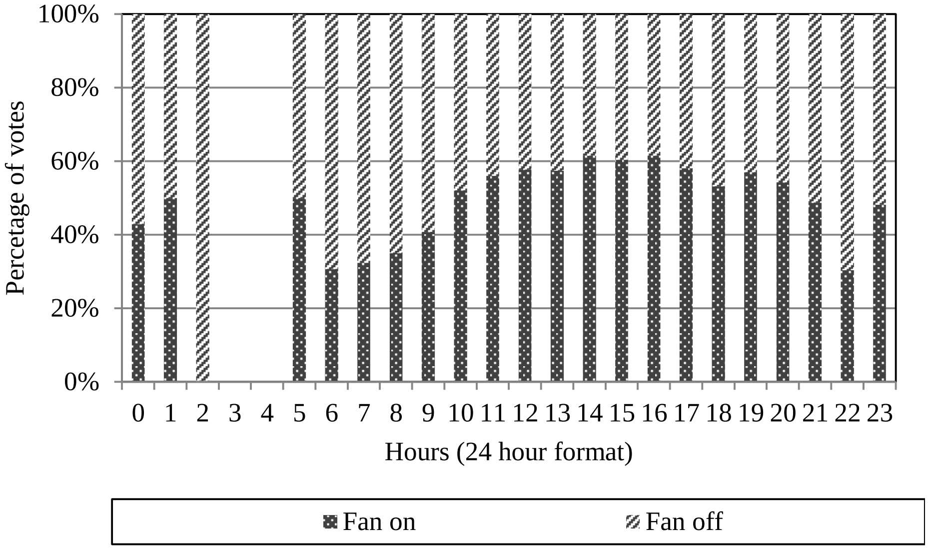

Figure 8.11. Proportion of votes during the day where fans are on or off

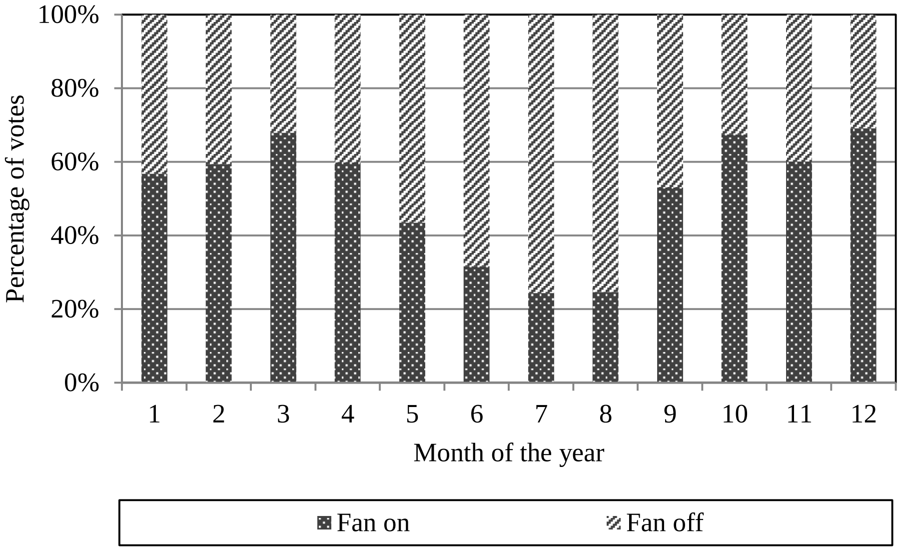

Figure 8.12. Proportion of votes during the year that fans are on or off

8.4 Verification of the *AccuRate* simulation engine

Whilst building performance simulation tools are used extensively worldwide, issues arise when the model is taken to represent a 'real' system without sufficient acknowledgement of the assumptions that have been incorporated into the formation of the model. In the Australian context this has caused some stakeholders to question the validity of the *AccuRate* simulation engine (Delsante, 2006). Addressing these concerns, Daniel et al (2015a) demonstrated that incorrect assumptions about the occupants and their behaviour are the primary cause of the gap between predicted and actual building performance. Therefore the problem exists within the framework or scheme rather than within the simulation tools themselves. Before the application of the proposed VURB methodology is demonstrated, it is important to insure the validity of the *AccuRate* simulation engine for predicting indoor thermal conditions.

To confirm the capacity of the *AccuRate* simulation engine to adequately model the two types of dwelling constructions addressed within this study, four of the case study dwellings were modelled (two from the Melbourne cohort and two from the Darwin cohort). The predicted internal temperatures of the living areas were compared with the corresponding measured data from those rooms. These four comparisons can be considered as validation investigations determining whether or not an *AccuRate* simulation model can provide an accurate representation of a 'real' system. The extent to which the results match will provide an indication of the level of confidence with which the software can be used within the proposed VURB process.

The four dwellings used for the validation study were chosen because they represent some of the key construction variations within the two cohorts. Dwellings 15 and 18 were chosen from the Melbourne sample, and Dwellings 34 and 35 from the Darwin sample.

Dwelling 15 is comprised of concrete-slab-on-ground floor construction, uninsulated mud brick external walls, a combination of mud brick and brick internal walls and a raked ceiling/roof with approximately R2.0 batt insulation. The total floor area of the house is $134m^2$. The main living area is open-plan with heavily shaded north (equator) facing glazing.

Dwelling 18 has a raised timber floor with an enclosed subfloor space below, uninsulated compressed earth block external walls, a combination of earth block and light weight stud internal walls and a raked ceiling/roof with approximately R2.5 batt insulation. The total floor area of the house is $260m^2$. The primary living areas face north-east and south-west. The entire house has deep 2m eaves.

Dwelling 34 consists of concrete-slab-on-ground floor construction, uninsulated concrete blockwork and cavity brick walls, and an uninsulated flat roof. The total floor area of the house is $146m^2$. The main living space faces south, with the south and east walls heavily shaded. The north and west walls are exposed. The dwelling is fairly protected by tall vegetation and surrounding houses.

Dwelling 35 has a raised timber floor with approximately 2.2m clearance from the ground, lightweight corrugated iron clad walls (uninsulated except for a bedroom addition), lightweight internal stud walls and a pitched roof with flat ceiling (uninsulated except for a bedroom addition). The floor area of the dwelling is $107m^2$. The open-plan living space has shaded north and south facing glazing.

See Appendix E for the plans of dwellings 15, 18, 34 and 35.

8.4.1 Calibration of models

The primary statistical indicator of correlation used to assess simulation validity in this study is the Coefficient of Variance of the Root Mean Square Error (CV(RMSE)), recommended in the ASHRAE *14-2002 Guideline for Measurement of Energy and Demand Savings*. Although this guideline is based on the analysis of energy use, the CV(RMSE) in this context is the predicted internal temperatures compared to the measured internal temperatures. A CV(RMSE) value of between 10-20% has been cited as acceptable for empirical models by several authors (Kreider & Haberl, 1994; Bou-Saada & Haberl, 1995; United States Department of Energy, 2002).

Custom *AccuRate* climate files were created for the Melbourne and Darwin locations. The climate file for the two Melbourne dwellings was compiled from measurements (temperature, relative humidity, wind speed & direction, and solar radiation) from the HOBO U30 weather station installed in Nillumbik Shire during the monitoring period. The Darwin climate file was compiled using a combination of hourly weather data from the BOM Darwin Airport weather station and solar radiation data derived from satellite measurements for that location (Lee, 2011).

The four house models were initially simulated in free-running mode, with no artificial heating or cooling. All of the input and assumptions (except for removing the heating and/cooling) in the initial simulation were as required by NatHERS protocols. For the validation exercise, best input data were derived from simulation iterations (e.g. material dimensions). Initial input were based on construction drawings, changes were then made to input data to reflect the in-use/actual situation (e.g. tapestries hung internally on walls). All simulations were completed for an entire year and comparisons of predicted and measured data made for the periods of available monitoring data (just under a year in most cases). All simulations were completed using *AccuRate Sustainability V2.3.3.13 (SP2)*.

Table 8.2 summarises the CV(RMSE) achieved for the four models, further detail regarding the calibration exercise for each house is given in the four following sub-sections.

Table 8.3. The CV(RMSE) of the predicted internal temperatures compared to the measured internal temperatures for the main living spaces of Dwellings 15, 18, 34 and 35

Dwelling ID	**15**	**18**	**34**	**35**
CV(RMSE)	11.9%	8.5%	3.1%	6.6%

Dwelling 15 - Melbourne

For periods of warmer weather where no cooling appliances were used within the home, the simulation model reasonably predicted the internal temperatures (see Table 8.2, Figure 8.13 and Figure 8.15), however in cooler periods when heating was used the predicted temperatures were consistently about 5°C lower than the measured temperatures (see Figure 8.14). Two key modifications were made to the model to improve its accuracy. Firstly, the default natural ventilation schedule was turned off because the occupants reported that their operation of windows and doors was infrequent. This removed a trough in predicted temperatures in the afternoon and evening (see Figure 8.13). Secondly, space heating was switched on. Limitations of the software precluded replicating how the occupants actually used their heating appliance; however 'turning on' the heating did align the troughs of the predicted and measured temperatures. This indicates that the model was able to reproduce the effects of thermal mass storage provided by the mud brick external walls and brick internal walls. All modifications made to improve the accuracy of the model were;

1. Increased the thickness of the timber ceiling lining to reflect mass provided by exposed structural timber;
2. Material layer added to the internal face of all walls to account for hung tapestries;
3. Increase the thickness a central internal wall (fireplace) that provided significant mass to the space;

4. Switched off default natural ventilation schedule;
5. Changed the default internal window coverings from ‘holland blinds’ to ‘heavy drapes and pelmets’;
6. Changed the colour of the exposed side of the roof sheeting; and
7. Added heating to the space (note that artificial cooling was never used in this space).

The final model produced a CV(RMSE) of 11.9% (see Table 8.2), however much of that variation can be attributed to the manner in which *AccuRate* models heating within a space; i.e. in the simulation the zone is continually heated according to a predetermined thermostat setting for set hours of the day. If only a short period of time when heating is not operating is considered, for example between the 19th and 22nd of March (Figure 8.15), the CV(RMSE) is as low as 3.7%, indicating good agreement between the predicted and measured temperatures.

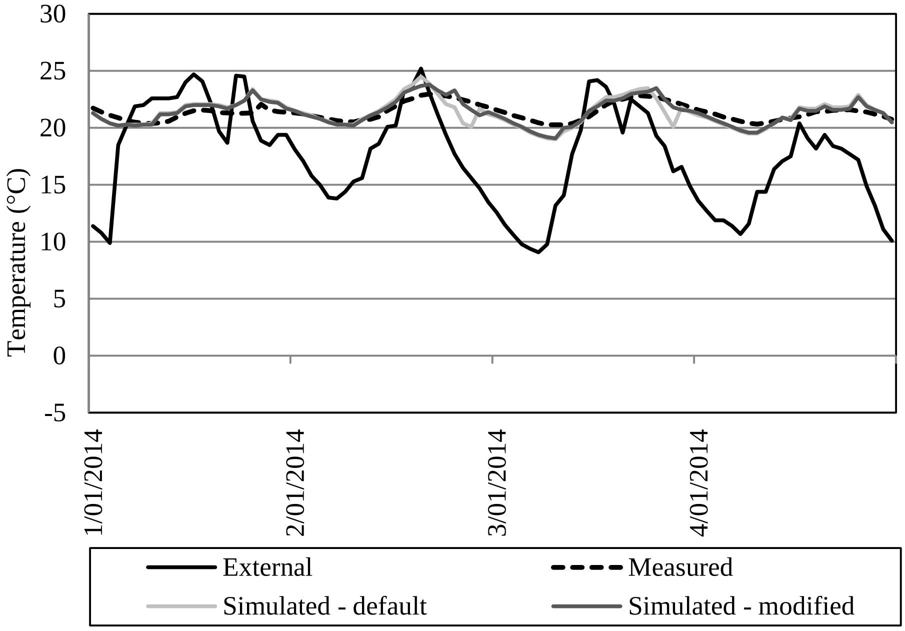

Figure 8.13. Comparison of external, measured internal and predicted internal temperatures for Dwelling 15 in a summer period 1st – 4th January 2014

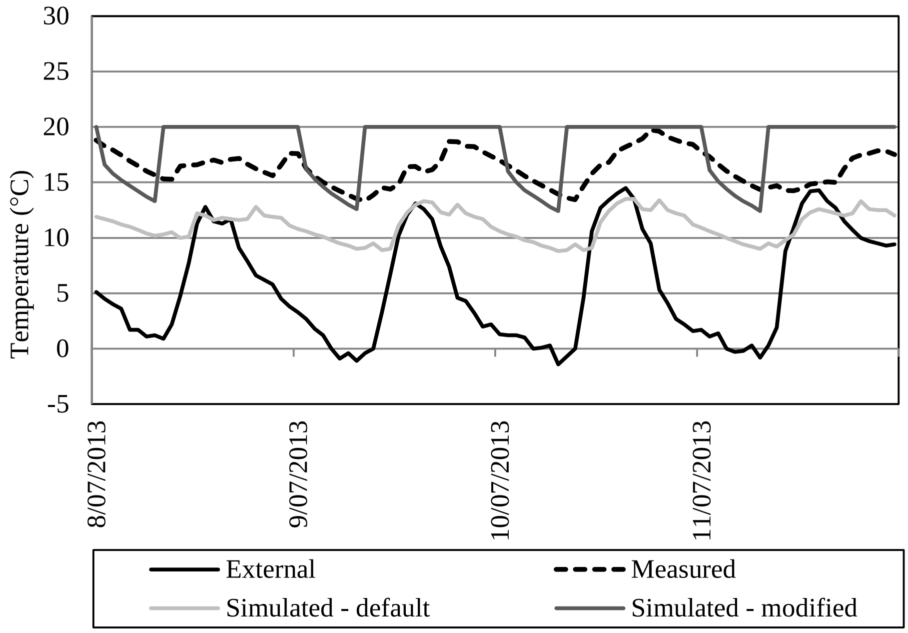

Figure 8.14. Comparison of external, measured internal and predicted internal temperatures for Dwelling 15 in a winter period 8th – 11th July 2013

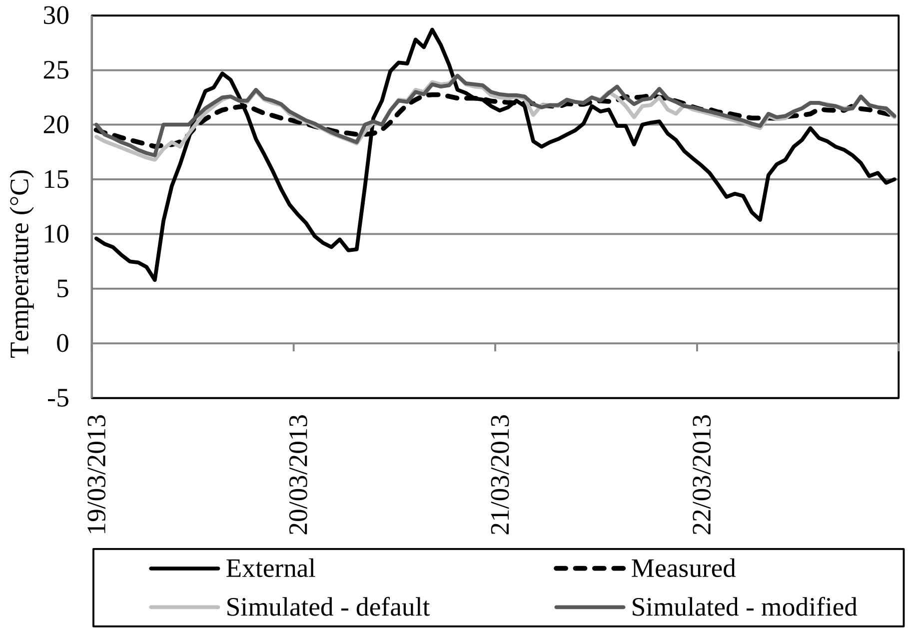

Figure 8.15. Comparison of external, measured internal and predicted internal temperatures for Dwelling 15 in a transition season 19th – 22nd March 2013

Dwelling 18 - Melbourne

The initial simulation model of Dwelling 18 demonstrated similar issues to those addressed in the model of Dwelling 15. The occupants of Dwelling 18 also reported little operation of windows and doors for ventilation so the default natural ventilation schedule was turned off. This resulted in a ‘flattening out’ of the troughs associated with afternoon and evening ventilation (see Figure 8.18). Adding space heating improved the accuracy of the model; however, the inability to correctly model the occupants’ actual heating practices is starkly visible in Figure 8.17. The occupants primarily employed a slow combustion stove for heating which they kept burning throughout winter and therefore maintained an almost constant temperature, unlike the heating schedule which turns heating off at night. The other modifications made to the standard assumption were;

1. Changed the dwelling exposure to ‘Open’;
2. Increased the thickness of the timber ceiling lining to reflect mass provided by exposed structural timber;
3. Switched off default natural ventilation schedule; and
4. Added heating to the space (note that the use of artificial cooling in this space was limited so was not modelled).

The final modified model resulted in a CV(RMSE) of 8.5%, again, this variance can largely be attributed to the simulation of heating. For the period shown in Figure 8.16 the CV(RMSE) in 3.3%, demonstrating adequate agreement between the predicted and measured temperatures.

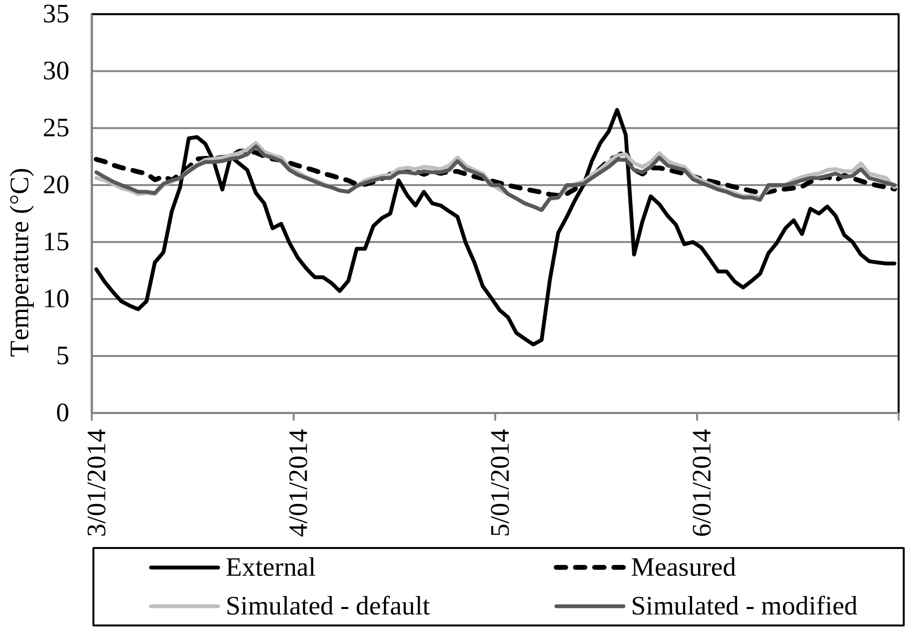

Figure 8.16. Comparison of external, measured internal and predicted internal temperatures for Dwelling 18 in a summer period 3rd – 6th January 2014

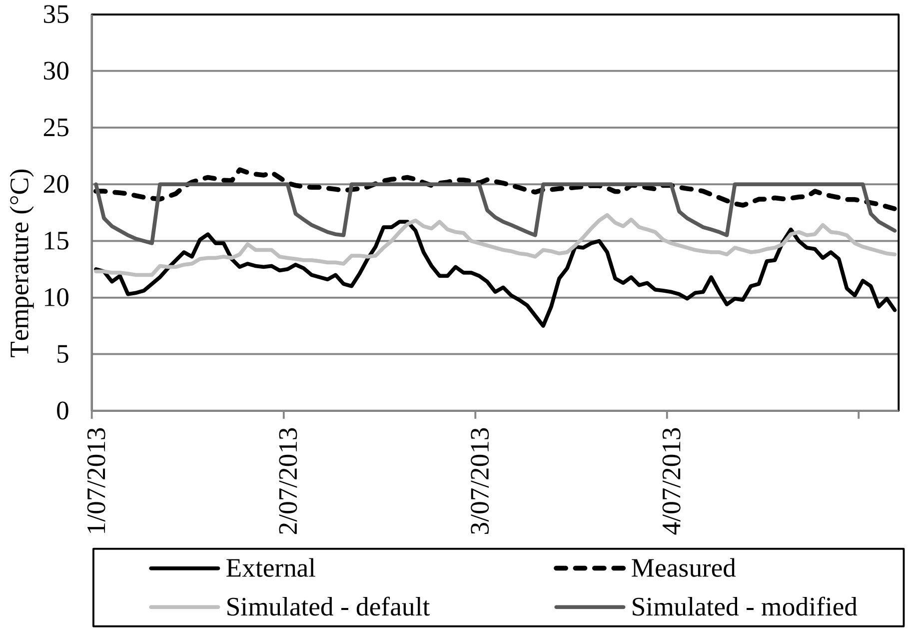

Figure 8.17. Comparison of external, measured internal and predicted internal temperatures for Dwelling 18 in a winter period 1st – 4th July 2013

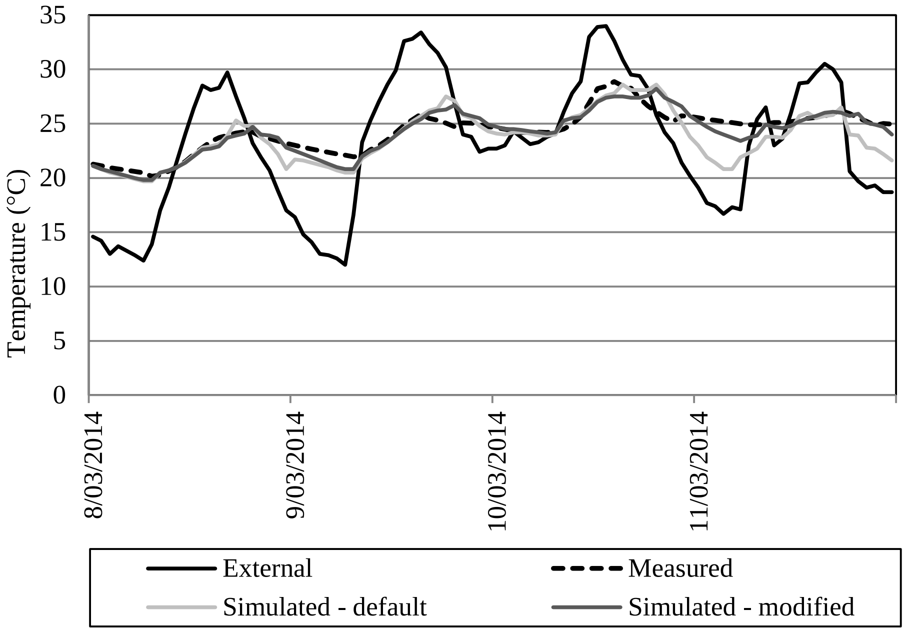

Figure 8.18. Comparison of external, measured internal and predicted internal temperatures for Dwelling 18 during a transition season 8th – 11th March 2014

Dwelling 34 - Darwin

The initial "default" model of Dwelling 34 was relatively accurate likely due to the narrow range of external temperatures experienced in the Darwin climate (see Figure 8.19 and Figure 8.20). Modifications made to the model included;

1. Changing the dwellings exposure to 'Protected' to account for surrounding vegetation and buildings;
2. Removing the internal window coverings (none present in house); and
3. Switching off the natural ventilation schedule to the kitchen window (occupants reported that it always remained closed).

These modifications slightly improved the agreement between predicted and measured temperatures with a CV(RMSE) of 3.1% (see Table 8.3). Note that this household did not use any artificial heating or cooling which simplified the calibration of the model.

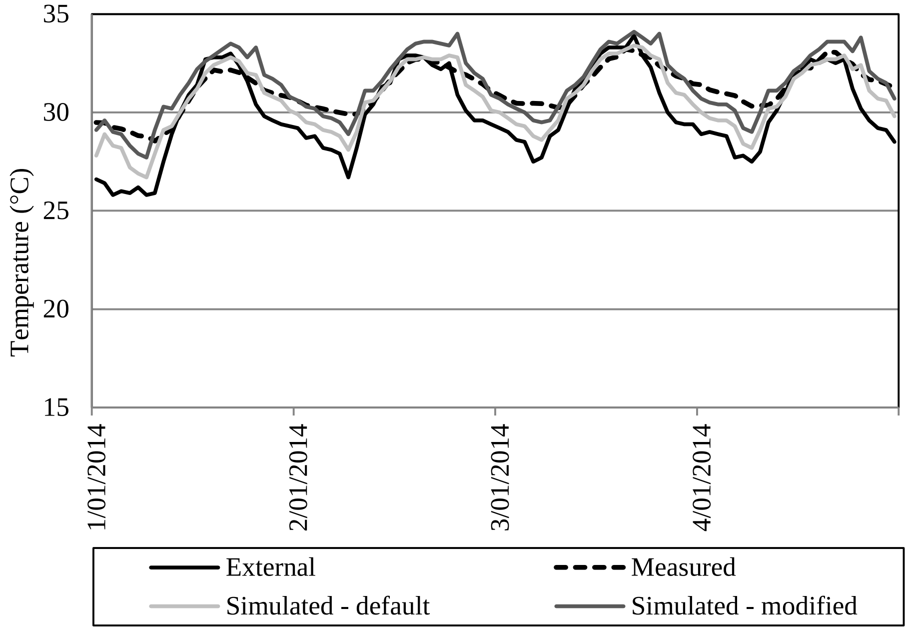

Figure 8.19. Comparison of external, measured internal and predicted internal temperatures for Dwelling 34 in the wet season 1st – 4th January 2014

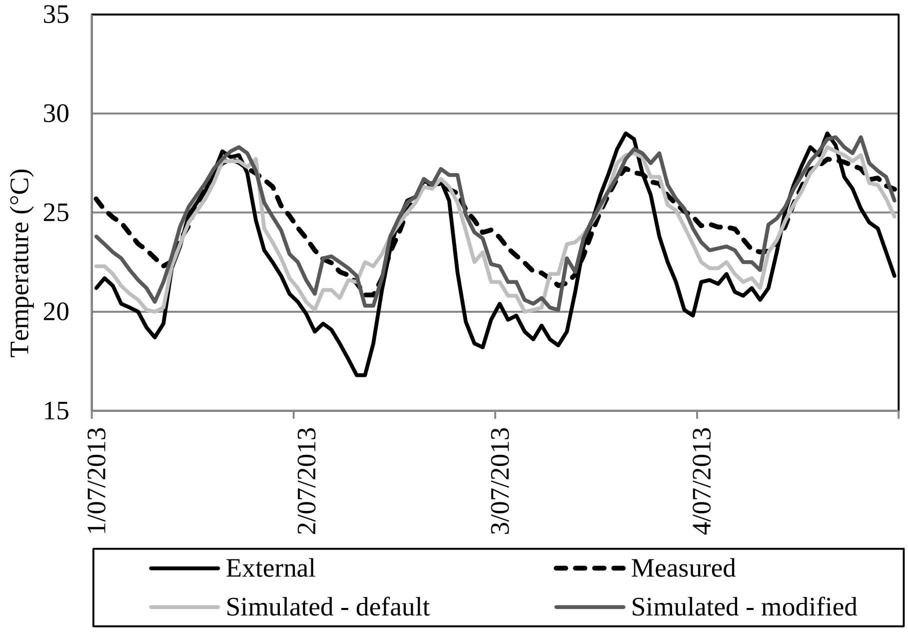

Figure 8.20. Comparison of external, measured internal and predicted internal temperatures for Dwelling 34 in the dry season 1st – 4th July 2013

Dwelling 35 - Darwin

The initial “default” model of Dwelling 35 demonstrated good agreement with the measured data (Table 8.2). Attempts were made to modify the model to replicate the lag evident in the overnight lows of the measured temperatures (see Figure 8.21 and Figure 8.22). Changes were made to the natural ventilation schedule to reflect different window operation scenarios. Neither restricting the ventilation to daytime hours nor to afternoons and overnight (i.e. closing up the house during working hours) improved the accuracy of the model. In fact, both scenarios resulted in over-heating during the daytime but did not serve to delay the overnight cooling effect. Note that this household did not use any artificial heating or cooling. Below are two minor changes to the model;

1. Changing the dwellings exposure to ‘Protected’ to account for surrounding vegetation and buildings; and
2. Increased the thickness of the timber flooring to reflect mass provided by exposed structural timber.

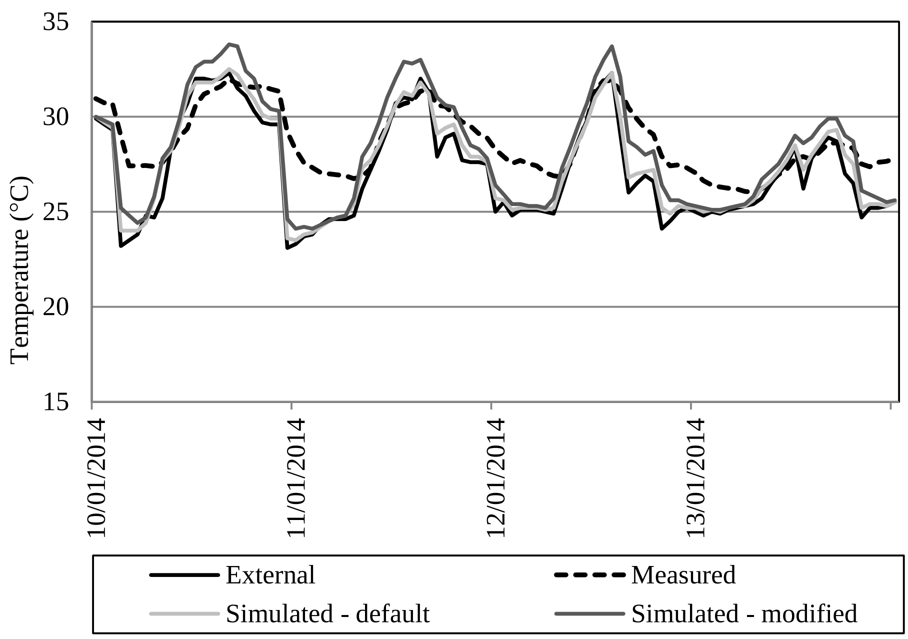

Figure 8.21. Comparison of external, measured internal and predicted internal temperatures for Dwelling 35 in the wet season 10th – 13th January

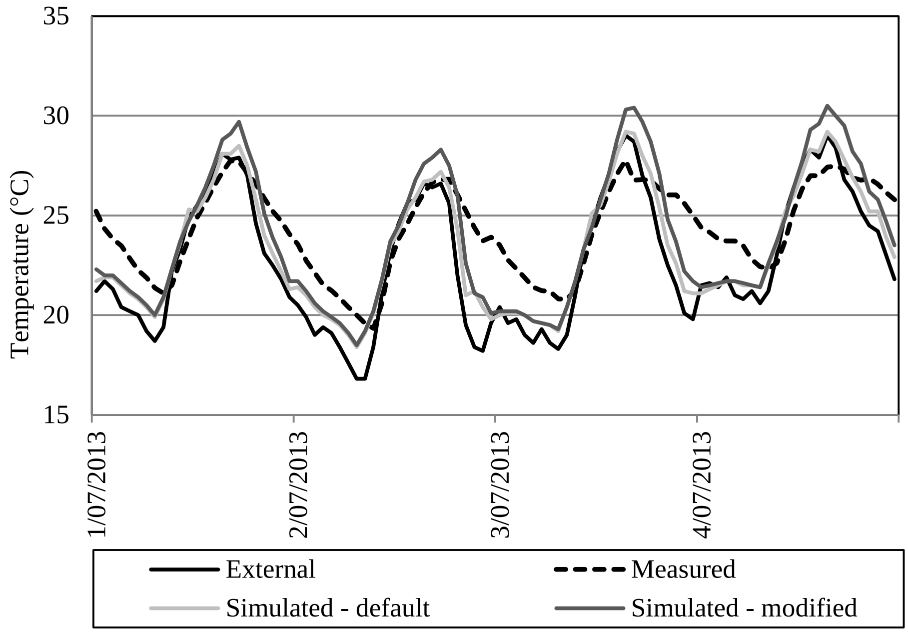

Figure 8.22. Comparison of external, measured internal and predicted internal temperatures for Dwelling 35 in the dry season 1st – 4th July 2013

The above comparison exercises confirm the capability of the *AccuRate* simulation engine to adequately predict the internal conditions within the two forms of atypical construction, therefore substantiating its use in the proposed VURB assessment methodology.

8.5 Application of the VURB process

This section demonstrates the application of the modified VURB process as set out in Table 8.1 by using it to assess the potential thermal performance of the four dwellings introduced in section 8.3. These four models are treated as 'proposed designs'. Note that all of the four houses were designed and built before the energy efficiency performance provisions were introduced to the NCC and are therefore not expected to comply with current requirements. They are, however, still representative of the key problematic construction features from either typology; i.e. uninsulated earth wall elements in the earth building designs, and a non-sealable building envelop in the naturally ventilated designs. None of the four dwelling designs are able to demonstrate compliance with the Energy Efficiency provisions using the Star Rating method, the Elemental Provisions or the existing VURB approach (See Table 8.4 and Table 8.5). Iterations to the building envelope to meet these requirements would be likely to result in significant changes to the construction and design of the dwellings.

The predicted internal conditions in the living area and main bedroom of the four ‘proposed’ simulation models were compared with those produced by the reference building models as described previously. Note these reference buildings comply with the NCC deemed-to-satisfy elemental approach.

Table 8.5 details the modifications made to the proposed models of the four dwellings in order to create the deemed-to-satisfy/reference buildings (i.e. simulation models where all building components comply with the Elemental Provisions). For the two houses in NCC Climate Zone 1 (Darwin), Dwellings 34 and 35, the upper limit of acceptable conditions was extended to compensate for the cooling effect of air movement. Assessment of the proposed building model output employed the model for the cooling effect of air movement described in section 8.4 in conjunction with the developed thermal preference model. However, assessment of the reference building simulation model output utilised the existing approach within ASHRAE 55 (2013) that allows the upper 80% acceptability limit to be increased for elevated air speeds (see Table 5.4.2.4 in ASHRAE 55, 2013). The percentage of predicted hourly temperatures outside of the respective ‘comfort’ models are given for the proposed and reference buildings in Table 8.6. All calculations to assess the simulation data were performed in *Excel*, however it is expected that this process could be managed by a simple program or module integrated with the existing *AccuRate* user interface (e.g. in a similar manner that lighting and water assessment modules have been included).

As seen in Table 8.6, Dwelling 18 does not demonstrate comfort conditions better than the reference building and therefore would fail to comply. For example, both the conditions within the living room and main bedroom are too cold; the living room is below acceptable comfort limits for 0.9% more hours than the reference building, while the bedroom is below acceptable comfort limits for 12.5% more hours than the reference building (Table 8.6). On the other hand, Dwellings 15, 34 and 35 do demonstrate comfort conditions better than their reference buildings. The results for each dwelling are discussed in further detail in the following sub-sections.

Table 8.4. NatHERS star rating, and heating and cooling loads (regulation mode), note: current provisions require a minimum 6.0 Star Rating for compliance certification (see section 2.2.2)

Dwelling ID	Location	NCC climate zone	NatHERS climate file	Conditioned floor area m^2	Star rating	Heating load MJ/m^2	Cooling load MJ/m^2
15	Melbourne	6	62	120.8	3.2	269	11
18	Melbourne	6	60	231.6	2.3	411	6
34	Darwin	1	1	137.2	4.7	0	433
35	Darwin	1	1	99.7	2.2	0	626

Table 8.5. Modifications made to dwelling models to fulfil the deemed-to-satisfy provisions (see Performance Requirement P2.6.2 – Option 2 Elemental Provisions of the NCC Volume 2, 2015)

Element	15	18	34	35
Glazing	Reduced shading to 100mm projection Double glazed all windows except for north facing windows in the living area	Double glazed all windows Reduced shading to all windows (projections between 100 – 500mm) Increased window sizes on the north-west and north-east facades	NA	Low-E glazing to all windows
External walls	Added insulation to the walls	Added insulation to the walls	Added insulation to the walls	Added insulation to the walls
Roof	Increased insulation in the roof	Increased insulation in the roof	Added insulation to the roof	Added insulation to the roof
Floor	NA	Added insulation to the floor construction	NA	Added insulation to the floors
Building sealing & air movement	All conditions satisfied			

Table 8.6. Proportion of hourly temperatures outside of the respective limits of thermal acceptability, note: bold formatting indicates compliance, italics indicate non-compliance, and greyed values indicate that the values are not used to determine compliance

Dwelling ID	NCC climate zone	Zone	Proposed model		Reference model	
			Below (too cold)	Above (too hot)	Below (too cold)	Above (too hot)
15	6	Living	**17.1%**	**1.7%**	46.5%	2.2%
		Bedroom	**13.0%**	**1.6%**	42.8%	2.1%
18	6	Living	*40.1%*	**1.1%**	39.2%	2.2%
		Bedroom	*51.4%*	**0.5%**	38.9%	3.3%
34	1	Living	2.3%	**12.0%**	2.1%	14.1%
		Bedroom	1.9%	**9.5%**	1.8%	16.8%
35	1	Living	8.2%	**15.0%**	5.4%	18.8%
		Bedroom	8.2%	**15.6%**	5.6%	16.9%

Dwelling 15 - Melbourne

The proposed model for Dwelling 15 has a lower proportion of temperatures outside of the limits of thermal acceptability than the reference model for all instances according to the proposed rules (Table 8.6).

Dwelling 18 - Melbourne

The proposed model for Dwelling 18 satisfies requirements in warmer weather, yet performs worse than the reference building in cooler weather. The proportion of temperatures outside of the acceptability limits for the proposed living room is only slightly higher than that of the reference building model (0.9%); however, the proportion of temperatures outside of the acceptability limits for the proposed bedroom is substantially higher (12.5%), (Table 8.6). For NCC Climate Zone 6 (Melbourne) both the proportion of temperatures above and below the comfort boundaries must be below those of the reference building model, in line with the existing VURB approach (see Table 8.1).

Iterations were made to the proposed building simulation model so that conditions within the living area and main bedroom were acceptable for a great proportion of hours than conditions produced by the reference building model;

- Eave depth for all eaves was reduced from 2m to 1m to allow for greater solar heat gains in the winter; and

- The width of a window on the north-east wall of the main bedroom was increased from 1.4m to 1.5m.

These changes retain the overall form and character of the dwelling whilst still improving internal conditions (see Table 8.7). According to the proposed rules, the improved proposed building would now be able to demonstrate compliance with the NCC Energy Efficiency provisions, and therefore be built.

Table 8.7. Proportion of hourly temperatures outside of the respective limits of thermal acceptability of improved proposed model, note: bold formatting indicates compliance

Dwelling ID	NCC climate zone	Zone	Proposed model - Improved		Reference model	
			Below (too cold)	Above (too hot)	Below (too cold)	Above (too hot)
18	6	Living	**29.4%**	**1.7%**	39.2%	2.2%
		Bedroom	**38.8%**	**0.9%**	38.9%	3.3%

Dwellings 34 and 35 - Darwin

Both the proposed models of Dwellings 34 and 35 demonstrate compliance by achieving a lower proportion of unacceptable conditions than the reference building models (Table 8.5). The designs of Dwellings 34 and 35 would need no further improvement to satisfy the Energy Efficiency provisions using the modified VURB approach.

Note that, according to the proposed rules only the proportion of hours spent above the upper limit of acceptable conditions are considered in NCC Climate Zone 1 using this method (see Table 8.1). Whilst the justification for this is to align the proposed assessment methodology with the existing approach (e.g. only cooling loads considered), it is also supported by results presented in Chapter 6. That is, the Darwin subjects rarely reported discomfort or desired change in cooler conditions (see section 6.3).

8.6 Summary

The application of the modified VURB process to four of the case study dwelling designs shows that this approach offers an appropriate way to assess the thermal performance of designs of dwellings incorporating earth construction components and naturally ventilated dwellings within the parameters of the current NCC process.

Whilst Dwellings 18 does require improvement to achieve the minimum performance requirements this is judged a reasonable outcome when considered in conjunction with the energy use data for the Melbourne case study cohort (see section 5.3). The Melbourne households consumed a similar amount of energy attributable to the operation of heating appliances when compared with the overall average gas consumption for the Nillumbik Shire area. This indicates that there is opportunity to enhance the thermal performance of these buildings during cooler seasons. Dwelling 15 would achieve compliance using this method with no modification to the proposed design. Table 8.8 demonstrates how the results of the proposed VURB assessment method may be presented for design compliance certification.

Both of the naturally ventilated dwellings (Dwellings 34 and 35) require no improvement to demonstrate compliance with the minimum performance standards. Again, if this outcome is observed in relation to the energy use figures from Chapter 5, it is quite reasonable, as the average electricity use of the Darwin case study cohort was considerably lower than the average figure for houses in the Northern Territory. The presence of thermal mass in the construction of Dwelling 34 appeared to show no advantage or disadvantage in its overall performance.

Table 8.8. Example of how the results of the modified VURB process may be presented

<table>
<tr><th colspan="5">Verification-Using a Reference-Building – alternative solution</th></tr>
<tr><td colspan="5"></td></tr>
<tr><th>Dwelling ID</th><th colspan="2">NCC climate zone</th><th colspan="2">Zone(s) Assessed</th></tr>
<tr><td rowspan="2">15</td><td colspan="2" rowspan="2">6</td><td colspan="2">Living</td></tr>
<tr><td colspan="2">Bedroom</td></tr>
<tr><td colspan="5"></td></tr>
<tr><th rowspan="3">Zone(s)</th><th colspan="4">Percentage of hourly temperatures uncomfortable</th></tr>
<tr><th colspan="2">Proposed</th><th colspan="2">Reference</th></tr>
<tr><th>Below</th><th>Above</th><th>Below</th><th>Above</th></tr>
<tr><td>Living</td><td>17.1%</td><td>1.7%</td><td>46.5%</td><td>2.2%</td></tr>
<tr><td>Bedroom</td><td>13.0%</td><td>1.6%</td><td>42.8%</td><td>2.1%</td></tr>
<tr><td colspan="5"></td></tr>
<tr><th colspan="3">Determination of compliance</th><th colspan="2"></th></tr>
<tr><td colspan="3">In climate zones 3, 4, 5 and 6 the proportions of time that temperatures in the proposed design are either above or below the comfort boundaries must be ≤ than those of the reference building</td><td colspan="2">Yes</td></tr>
<tr><td colspan="5"></td></tr>
</table>

The design assessment methodology using comfort criteria as a performance indicator, as presented above, offers a pathway for designs of the two forms of atypical housing studied to comply with current regulatory thermal performance requirements. Whilst this approach addresses weaknesses within the current processes available to demonstrate compliance, it maintains sufficient similarities with the existing VURB process which increases the likelihood of adoption.

The *Australian Government Endorsed calculation engine, AccuRate*, has the capacity to adequately model both dwellings incorporating large proportions of thermal mass as well as naturally ventilated dwellings. Whilst the necessary data for calculating the cooling effect of air movement are not current outputs of the publically released versions of the software, the engine can be easily modified to produce these data. It is also reasonable to assume that other validated thermal performance simulation programs with equal or increased functionality may be used for this process.

The models for thermal preference and the cooling effect of air movement enable the thermal performance of the dwelling designs to be judged in line with the expectations and preferences of the actual building user cohorts. Whilst the applicability of the proposed models is confined to the types of houses presently studied, it is expected that its application could be broadened to other forms of housing, where occupants demonstrate comparable levels of environmental concern.

The application of this method to four of the case study dwellings shows that the designs of the two forms of atypical housing are potentially able to reduce energy consumption by demonstrating that an acceptable level of comfort can be achieved without the use heating and/or cooling appliances. Consequently, this addresses the objective of the Energy Efficiency performance provisions to *"Reduce greenhouse gas emissions"* (ABCB, 2015) associated with maintaining 'comfort' conditions within residential buildings.

As an alternative to performing two simulations (proposed and reference designs) parametric studies could be conducted, for all NCC climate zones, where large numbers of simulations of reference building models of various designs are performed to define the limits of acceptable comfort (above and below). In operation, the proposed design would simply be compared to these pre-defined limits. This is a similar approach to that employed by the voluntary house rating scheme for naturally ventilated dwellings in Brazil (Cândido et al, 2011; Scalco et al, 2012).

8.6.1 The unknown future occupant

The application of a thermal comfort assessment as a general alternative method assumes that the occupants will not apply significant heating or cooling to the rooms being assessed. A consistent argument against design for specific occupants or specific use patterns is the unknown future occupant who may operate the house differently or install heating and/or conditioning appliances. It is clear from the results in the preceding chapters that this argument holds no weight to the houses studied in this research. The occupants of these houses have a clearly defined environmental value system which is why they live in these forms of housing. Future persons looking to buy these forms of housing without these environmental values are most unlikely to find these houses an attractive proposition. If regulatory control was necessary it is conceivable that these forms of houses could be identified as such with appropriate labelling.

Chapter 9. Conclusions

> *"Society should be embarking on a much more searching debate about the meaning of comfort and the ways of life associated with it. In this way, it might be possible to exploit existing diversity and variety both in peoples' expectations and in the built environment and so avoid a commitment to an unsustainably standardised future." (Chappells & Shove, 2005, p39)*

In Australia, occupants and/or architects often have difficulty in demonstrating that designs of dwellings with atypical construction comply with current National Construction Code (NCC) Energy Efficiency provisions. This is largely because the provisions in the NCC have been developed to respond to failures within the mass market residential building sector which is typified by common construction practices and methods, and therefore employ standardised assumptions about how occupants operate their homes. In order to address this deficiency within the current regulatory building performance assessment framework, this research has sought to determine how the performance of these atypical dwellings could be meaningfully assessed. This was done by investigating the influence of occupants’ environmental attitudes on their behaviour, expectations and preferences relating to the thermal performance of their dwelling. The research hypothesis suggested in this work is that due to higher levels of environmental concern, occupants of dwellings incorporating earth construction components in a cool temperate climate and naturally ventilated dwellings in a hot humid climate operate their houses in a manner that results in lower energy consumption than typical houses in the same locations.

This chapter consists of five sections; the following section will synthesise the main themes discussed in the preceding chapters and demonstrate how the findings meet the objectives of the research outlined in section 1.4. The second section will outline the key recommendations arising from this research, while the third section will present an argument for the broader theoretical implications of the research. The forth section will review the opportunities for future work. Finally, the thesis will conclude with short closing remarks.

9.1 Findings

The research presented in this thesis has responded to the aim and met objectives outlined in the introductory chapter. The review of exiting literature demonstrates opportunities to address issues concerning residential thermal performance assessment, the influence of occupants' behaviour and preferences, thermal comfort and environmental attitudes. Sufficient data were collected through national surveys, in-depth case studies, thermal comfort survey and Environmental Attitudes Inventory (EAI) surveys to address Objectives 3 and 4. Analysis of the data clearly demonstrated that occupants of atypical dwellings have alternative expectations, behaviour and preferences in relation to the thermal performance of their housing. A design assessment methodology aligned with both the preferences of the occupants studied and the current regulatory assessment context offers a rigorous way by which it can be demonstrated that these types of houses meet minimum performance requirements.

9.1.1 Objective 1

To discuss the current state of thermal performance and energy efficiency assessment for residential construction in Australia

The literature review revealed that there is great potential to build upon a rich history of building performance research by Australian researchers. Whilst much of the research concerning energy efficiency addresses the needs of mass market housing, there is a unique opportunity to encourage the continuation of relevant, climatically appropriate house design.

Those wishing to build housing designed to use little or no heating and/or cooling are facing barriers in demonstrating compliance with the current NCC Energy Efficiency provisions. It is argued that this is due to ill-fitting assumptions about occupant behaviour and preferences incorporated within the Nationwide House Energy Rating Scheme (NatHERS), one of the main methods used to demonstrate compliance with the NCC Energy Efficiency provisions. It was demonstrated in the literature review that within these atypical forms of housing it is likely that some aspect of the households' socio-cultural context motivates their expectations, behaviours and preferences relating to the thermal performance of their dwellings. Therefore, the design, construction and operation of the dwelling can be considered an expression of some aspect of the occupants' value system. The literature surrounding the Energy Efficiency provisions and NatHERS exposes a lack of understanding of the fundamental difference between the design of naturally ventilated houses and houses intended to be fully conditioned.

Similarly, there is no regard for the diversity in the manners in which occupants operate their dwellings. From this review, there is a clear need to further explore these issues in order formulate an equitable way to assess the thermal performance of these buildings, with the broader aim of reducing reliance on energy consumption to achieve acceptable thermal comfort conditions.

9.1.2 Objective 2

To gather data on the behaviour, preferences and attitudes of occupants living in dwellings incorporating earth construction components in a cool temperate climate and naturally ventilated dwellings in a hot humid climate

This research is the first in Australia of residential buildings that combines both the use of traditional thermal comfort and post occupancy evaluation methods with a measure from environmental psychology to provide contextual information about the actual operation and performance of two distinct forms of housing.

The two national surveys received 176 responses from occupants living in earth houses, and 102 responses from occupants living in naturally ventilated houses. Forty households, 20 from Melbourne and 20 from Darwin, formed the basis of an in depth case study of occupant behaviour, energy use, and thermal environment. A total of 6179 thermal comfort vote survey responses were collected across the two case study cohorts in Melbourne and Darwin. Finally the psychological measure, the EAI survey (Milfont & Duckitt, 2010), used to gauge the levels of environmental concern of the case study households as well as the two samples of from the general population, yielded 60 responses from the Melbourne and Darwin case study households and 149 responses from the control samples.

Sufficient data on the behaviour, preferences and attitude of occupants living in dwellings incorporating earth construction components in a cool temperate climate and those naturally ventilated dwellings in a hot humid climate were collected to test the research hypothesis.

9.1.3 Objective 3

To analyse the data and draw conclusions to reveal and describe trends in the behaviour, preferences and attitudes of these occupants and whether these trends are alternative when compared to those of the general population and standardised assumption used in regulatory performance assessment

Analysis of the data in Chapters 4, 5, 6 and 7 clearly demonstrates that the behaviour, preferences and attitudes of occupants living in dwellings of atypical construction are different to those of the general population and standardised assumptions incorporated within the NatHERS protocols for design assessment. The three proceeding sections review and synthesize these key findings within the broader themes of occupant behaviour, thermal comfort and environmental awareness.

Occupant behaviour

The findings relating to occupant behaviour demonstrate the energy savings that can be achieved through behavioural means. They also highlight the variety of ways in which the occupants operate their households, responding, not just to thermal conditions, but also to socio-cultural factors;

- The ways in which respondents from both cohorts manage indoor thermal conditions are alternative when compared to relevant national statistics (see Chapter 4);
- Behavioural strategies were the main means used to achieve ‘comfort’ within the case study households, complimented by judicious use of heating and/or cooling appliances (see Chapter 5);
- Overall, the average energy consumption of the case study households was lower than average figures for the two locations, however the use of heating appliances in the Melbourne households contributed considerably to overall energy consumption (see Chapter 5); and
- The operation of windows and heating appliances by the Melbourne cohort was closely linked to prevailing mean outdoor temperature, while the operation of fans by both cohorts was closely linked to indoor operative temperature (see Chapter 6).

Thermal comfort

The findings related thermal comfort emphasise the importance of describing the range of conditions that occupants find acceptable rather than specifying a single neutral temperature when making some kind of judgement of thermal conditions in actual buildings, especially in residential buildings;

- The occupants generally expressed satisfaction with the thermal performance of their dwelling, despite the thermal conditions within both cohorts of dwellings been largely outside of commonly referenced thermal comfort zones (see Chapter 5);

- These thermal maverick occupants expressed acceptance of a wide range of thermal conditions not encompassed by existing widely used thermal comfort models (see Chapter 6);
- The use of a single temperature to describe the comfort of each cohort was not useful because of the variation possible through the use of different methods of calculation (Chapter 6); and
- Rather it may be more useful to describe the extent of conditions that these occupants find acceptable; consistency in the relationships between prevailing mean outdoor temperature and acceptable indoor conditions for both cohorts demonstrates that the thermal preference of the two cohorts may be reflected in a single model (see Chapter 6).

Environmental awareness

Overall, the investigation of environmental attitudes revealed that these values inform many aspects of the households' approach to the design, construction and operation of their homes. Their attitudes towards the environment appear to be largely implicit, more of an understanding of the world than conspicuous housing aspirations;

- The responses to both national surveys demonstrate an awareness of environmental issues in the choice and operation of their homes, as well as a desire for connection with the natural environment (see Chapter 4);
- This was similarly reflected in the design, construction and operation of the case study dwellings which was highly responsive to the local climate and context (see Chapter 5); and
- The occupants of the case study households had higher levels of environmental concern than samples of the general population in the two locations (see Chapter 7).

9.1.4 Objective 4

To develop a thermal performance assessment method for dwellings of atypical construction capable adequately responding to the behaviour, preferences and attitudes of these occupants.

A design assessment method was presented in Chapter 8. Whilst this method is aligned with the existing Verification Using a Reference Building (VURB) process within the NCC Energy Efficiency provisions, it provides more equity in the assessment of houses that are intended to use little or no heating and/or cooling. Importantly, these buildings are judged in line with actual user expectations and preferences of thermal performance. Many of the inappropriate behavioural assumptions incorporated within existing methods relate to the simulation of heating and/or cooling, and are therefore eliminated by directly assessing thermal conditions instead. The model by which predicted thermal conditions are tested against was developed using collected data, reflecting the actual preferences of occupants in these types of houses.

9.2 Recommendations

Based on the findings summarised above, it is recommended that the proposed assessment methodology in the form of a VURB process be included in the NCC Energy Efficiency provisions as a means to demonstrate compliance with the minimum performance requirements. The merit of assessing dwellings of atypical construction in such a manner is that it encourages behaviour and preferences that has been shown to result in energy conservation. While the housing aspirations of the occupants are unlikely to be explicitly linked to the NCC Energy Efficiency objective per se (reducing greenhouse gas emissions), their actions naturally achieve this outcome.

Adopting the proposed assessment methodology would not be to the detriment of existing assessment methods; instead it would be applied in cases where designs of the two forms of housing studied fail to achieve compliance certification using current methods, or the design is not suitable for assessment by the current methods (e.g. NatHERS simulation cannot produce a sensible rating for houses that are not fully sealed such as some of the naturally ventilated designs in Darwin). In these cases, the potential extra costs associated with completing the proposed VURB assessment would be a fraction of costs involved with completing ‘improvements’ to the building envelope under the current system.

This boarder approach to housing performance assessment is not only confined to the two types of dwellings studied. Other forms of atypical housing in temperate climates in Australia have faced similar issues (Williamson et al, 2010). Whilst the relevant preference data for these other types of dwellings would need to be attained, the approach of assessing thermal conditions in terms of achieved comfort is transferable.

Similarly, if future Australian Governments introduced stronger policies aimed at reducing carbon emissions, it is conceivable that this methodology would provide a useful platform for further development of a more holistic and inclusive approach to the thermal performance assessment of residential buildings.

9.3 Theoretical implications

On an international scale, this work offers an exciting pathway towards the creation of less energy intensive built environments, not just through the rationalisation of technical systems, but also through consideration of how individuals' thermal preferences may be informed by their value system. The consideration of the role of an individual's value system on their expectations and perceptions of performance may offer a way in which behaviours can be modified through the 'tuning' of individuals' attitudes. It provides a tangible mechanism to realise behavioural change that complements the well-established technical systems aimed at reducing energy consumption in the built environment.

9.4 Opportunities for future research

During this research project it has become apparent that more research in the field of thermal comfort and how it relates to building performance assessment in Australia is needed. There is great scope to survey a representative sample of 'normal' houses during 'normal' conditions. This would enable existing models of thermal comfort to be tested or new models to be developed. A context specific model of thermal comfort would provide a fundamental platform for the continuation of building performance assessment research and policy development in Australia.

9.5 Closing remarks

The motivation for this research project has been driven by an aspiration to create change in how thermal performance assessment is approached. It is essential that we are able to account for the diversity in which people live, in doing so encouraging ownership of aspects of thermal performance in housing. The approach of this study was to consider the context in which buildings are operated. Out of necessity, often the occupants are removed from consideration in thermal performance assessment. They are, however, the most important factor in determining actual building performance; their behaviours determine how the building is operated, while their expectations and preferences signal what can be considered as 'good' performance. Within houses these issues are of heightened relevance as occupants are free to operate their dwellings as they see fit in contrast to an office building where users are subjected to particular 'approved' thermostat settings. Throughout this thesis it has been made clear that dwellings offer more than simply shelter – they can offer delight in the thermal conditions experienced. Imagine on a hot summers day, retreating to the cool, quiet, softly lit interior of an earth building or the sensation of a gentle evening breeze in tropical

Darwin after the clinging humidity of the day – the relief from the heat and the harsh Australian sun is something that cannot be captured if one fails to consider the occupants' own experiences. These experiences are why people desire to live in dwellings that are open to the natural environment; to regulate them out of existence would be to lose sensory cues that contribute to the development of connections with home, community and culture.

> *"Perhaps the simple bodily experience of thermal conditions is sensed as a metaphor for the more abstract meanings represented by a place: the comfort, the delight, the social affinity, each reinforcing the overall significance of the place in people's lives." (Heschong, 1979, p65)*

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Appendices

Appendix A. Low Risk Human Research Ethics Approval..A1-A2

Appendix B. National surveys B1-B24

Appendix C. Information sheet... C1-C5

Appendix D. Semi-structured interview D1-D18

Appendix E. House plans...E1-E30

Appendix F. Thermal comfort vote survey.. F1-F3

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Appendix H. *AccuRate* Fan Speed Calculation H1

Appendix I. Associated publications I1-I74

Appendix J. Thermal comfort and EAI survey data CD insert

Appendix A. Low Risk Human Research Ethics Approval

THE UNIVERSITY of ADELAIDE

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22 August 2012

Associate Professor T Williamson
School of Architecture, Landscape Architecture and Urban Design

Dear Associate Professor Williamson

ETHICS APPROVAL No: HP-2012-063
PROJECT TITLE: Thermal Preferences in Dwellings of Alternative Constructions

I write to advise that the Low Risk Human Research Ethics Review Group (Faculty of Humanities and Social Sciences and Faculty of the Professions) has approved the above project. The ethics expiry date for this project is **31 Aug 2015**.

Ethics approval is granted for three years subject to satisfactory annual progress and completion reporting. The form titled *Project Status Report* is to be used when reporting annual progress and project completion and can be downloaded at http://www.adelaide.edu.au/ethics/human/guidelines/reporting. On expiry, ethics approval may be extended for a further period.

Participants in the study are to be given a copy of the Information Sheet and the signed Consent Form to retain. It is also a condition of approval that you **immediately report** anything which might warrant review of ethical approval including:

- serious or unexpected adverse effects on participants,
- previously unforseen events which might affect continued ethical acceptability of the project,
- proposed changes to the protocol; and
- the project is discontinued before the expected date of completion.

Please refer to the following ethics approval document for any additional conditions that may apply to this project.

Yours sincerely

ASSOCIATE PROFESSOR RACHEL A. ANKENY
Convenor
Low Risk Human Research Ethics Review Group (Faculty of Humanities and Social Sciences and Faculty of the Professions)

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Applicant:	Associate Professor T Williamson
School:	Architecture, Landscape Architecture and Urban Design
Application/RM No:	13928
Project Title:	**Thermal Preferences in Dwellings of Alternative Constructions**

Low Risk Human Research Ethics Review Group (Faculty of Humanities and Social Sciences and Faculty of the Professions)

ETHICS APPROVAL No: HP-2012-063

APPROVED for the period until: 31 Aug 2015

This study is to be conducted by Ms Lyrian Daniel, PhD Candidate.

ASSOCIATE PROFESSOR RACHEL A. ANKENY
Convenor
Low Risk Human Research Ethics Review Group (Faculty of Humanities and Social Sciences and Faculty of the Professions)

Appendix B. National surveys

Earth Building Questionnaire B2 – B12

Tropical Building Questionnaire B13 – B24

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Earth Building Questionnaire

This research is being conducted by a research team at the University of Adelaide in conjunction with the Earth Building Association of Australia and the Nillumbik Mudbrick Association. The research project is titled the *Energy-efficiency of Earth Construction*.

The study aims to find out how people use and think about their houses. Your knowledge of what it is really like to live in an earth building and your feelings about the comfort of your home are the main things of interest. The more that is known about such factors, the better are the chances of designing earth houses that are sustainable and suitable for different people in different places. This survey is being sent to households across Australia.

You are asked to contribute to the study by filling out the attached questionnaire which will take around 15 minutes to complete.

Preferably the questionnaire should be filled out by the person of the household over the age of 25 years who spends most of the time at home, but really any household member over this age may fill out the questionnaire.

You will notice that you are not asked to identify yourself in the questionnaire. All information will be strictly confidential and no single result will be identified in the reporting of data. When completed the results of this study will be available on the EBAA & NMA websites.

You will see that the last question asks if you would like to help further in this research. This may include willingness for you to have the temperatures in your house monitored in an unobtrusive way over an extended period. If you indicate an interest in further participation please complete the separate sheet that gives your details and the research team will contact you later with more information.

Please fill out the questionnaire and return it in the pre-paid envelop. By completing and returning the questionnaire you are consenting to be part of this project.

If you have any queries please contact the research leader Associate Professor Terry Williamson.

Associate Professor Terry Williamson
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Earth Building Questionnaire

Please answer the following questions by putting a cross [x] in the appropriate box. You may mark several boxes if more than one answer is appropriate.

Q1. Which walls of your house incorporate an earth construction method?

External ☐
Internal ☐
None ☐

If "None" thank you for your interest you need go no further.

Q2. What percentage of your home's EXTERNAL walls are made of earth?
(enter a whole number from 0-100)

☐

Q3. What percentage of your home's INTERNAL walls are made of earth?
(enter a whole number from 0-100)

☐

Q4. How would you describe the main earth construction method used in the walls of your house?

Rammed earth or stabilized earth or Pisé ☐
Mud brick or adobe ☐
Pressed earth bricks ☐
Cob ☐
Other, please describe ____

____

Q5. Do the external walls include a separate layer of thermal insulation?

Yes ☐

No ☐

(if *No* please go to Q8)

Q6. If the external walls of your home have some form of insulation, please indicate where the insulation is located.

Inside ☐ Outside ☐ Within the wall ☐ Other (please specify) ☐

If other please specify ____

Q7. What percentage of your external walls are insulated?
(enter a whole number from 0-100)

☐

Q8. About how old is your house? _______________ years

Q9. How long have you lived in your present house?_______________ years

1

Q10. Why did you choose to build or buy your house with earth wall construction?
(you can pick several reasons if appropriate)

- Appearance ☐
- Cost ☐
- Natural/renewable material ☐
- Low energy impact ☐
- Healthy ☐
- DIY ☐
- Protection from bushfires ☐
- Other, please explain ____

Q11. The number of people who generally live in your house are:

60 years old and over __________

50 to 59 years old __________

20 to 49 years old __________

15 to 19 years old __________

5 to 14 years old __________

0 to 4 years old __________

Q12. What is your post code _____________

Q13. Is your house a;

- Terrace house, duplex or maisonette, or other attached house ☐
- A separate house ☐
- A flat or single unit ☐
- Other? Please describe ____

Q14. Is your house;

- Single storey ☐
- Split level ☐
- Two or more storeys ☐

Q15. What is the construction of the floors of your house?

- Concrete slab on the ground (sometimes called a "raft footing") ☐
- Concrete slab, suspended above the ground ☐
- Timber floor ☐
- Earth floor ☐
- Other, please describe ____

Q16. Are the ceiling or roof of your house insulated?
(select one box only)

- No ☐
- Yes, with bulk insulation eg fiberglass, rockwool, or similar ☐
- Yes, with reflective foil ☐
- Yes, with bulk insulation & reflective foil ☐
- Don't know ☐
- Yes, but with other method (please specify).

____

Q17. On the whole, do you like or dislike the climate where your house is located?
Put a cross [x] in the space that corresponds to your feelings. Use the middle space if you have an in-between opinion.

Like very much   **Dislike very much**

Please try to explain why

____

____

Q18. On the whole, how would you describe the conditions in your house during the following times of the year and time of day?
Place a cross [x] in the space that best corresponds to your perceptions.

Winter during the nighttime

Very uncomfortable   **Very comfortable**

Winter during the daytime

Very uncomfortable   **Very comfortable**

Summer during the nighttime

Very uncomfortable   **Very comfortable**

Summer during the daytime

Very uncomfortable   **Very comfortable**

Q19. What kind of heating do you have in your house?

- Gas space heater ☐
- Built-in electric heater ☐
- Portable electric heater(s) ☐
- Reverse cycle air-conditioning ☐
- Open fire ☐
- Slow combustion stove or pot-belly stove ☐
- Kerosene heater ☐
- None ☐
- Other, please specify ________________________

If you answered “None” to the previous question do you think there would ever be the need to install a heater?

- Yes ☐
- No ☐

Please try to explain why

____

____

If “None” please now skip the next few questions and go to Question 25

Q20. If you usually use more than one heater, which of those listed above are your main ones?

- Gas space heater ☐
- Built-in electric heater ☐
- Portable electric heater(s) ☐
- Reverse cycle air-conditioning ☐
- Open fire ☐
- Slow combustion stove or pot-belly stove ☐
- Kerosene heater ☐
- Other, please specify ________________________

Q21. What rooms do you usually heat?

- About half the house – the living areas ☐
- Living room ☐
- One bedroom ☐
- All bedrooms ☐
- Bathroom ☐
- Kitchen ☐
- Study/office, etc ☐

Any additional information about which rooms you heat?

____

____

4

Q22. At what times of the day or night do you usually use heaters during cold weather?

- All the time, day and night ☐
- All the time, except overnight ☐
- Afternoons ☐
- Evenings until bedtime ☐
- Over night ☐
- Mornings ☐

Any additional information about the use of heaters?

____

____

Q23. How many days in the year do you usually use a heater(s)? _______ days

Q24. How satisfied are you with your main heater(s)?
Put a cross [x] in the space that corresponds to your view. Use the middle space if you have an in-between opinion.

|___|___|___|___|___|___|___|

Very dissatisfied **Very satisfied**

Please try to explain why

____

____

Q25. Do you have fans in your house?

- No fans ☐
- Portable fan or fans ☐
- Ceiling fan or fans ☐

Q26. What kind of coolers do you have in your house?

- Portable evaporative cooler(s) ☐
- Fixed evaporative cooler for one room(s) ☐
- Ducted evaporative cooling ☐
- Reverse cycle air-conditioning for one room(s) eg split system ☐
- Ducted reverse cycle air-conditioning ☐
- None ☐
- Other, please specify ____

Q27. If you answered "None" to the previous question do you think there would ever be the need to install a cooler?

Yes ☐
No ☐

Please try to explain why

____

____

If "None" please now skip the next few questions and go to Question 33

Q28. If you usually use more than one cooler, which of those listed above are your main cooler(s)?

Portable evaporative cooler(s) ☐
Fixed evaporative cooler for one room(s) ☐
Ducted evaporative cooling ☐
Reverse cycle air-conditioning for one room(s) eg split system ☐
Ducted reverse cycle air-conditioning ☐
Other, please specify ____________________________________

Q29. What rooms do you usually cool?

About half the house – the living areas ☐
Living room ☐
One bedroom ☐
All bedrooms ☐
Bathroom ☐
Kitchen ☐
Study/office, etc ☐

Any additional information about which rooms you cool?

____

____

Q30. At what times of the day or night do you usually use coolers during hot weather?

All the time, day and night ☐
All the time, except overnight ☐
Afternoons ☐
Evenings until bedtime ☐
Over night ☐
Mornings ☐

Any additional information about the use of coolers?

____

____

Q31. How many days in the year do you usually use a cooler(s)? _______ days

Q32. How satisfied are you with your main cooler(s)?
Put a cross [x] in the space that corresponds to your view. Use the middle space if you have an in-between opinion.

|_____|_____|_____|_____|_____|_____|_____|

Very dissatisfied **Very satisfied**

Please try to explain why

____

____

Q33. Since you moved into your house have you made any of the following changes to it?

- Added insulation to ceiling or roof ☐
- Added insulation to the walls ☐
- Installed ceiling fans ☐
- Added a verandah or pergola ☐
- Planted trees to shade the house ☐
- Installed a built-in heater ☐
- Installed a built-in cooler ☐
- No changes ☐
- Any other changes to make the house feel more comfortable

____

____

Q34. Do you have patio, courtyard, verandah, pergola or the like outside your house that your household would use regularly for meals, entertaining, playing, relaxing, etc?

- Yes ☐
- No ☐

Q35. If you answered "Yes" to the previous question, is the outdoor space protected from the elements?

Protected from sun ☐ Protected from rain ☐ Protected from wind ☐

Q36. How would you best describe the situation surrounding your house?

- Suburban with close neighbours ☐
- Inner town/city built-up ☐
- Rural, open countryside/farmland ☐
- Rural, bush land ☐
- Other, please explain ______________________________

Q37. On the whole what do you think about the quality of air in your house, do you find it too fresh or too stuffy?
Put a cross [x] in the space that corresponds to your feelings.

|___|___|___|___|___|___|___|

Too fresh	About right	Too stuffy

Please try to explain why

____

____

Q38. On the whole what do you think about the quality of air in your house, do you find it too dry or too humid?

Put a cross [x] in the space that corresponds to your feelings.

|___|___|___|___|___|___|___|

Too dry	About right	Too humid

Please try to explain why

____

____

Q39. Do you think that the windows of your house let in too much sun or not enough?
Put a cross [x] in the space that corresponds to your feelings.

Winter

|___|___|___|___|___|___|___|

Too much	About right	Not enough

Summer

|___|___|___|___|___|___|___|

Too much	About right	Not enough

8

Q40. What best describes the most common internal covering of your windows?

- Open weave curtain ☐
- Closed weave curtains ☐
- Heavy drapes ☐
- Curtains with pelmets ☐
- Heavy drapes with pelmets ☐
- Holland blinds ☐
- Venetian blinds ☐
- None ☐
- Other, please specify ______________________

Q41. What best describes the way your windows are shaded from the outside in hot weather?

- Verandah or pergola ☐
- Eaves of building ☐
- Awning of canvas or similar material ☐
- Outside blind ☐
- Shutters ☐
- Vegetation, trees, vines, etc ☐
- None ☐
- Other, please specify ______________________

Q42. Thinking about your response to hot and cold weather, in hot weather do you keep some doors and windows open during the day?

Yes ☐ No ☐

Q43. Thinking about your response to hot and cold weather, on hot nights do you open most windows?

Yes ☐ No ☐

Q44. Thinking about your response to hot and cold weather, during hot days do you close your drapes / curtains / blinds?

Yes ☐ No ☐

Q45. Thinking about your response to hot and cold weather, during cold nights in winter do you close your drapes / curtains / blinds?

Yes ☐ No ☐

Q46. From time to time a few people report some concerns when living in a house incorporating earth construction. Can you say if you have found any of these issues in your house?

- No issues or concerns ☐
- Too much dust ☐
- More maintenance than expected ☐
- Dampness in walls ☐
- Any other concerns, please explain ___________________________________

____

____

9

Q47. Would you be interested in contributing further with this research?

Yes ☐

Please complete the attached sheet with your name and contact details and the research team will be in touch with you.

No ☐

Thank you very much for completing this questionnaire
Please use the reply paid envelope to return it to us.

Energy-efficiency of Earth Construction Project
School of Architecture, Landscape Architecture & Urban Design
The University of Adelaide
ADELAIDE SA 5001

Tropical Building Questionnaire

This research is being conducted as part of a PhD research project at the University of Adelaide, in conjunction with *CSIRO* and *COOLmob*. The research project is titled *Thermal Comfort in Naturally Ventilated Dwellings in a Hot Humid Climate*.

The study aims to find out how people use and think about their houses. Your knowledge of what it is really like to live in lightweight dwellings designed to be primarily naturally ventilated in a hot humid climate and your feelings about the comfort of your home are the main things of interest. The more that is known about such factors, the better are the chances of designing naturally ventilated houses that are sustainable and suitable for different people in different places. This survey is being sent to households throughout northern Australia.

You are asked to contribute to the study by filling out the attached questionnaire, which will take around 15 minutes to complete. Preferably, the questionnaire should be filled out by the person of the household, over the age of 25 years, who spends most of the time at home, however any household member over this age may fill out the questionnaire. Please only fill out one questionnaire per household.

You will notice that you are not asked to identify yourself in the questionnaire. All information will be strictly confidential and no single result will be identified in the reporting of data. When completed updates of this study will be available on *the University of Adelaide* website.

You will see that the last question asks if you would like to help further in this research. This may include willingness for you to have the temperatures in your house monitored in an unobtrusive way over an extended period. If you indicate an interest in further participation please complete the separate sheet that gives your details and the research team will contact you later with more information.

Please fill out the questionnaire and return it in the reply-paid envelop. By completing and returning the questionnaire, you are consenting to be part of this project.

If you have any queries please contact the primary researcher Lyrian Daniel, or research supervisors Terry Williamson and Veronica Soebarto;

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Tropical Buildings Questionnaire

Please answer the following questions by putting a cross [x] in the appropriate box. You may mark several boxes if more than one answer is appropriate.

Q1. Is your house designed to be primarily or partially naturally ventilated and situated in a hot humid climate (e.g., Darwin)?

YES ☐
NO ☐

If "NO" thank you for your interest you need go no further.

Q2. What season is it currently? *Please mark one box only.*

The build up ☐
The wet ☐
The hot and dry ☐
The cool and dry ☐

Q3. What is you postcode?

____

Q4. How long have you lived in a hot humid climate?

____

Q5. If you answered less than 5 years in Q4, what was your previous primary location? *If you have lived in a hot humid climate for longer than 5 years please select the N/A option*

Residing in Australia ☐ *(postcode)* ______________

Residing overseas ☐ *(country)* ______________

N/A Resided in a hot humid climate more than 5 years ☐

Q6. Approximately how old is your house in years?

Less than 5 years ☐
5 – 10 years ☐
10 – 20 years ☐
20 – 40 years ☐
Older than 40 years ☐
I don't know ☐

Q7. How long have you lived in your present house in years?

____

Q8. The number of people who generally live in your house are;

- 0 – 4 years old ☐
- 5 – 14 years old ☐
- 15 – 19 years old ☐
- 20 – 49 years old ☐
- 50 – 59 years old ☐
- 60 years old and over ☐

Q9. Is your house a;

- Townhouse, duplex or other attached house ☐
- A separate house ☐
- A flat or unit ☐
- Other *please describe* ☐

Q10. Is your house;

- Single storey (Low set) ☐
- Two or more storeys (High set) ☐
- Other *please describe* ☐

Q11. How would you best describe the situation surrounding your house?

- Inner town/built up city ☐
- Suburban with close neighbours ☐
- Seaside; within 200m ☐
- Rural; open countryside farmland ☐
- Rural; bushland ☐
- Other *please describe* ☐

Q12. Why did you build, buy or rent a house designed to be primarily naturally ventilated in a hot humid climate? *You may mark several boxes if more than one answer is appropriate.*

- Lifestyle ☐
- Cost ☐
- Low energy ☐
- Environmental impact ☐
- Healthy ☐
- Other *please describe* ☐

Q13. What is the main construction type of your external walls?

Steel clad ☐
Timber clad ☐
Fibro cement clad ☐
Other *please describe* ☐

Q14. Approximately what percentage of the external walls is openable (louvers, windows, doors, etc) to allow ventilation?

Living areas
Less than 20% ☐
20-40% ☐
40-60% ☐
60-80% ☐
Greater than 80% ☐

Bedrooms
Less than 20% ☐
20-40% ☐
40-60% ☐
60-80% ☐
Greater than 80% ☐

Q15. Do the external walls include a separate layer of thermal insulation

YES ☐
NO ☐
If "NO" go to Q17.

Q16. If the external walls of your home have some form of insulation, please indicate where the insulation is located;

Outside the wall ☐
Within the wall ☐
Other *please describe* ☐

Q17. What is the construction of the floors of your house?

Concrete slab on ground (i.e., raft footing) ☐
Suspended concrete slab ☐
Timber floor less than 500mm above ground ☐
Timber floor greater than 500mm above ground ☐
Other *please describe* ☐

Q18. What is the construction of the roof of your house?

Corrugated steel ☐
Tile ☐
Other *please describe* ☐

Q19. What best describes the ceiling in the majority of the house?

- Raked, cathedral ceiling ☐
- Flat ceiling (with roof/attic space) ☐
- Other *please describe* ☐

Q20. Is the ceiling or roof of your house insulated? *Only select one box.*

- No ☐
- Don't know ☐
- Yes; with bulk insulation (i.e., fibreglass, rockwool) ☐
- Yes; with reflective foil ☐
- Yes; with bulk insulation & reflective foil ☐
- Yes; but with other *please describe* ☐

Q21. Do you have a patio, courtyard, verandah, pergola or similar outside your house that your household would use regularly for meals, entertaining , playing, relaxing, etc?

- YES ☐
- NO ☐

Q22. If you answered "YES" to the previous question, which of the below questions are applicable to your outdoor living space? *You may mark several boxes if more than one answer is appropriate.*

- Protected from the sun ☐
- Protected from the rain ☐
- Protected from the wind ☐
- Ceiling or other fixed fan ☐
- None of the above ☐

Q23. Since you moved into your house have you made any of the following changes to it? *You may mark several boxes if more than one answer is appropriate.*

- No changes ☐
- Additional rooms or extension ☐
- Added insulation to the ceiling or roof ☐
- Added insulation to the walls ☐
- Installed ceiling fans ☐
- Added a verandah or pergola ☐
- Installed a built in cooler ☐
- Any other changes to make the house feel more comfortable *please describe* ☐

Q24. Since you moved into your house have you complete any major renovations?

- YES ☐
- NO ☐

If 'YES' please briefly describe

Q25. On the whole, do you like or dislike the hot humid climate in which your house is located?

Put a cross [x] in the space that corresponds to your feelings.

Like very much — Dislike very much

Please try to explain why;

____

____

Q26. On the whole, how would you describe the conditions in your house during the following times of the year and day?

Put a cross [x] in the space that corresponds to your perceptions.

The build-up during the daytime

Very un-comfortable — Very comfortable

The build-up during the nighttime

Very un-comfortable — Very comfortable

The wet season during the daytime

Very un-comfortable — Very comfortable

The wet season during the nighttime

Very un-comfortable — Very comfortable

The hot and dry season during the daytime

Very un-comfortable — Very comfortable

The hot and dry season during the nighttime

Very un-comfortable — Very comfortable

The cool and dry season during the daytime

Very un-comfortable — Very comfortable

The cool and dry season during the nighttime

Very un-comfortable — Very comfortable

5

Q27. **On the whole, what do you think about the quality of air in your house, when the windows, doors, etc are *closed?*** *Put a cross [x] in the space that corresponds to your feelings.*

Too fresh About right Too stuffy

Please try to explain why;

____

____

Q28. On the whole, what do you think about the quality of air in your house, when the windows, doors, etc are *open*? *Put a cross [x] in the space that corresponds to your feelings.*

The build up

Too fresh About right Too stuffy

The wet season

Too fresh About right Too stuffy

The hot and dry season

Too fresh About right Too stuffy

The cool and dry season

Too fresh About right Too stuffy

Please try to explain why;

____

____

Q29. Do you think that the windows of your house let in too much direct sunlight or not enough?

Too much About right Not enough

Q30. What best describes the most common internal covering of your windows?

None	
Open weave curtain	
Closed weave curtains	
Heavy drapes	
Curtains with pelmets	
Matchstick or bamboo blinds	
Holland blinds	
Venetian blinds	
Other *please describe*	

____

6

Q31. What best describes the way your windows are shaded from the outside in hot weather?

- Nothing ☐
- Verandah or pergola ☐
- Eaves of house ☐
- Awning of canvas or similar material ☐
- Outside blind ☐
- Shutters ☐
- Vegetation, trees, vines, etc ☐
- Other *please describe* ☐

Q32. What rooms of your house are designed to be naturally ventilated?

- The whole house ☐
- Living room ☐
- Bedrooms ☐
- Study/Office ☐
- Bathroom ☐
- Kitchen ☐
- Other *please describe* ☐

Q33. Thinking about your response to temperature; at what times of the day and year do you operate/open your windows and doors in these rooms for natural ventilation?

You may mark [x] several boxes if applicable.

Daytime

- Build-up ☐
- Wet season ☐
- Hot and dry season ☐
- Cool and dry season ☐
- Never ☐

Any other information about when you operate your windows and doors for natural ventilation.

Nighttime

- Build-up ☐
- Wet season ☐
- Hot and dry season ☐
- Cool and dry season ☐
- Never ☐

Any other information about when you operate your windows and doors for natural ventilation.

Q34. Approximately what percentage of time per year are these rooms naturally ventilated with no artificial cooling (i.e., air conditioning)?

Less than 20% ☐
20-40% ☐
40-60% ☐
60-80% ☐
Greater than 80% ☐

Any other information about when your house is naturally ventilated.

Q35. What are the primary types of windows and doors you have?

Living areas

Sliding	☐	Solid casement door	☐
Double or single hung	☐	Glazed casement door	☐
Awning	☐	Glazed bi-fold doors	☐
Louvres	☐	Glazed French doors	☐
Casement	☐	Glazed sliding door	☐
Other *please describe*	☐	Other *please describe*	☐

Bedrooms

Sliding	☐	Solid casement door	☐
Double or single hung	☐	Glazed casement door	☐
Awning	☐	Glazed bi-fold doors	☐
Louvres	☐	Glazed French doors	☐
Casement	☐	Glazed sliding door	☐
Other *please describe*	☐	Other *please describe*	☐

Q36. Do you have fans in your house?

No fans ☐
Portable fan(s) ☐
Ceiling fan(s) ☐

Q37. What rooms are the fixed fans located in?

Living room ☐
One bedroom ☐
All bedrooms ☐
Bathroom ☐
Kitchen ☐
Study/Office ☐

Any other information about where your fixed fan(s) are located.

___

Q38. At what times of the day and year do you operate you portable or ceiling fan(s)?

You may mark [x] several boxes if applicable.

Daytime
Build-up ☐
Wet season ☐
Hot and dry season ☐
Cool and dry season ☐
NA ☐

Any other information about when you operate your fan(s).

___

Nighttime
Build-up ☐
Wet season ☐
Hot and dry season ☐
Cool and dry season ☐
NA ☐

Any other information about when you operate your fan(s).

___

___

Q39. What kind of coolers do you have in your house?

- None ☐
- We have a cooler but never use it *(please skip to Q45)* ☐
- Split cooler air conditioning for one room (s) ☐
- Ducted cooler air conditioning ☐
- Other *please describe* ☐

Q40. If you answered "None" to the previous question, do you think there would ever be the need to install a cooler?

- YES ☐
- NO ☐

Please try to explain why

If "None" please now skip the next few questions and go to Q45.

Q41. What rooms do you usually cool?

- About half the house – the living areas ☐
- Living room ☐
- One bedroom ☐
- All bedrooms ☐
- Bathroom ☐
- Kitchen ☐
- Study/Office ☐

Any other information about which rooms you cool?

Q42. At what times of the day of night do you usually use cooler(s) during hot weather?

- All the time; day and night ☐
- All the time; except overnight ☐
- Afternoons ☐
- Evenings until bedtime ☐
- Over night ☐
- Mornings ☐

Any other information about the use of coolers?

Q43. Approximately how many days in the year do you usually use a cooler(s)?

Q44. How satisfied are you with your main cooler(s)?

Very dissatisfied						Very satisfied

Please try to explain why

10

Q45. From time-to-time a few people report some concerns when living in a naturally ventilated house in a hot humid climate. Can you say if you have found any of these issues is your house?

- No issues or concerns ☐
- Mould ☐
- Noise (e.g., barking dogs) ☐
- Problem with outside air quality ☐
- Dust or smoke ☐
- Unwanted insects or wildlife ☐
- Security ☐
- Other issues or concerns *please describe* ☐

____

____

Appendix C. Information sheet

Earth Building Information Sheet C2 – C3

Naturally Ventilated Buildings Information Sheet C4 – C5

THE UNIVERSITY of ADELAIDE

Thermal Preferences in Dwellings Incorporating Earth Construction Components

Information sheet for participants

This is an information sheet for those volunteering to take part in the study; *Thermal Preferences in Dwellings Incorporating Earth Construction Components*. The research is being conducted by a research team at the University of Adelaide in conjunction with *EBAA* and *NMA*.

The study aims to find out how people use and think about their houses. Your knowledge of what it is really like to live in an earth building and your feelings about the comfort of your home are the main things of interest. The more that is known about such factors, the better are the chances of designing earth houses that are sustainable and suitable for different people in different places.

How you can be involved

We need households that live in dwellings incorporating earth construction elements to participate in a dwelling audit, monitoring and comfort surveys. The dwelling audit/interview will take approximately 1.5hours and will ask questions about the construction of your house and the way you use your house. Whilst we conduct the interview we will set up unobtrusive equipment to monitor the internal air temperature, relative humidity and air velocity within the main living space of your home. It is hoped that this equipment will remain in place for 10-12 months to gather a sample representative of all seasons. Two researchers will be present at each visit. During this period we will occasionally prompt you to answer a short comfort survey (2 minutes) about your personal thermal comfort. This information will be used to gain an understanding of what it is like to live in an earth dwelling.

If you think your household would be suitable for this study, please fill in the *Contact Details Form* and the *Consent Form* (green forms), and return to us using the reply paid envelope.

Confidentiality and use of the data

The data we collect from you will be made anonymous for analysis and publication. No individual will be identified or risk being indentified through the disclosure of identifying information. Personal information will be stored in secure facilities at the University of Adelaide and will only be accessed by the research team.

The data will contribute to a PhD thesis, and further conference and journal publications. If you wish to withdraw from the study, please notify the research team before the completion of monitoring.

Ethics clearance

The University of Adelaide Human Research Ethics approval number for this project is HP-2012-063.

The main imposition will be on your time; however we have designed the study to be as efficient and unobtrusive as possible.

Whilst there may be no direct benefits to participants from this project, it is hoped that this research will assist in promoting equity in residential building assessment and support context specific design.

CRICOS PROVIDER 00123M

Life Impact | The University of Adelaide

Funding

This project is funded by an Australian Postgraduate Award, through the Australian Federal Government.

If you have any more questions please contact...

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Image provided by Stephen Dobson, *RAMTEC*

Life Impact | The University of Adelaide

THE UNIVERSITY of ADELAIDE

Thermal Comfort in Naturally Ventilated Dwellings in a Hot Humid Climate

Information sheet for participants

This is an information sheet for those volunteering to take part in the study; *Thermal Preferences in Naturally Ventilated Dwellings in a Hot Humid Climate*. The research is being conducted as part of a PhD research project at the University of Adelaide in conjunction with *CSIRO*.

The study aims to find out how people use and think about their houses. Your knowledge of what it is really like to live in naturally ventilated building in a hot humid climate and your feelings about the comfort of your home are the main things of interest. The more that is known about such factors, the better are the chances of designing naturally ventilated houses that are sustainable and suitable for different people in different places.

How you can be involved

We need households that live in primarily naturally ventilated dwellings in a hot humid climate to participate in a dwelling audit, monitoring and comfort surveys. The dwelling audit/interview will take approximately 1.5hours and will ask questions about the construction of your house and the way you use your house. Whilst we conduct the interview we will set up unobtrusive equipment to monitor the internal air temperature, relative humidity and air velocity within the main living space of your home. It is hoped that this equipment will remain in place for 10-12 months to gather a sample representative of all seasons. Two researchers will be present at each visit. During this period we will occasionally prompt you to answer a short comfort survey (2 minutes) about your personal thermal comfort. This information will be used to gain an understanding of what it is like to live in a naturally ventilated dwelling in a hot humid climate.

If you think your household would be suitable for this study, please fill in the *Contact Details Form* and the *Consent Form* (green forms), and return to us using the reply paid envelope.

Confidentiality and use of the data

The data we collect from you will be made anonymous for analysis and publication. No individual will be identified or risk being indentified through the disclosure of identifying information. Personal information will be stored in secure facilities at the University of Adelaide and will only be accessed by the research team.

The data will contribute to a PhD thesis, and further conference and journal publications. If you wish to withdraw from the study, please notify the research team before the completion of monitoring.

Ethics clearance

The University of Adelaide Human Research Ethics approval number for this project is HP-2012-063.

The main imposition will be on your time; however we have designed the study to be as efficient and unobtrusive as possible.

Whilst there may be no direct benefits to participants from this project, it is hoped that this research will assist in promoting equity in residential building assessment and support context specific design.

CRICOS PROVIDER 00123M

Life Impact | The University of Adelaide

Acknowledgements

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Image provided by Joanna Rees, Ajar Architects

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Appendix D. Semi-structured interview

Dwelling Audit (semi-structured interview) – Melbourne D2 – D10

Dwelling Audit (semi-structured interview) – Darwin D11 – D18

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Dwelling Audit – Melbourne

Interviewer	
Dwelling number	
Date of interview	
Dwelling address	
Postcode	

Construction drawings	
Energy accounts for past 2-3 years	

Q1. When was your house built?

Q2. Is this house owned by you?

YES ☐
NO ☐
Renting ☐
Other *please describe* ☐

Q3. Have any alterations or renovations been made that are not documented on the construction drawings?

YES ☐
NO ☐

If "YES" please measured, sketch/check accuracy of construction drawings.

Q4. Have you lived in this house for at least three years?

YES ☐
NO ☐

Q5. Apart from holidays, have you lived continuously for this time?

YES ☐
NO ☐

Q6. Was the house empty for any time over two months for this three-year period?

2013	
2012	
2011	
2010	

House selection

Q7. **Why did you choose to buy/build a dwelling incorporating earth components?**

- Appearance ☐
- Cost ☐
- Low energy impact ☐
- Healthy ☐
- Other *please describe* ☐

Q8. **When building/buying did you have any design intentions to make the home energy efficient?**

- YES ☐
- NO ☐

If "YES" please describe below.

Q9. **Have you incorporated any 'environmental' systems into the home or property?**

- YES ☐
- NO ☐

If "YES" please describe below.

Q10. **If you answered "YES" to the previous question, are you happy with these systems?**

- YES ☐
- NO ☐

Q11. **Do you have any issues or concerns with your house?**

- YES ☐
- NO ☐

If "YES" please describe below.

Q12. **If you answered "YES" to the previous question, do you have any plans to address these concerns?**

- YES ☐
- NO ☐

If "YES" please describe below.

Q13. **Was your previous house of a similar construction/design to your current home?**

- YES ☐
- NO ☐

Q14. **If you had the opportunity to build/buy, would you choose a similar method of construction?**

- YES ☐
- NO ☐

Please try to explain below.

Space heating and cooling

Q15. What kind of heating do you have in your house?

None		
Gas space heater		
Built-in electric heater		
Portable heater(s)		
Reverse cycle air conditioning		
Open fire		
Slow combustion stove or pot belly		
Kerosene heat		
Other *please describe*		

Q16. If you answered "None" to the previous question, do you think there would ever be the need to install a heater?

YES ☐
NO ☐

Please try to explain why

If "None" please now skip the next few questions and go to Q22.

Q17. If you usually use more than one heater, which of those listed above are your main ones?

Gas space heater ☐
Built-in electric heater ☐
Portable heater(s) ☐
Reverse cycle air conditioning ☐
Open fire ☐
Slow combustion stove or pot belly ☐
Kerosene heat ☐
Other *please describe* ☐

Q18. What rooms do you usually heat?

About half the house – the living areas ☐
Living room ☐
One bedroom ☐
All bedrooms ☐
Bathroom ☐
Kitchen ☐
Study/Office ☐

Any other information about which rooms you heat.

Q19. At what times of the day of night do you usually use heater(s) during colder weather?

All the time; day and night ☐
All the time; except overnight ☐
Afternoons ☐
Evenings until bedtime ☐
Over night ☐
Mornings ☐
Any other information about the use of heaters.

Q20. Approximately how many days in the year do you usually use a heater(s)?

Q21. How satisfied are you with your main heater(s)?

Very dissatisfied — Very satified

Please try to explain why

Q22. Do you have fans in your house?

No fans ☐
Portable fan(s) ☐
Ceiling fan(s) ☐

Q23. What kind of coolers do you have in your house?

None		
Portable evaporative cooler(s)		
Fixed evaporative cooler for one room(s)		
Ducted evaporative cooling		
Reverse cycle air conditioning for one room (s)		
Ducted reverse cycle air conditioning		
Other *please describe*		

Q24. If you answered "None" to the previous question, do you think there would ever be the need to install a cooler?

YES ☐
NO ☐
Please try to explain why

If "None" please now skip the next few questions and go to ***Error! Reference source not found.***.

Q25. If you usually use more than one cooler, which of those listed above are your main ones?

- Portable evaporative cooler(s) ☐
- Fixed evaporative cooler for one room(s) ☐
- Ducted evaporative cooling ☐
- Reverse cycle air conditioning for one room (s) ☐
- Ducted reverse cycle air conditioning ☐
- Other *please describe* ☐

Q26. What rooms do you usually cool?

- About half the house – the living areas ☐
- Living room ☐
- One bedroom ☐
- All bedrooms ☐
- Bathroom ☐
- Kitchen ☐
- Study/Office ☐

Any other information about which rooms you cool.

Q27. At what times of the day of night do you usually use cooler(s) during hot weather?

- All the time; day and night ☐
- All the time; except overnight ☐
- Afternoons ☐
- Evenings until bedtime ☐
- Over night ☐
- Mornings ☐

Any other information about the use of coolers.

Q28. Approximately how many days in the year do you usually use a cooler(s)?

Q29. How satisfied are you with your main cooler(s)?

Very dissatisfied						Very satified

Please try to explain why

Energy management

Q30. When are the hottest conditions in the house?

Month(s)	
Time	
Room	

Q31. When are the coldest conditions in the house?

Month(s)	
Time	
Room	

Q32. What would you do if you felt that the temperature in the house is too warm?

Turn on A/C	☐
Open windows	☐
Open doors	☐
Changes clothes	☐
Turn on fans	☐
Go outside	☐
Take a shower	☐
Other *please describe*	☐

Q33. What would you do if you felt that the temperature in the house is too cold?

Turn on a heater	☐
Close windows	☐
Close doors	☐
Changes clothes	☐
Draw/open blinds	☐
Go outside	☐
Move to a different room	☐
Other *please describe*	☐

Q34. What would you do if you felt that it was too stuffy in the house?

Turn on A/C	☐
Open windows	☐
Open doors	☐
Turn on fans	☐
Nothing	☐
Other *please describe*	☐

Q35. Do you find that opening windows and doors allows for adequate cross ventilation?

YES, all the time	☐
YES, but not all the time	☐
NO	☐

Q36. Do you have any concerns about opening windows?

Noise	☐
Dust	☐
Smell	☐
Security	☐
Insects/wildlife	☐
Other *please describe*	☐

Occupancy assessment

Q37. **The number of people who generally live in your house are;**

Persons	0 to 17 years old	18 to 29 years old	30 to 49 years old	50 to 59 years old	60 years old and over
A.					
B.					
C.					
D.					
E.					
F.					

Q38. **The times the household generally use the main living areas on weekdays are;**

Person	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A.																								
B.																								
C.																								
D.																								
E.																								
F																								

Q39. **The times the household generally use the main living areas on weekends are;**

Person	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A.																								
B.																								
C.																								
D.																								
E.																								
F																								

Q40. On the whole, do you like or dislike the climate where your house is located?

Put a cross [x] in the space that corresponds to your feelings. Use the middle space if you have an in-between opinion.

Like very much — Dislike very much

Please try to explain why;

Q41. On the whole, how would you describe the conditions in your house during the following times of the year and day?

Put a cross [x] in the space that corresponds to your perceptions.

Winter during the daytime

Very un-comfortable — Very comfortable

Winter during the nighttime

Very un-comfortable — Very comfortable

Summer during the daytime

Very un-comfortable — Very comfortable

Summer during the nighttime

Very un-comfortable — Very comfortable

Q42. On the whole, what do you think about the quality of air in your house, do you find it too fresh or too stuffy?

Put a cross [x] in the space that corresponds to your feelings.

Too fresh — About right — Too stuffy

Please try to explain why

Q43. On the whole, what do you think about the quality of air in your house, do you find it too dry or too humid?

Put a cross [x] in the space that corresponds to your feelings.

Too dry — About right — Too humid

Please try to explain why

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Dwelling Audit – Darwin

Interviewer	
Dwelling number	
Date of interview	
Dwelling address	
Postcode	

Construction drawings	
Energy accounts for past 2-3 years	

Q1. When was your house built?

Q2. Is this house owned by you?

YES ☐
NO ☐
Renting ☐
Other *please describe* ☐

Q3. Have any alterations or renovations been made that are not documented on the construction drawings?

YES ☐
NO ☐

If "YES" please measured, sketch/check accuracy of construction drawings.

Q4. Have you lived in this house for at least three years?

YES ☐
NO ☐

Q5. Apart from holidays, have you lived continuously for this time?

YES ☐
NO ☐

Q6. Was the house empty for any time over two months for this three-year period?

2013	
2012	
2011	
2010	

House selection

Q7. Why did you choose to buy/build a naturally ventilated dwelling in a hot humid climate?

Appearance ☐
Cost ☐
Low energy impact ☐
Healthy ☐
Other *please describe* ☐

Q8. When building/buying did you have any other design intentions to make the home energy efficient?

YES ☐
NO ☐
If "YES" please describe below.

Q9. Have you incorporated any 'environmental' systems into the home or property?

YES ☐
NO ☐
If "YES" please describe below.

Q10. If you answered "YES" to the previous question, are you happy with these systems?

YES ☐
NO ☐

Q11. Do you have any issues or concerns with your house being naturally ventilated?

YES ☐
NO ☐
If "YES" please describe below.

Q12. If you answered "YES" to the previous question, do you have any plans to address these concerns?

YES ☐
NO ☐
If "YES" please describe below.

Q13. Was your previous house of a similar construction/design to your current home?

YES ☐
NO ☐

Q14. If you had the opportunity to build/buy, would you choose another naturally ventilated house?

YES ☐
NO ☐
Please try to explain below.

2

Space cooling

Q15. Do you have fans in your house?

No fans ☐
Portable fan(s) ☐
Ceiling fan(s) ☐

Q16. What kind of coolers do you have in your house?

None		
Portable evaporative cooler(s)		
Fixed evaporative cooler for one room(s)		
Ducted evaporative cooling		
Reverse cycle air conditioning for one room (s)		
Ducted reverse cycle air conditioning		
Other *please describe*		

Q17. If you answered "None" to the previous question, do you think there would ever be the need to install a cooler?

YES ☐
NO ☐
Please try to explain why

If "None" please now skip the next few questions and go to ***Error! Reference source not found.***.

Q18. If you usually use more than one cooler, which of those listed above are your main ones?

Portable evaporative cooler(s) ☐
Fixed evaporative cooler for one room(s) ☐
Ducted evaporative cooling ☐
Reverse cycle air conditioning for one room (s) ☐
Ducted reverse cycle air conditioning ☐
Other *please describe* ☐

Q19. What rooms do you usually cool?

About half the house – the living areas ☐
Living room ☐
One bedroom ☐
All bedrooms ☐
Bathroom ☐
Kitchen ☐
Study/Office ☐
Any other information about which rooms you cool.

Q20. At what times of the day of night do you usually use cooler(s) during hot weather?

All the time; day and night	☐
All the time; except overnight	☐
Afternoons	☐
Evenings until bedtime	☐
Over night	☐
Mornings	☐

Any other information about the use of coolers.

Q21. Approximately how many days in the year do you usually use a cooler(s)?

Q22. How satisfied are you with your main cooler(s)?

Very dissatisfied						Very satified

Please try to explain why

4

Energy management

Q23. Where are the hottest conditions in the house?

Month(s)	
Time	
Room	

Q24. Where are the coolest conditions in the house?

Month(s)	
Time	
Room	

Q25. What are your normal immediate responses to temperatures in the house that are too hot?

- Turn on A/C ☐
- Open windows ☐
- Open doors ☐
- Changes clothes ☐
- Turn on fans ☐
- Go outside ☐
- Take a shower ☐
- Other *please describe* ☐

Q26. What would you do if you felt that it was too stuffy in the house?

- Turn on A/C ☐
- Open windows ☐
- Open doors ☐
- Turn on fans ☐
- Nothing ☐
- Other *please describe* ☐

Q27. Do you find that opening windows and doors allows for adequate cross ventilation?

- YES, all the time ☐
- YES, but not all the time ☐
- NO ☐

Q28. Do you have any concerns about opening windows?

- Noise ☐
- Dust ☐
- Smell ☐
- Security ☐
- Insects/wildlife ☐
- Other *please describe* ☐

Occupancy assessment

Q29. The number of people who generally live in your house are;

Persons	0 to 17 years old	18 to 29 years old	30 to 49 years old	50 to 59 years old	60 years old and over
A.					
B.					
C.					
D.					
E.					
F.					

Q30. The times the household generally use the main living areas on weekdays are;

Person	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A.																								
B.																								
C.																								
D.																								
E.																								
F																								

Q31. The times the household generally use the main living areas on weekends are;

Person	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
A.																								
B.																								
C.																								
D.																								
E.																								
F																								

Q32. On the whole, do you like or dislike the climate where your house is located?

Put a cross [x] in the space that corresponds to your feelings. Use the middle space if you have an in-between opinion.

Like very much ... Dislike very much

Please try to explain why;

Q33. On the whole, how would you describe the conditions in your house during the following times of the year and day?

Put a cross [x] in the space that corresponds to your perceptions.

The build-up during the daytime

Very un-comfortable ... Very comfortable

The build-up during the nighttime

Very un-comfortable ... Very comfortable

The wet season during the daytime

Very un-comfortable ... Very comfortable

The wet season during the nighttime

Very un-comfortable ... Very comfortable

The hot and dry season during the daytime

Very un-comfortable ... Very comfortable

The hot and dry season during the nighttime

Very un-comfortable ... Very comfortable

The cool and dry season during the daytime

Very un-comfortable ... Very comfortable

The cool and dry season during the nighttime

Very un-comfortable ... Very comfortable

Q34. On the whole, what do you think about the quality of air in your house, do you find it too fresh or too stuffy?

Put a cross [x] in the space that corresponds to your feelings.

Too fresh | About right | Too stuffy

Please try to explain why

Q35. On the whole, what do you think about the quality of air in your house, do you find it too dry or too humid?

Put a cross [x] in the space that corresponds to your feelings.

Too dry | About right | Too humid

Please try to explain why

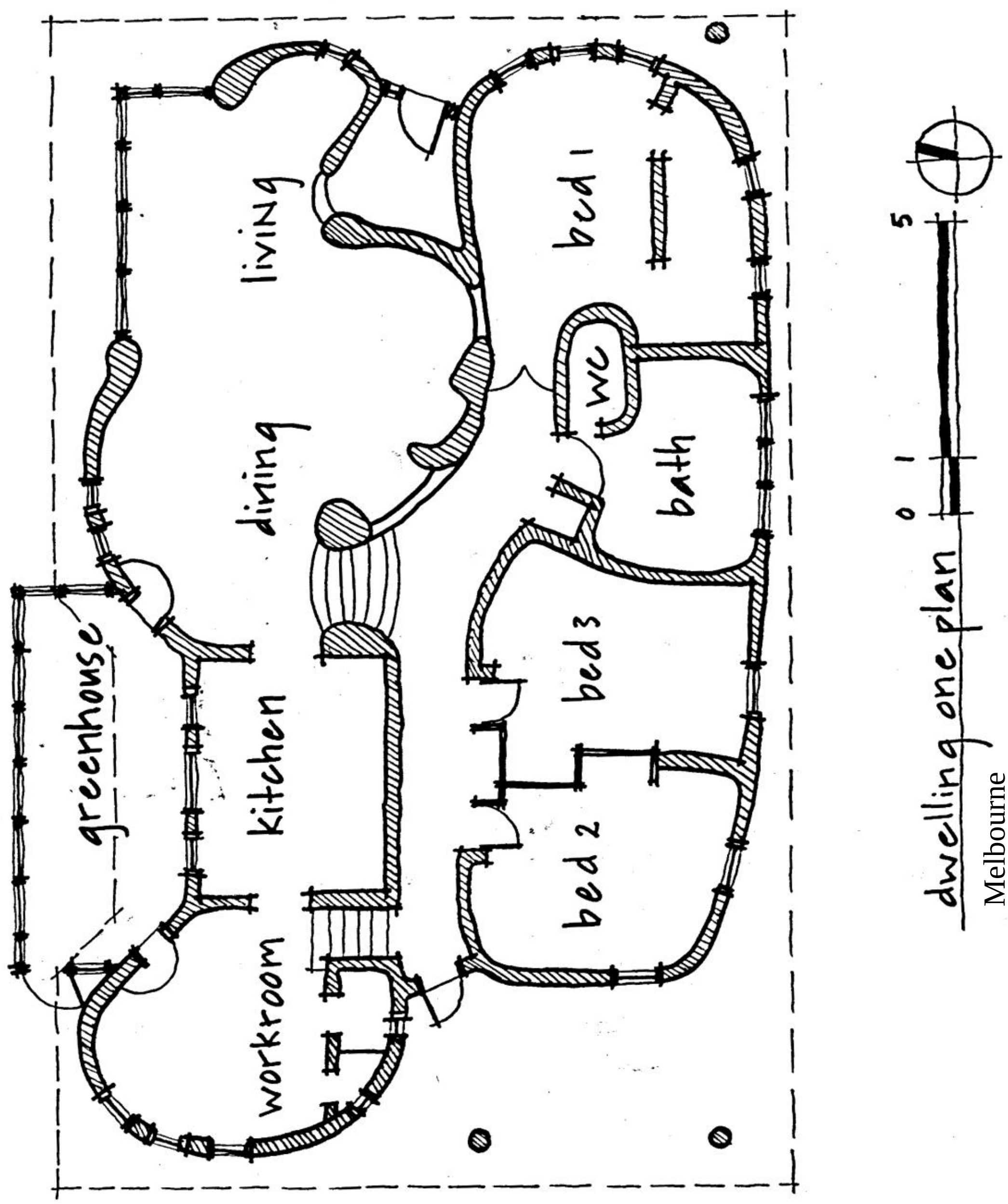
Appendix E. House plans

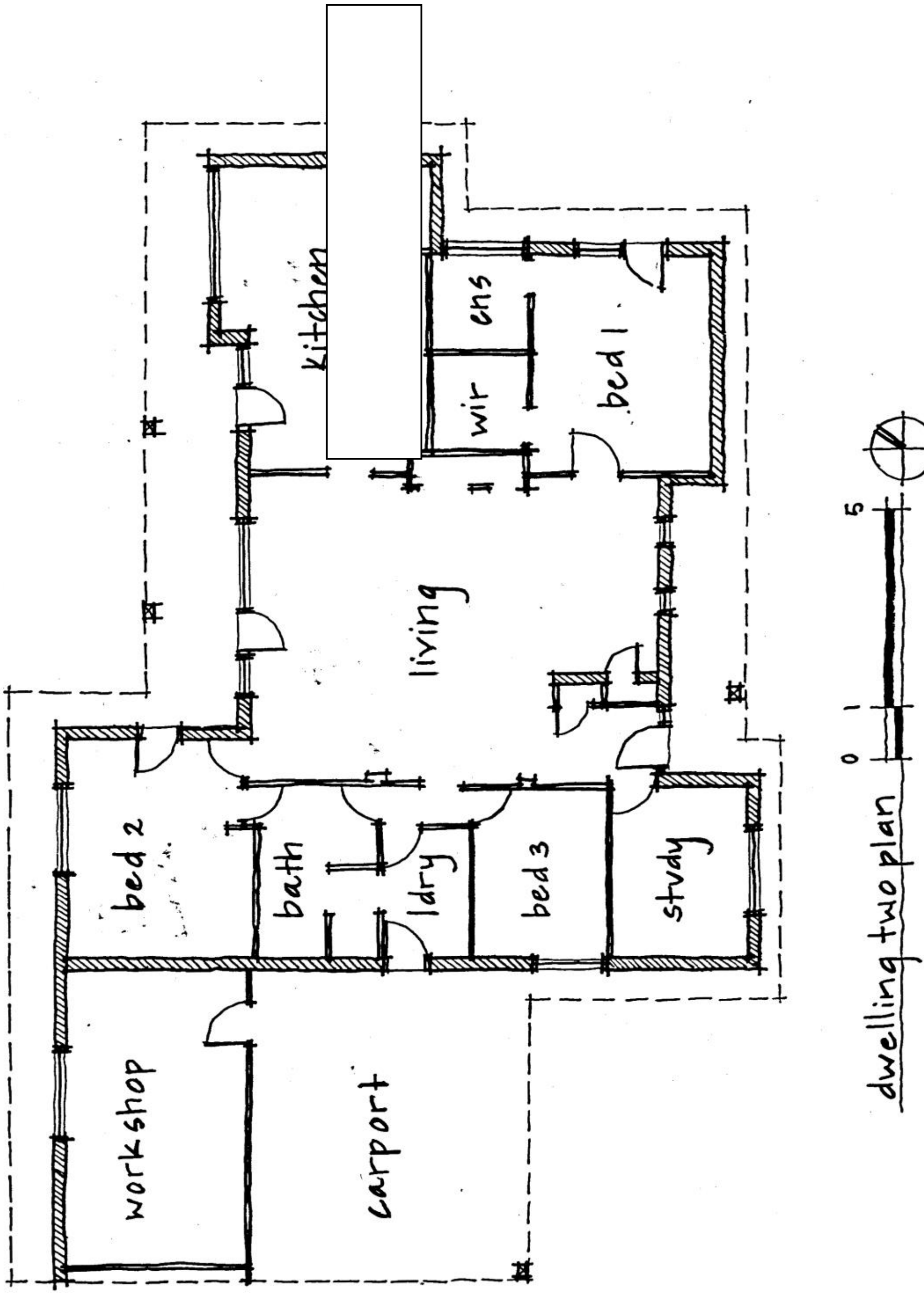
House plans – Melbourne E2 – E16

Note: no plans available for Dwellings 3, 8, 10, 12 and 14

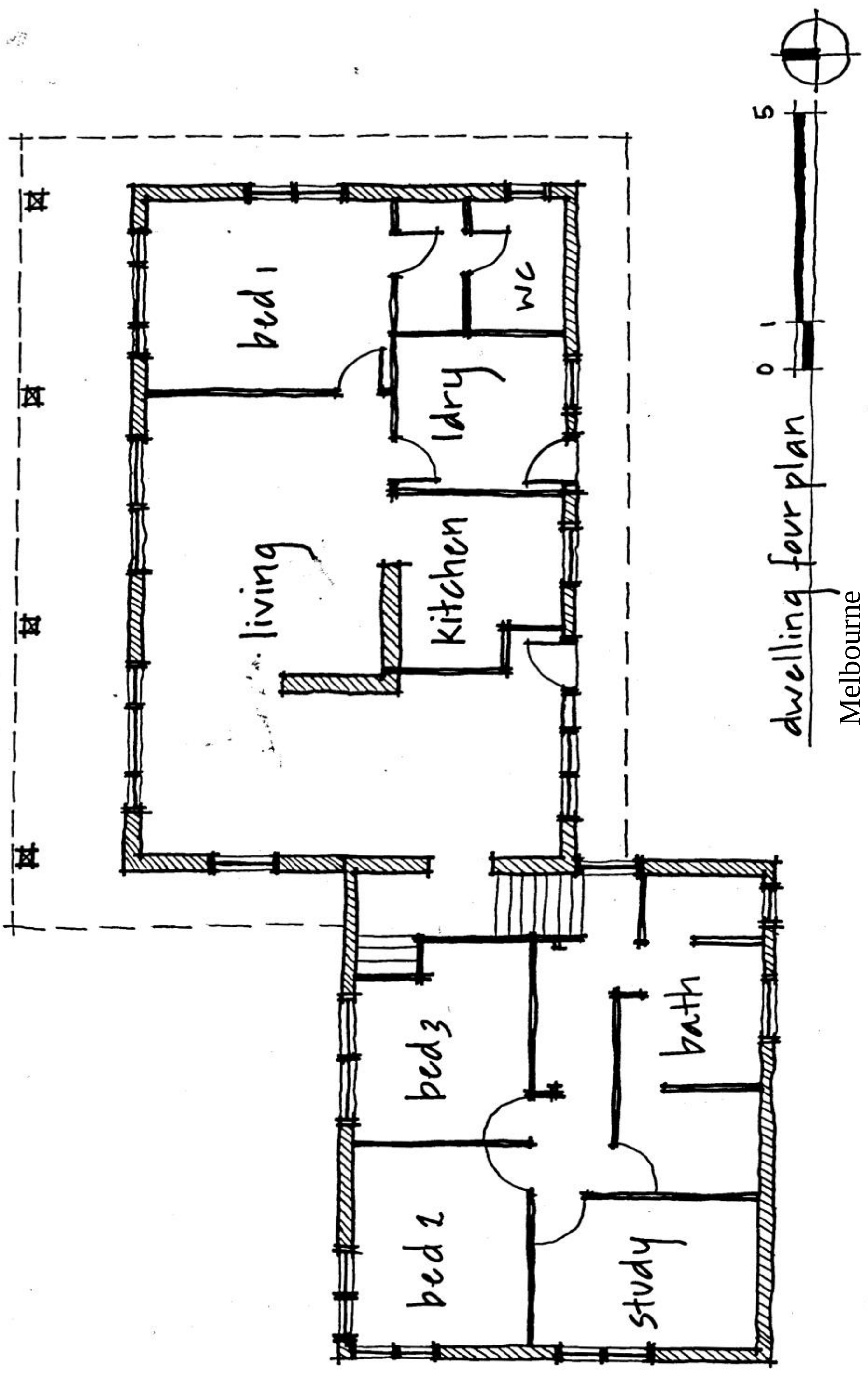
House plans – Darwin E17 – E30

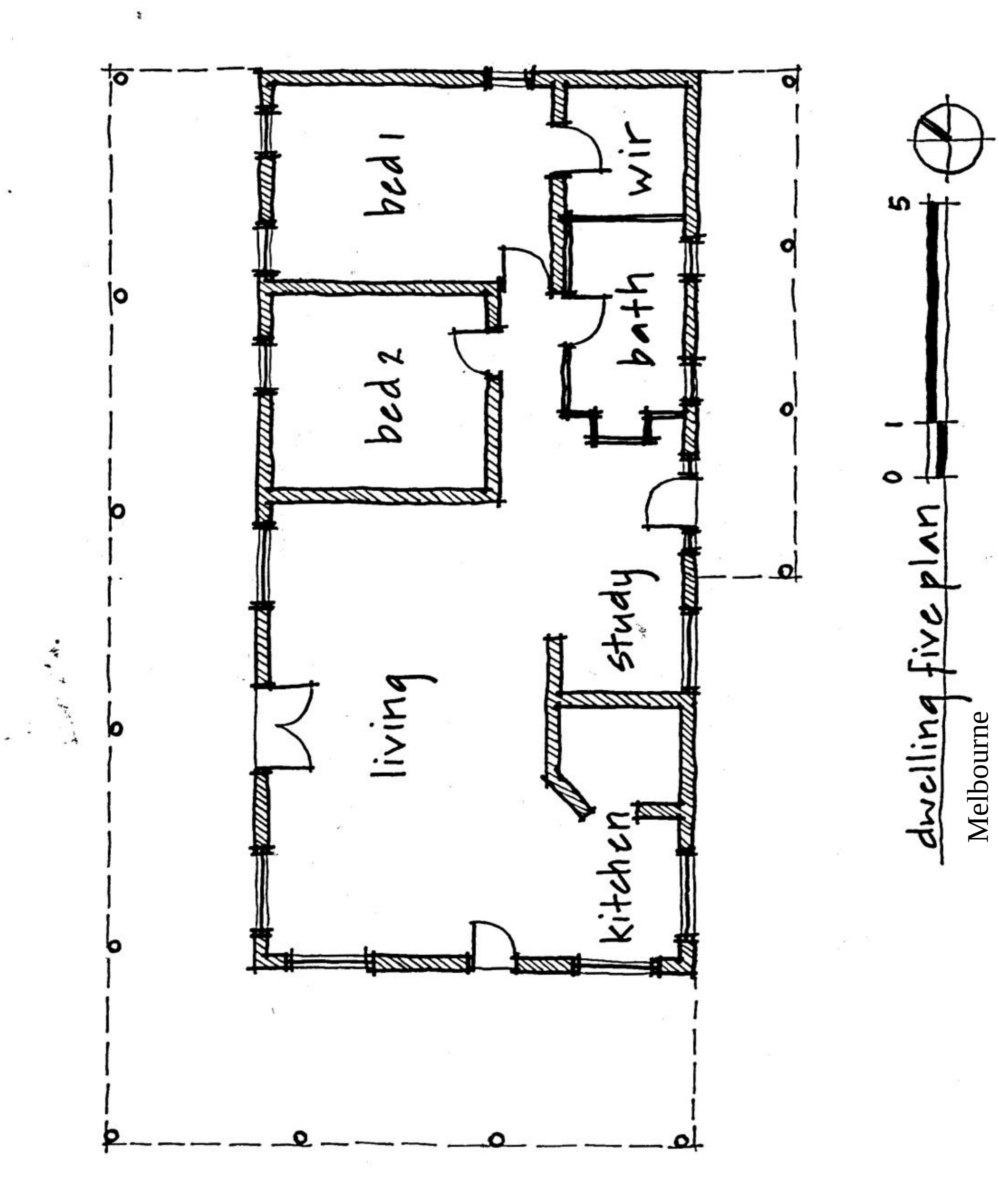
Note: no plans available for Dwellings 21, 23, 26, 30, 31 and 40


greenhouse
workroom
kitchen
dining
living
bed 1
wc
bath
bed 3
bed 2
0
1
5
dwelling one plan
Melbourne

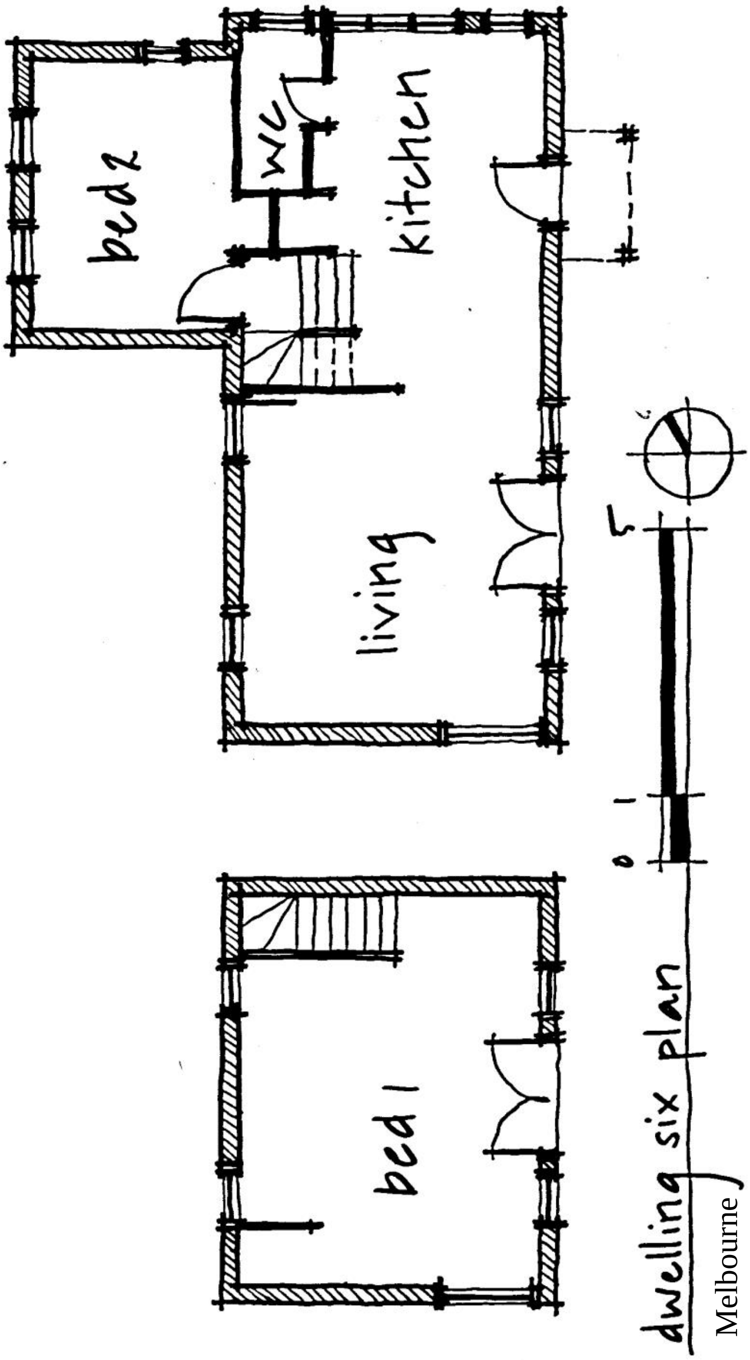

kitchen
wir
ens
bed 1
living
bed 2
bath
ldry
bed 3
study
workshop
carport
0
5
dwelling two plan

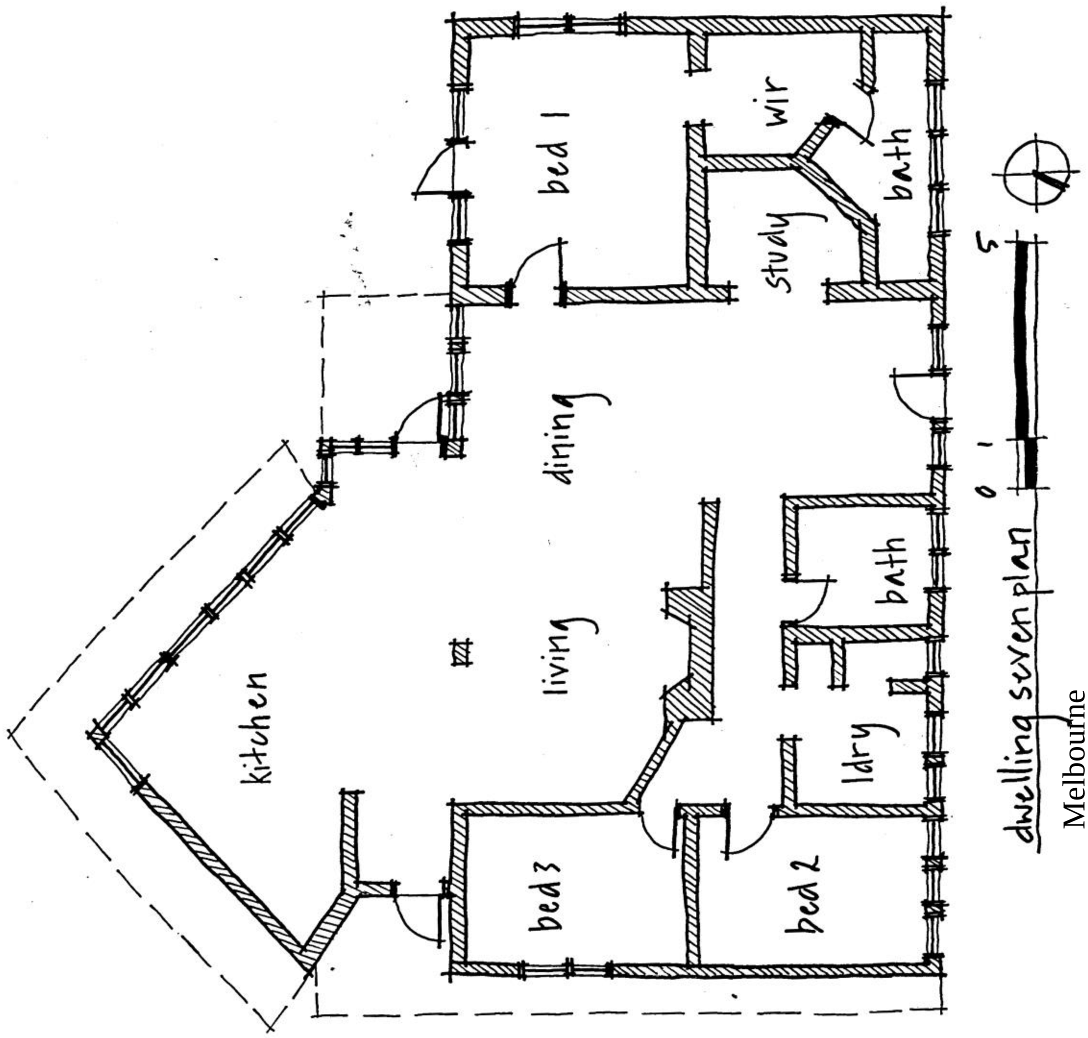
Melbourne

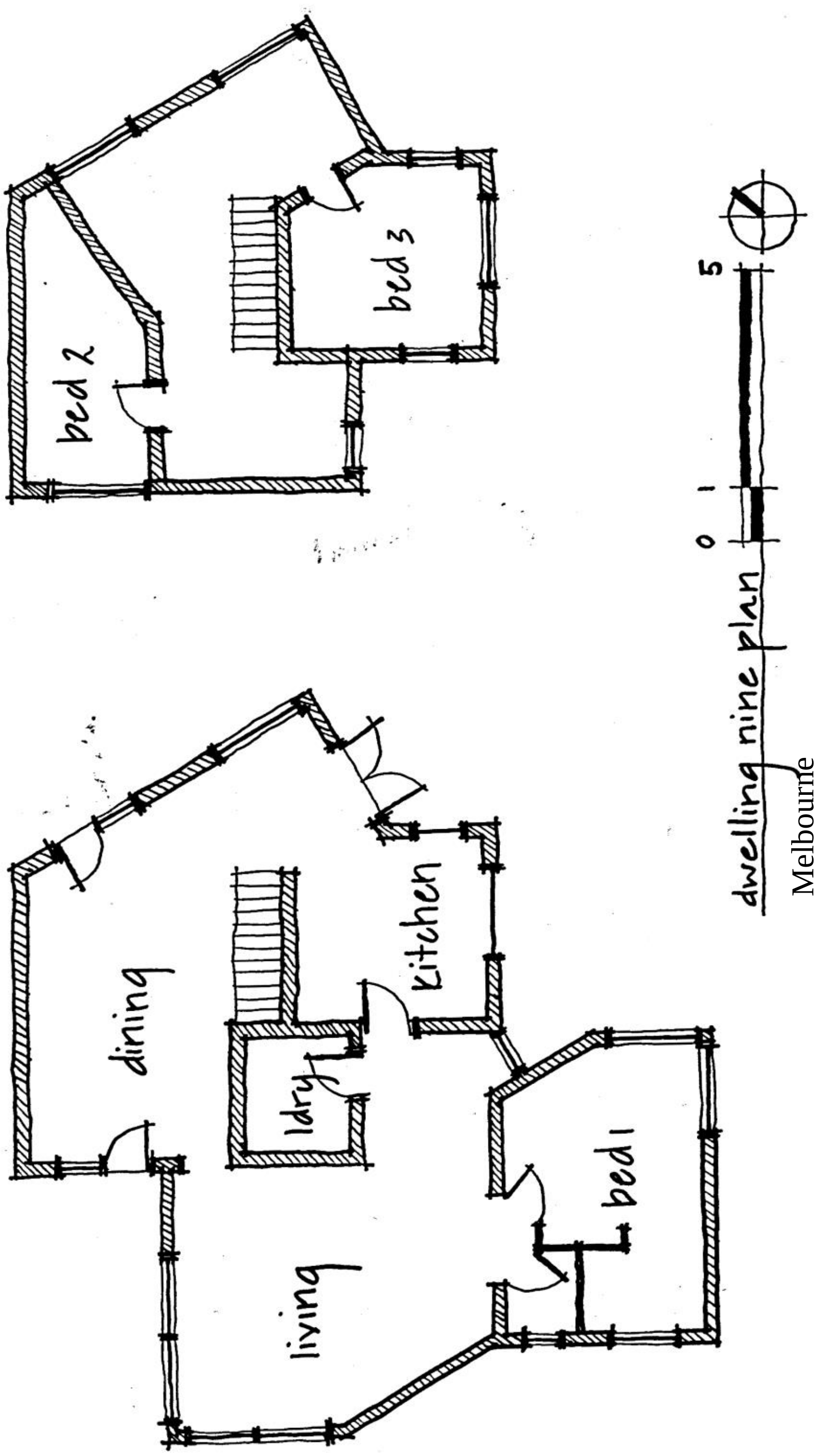

bed 1
wc
ldry
living
kitchen
bed 3
bath
bed 2
study
0
1
5
dwelling four plan
Melbourne

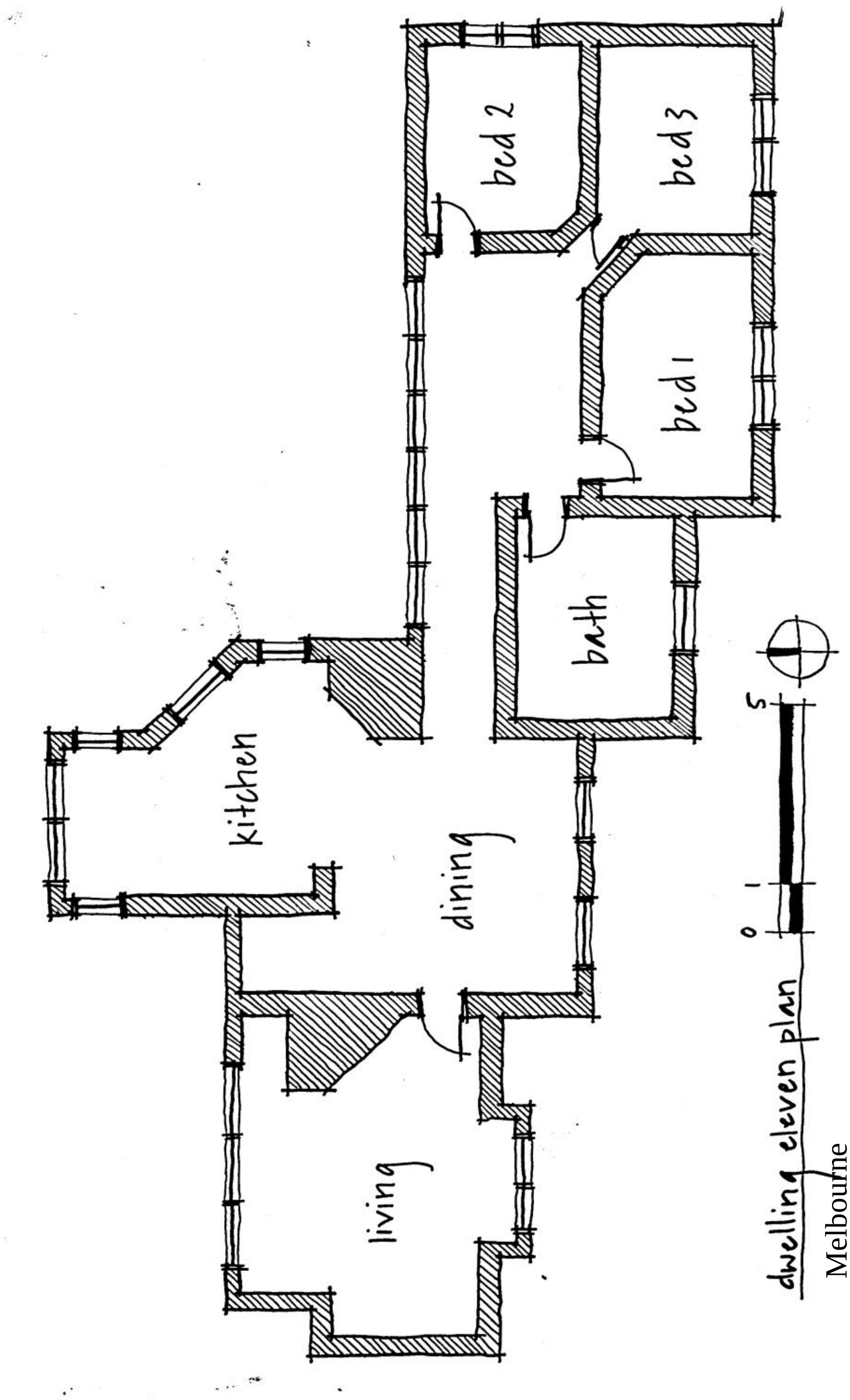

bed 1
wir
bed 2
bath
study
living
kitchen
0 1 5
dwelling five plan

Melbourne

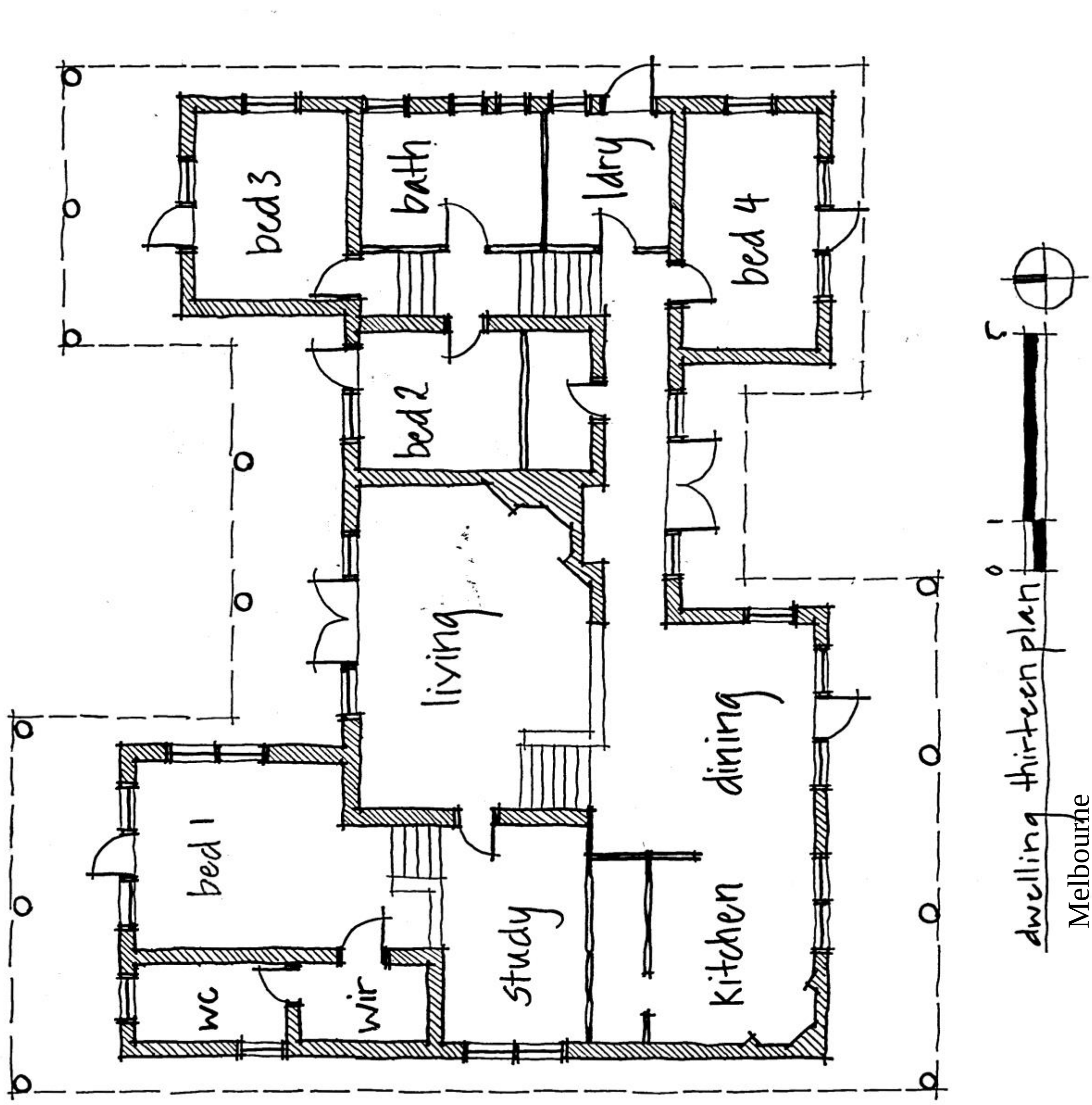

bed 2
wc
kitchen
living
bed 1
0
1
5
dwelling six plan
Melbourne

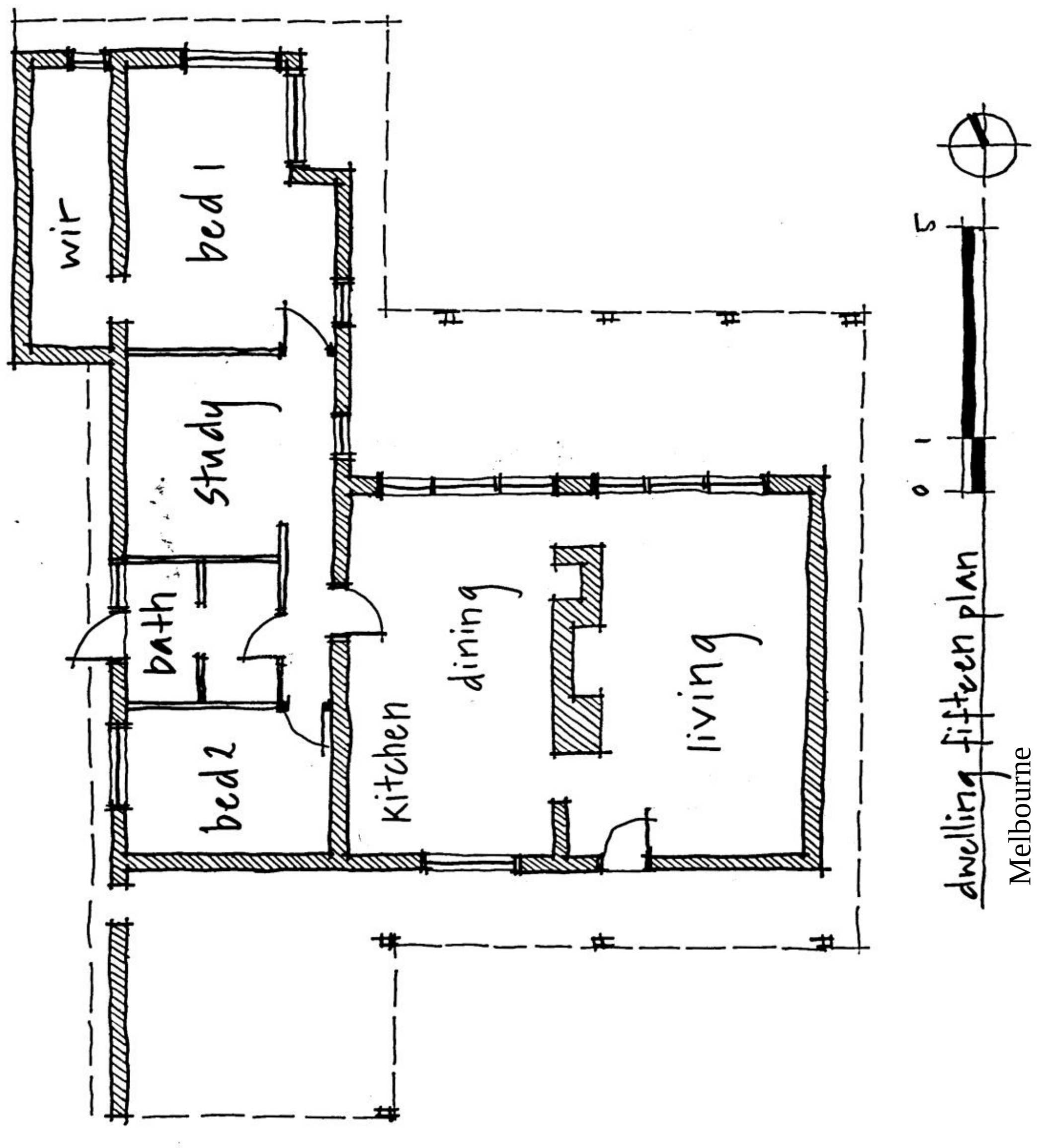

kitchen
living
dining
bed 1
wir
bath
study
bath
ldry
bed 3
bed 2
0
1
5
dwelling seven plan
Melbourne

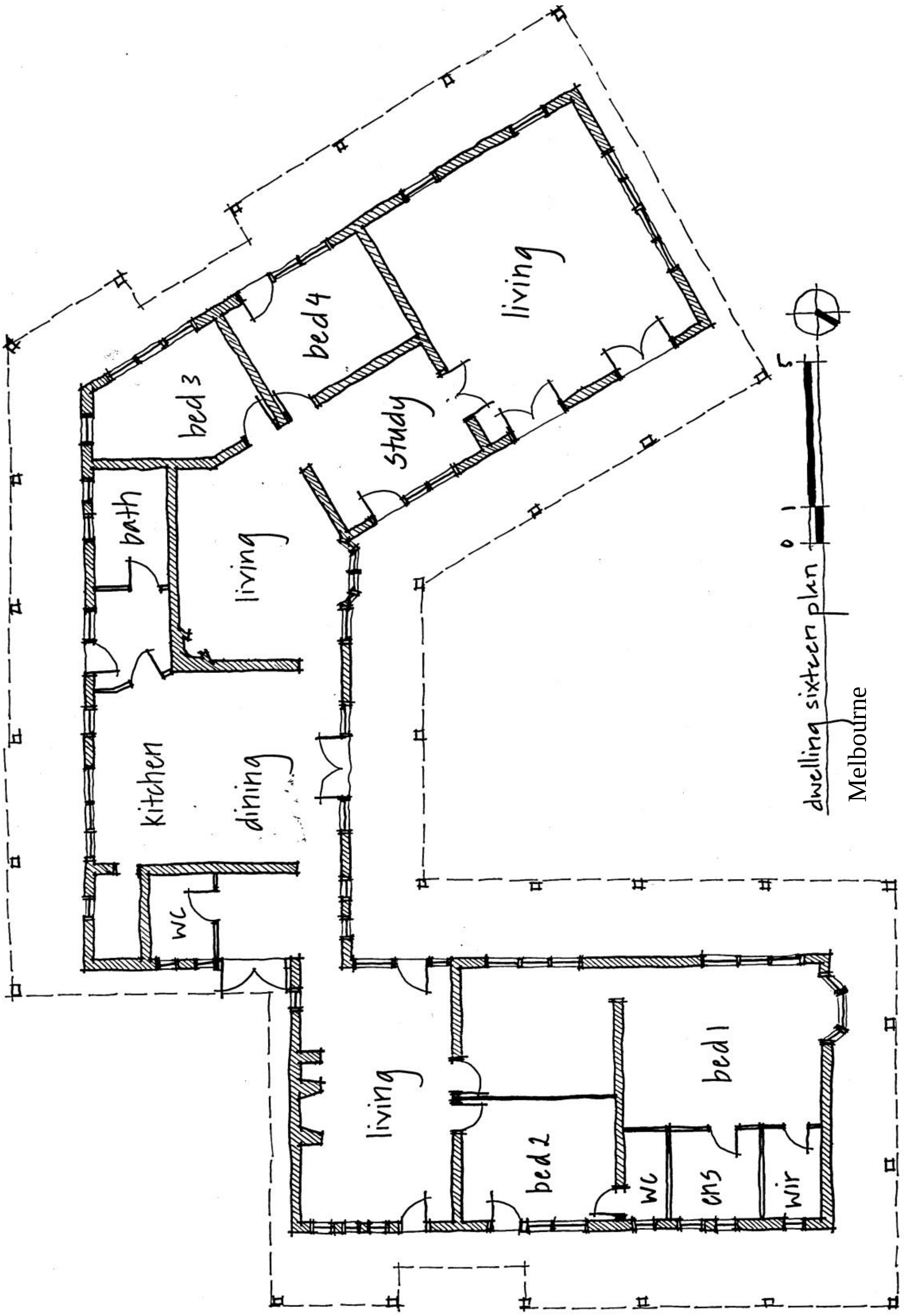

bed 2
bed 3
dining
kitchen
ldry
living
bed 1
0
1
5
dwelling nine plan
Melbourne

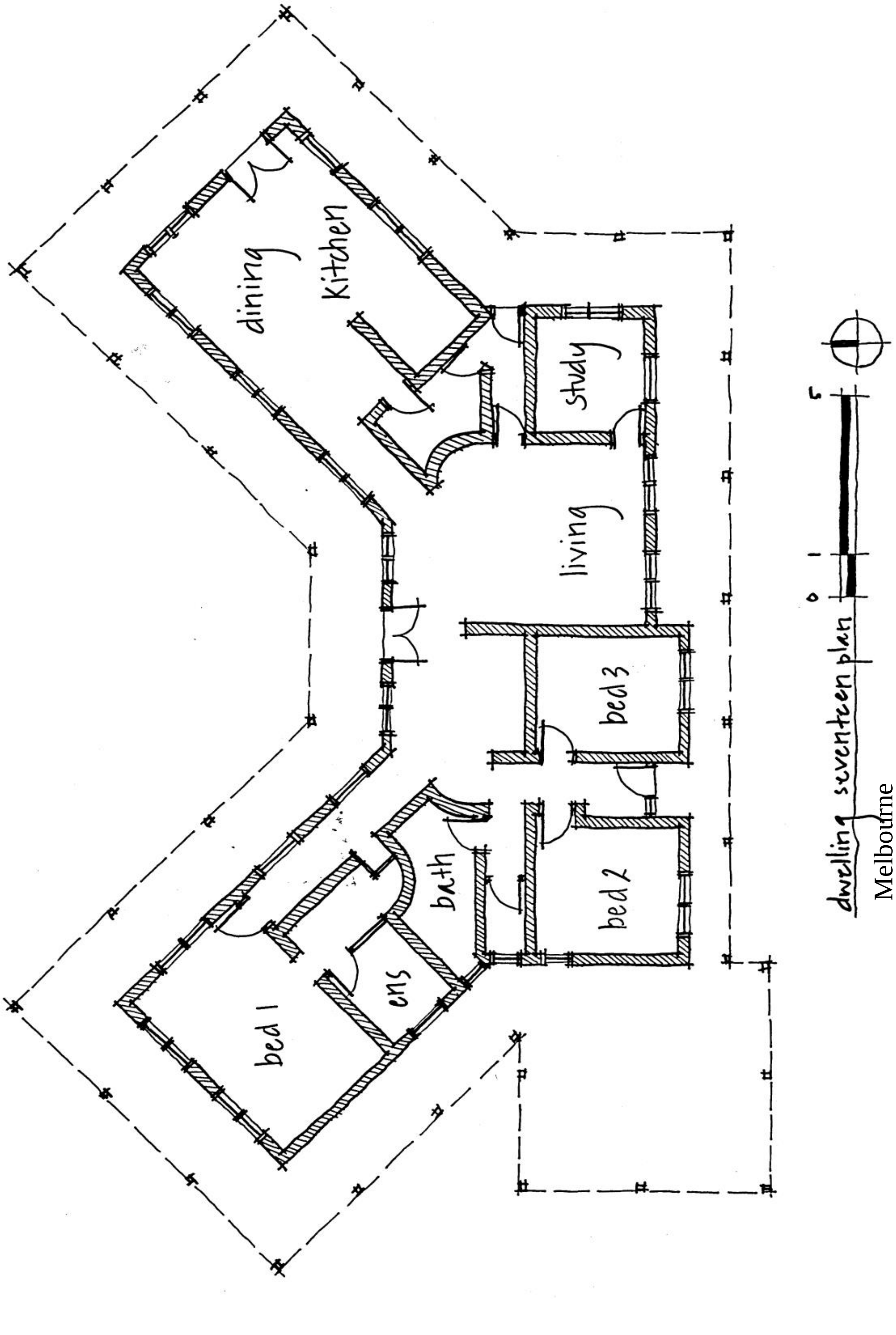

bed 2
bed 3
bed 1
bath
kitchen
dining
living
0
1
5
dwelling eleven plan

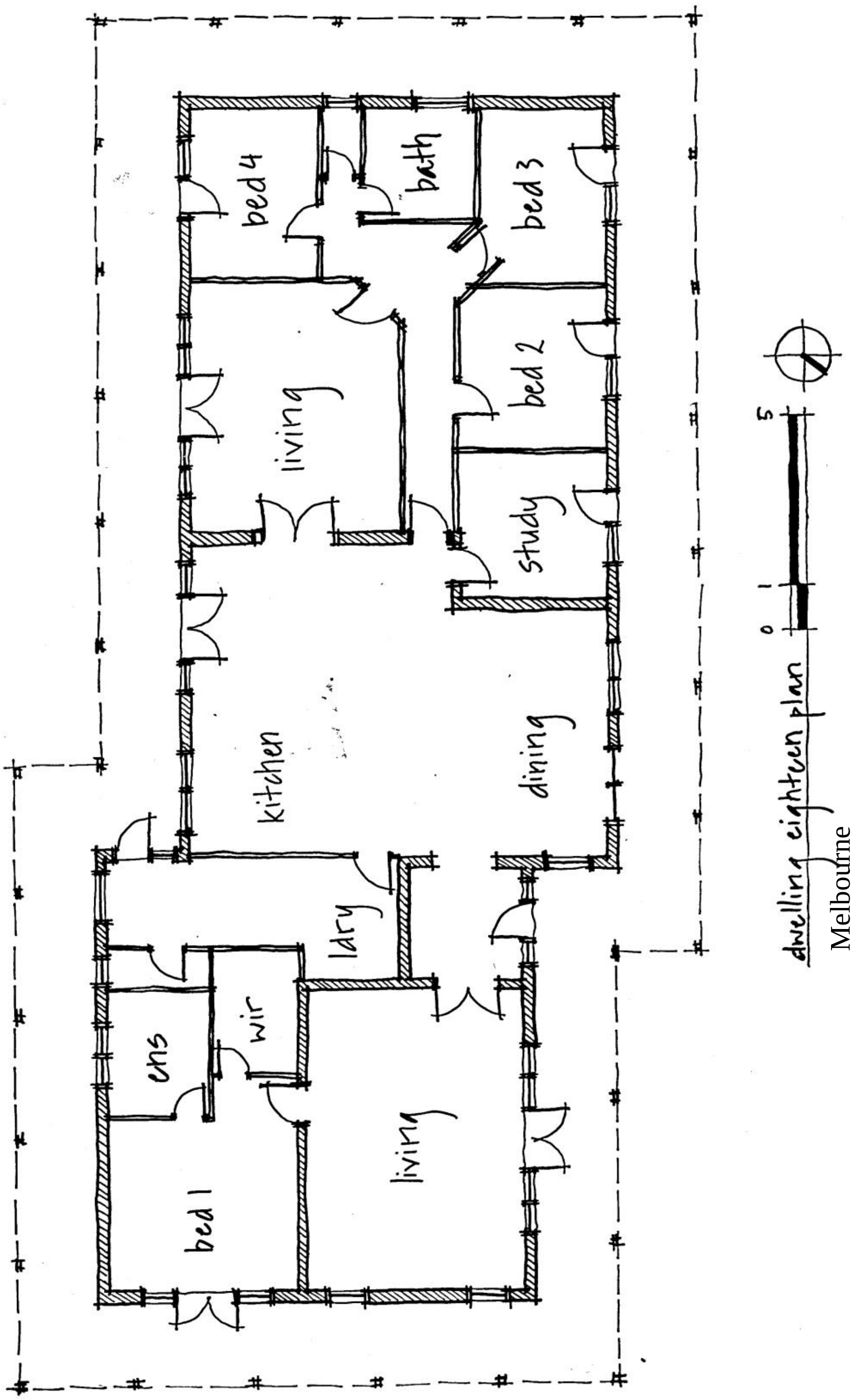
Melbourne


bed 3
bath
ldry
bed 4
bed 2
living
dining
bed 1
study
kitchen
wc
wir
0 1 5
dwelling thirteen plan
Melbourne

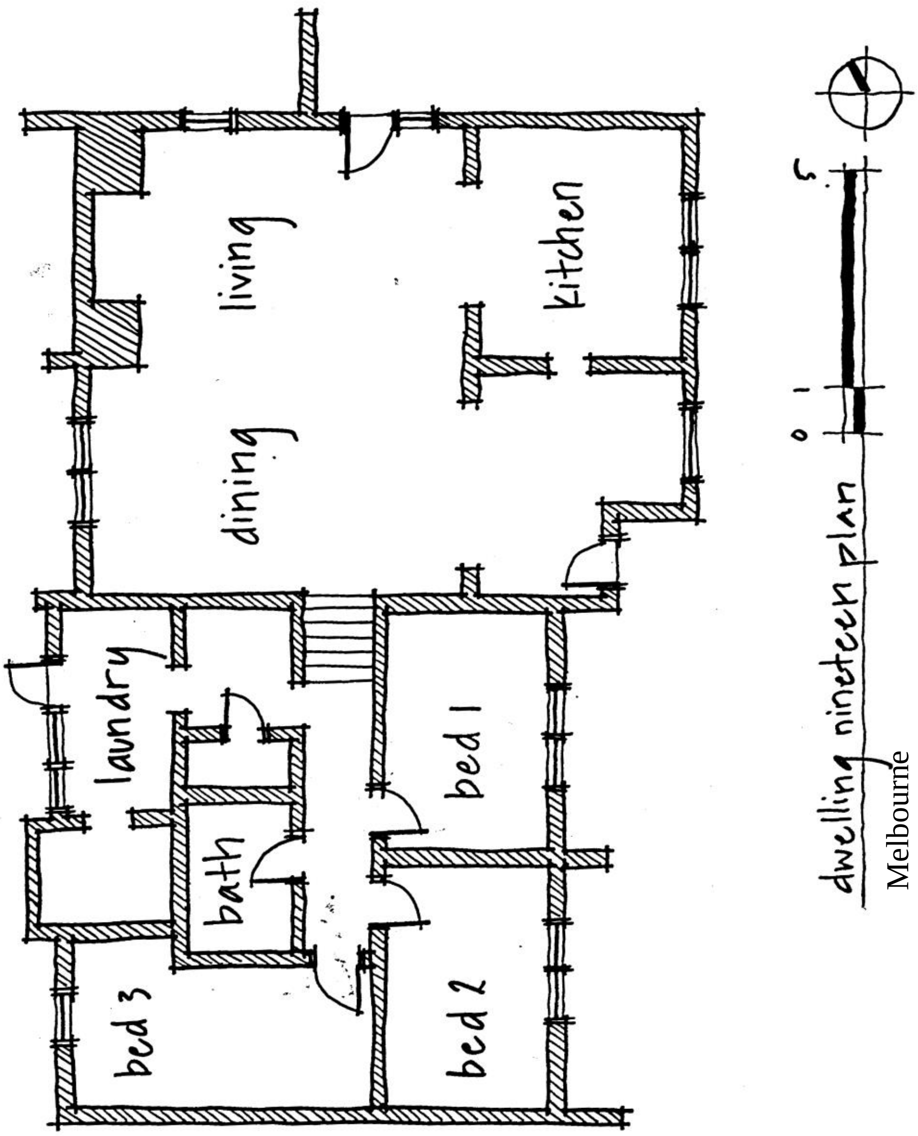

wir
bed 1
study
bath
bed2
kitchen
dining
living
0
1
5
dwelling fifteen plan
Melbourne

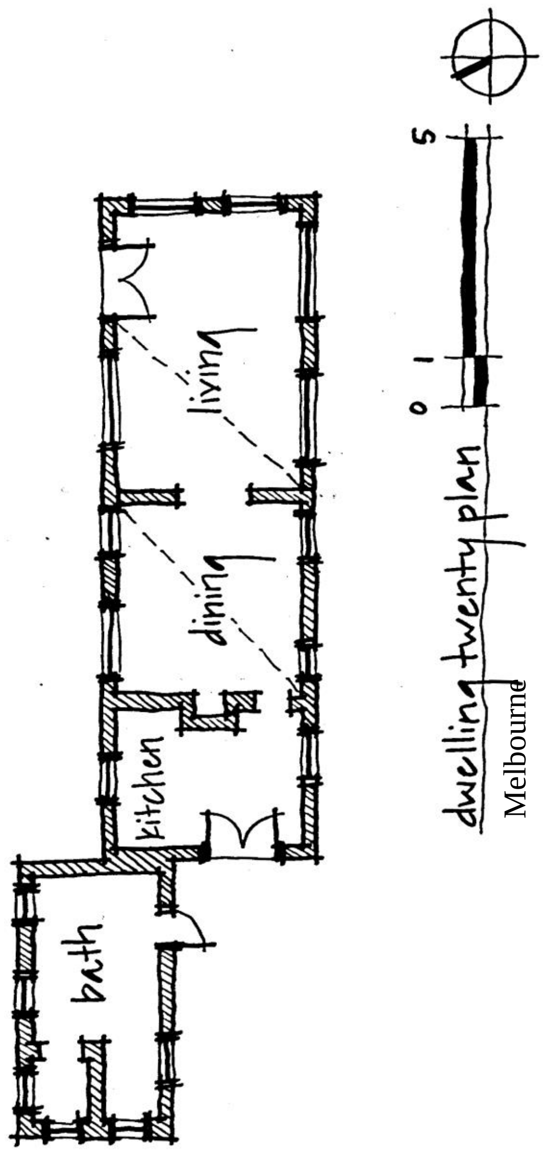

living
bed 4
bed 3
study
bath
living
kitchen
dining
wc
living
bed 1
bed 2
wc
ens
wir
0 1 5
dwelling sixteen plan
Melbourne

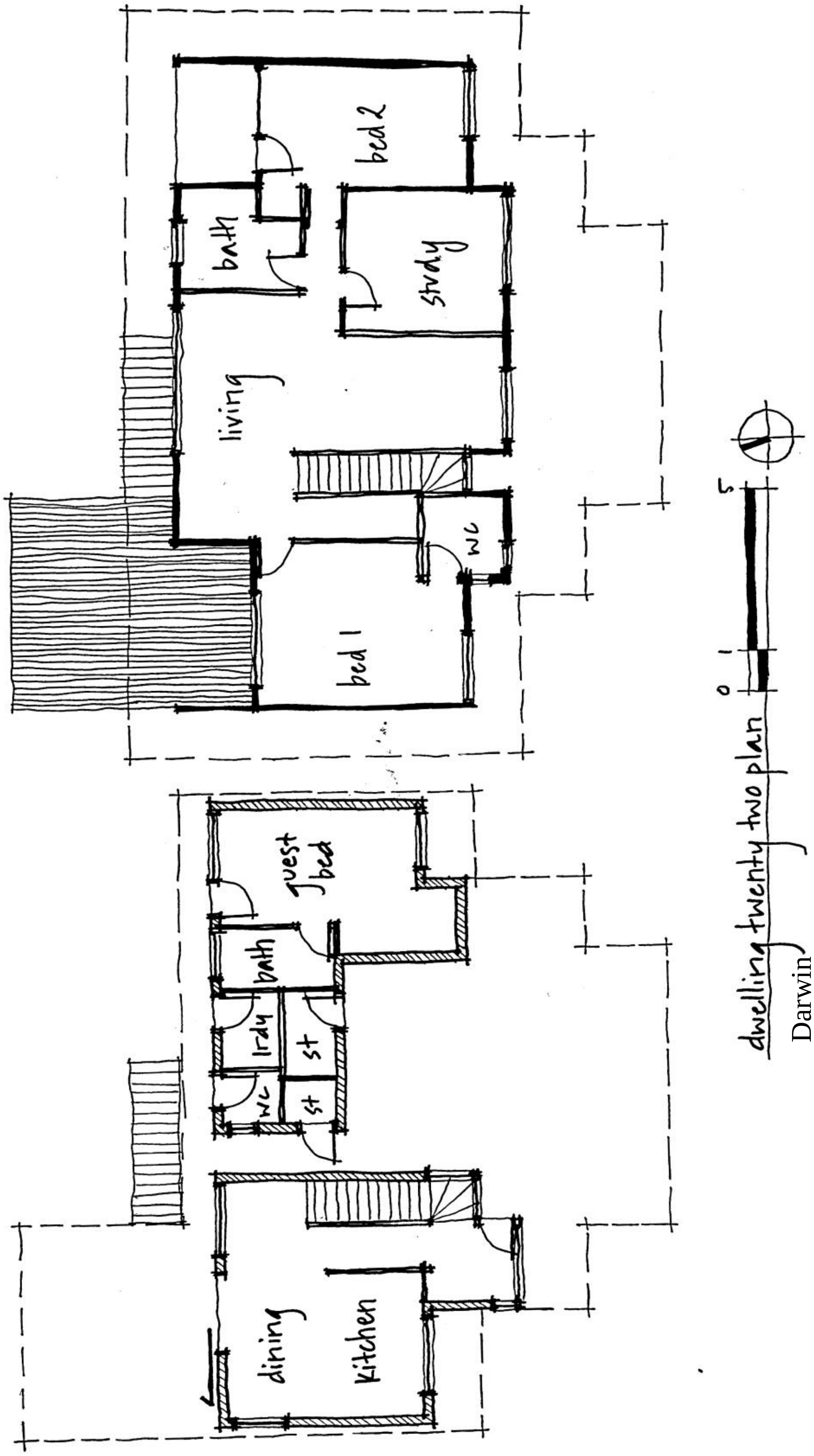

dining
kitchen
study
living
bed 3
bed 2
bath
ens
bed 1
dwelling seventeen plan
Melbourne



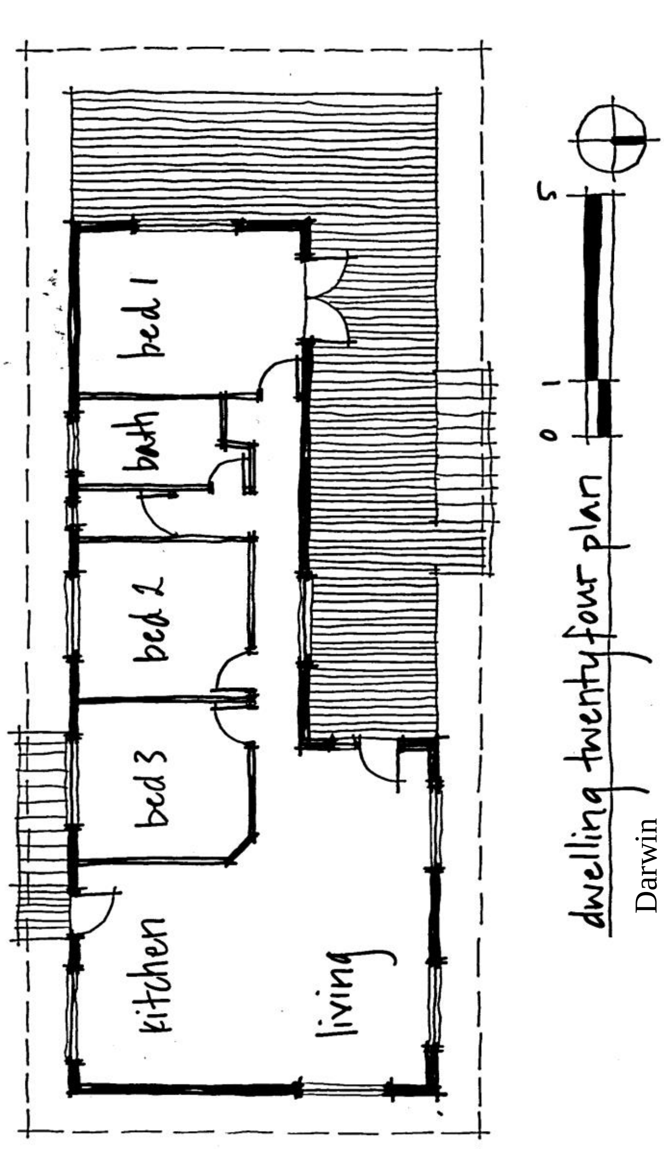
dwelling eighteen plan
Melbourne


living
kitchen
dining
laundry
bed 1
bath
bed 2
bed 3
0 1 5
dwelling nineteen plan
Melbourne

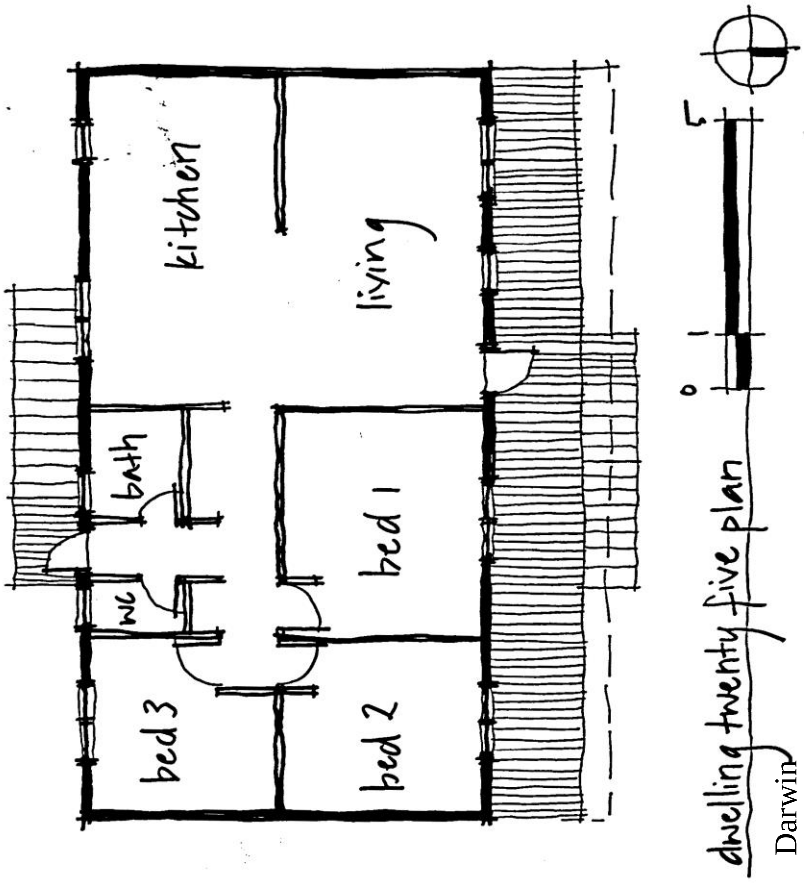

dwelling twenty plan
Melbourne
kitchen
dining
living
bath
0
1
5



dwelling twenty two plan
Darwin


bed 1
bath
bed 2
bed 3
kitchen
living
0
1
5
dwelling twentyfour plan

Darwin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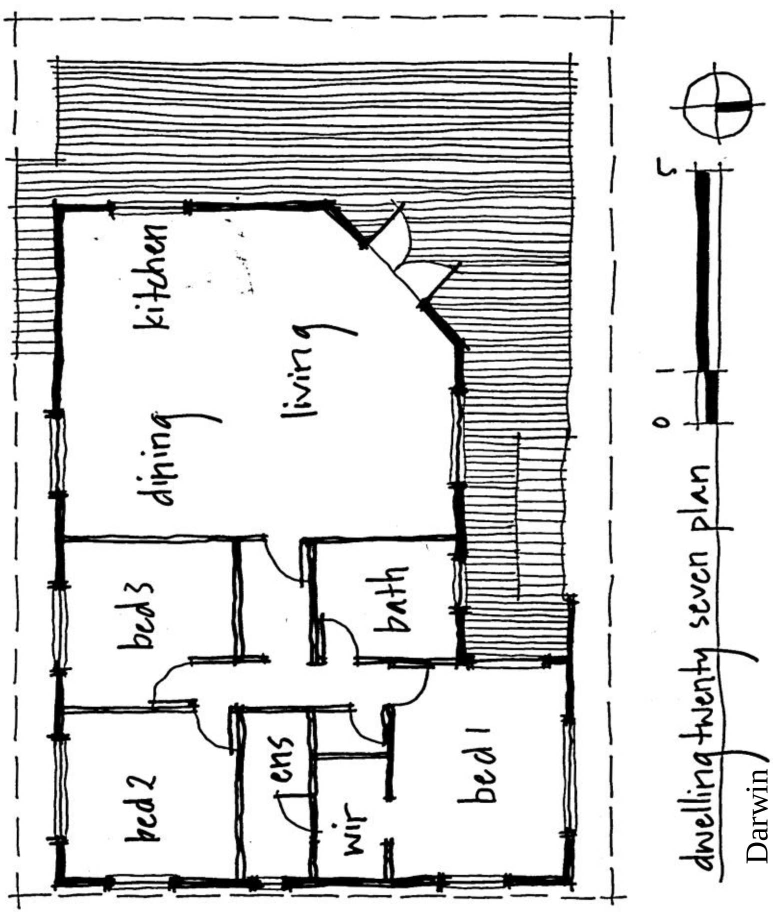
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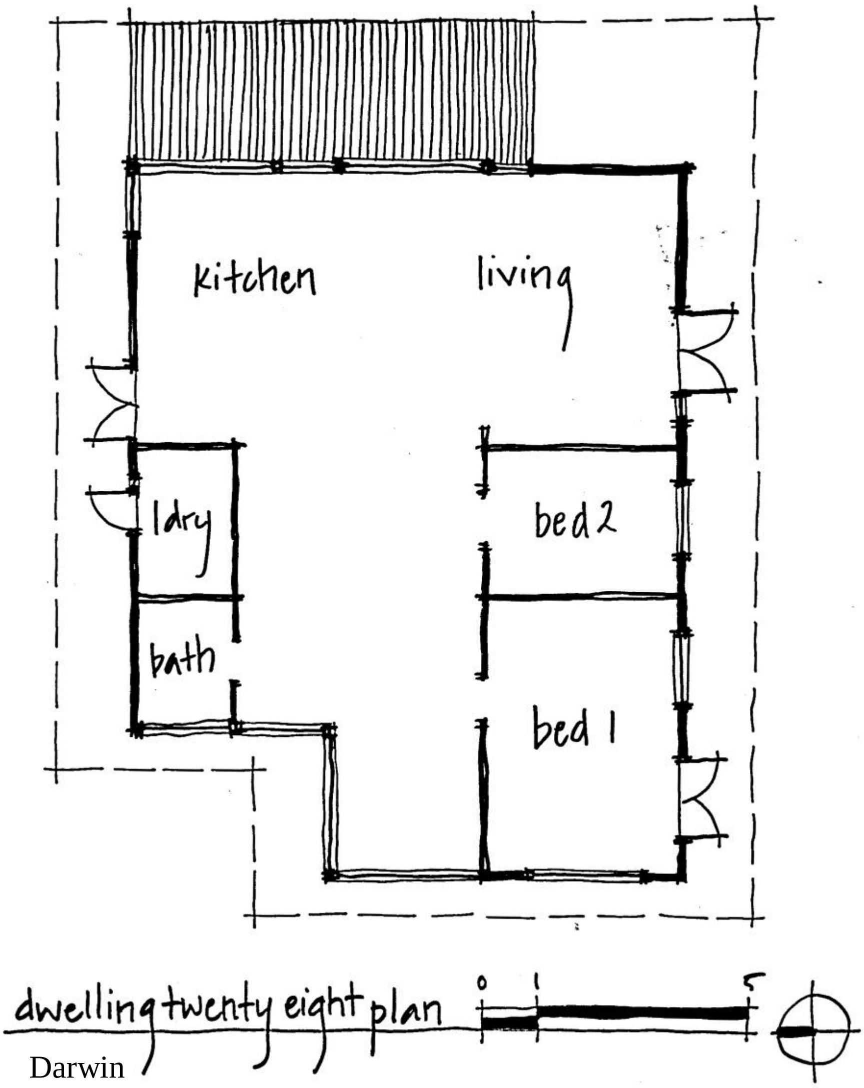
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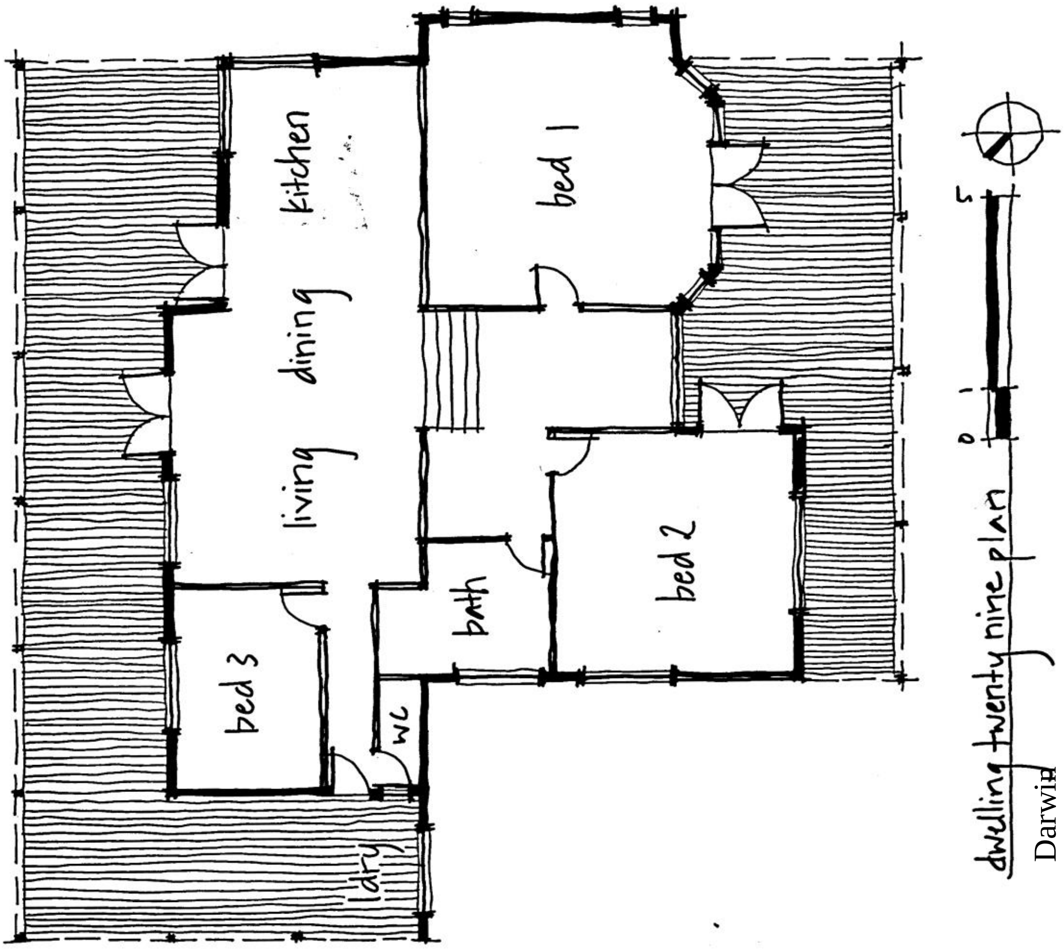
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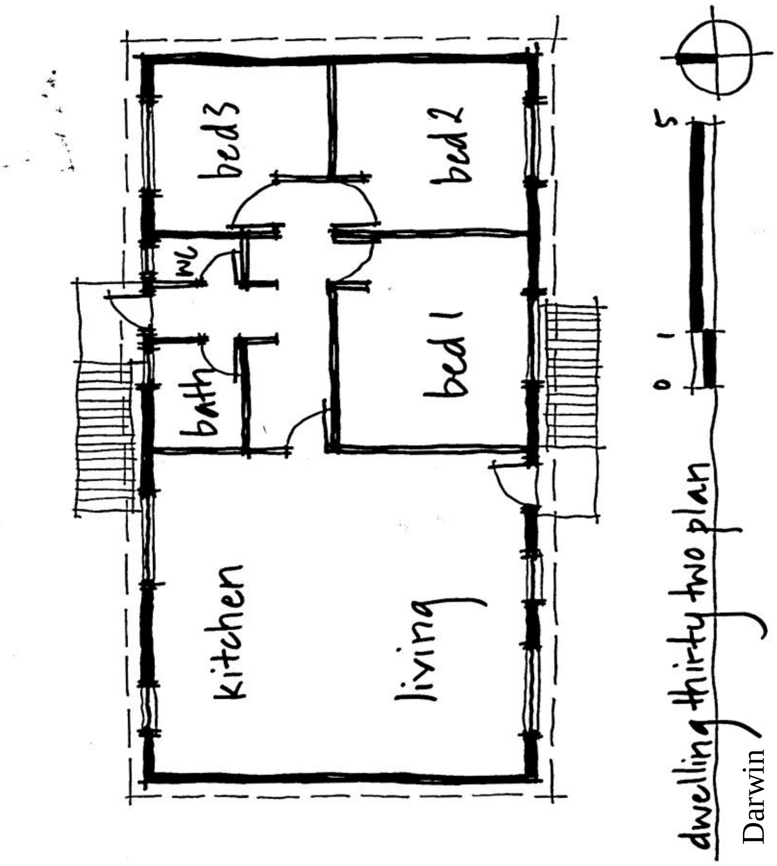
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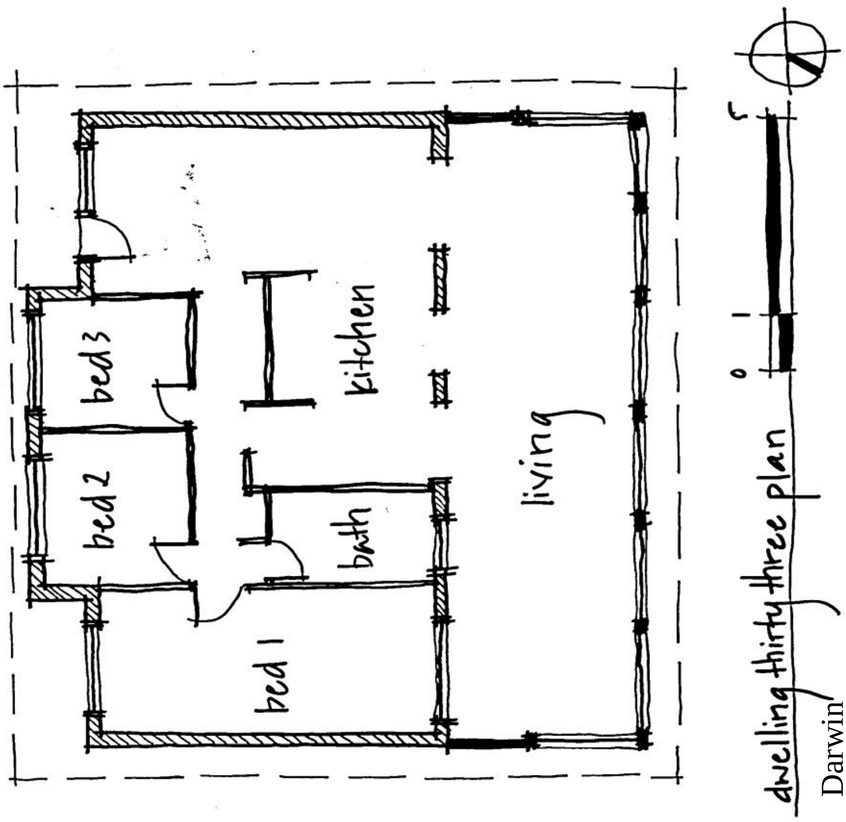
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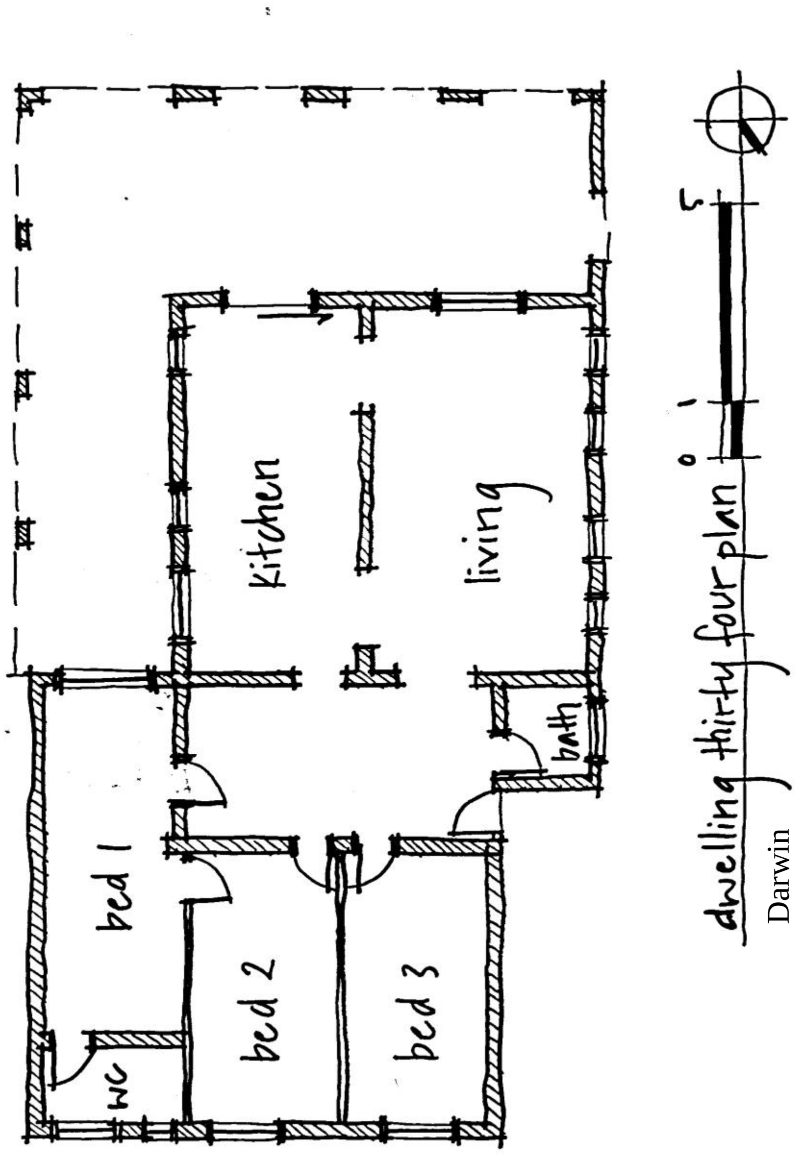
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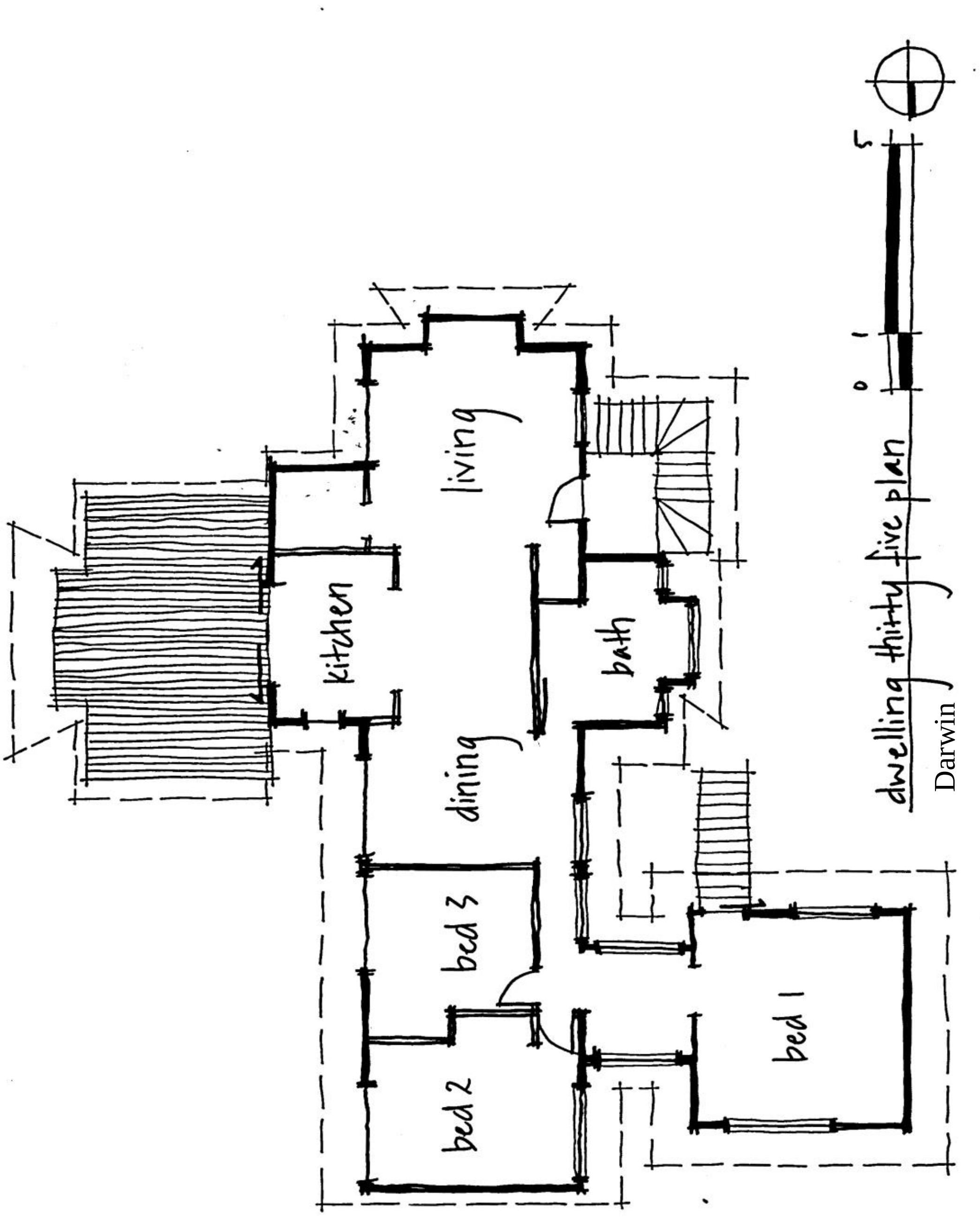
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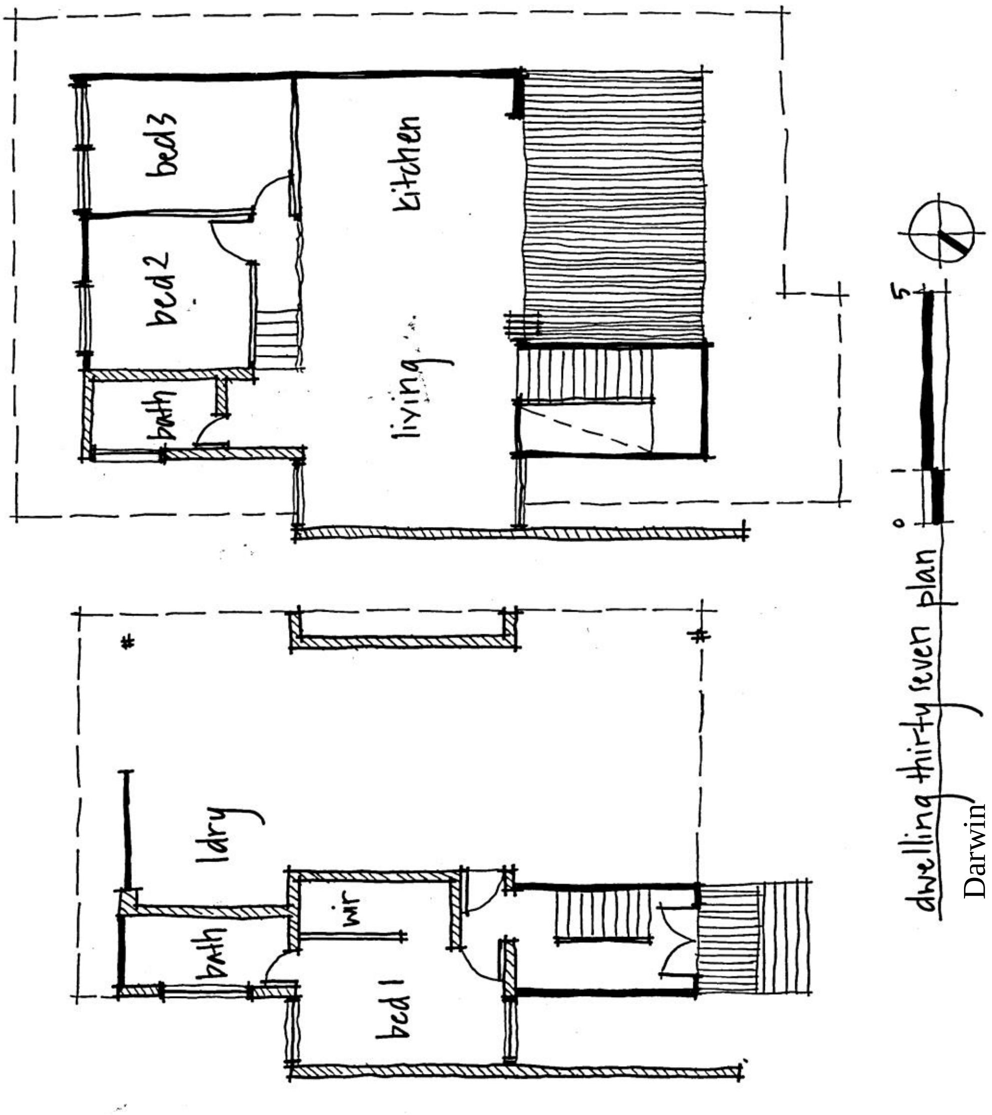
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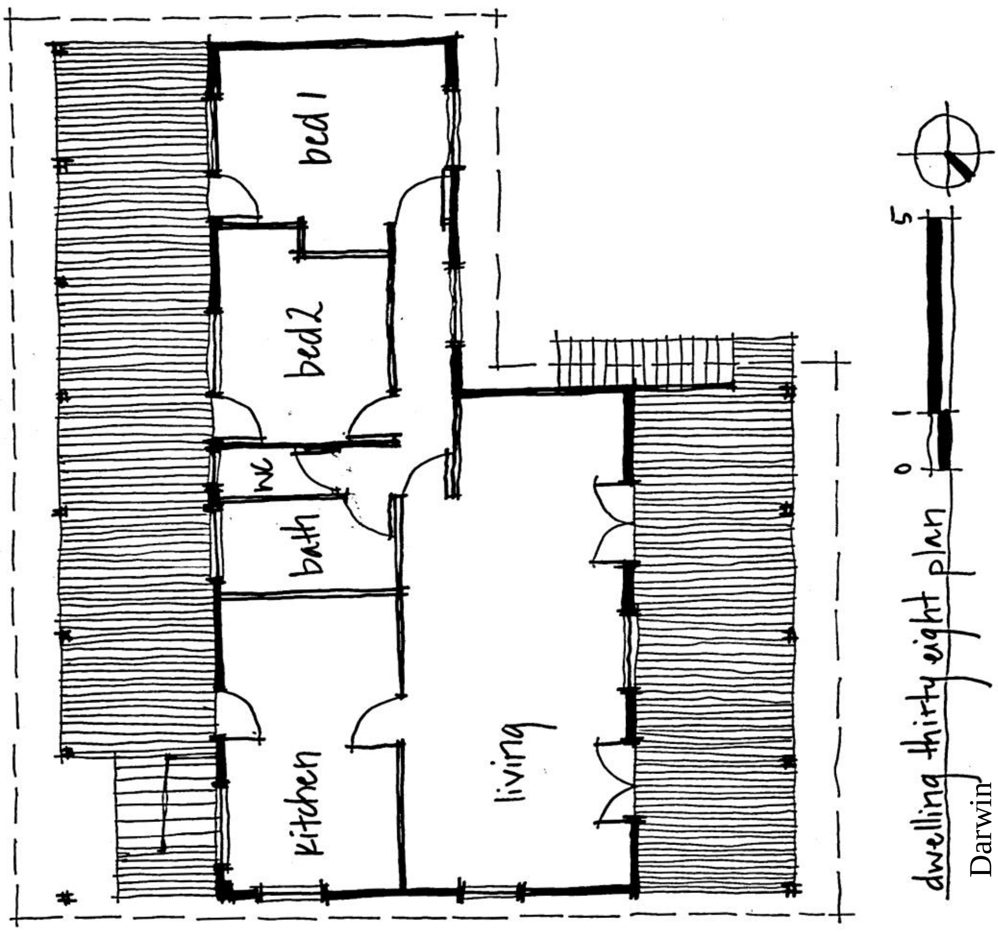
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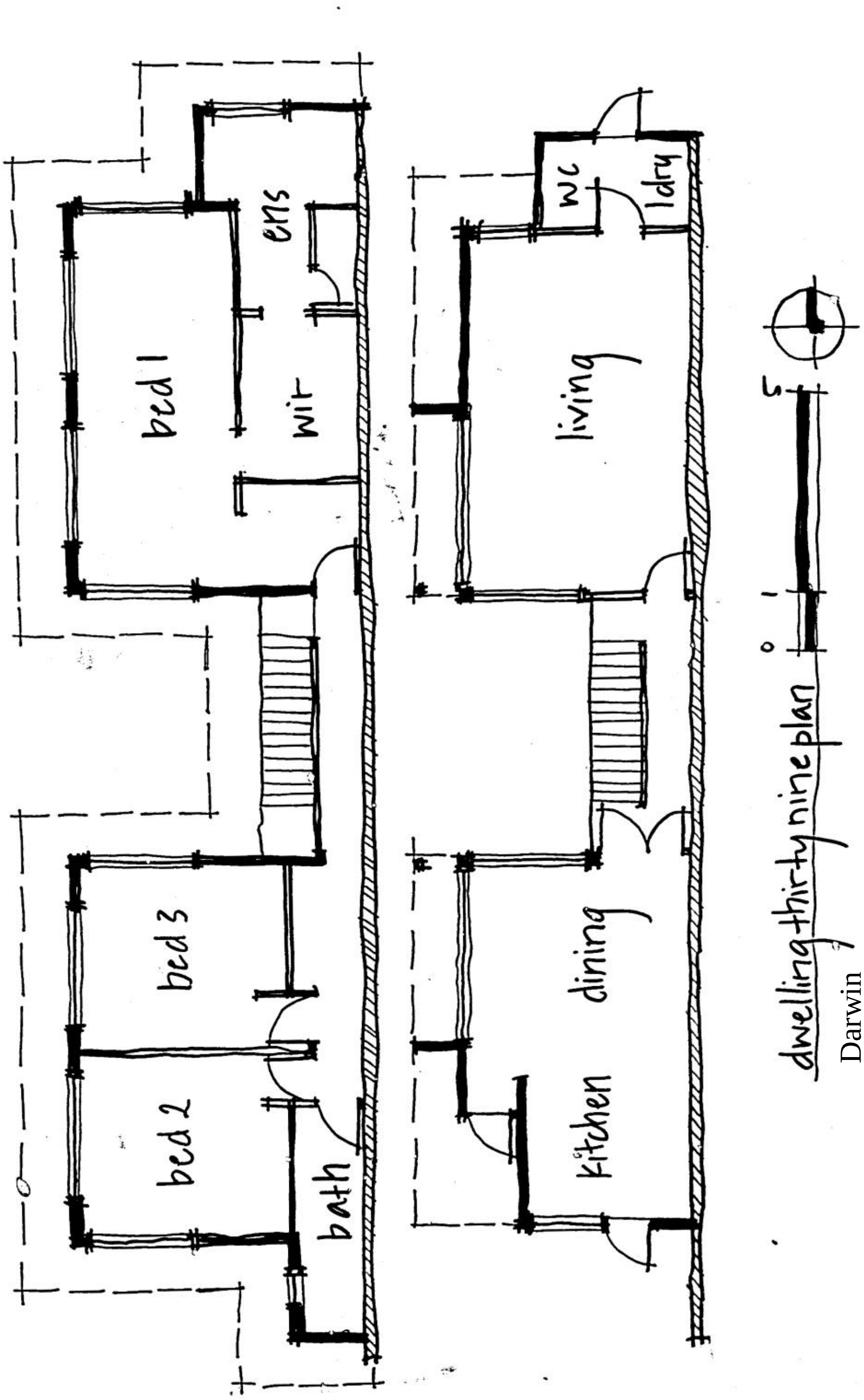
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Appendix F. Thermal comfort vote survey

Survey Instructions

When to vote?

If possible, vote once a day at varying times of the day with varying indoor conditions (e.g., windows open/closed; fan on/off)

You should only register a vote when you have been in a room where a logger is placed for at least 15 minutes, and when your clothing and activity level haven't varied much during this period.

Do not vote if you are ill, as illness may affect your comfort level. Do not vote within 30 minutes of doing highly energetic work or exercise.

Do not worry if you are unable to vote because of not being at home, or because of not being in the rooms where the loggers are for a long enough periods. It is more important to vote carefully than to vote often.

Where to vote?

Only vote in rooms where the loggers are placed, these rooms are most likely to be your main living space and/or bedroom or secondary living space. Please do not move the loggers during the monitoring period.

Who can vote?

Generally, anyone living in the house over the age of 18 years old can vote. Occupant identification numbers will be assigned to each occupant at the start of the monitoring period.

Clothing

Please mark which clothing option best describes what you are currently wearing when you vote. This will help us to identify how much insulation is being provided by your clothing.

Activity

Please mark which activity level best describes what you have been doing in the last 15 minutes. The diagrams correspond to different levels of activity;

- First diagram: reclining, very relaxed, almost sleeping, etc;
- Second diagram: sitting, relaxed, watching TV, reading, etc;
- Third diagram: standing, relaxed, moving around quietly, etc; and
- Forth diagram: moving around, housework, light household chores, etc.

Occupant Identification:

A ☐ B ☐ C ☐ D ☐

1. *How do you feel?*

☐	☐	☐	☐	☐	☐	☐
Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot

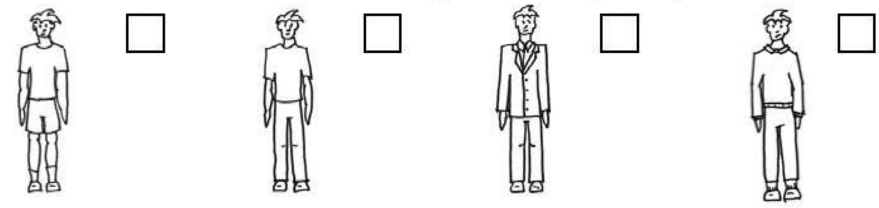
2. *How would you like to feel?*

☐	☐	☐
Cooler	No Change	Warmer

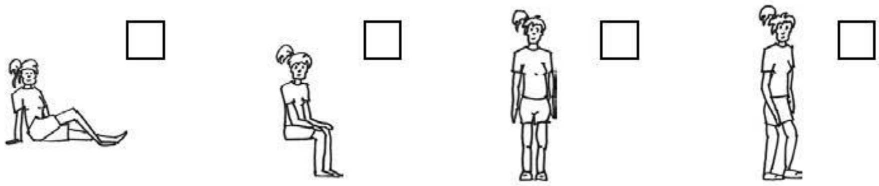
3. *Are you …*

☐	☐	☐	☐	☐	☐
Very Un-comfortable	Un-comfortable	Slightly Un-comfortable	Slightly Comfortable	Comfortable	Very Comfortable

4. *What best describes the level of clothing you are currently wearing?*



5. *What best describes the activity you have been doing in the last 15 minutes?*



6. *Do you have any windows or doors open for ventilation?*

Yes ☐ No ☐

7. *Do you have a portable or fixed fans operating?*

Yes ☐ No ☐

8. *Do you have heating or cooling appliances operating?*

Yes ☐ No ☐

9. *If you reported to be uncomfortable, how would you best describe the source of this discomfort?*

Too Drafty ☐ Too Stuffy ☐ Too Dry ☐ Too Humid ☐

Other *please explain* ____________________

Date: / / Time: : am/pm Room:

Occupant Identification:

A ☐ B ☐ C ☐ D ☐

1. *How do you feel?*

☐	☐	☐	☐	☐	☐	☐
Cold	**Cool**	**Slightly cool**	**Neutral**	**Slightly warm**	**Warm**	**Hot**

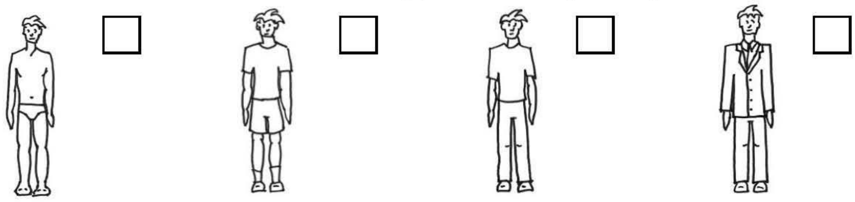
2. *How would you like to feel?*

☐	☐	☐
Cooler	**No Change**	**Warmer**

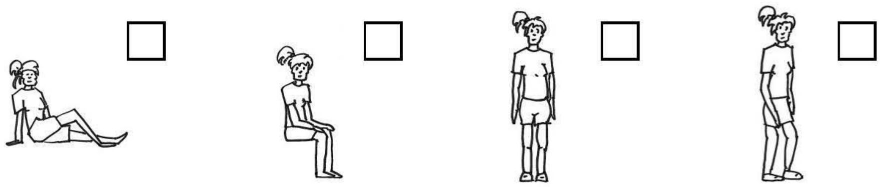
3. *Are you ...*

☐	☐	☐	☐	☐	☐
Very Un-comfortable	**Un-comfortable**	**Slightly Un-comfortable**	**Slightly Comfortable**	**Comfortable**	**Very Comfortable**

4. *What best describes the level of clothing you are currently wearing?*



5. *What best describes the activity you have been doing in the last 15 minutes?*



6. *Do you have any windows or doors open for ventilation?*

Yes ☐ **No** ☐

7. *Do you have a portable or fixed fans operating?*

Yes ☐ **No** ☐

8. *Do you have artificial cooling appliances operating?*

Yes ☐ **No** ☐

9. *If you reported to be uncomfortable, how would you best describe the source of this discomfort?*

Too Drafty ☐ **Too Stuffy** ☐ **Too Dry** ☐ **Too Humid** ☐

Other *please explain* ____________________

Date: / / Time: : am/pm Room:

Appendix G. Environmental Attitudes Inventory survey

1

THE UNIVERSITY of ADELAIDE

Environmental Attitudes Survey

Gender	Male		Female	
Age	18-29 yo	30-49yo	50-59yo	60yo and over
Do you …	Own your home	Rent you home	Other …	
Postcode				

Environmental attitudes

Please indicate the extent to which you agree or disagree with each of the following statements by marking the number that best reflects you degree of agreement or disagreement according to the following scale;

Strongly disagree	*Disagree*	*Somewhat disagree*	*Unsure/ neutral*	*Somewhat agree*	*Agree*	*Strongly agree*
1	2	3	4	5	6	7

Q1.	I really like going on trips into the countryside, for example to forests or fields.	1	2	3	4	5	6	7
Q2.	I do NOT believe humans were created or evolved to dominate the rest of nature.	1	2	3	4	5	6	7
Q3.	Protecting the environment is more important than protecting peoples' jobs.	1	2	3	4	5	6	7
Q4.	Whenever possible, I try to save natural resources.	1	2	3	4	5	6	7
Q5.	We need to keep rivers and lakes clean in order to protect the environment, and NOT as places for people to enjoy water sports.	1	2	3	4	5	6	7
Q6.	I think spending time in nature is boring.	1	2	3	4	5	6	7
Q7.	I do not believe that the environment has been severely abused by humans.	1	2	3	4	5	6	7
Q8.	I would much prefer a garden that is well groomed and ordered to a wild and natural one.	1	2	3	4	5	6	7
Q9.	Modern science will solve our environmental problems.	1	2	3	4	5	6	7
Q10.	One of the most important reasons to keep lakes and rivers clean is so that people have a place to enjoy water sports.	1	2	3	4	5	6	7

Strongly disagree	*Disagree*	*Somewhat disagree*	*Unsure/ neutral*	*Somewhat agree*	*Agree*	*Strongly agree*
1	2	3	4	5	6	7

2

Strongly disagree	Disagree	Somewhat disagree	Unsure/ neutral	Somewhat agree	Agree	Strongly agree
1	2	3	4	5	6	7

Q11. Protecting peoples' jobs is more important than protecting the environment.	1	2	3	4	5	6	7
Q12. Humans are severely abusing the environment.	1	2	3	4	5	6	7
Q13. Governments should control the rate at which raw materials are used to ensure that they last as long as possible.	1	2	3	4	5	6	7
Q14. Modern science will NOT be able to solve our environmental problems.	1	2	3	4	5	6	7
Q15. I would like to join and actively participate in an environmentalist group.	1	2	3	4	5	6	7
Q16. A married couple should have as many children as they wish, as long as they can adequately provide for them.	1	2	3	4	5	6	7
Q17. It makes me sad to see forests cleared for agriculture.	1	2	3	4	5	6	7
Q18. I would NOT get involved in an environmentalist organization.	1	2	3	4	5	6	7
Q19. Human beings were created or evolved to dominate the rest of nature.	1	2	3	4	5	6	7
Q20. I am NOT the kind of person who makes efforts to conserve natural resources.	1	2	3	4	5	6	7
Q21. I am opposed to governments controlling and regulating the way raw materials are used in order to try and make them last longer.	1	2	3	4	5	6	7
Q22. Families should be encouraged to limit themselves to two children or less.	1	2	3	4	5	6	7
Q23. I'd prefer a garden that is wild and natural to a well groomed and ordered one.	1	2	3	4	5	6	7
Q24. It does NOT make me sad to see natural environments destroyed.	1	2	3	4	5	6	7

Strongly disagree	Disagree	Somewhat disagree	Unsure/ neutral	Somewhat agree	Agree	Strongly agree
1	2	3	4	5	6	7

Appendix H. *AccuRate* Fan Speed Calculation

AccuRate Fan Speed Calculation

by

Dong Chen

CSIRO Sustainable Ecosystems

December 2011

For 900mm diameter ceiling fan, air speed is 0.5 m/s.
For 1200mm diameter ceiling fan, air speed is 0.66 m/s.
For 1400mm diameter ceiling fan, air speed is 0.77 m/s.

The cooling benefit due to air movement is calculated as

$$\Delta T = 6*(v - 0.2) - 1.6*(v - 0.2)^2 \quad (1)$$

where v is the indoor air speed (m/s) and is limited to 1.5 m/s.

However, a fan has a limited target area for the cooling benefit.

The target area of a 900mm diameter ceiling fan is 2.54 m^2.
The target area of a 1200mm diameter ceiling fan is 4.52 m^2.
The target area of a 1400mm diameter ceiling fan is 6.16 m^2.

The averaged ceiling fan cooling benefit is then calculated as

$$\Delta T_{ave} = Minimum\ (\Delta T,\ \ \Delta T*ZoneCeilingFanNumber*TargetArea/ZoneFloorArea) \quad (2)$$

Considering the average ceiling fan cooling benefit, the effective fan speed for this zone for cooling benefit is obtained by back-ward calculation from Eqs. (1) and (2).

$$v_{eff} = 2.075-(3.5156-0.625*\Delta T_{ave})^{0.5}$$

Appendix I. Associated publications

A model for the cooling effect for air movement I2 – I11

House energy rating schemes and low energy dwellings: the impact of occupant behaviours in Australia I12 – I22

Learning from thermal mavericks in Australia: comfort studies in Melbourne and Darwin I23 – I33

Development and application of air movement logger for thermal comfort research I34 – I41

A study of thermal mavericks in Australia I42 – I57

Assessing the simulation capability of the AccuRate engine in modelling massive construction elements I58 – I66

Evaluating the suitability of the AccuRate engine for simulation of massive construction elements I67 – I74

Daniel, L.R., Williamson, T., Soebarto1, V. and Chen, D. (2015) A model for the cooling effect of air movement. In R.H. Crawford and A. Stephan (Eds.) *Living and Learning: Research for a Better Built Environment: 49th International Conference of the Architectural Science Association,* Melbourne, Victoria, 2015. pp.1077–1086

NOTE: This publication is included in the print copy of the thesis held in the University of Adelaide Library.

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House energy rating schemes and low energy dwellings: The impact of occupant behaviours in Australia

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ABSTRACT

In assessing the energy efficiency of a house design, particularly methods incorporating building performance simulation, assumptions are made about how the occupants operate the building. Often these assumptions are standardised to simplify the assessment process with the intention of enabling a straight forward comparison between designs. Assessment of performance using standardised operations may pose a disadvantage to house designs that are intended for households who are likely to operate the house outside of the assumed norm. This paper examines occupant behaviour in *low energy* houses in the context of the Australian regulatory house energy rating scheme and, using simulation, demonstrates the impact of alternative occupancy settings on the validity of the predicted house energy rating. The results clearly show that current occupant assumptions within the scheme fail to adequately reflect actual heating and cooling practices in *low energy* dwellings and, as such, overestimate energy consumption within these households. Based on these results it is suggested that, for equitable assessment of these households, settings within the simulation engine used for assessment must be modified to align with actual user behaviour.

1. Introduction

House energy rating schemes (HERS) around the world have been developed in an attempt to mitigate the amount of energy consumed in the building sector during the operation phase of the building [1–4]. Often these schemes employ building performance simulation to benchmark the proposed design based on the predicted energy loads needed to maintain prescribed comfort conditions [5]. The United States of America (USA), Canada, United Kingdom, Denmark and Australia all use some form of HERS in a regulatory manner [6]. Despite the inherent and regulatory goals of HERS, substantial failings in their effectiveness in reducing energy consumption have been noted, including: the take back effect [7], accuracy of simulation tools [8,9], appropriateness for passive architectural designs [6,10], reporting of results [11,12] and standardisation of user behaviour [13,14].

Within a regulatory context, these failings become increasingly important as the HERS outcome can ultimately affect whether a home attains building approval certification. The purpose of this paper is to investigate the influence of the generic assumptions about occupant behaviour in the Australian regulatory HERS: the Nationwide House Energy Rating Scheme (NatHERS). The hypothesis of this research is that low energy forms of housing are likely to attract occupants that are more active in the operation of their home and therefore have the potential to reduce the amount of energy consumed in relation to heating and cooling, over and above the HERS predicted consumption based on standardised or normalised user profiles. If demonstrated, it would seem intuitive that these types of houses should be assessed under a different basis than standard forms of housing. Whilst this is a context specific study, it is possible that the implications of this study are relevant to HERS worldwide.

This paper examines dwellings incorporating earth construction methods (e.g., mud brick, pise, rammed earth, adobe) as a specific example of *low energy* housing. Preliminary findings from a recent study of earth housing in Melbourne, Australia [15] support the consideration of earth buildings as *low energy* dwellings. Additionally, this form of construction has also previously been shown to attract occupants with higher levels of environmental concern than the general population [15–18], influencing behaviour and perception of building performance.

1.1. House energy rating in Australia

The Nationwide House Energy Rating Scheme (NatHERS) forms one of the primary methods of mandatory residential building

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0378-7788/

Table 1
NatHERS fixed user assumptions.

User variable	NatHERS regulatory setting	
Heating and cooling energy loads	Heating and cooling load potential during all occupancy hours, all days of the year	
Rooms conditioned	All habitable[a] rooms	
Thermostat settings	Heating	Minimum 20 °C in living areas between 7 AM and 12 AM Minimum 18 °C in bedroom between 7 AM and 9 AM & 4 PM–12 AM, minimum 15 °C in bedrooms between 12 AM and 7 AM
	Cooling	Ranges from 22.5 to 28 °C during hours of occupancy based on climatic zone
Hours of occupancy	Living areas 7 AM–12 AM Bedrooms 4 PM–9 AM	
Sensible and latent heat gains	Living areas with kitchen	8740 W/day sensible* 2950 W/day latent*
	Living areas	4590 W/day sensible* 1365 W/day latent*
	Bedrooms	2200 W/day sensible* 900 W/day latent*

* Sensible and latent heat gains based on 160 m² dwelling with 2 adults, 2 children, 80 m² for living, 80 m² for bedroom, an algorithm to adjust these occupancy variables are based on the floor area allocated to living space.
[a] 'Habitable rooms' refers to living areas, bedrooms, etc. that can be reasonably expected to be heated and/or cooled.

energy efficiency compliance assessment. NatHERS was developed in the 1990s as a response to Australia's signing of the United Nations (UN) Framework Convention on Climate Change in 1992 and the resulting national greenhouse response strategy [19]. Based on the glass, mass, insulation (GMI) rating scheme and *Cheenath* simulation engine, NatHERS was not intended for mandatory use, but rather, as a design tool to assist the public and building industry [19]. In January 2003, when the energy efficiency regulations were first introduced to the National Construction Code (NCC) of Australia (formerly the Building Code of Australia), it was decided that NatHERS would be used as the framework for the thermal simulation compliance assessment process [20].

1.1.1. Simulation assessment method

The NatHERS simulation software, *Australian Government Endorsed calculation engine* second generation *AccuRate*, simulates the thermal performance of the building envelope and, based on predicted heating and cooling loads, produces a star rating from 0 to 10. A 10 star rating infers that the dwelling will require almost no additional heating and cooling to maintain the prescribed 'comfort range'. The current requirement for building compliance certification is a minimum rating of 6.0 stars. Currently the star rating method to demonstrate compliance with the energy efficiency requirements is the primary form of assessment used in most States and Territories [21].

Input required for simulations include detailed information about construction, layout, shading, glazing and ventilation, while the program assumes other non-variable data such as occupancy profiles, casual heat loads and appliance use, summarised in Table 1. The fixed or generic user profile is explained on the NatHERS website by the following statement:

> Every house is used in a unique way every day of every year and therefore it would be impossible to assess a building according to its actual use. To allow houses to be compared fairly a standard occupancy pattern is applied to represent a reasonable expectation of how a room (or space) is used (its function). [22]

Changes made to any of the input can result in a critical variation in the star rating realised and ultimately whether or not compliance with the energy efficiency regulation is satisfied. This paper argues that, similarly, changes to non-variable data in particular the occupancy profiles can also influence the star rating achieved.

1.2. Software validation

Throughout the development of *AccuRate*, validation studies have sought to test the adequacy of the core computational engine to model the thermal performance of the building envelope. The original iteration of the simulation engine, *Cheetah*, was included in a substantial validation study completed in 1992 [23]. The study assessed the predicted temperatures of 25 dynamic thermal simulation programs against measured temperatures from three constructed test cells and demonstrated a general level of comparability between *Cheetah*, the other simulation programs and the measured data. Following the progression of *Cheetah* to *Chenath*, inter-program (inter-modal) and empirical validation exercises (using International Energy Agency (IEA) methodologies) were completed to test the recent enhancements of the tool [24,25]. Whilst minor discrepancies were reported, it was concluded that the evolution from *Cheetah* to *Chenath* did not result in the corruption of the original engine and that the findings *should lead to increased confidence in its use* [24]. In 2004, a subsequent inter-program validation of the *AccuRate* simulation engine was completed, again using the International Energy Agency building energy simulation test and diagnostic method (IEA BESTEST). Results similarly indicated a good agreement with the reference programs and only produced minor over estimation of heating and cooling demands due to the temperature calculation and control algorithms [26]

1.3. Performance gap: Earth wall houses

In spite of the validation studies, concerns have been voiced about the observed gap between NatHERS predicted performance, and the measured performance of some forms of housing [10]. This gap has been particularly noted in dwellings that incorporate heavyweight construction elements, primarily arising from the often 'poor' predicted thermal performance as opposed to the anecdotal 'good' performance expressed by occupants of earth buildings. Two key explanations are offered: the first is that the simulation engine cannot adequately model massive construction and, in particular, account for thermal lag, and the second is that the actual operation of the house (heating and cooling appliances) is not reflected by the NatHERS assumptions of occupancy and user profiles.

Addressing the former issue, predicted data from *AccuRate* with measured data from a mud brick house were compared [27]. The study found that there was no significant discrepancy between

Table 2
Responses disaggregated by state.

State or territory	Count	Percentage
New South Wales (NSW)	24	13.7
Victoria (VIC)	99	56.6
Queensland (QLD)	10	5.7
South Australia (SA)	16	9.1
Western Australia (WA)	24	13.7
Northern Territory (NT)	2	1.1
Total	175	100.0

AccuRate simulation results and measured data. Importantly, the author suggests that any discrepancies may be attributable to the difference between behaviour and occupant assumptions included within the program and actual occupant perceptions. This is similarly supported by findings from a 2009 study in reference to houses incorporating rammed earth walls that lower energy bills were not directly attributable to the use of rammed earth wall construction but instead the occupants' perceptions that influence behaviour related to energy use [28]. This paper seeks to clarify these issues by isolating the capability of the simulation engine from the NatHERS prescribed user assumptions through validation studies and, subsequently demonstrate the impact of changing these assumptions in relation to NatHERS compliance.

2. Occupant behaviour assumptions

2.1. Earth wall housing survey

A survey was conducted in 2011 to better understand actual occupant behaviours of households living in earth constructed dwellings in Australia. The survey aimed to gather information about heating and cooling practices and appliances, dwelling construction, and demographics in all major states in Australia, namely New South Wales (NSW), Victoria (VIC), South Australia (SA), Western Australia (WA), Queensland (QLD) and Northern Territory (NT). Analysis of this survey in conjunction with national statistics from the Australian Bureau of Statistics (ABS) and NatHERS occupancy assumptions demonstrates that the responses significantly differed in key areas of occupant behaviour that impact on energy consumption within the home. The preliminary results of the survey were previously reported in [29].

2.1.1. Distribution and response

Hardcopy and online versions of the survey were distributed by earth building industry associations and interest groups. A total of 175 valid responses were received. The response rate, disaggregated by state, is expressed in Table 2. Victoria produced a significantly higher proportion of responses due to the use of groups based in that state to distribute the questionnaire. All of the respondents lived in homes with some form of external or internal earth wall construction.

2.1.2. Occupancy

The average occupancy rate of participants was 2.81 persons per dwelling, slightly higher than the 2011–2012 national figure of 2.6 persons per dwelling [30]. This figure is, however, much lower than the minimum occupancy rate of 4 persons per dwelling assumed in NatHERS [22]. Just over 50% of all respondents were aged 50 years and above, indicating that the cohort was predominantly established households.

On average, the houses were 22.5 years old, with the newest one year old and the oldest house 200 years old. The average period of respondents living in their house was 15 years. Almost all of the houses were detached dwellings (98.3%), higher than the 2011 national figure of 85.5% [31].

The dwellings surveyed were set in a wide range of contexts, from suburban with close neighbours (26%), rural bushland (32%), rural open countryside/farmland (20%), *other* (21%), to inner town suburban (1%). Responses to *other* were predominantly large bushland blocks in suburban settings, and eco-villages communities.

When queried about the comfort levels in their homes during different seasons and times of the day, the majority respondents perceived the house to be comfortable all year round, indicating a general satisfaction with the thermal performance of their house.

2.1.3. Heating and cooling practices

The households were asked to estimate their heater and cooler usage over a year; Tables 3 and 4 compare the responses with 2011 national averages for all housing types. The questionnaire results for heater use in NSW, VIC and WA were fairly comparable, while

Table 3
Number of heating months disaggregated by state.

		NSW (%)	VIC (%)	QLD (%)	SA (%)	WA (%)	NT (%)
Survey	Less than 1 month	14.29	2.02	33.33	***37.50***	19.05	0.00
	One month to less than 3 months	28.57	21.21	***66.67***	18.75	***42.86***	***100.00***
	Three months to less than 6 months	***57.14***	***60.61***	0.00	***37.50***	38.10	0.00
	Six months or more	0.00	16.16	0.00	6.25	0.00	0.00
ABS data (2011)	Less than 1 month	10.95	6.29	***48.79***	9.28	11.98	17.89
	One month to less than 3 months	***43.11***	20.16	39.73	35.53	42.24	***47.37***
	Three months to less than 6 months	41.92	***53.35***	11.48	***48.89***	***43.13***	34.74
	Six months or more	4.03	20.19	0.00	6.30	2.64	0.00

Table 4
Number of cooling months disaggregated by state.

		NSW (%)	VIC (%)	QLD (%)	SA (%)	WA (%)	NT (%)
Survey	Less than 1 month	***100.00***	***77.78***	***50.00***	***85.71***	***55.56***	0.00
	One month to less than 3 months	0.00	19.44	***50.00***	14.29	22.22	***50.00***
	Three months to less than 6 months	0.00	2.78	0.00	0.00	22.22	*50.00*
	Six months or more	0.00	0.00	0.00	0.00	0.00	0.00
ABS data (2011)	Less than 1 month	17.51	34.84	28.47	15.86	5.61	6.54
	One month to less than 3 months	***50.81***	***46.01***	***38.11***	***43.18***	33.27	10.55
	Three months to less than 6 months	29.33	17.78	23.51	38.10	***52.61***	25.50
	Six months or more	2.36	1.37	9.91	2.86	8.51	***57.41***

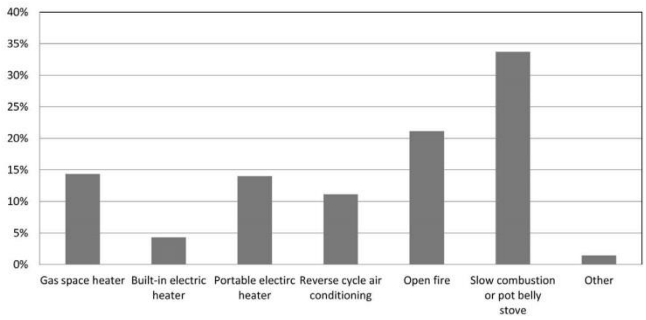

Fig. 1. Heating appliance type.

the data for SA showed a slightly lower trend in heater use. The heating data from QLD and NT were too limited to draw any conclusions. The questionnaire data for cooler use for NSW, QLD and NT again were limited; however in VIC, SA and WA, where the data were more representative, it is possible to distinguish a lower trend in cooler use.

All of the households surveyed had some form of space heating (see Fig. 1). The percentage of households with space heating was higher than the national average, likely due to a high proportion of responses originating from the southern states with cool and cold temperate climates. The main types of heating were open fires, and slow combustion stoves, divergent from the most common heaters used over the broader population: gas space heater (23.5%), reverse cycle air-conditioners (23.3%) and ducted gas heaters (14.5%) [31]. A number of respondents commented on the thermostat settings of their heaters; they indicated a range was between 13 and 22 °C, with common settings being 17, 18 and 19 °C. This clearly demonstrates the varying comfort levels of different households and occupants, indicating that heating set point of 20 °C in the benchmark thermal simulation software inadequately responds to the comfort perceptions and expectations of many of the households.

The majority (67.1%) of the respondents did not have any cooling appliances, while in the households that did, reverse cycle air-conditioning for one room was most prevalent (see Fig. 2). While this was the most predominant cooling appliance, it is apparent that it was mainly used only for cooling and not heating as well. Interestingly, in the comments section many respondents acknowledged the cooling potential of cross ventilation, fans and thermal mass. Of the households that did not have coolers, few thought there would ever be a need to install a cooler, with many respondents citing environmental concerns and the (good) performance of their homes as reasons. On the contrary, it was reported by the Australian Bureau of Statistics that in 2011, 71.3% of Australian households had a cooler [31]. This figure is significantly higher than that of the cohort studied (32.9%). In a similar way, households in the study indicated that they infrequently used the heaters and coolers (as seen in Tables 3 and 4) whereas NatHERS assumes heating *and cooling* potential for 365 days of the year.

The majority of the respondents reported only heating half the house—the living areas, with just a small proportion heating the bedrooms or study rooms. Similarly, those households that had coolers mostly used them in either the living area or one bedroom (see Fig. 3). Again, this does not align with the NatHERS assumption that all habitable rooms are conditioned.

Most of the respondents only operated their heaters during the afternoon and in the evening until bedtime (see Fig. 4). The respondents who reported to heat their houses all day and night were generally those with hydronic in-slab systems (most common response to *other* for heating appliances) used constantly throughout the cooler months. The afternoons and evenings were the most common times when cooling appliances were operated. Many respondents cited periods of prolonged extreme heat as the key precipitator for cooler use. The NatHERS protocols, on the other hand, specify potential heating and cooling between 7:00 AM to 12:00 AM in living areas and 4:00 PM to 9:00 PM in bedrooms, clearly not reflective of actual appliance use in the surveyed households.

The results presented above demonstrate discrepancies between how the surveyed households operate their homes and NatHERS user assumptions. Additionally, many of the NatHERS assumptions do not align with recent national statistics; therefore they fail to represent even a 'typical' Australia family.

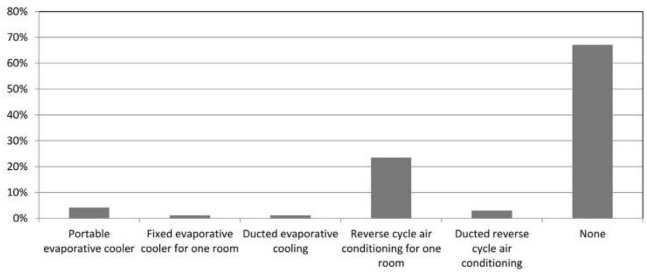

Fig. 2. Cooling appliance type.

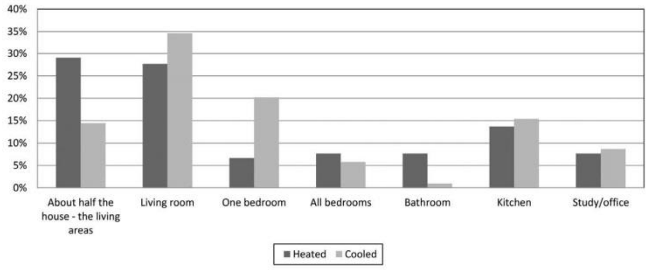

Fig. 3. Rooms conditioned.

3. Validation studies

This study uses intermodal and empirical comparisons to verify the adequacy of the *Chenath* computational engine to model with sufficient accuracy the behaviour of a building. The intention is to isolate the general inadequacies of NatHERS to issues of occupancy and user behaviours.

The intermodal study used the simulation tools *EnergyPlus* (with *DesignBuilder* as the interface) and *EnerWin* for comparison with the *Chenath* engine. *EnergyPlus* was chosen because of its use worldwide and the numerous validation studies it has been subject to. The heat flow calculation is based on determining a surface heat balance using a finite-difference technique [32]. *EnerWin*, the second comparison tool selected, was developed in the USA and is used predominantly in research and calculates heat flow based on the modified total equivalent temperature differential values and a system of time average (TETD/TA) method [33]. These two simulation engines were selected because of their similar features and input requirements to *Chenath*. For clarity, from this point onward in this paper the *Chenath* simulation engine will be referred to as *AccuRate*.

The comparisons were conducted for two constructed test cells and three occupied residences. All five models were simulated in 'free running' mode, with no artificial heating or cooling. These five comparisons can be considered as validation investigations determining whether the *AccuRate* simulation model is an accurate representation of a 'real' system. The extent to which the results match will provide an indication of the level of confidence with which the software can be used.

The primary statistical indicator of correlation used was the coefficient of variance of the root mean square error (CV(RMSE)), recommended in the ASHRAE *14-2002 Guideline for Measurement of Energy and Demand Savings*. Although this guideline is based on the analysis of energy use, the CV(RMSE) in this context is the predicted internal temperatures compared to the measured internal temperatures. No guideline on statistical comparison of hourly temperature data could be found by the authors. A CV(RMSE) value of between 10 and 20% has been cited as acceptable for empirical models by several other authors [34–36]. In this study iterations were made to refine the simulation models until a CV(RMSE) of <15% was achieved for the period of measured data. All simulations were completed for an entire year, however for the purposes of this exercise, comparison was only made for the periods that monitored data were available.

3.1. Test cells

The first analysis comprised of intermodal and empirical comparison of the measured and predicted internal temperatures from two constructed test cells (see Fig. 5). Built by The University of Technology Sydney (UTS) as part of a collaborative study, the test cells are identical except for the walling materials [37,38]. This study utilises data from the test cells with mud brick walls and brick veneer walls. Both cells were unconditioned and unventilated throughout the monitoring period (December 2006–January 2007). The test cells are located in Yarramundi, New South Wales, Australia, which has the Köppen climate *classification Cfa Humid subtropical*. The climate file used for simulation of the test cells was created using a 'base' file in the *Chenath* required *.TXT format for the Richmond RAAF location approximately 12 km from Yarramundi (measured weather data from December 2006–January 2007). Synthetic hourly solar radiation figures derived Bureau of Meteorology (BOM) satellite data, and

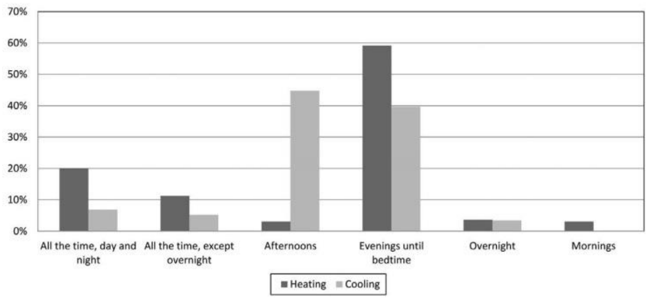

Fig. 4. Times of heating and cooling.

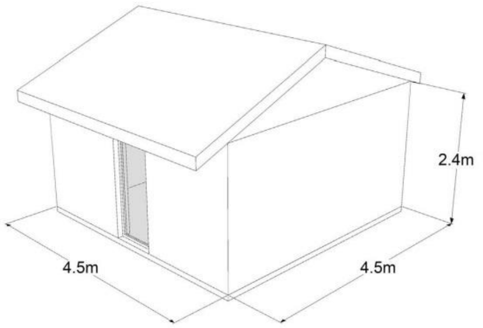

Fig. 5. Test cell configuration.

measured external temperatures for the actual location replaced the generic Richmond RAAF figures for greater accuracy. The *.TXT file was then converted to the appropriate formats for *EnergyPlus* and *EnerWin*.

3.2. Occupied dwellings

In order to increase the complexity of the test and identify the impact of occupants on performance simulation, three occupied residences were modelled. All dwellings incorporated some form of earth wall construction. Residence A, located in Ironbank, South Australia (Köppen climate classification *Cfb Marine west coastal*), has predominantly 250 mm mud brick walls both internally and externally. Residence B, located in Aldinga, South Australia (Köppen climate *classification Csa Dry-summer subtropical*), has approximately 20% insulated 400 mm rammed earth walls and 80% insulated timber framed construction. Residence C, also in Aldinga, has an internal spine wall of 250 mm compressed earth block with insulated timber framed external walls.

The three occupied dwellings used in this study were chosen from a number who responded to the initial survey and indicated a willingness to participate in further research. The households were self-selecting and not known to the authors. The participating households were selected because of their proximity to the authors' location and access to energy use records and construction drawings. Indoor air temperature and relative humidity measurements were taken and recorded at hourly intervals using Onset® HOBO U08-004 data loggers. The monitoring equipment was installed in Residence A from April–May 2011, in Residence B from June to August 2011 and in Residence C from June to September 2011.

Climate files using weather data appropriate to the location of the dwelling and the period of monitoring were created for use in all three simulation engines. The climate file for Residence A was compiled from measurements (temperature, relative humidity, wind speed & direction, and solar radiation) from an Onset® HOBO weather station installed approximately 1 km from the residence from January to July 2012. The climate file for the occupied Residence B and C simulations was created by *Energy Partners* using a similar method as Yarramundi climate file; a base file utilised weather data from Adelaide Airport (approximately 40 km north from Aldinga) and synthetic solar radiation data for the actual location. External temperatures were replaced with measured data from a weather station located approximately 15 km north of the two residences.

Table 5
CV(RMSE), mean difference and maximum difference of AccuRate, EnergyPlus and EnerWin predicted results compared to measured results for the test cells from 14th December 2006 to 18th January 2007.

Simulation engine	CV(RMSE) (%)	Mean difference (°C)	Max difference(°C)
Mud brick test cell			
AccuRate	3.33	0.70	4.37
EnerWin	4.08	0.84	5.17
EnergyPlus	5.50	1.14	4.33
Brick veneer test cell			
AccuRate	3.39	0.66	3.87
EnerWin	5.37	1.14	4.67
EnergyPlus	9.03	1.78	6.11

4. Results

4.1. Simulation engine validation study

4.1.1. Test cell simulations

The predicted temperatures from the three simulations engines generally show good agreement with the measured internal temperatures for both the mud brick and brick veneer test cells (see Table 5). The *AccuRate* results give the lowest CV(RMSE) value for both test cells, while the *EnergyPlus* predicted temperatures displayed the largest divergence from the measured, particularly for the brick veneer test cell. The sporadic deviation of the *AccuRate* temperatures from the measured temperatures in the lead up to the daily external peak is likely due to over estimation of solar radiation heat gains from the glazed door facing the equator. The *EnerWin* model predicts considerably more thermal lag for both test cells than the *AccuRate* or *EnergyPlus* models (see Fig. 6). The *EnergyPlus* results for the brick veneer test cell more closely correspond to external temperature, peaking higher than the other two simulation engines, appearing to act more like a lightweight building when compared to the mud brick test cell *EnergyPlus* results (see Fig. 7).

4.2. Occupied dwelling simulations

4.2.1. Occupied Residence A

Initially two simulations of Residence A were performed in regulatory mode to demonstrate the effect of the NatHERS user settings on the prediction of internal conditions (see Fig. 8). One simulation uses the NatHERS climate file required for simulation in regulatory mode, whilst the second simulation uses the custom climate file from meteorological data form the monitoring period. Neither simulation shows any sort of correlation to the measured internal temperatures.

When the models were modified to appropriately reflect the actual practices within this households results from the three simulation engines produced CV(RMSE)s between 7.25% and 13.5% when compared to measured data (see Table 6). The *AccuRate* predictions tended to overestimate internal temperatures particularly when the external daily maximum is between 20 and 30 °C, less divergence is present at lower daily maximums (see Fig. 9). The *EnerWin* results demonstrate the best agreement with the measured data in both the living and kitchen area and the bedroom. The *EnergyPlus* model consistently under estimates internal temperatures, displaying considerably lower turning points than the measured temperatures, exhibited by the high maximum difference of 6.7 °C in the living and kitchen area.

4.2.2. Occupied Residence B

The CV(RMSE)s for occupied Residence B range from 6.09%, the lowest CV(RMSE) for the occupied residence simulations, to 13.07%

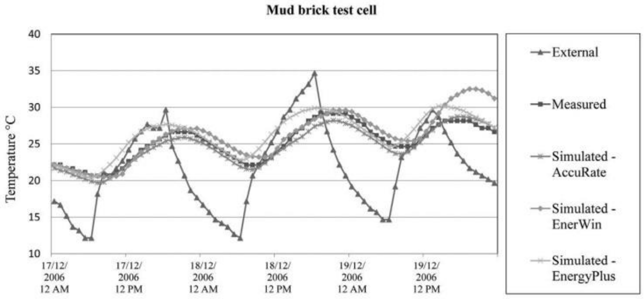

Fig. 6. Mud brick test cell measured and predicted indoor temperatures from 17th to 19th December 2006.

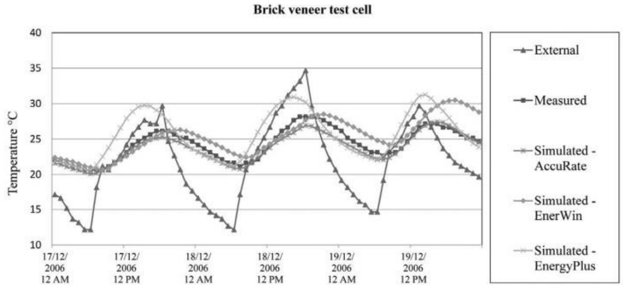

Fig. 7. Brick veneer test cell measured and predicted indoor temperatures from 17th to 19th December 2006.

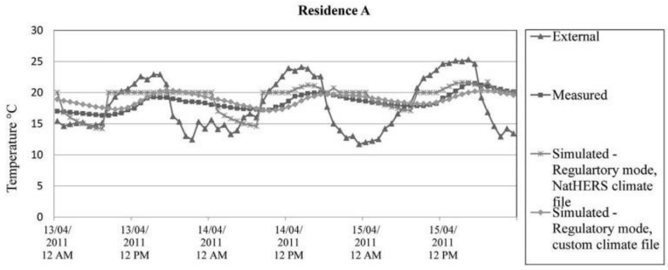

Fig. 8. Occupied Residence A living/kitchen area measured and predicted indoor temperatures using the NatHERS climate file and the custom climate file created from meteorological data from 13th to 15th April 2011.

Table 6
CV(RMSE), mean difference and maximum difference of AccuRate, EnergyPlus and EnerWin predicted results compared to measured results for Occupied Residence A from 1st April to 31st May 2011.

Simulation engine	CV(RMSE) (%)	Mean difference (°C)	Max difference (°C)
Living/kitchen area			
AccuRate	10.8	1.52	5.40
EnerWin	7.25	1.01	4.05
EnergyPlus	13.50	1.87	6.70
Main bedroom			
AccuRate	11.22	1.57	5.14
EnerWin	8.22	1.20	4.28
EnergyPlus	11.26	1.59	4.36

(see Table 7). The predicted temperatures from all three models align more closely with the measured temperatures in the living and kitchen area than the measured temperatures in the bedroom. The *AccuRate* and *EnergyPlus* predicted temperatures for the living and kitchen area generally peak higher than the measured temperatures, while the *EnerWin* predictions peak noticeably lower. The predicted lower turning points of the predicted temperatures from all three engines correspond well with those of the measured data (see Fig. 10). The *EnerWin* model again predicts more thermal lag than the *AccuRate* or *EnergyPlus* models, resembling observations of the *EnerWin* test cell results.

4.2.3. Occupied Residence C

The predictions from the three simulation engines produce CV(RMSE)s between 7.48% and 10.29% when compared to the

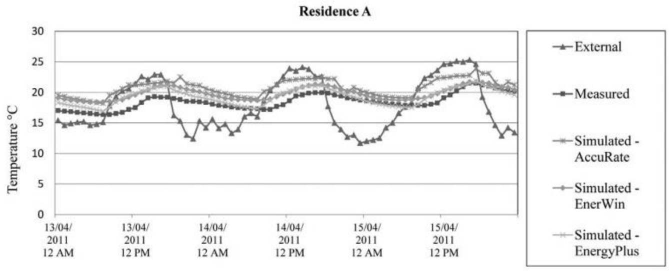

Fig. 9. Occupied Residence A living/kitchen area measured and predicted indoor temperatures from 13th to 15th April 2011.

Table 7
CV(RMSE), mean difference and maximum difference of AccuRate, EnergyPlus and EnerWin predicted results compared to measured results for Occupied Residence B from 6th May to 28th August 2011.

Simulation engine	CV(RMSE) (%)	Mean difference (°C)	Max difference (°C)
Living/kitchen area			
AccuRate	7.86	0.97	4.80
EnerWin	10.43	1.33	4.80
EnergyPlus	6.09	0.73	4.21
Main bedroom			
AccuRate	12.12	1.42	7.12
EnerWin	13.07	1.65	5.34
EnergyPlus	11.98	1.28	7.34

Table 8
CV(RMSE), mean difference and maximum difference of AccuRate, EnergyPlus and EnerWin predicted results compared to measured results for Occupied Residence C from 6th May to 11th September 2011.

Simulation engine	CV(RMSE) (%)	Mean difference (°C)	Max difference (°C)
Living/kitchen area			
AccuRate	7.48	1.02	5.00
EnerWin	9.69	1.27	9.80
EnergyPlus	10.29	1.58	5.72

measured temperatures (see Table 8). The maximum differences from all three engines are generally high than those from the occupied Residence A and B simulations, however the mean differences remain comparable. The predicted temperatures are all consistently lower than the measured temperatures (see Fig. 11). *AccuRate* and *EnerWin* occasionally have comparable peaks with the measured data, generally coinciding with periods of consistent diurnal range. The *EnergyPlus* predictions share a similar pattern to the measured data; however the temperatures are persistently one to two degrees lower.

It is important to note that in the above simulations the rating required occupancy profiles were modified in the input file (*.SCRATCH) to better replicate the actual behaviour of the occupants. A key example was the way in which natural ventilation was modelled in Residence B. The initial *AccuRate* simulations used the default natural ventilation algorithms based on the relationship between indoor and outdoor temperature, and hours of zone occupancy. These initial results displayed considerably higher peaks when compared with the measured indoor temperatures, this is because the occupant usually opened the windows in the morning and closed them in the evening with little regard for outdoor temperature. Modifying the input to reflect this had a noticeable impact on the correlation of the predicted and measured temperatures; aligning predicted peaks with the measured. This situation quite clearly demonstrates the impact of assumptions of user behaviour on predicted and actual building performance.

4.3. Predicted vs actual energy load

In regulatory mode, *AccuRate* gives the Star rating based on the sum of the heating and cooling energy loads expressed in MJ/m^2; that is, the energy required to be added to or subtracted from a space to maintain ‘comfort’ conditions. Using this output, in combination with assumed heating and cooling appliance efficiencies, the predicted heating and cooling energy consumption of a dwelling can be compared to actual energy use records. Where electricity is used the energy use attributable to heating and cooling can, with some accuracy, be disaggregated from long-term electricity billing records [5]. Using this technique a strong correlation ($r^2 = 0.70$) was found for Residence A between long-term electricity billing records and meteorological data in the billing period; however, for Residences B and C there was no significant correlation. This was likely due to the use of photovoltaic (PV) panels on these two

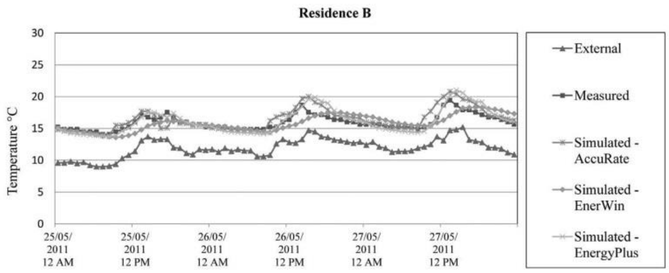

Fig. 10. Occupied Residence B Living/kitchen area measured and predicted indoor temperatures from 25th to 27th May 2011.

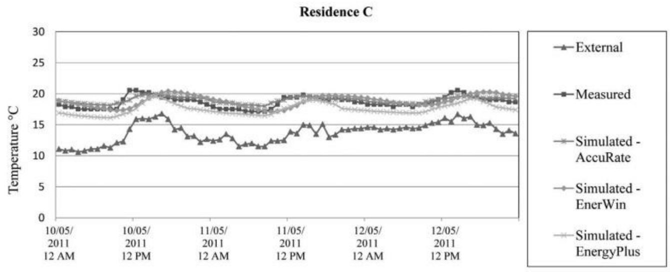

Fig. 11. Occupied Residence C living/kitchen area measured and predicted indoor temperatures from 10th to 12th May 2011.

dwellings. Electricity accounts do not record the quantity of electricity produced by these PV panels and no records were kept by the occupants.

Residence A primarily used a slow combustion wood burning stove for heating during the 2007–2011 period, supplemented with the limited use of a small electric fan heater. No air-conditioning appliances were used, with the exception of pedestal fans; therefore because of the insignificant amount of electricity use attributable to the use of pedestal fans, only the heating energy use is compared here. The estimated amount of wood consumed: 1.5 tonnes per annum, is converted into MJ per annum and added to the disaggregated electricity used for heating to give a total actual energy use of 27,703.0 MJ per annum (88% wood, 12% electricity).

The predicted heating energy load from *AccuRate* operating in regulatory mode was 554.5 MJ/m^2 for 68 m^2 of conditioned floor area giving a total heating load of 37,705.0 MJ per annum for the residence as a whole. The wood energy proportion of the total heating load (88%) was then divided by the assumed efficiency of the wood burning stove, which is 50% [39]. The total predicted heating energy use was therefore determined as 70,772.0 MJ per annum. This predicted heating requirement for the Residence A over-estimates the actual heating energy used by the household by a factor of 2.6.

4.4. *Impact of occupant behaviour assumptions on HERS outcome*

In order to demonstrate the impact of changing occupancy variables within *AccuRate* based on the behavioural trends shown in the surveyed cohort, Residence A was simulated using the NCC regulatory climate zones 5 (NatHERS climate zone 16) and 6 (NatHERS climate zone 59). These climate zones are broadly representative of the climates in which the majority of earth construction is located within Australia: temperate and cold temperate.

The user settings were modified to reflect the limited use of heating or cooling appliances in the surveyed households (see Table 9). Using these settings in simulations, Table 10 shows a considerable reduction in the predicted heating load from the simulation conducted in the NatHERS regulatory mode to that with the alternative user settings. Note that there is no cooling load in these modified simulations because in general, there were no cooling appliances in the surveyed households.

5. Discussion

It is clear from the investigation presented above that current static occupant related settings within the Nationwide house energy rating scheme thermal performance simulation software do not adequately reflect actual practices within a cohort of *low energy* households in Australia.

The regulatory provisions in the NCC, aimed at making buildings more energy efficient, are based assumptions on generic occupant use patterns and behaviours. The results presented above demonstrate that, at least for earth constructed dwellings, the assumptions do not represent the actual situation. This mismatch disadvantages people wishing to construct such dwellings by "imposing" upon them design solutions which potentially result in an unnecessary cost burden. For example, a house design that is initially assessed with NatHERS and achieves less than 6 Star rating will have to be improved, perhaps by adding more thermal

Table 9
Occupancy changes.

User variable	NatHERS regulatory settings	Alternative settings based on survey
Heating and cooling energy loads	Heating and cooling load potential during all occupancy hours, all days of the year	• Heating seasons 3 months over winter • Cooling load removed
Rooms conditioned	All habitable rooms	Living only
Thermostat settings	Heating Minimum 20 °C in living areas between 7 AM and 12 AM	Reducing thermostat settings—to 18 °C and hours of potential operation to afternoons and evenings 12 PM–12 AM

Table 10
Simulation results to demonstrate the effect on estimated heating and cooling loads of changes to occupancy related settings.

Run	Conditioned floor area (m^2)	Heating load (MJ/m^2)	Cooling load (MJ/m^2)	Total (MJ/m^2)
Climate zone 16				
Using NatHERS regulatory settings	68	115.5	171.6	287.1
Using alternative settings	46	32.4	0	32.4
Climate zone 59				
Using NatHERS regulatory settings	68	554.5	17.2	571.7
Using alternative settings	46	218.7	0	218.7

insulation or using better glazing, in order to meet this minimum requirement. If a more realistic assumption of user pattern and behaviour is used, it is likely that this house design can achieve higher than 6 Star rating without requiring such improvements that will increase the construction cost.

The inadequacy of current user related settings and the need to better conceptualise occupant behaviour in building performance assessment are sentiments widely shared [40]. Within the Australian NatHERS context, these issues were acknowledged in a report for the Australian Government in 2010. This report stated that a number of the assumptions within NatHERS did not adequately reflect user behaviour and recommended that adjustments be made to occupancy and thermostat settings to better reflect actual practices [41]. Ren et al. [42] sought to address this issue by adding or extending modules in *AccuRate* and changing occupancy patterns to reflect trends in national ABS data. While their approach may be appropriate for the wider population it demonstrates that accounting for nuanced occupant behaviour is largely unresolved. Internationally, others have reached similar findings; Tweed et al. [43] in a study of a small number of dwellings in the UK found that the drivers of occupant-building interaction were inconsistent. Reflecting the findings by Tweed et al., Mavrogianni et al. [44], through a study into the increased risk of summer overheating in UK housing stock, concluded that more than one set of standard occupancy assumptions are required for assessment, while Hernandez and Kenny [45] finish with contradicting suggestions about how to address behaviour in building codes and regulation. More broadly others have sought to address this deficiency through proposals including the use of stochastic modelling [46], agent based modelling [47], theory of planned behaviour [48] and practice theory [49], amongst others.

In a discussion about housing performance in relation to human needs more generally Stevenson and Leaman [50] have suggested that:

> . . .occupants' individual aspirations and living requirements are often out of step with regulatory demands, but in some cases a building design that fails to meet regulation does not necessarily diminish its ability to perform as a low-energy building. Regulations and standards can actually 'fail' peoples' attempts to be more energy efficient precisely because these attempts do not align with conventions at the individual building level. . .even if the building fabric is robust and well insulated with suitable thermal mass, and the home has an efficient energy source, it will still be the inhabitant who ultimately determines how energy efficient a home will be.

These sources, coupled with the findings presented in this paper suggest that greater flexibility within the assessment of housing performance must be considered, both within NatHERS and the context of house rating schemes worldwide.

6. Conclusion

The empirical and intermodal validation study of the simulation software confirmed its capacity to model heavyweight building elements and, therefore, isolated the cause of the scheme's deficiencies to the assumptions made about the users. The initial empirical validation exercise comparing internal predicted temperatures from the *Australian Government Endorsed calculation engine*, second generation *AccuRate* (*Chenath* computational engine), with measured temperatures from two unoccupied test cells demonstrated good match between predicted and actual conditions. The *AccuRate* simulation results also proved to be the closest match when this exercise was completed with two other widely used simulation engines. These simulations confirmed the capacity of the simulation engine to adequately predicted internal conditions in simple unoccupied buildings.

To further test the capacity of *AccuRate* similar comparisons were applied to models of occupied houses. When the simulations were run in regulatory mode there was no match between the predicted internal conditions and actual measured temperatures, demonstrating that when the simulation is applied to real houses the practices of the occupants had to be properly modelled to ensure that the predicted results reflect actual conditions. This study finds that some of the practices that are not sufficiently represented in the regulatory mode include the use of heating and cooling appliances (hours/type/thermostat), conditioned spaces and operation of windows and doors for natural ventilation.

Based on a survey of 175 households living in dwellings incorporating earth construction components across Australia, similar trends in heating and cooling practices were detectable. These trends were alternate to assumptions about these practices in NatHERS. Modifications to these assumed settings based on the trends in the collected survey data and the application of these modified settings in the simulations have resulted in predicted heating and cooling loads that are much closer to the actual loads. This reveals a considerable over-estimation of the predicted heating and cooling energy loads in the regulatory mode of the software. It also identifies a distinct disadvantage to those wishing to build in this manner, furthering the suggestion that this type of housing may need to be assessed in a different manner to support equitable assessment.

Any effective approach to energy efficiency regulation should allow occupants to feel empowered rather than apologetic for their lifestyle choices [50]. This study has demonstrated that properly modelling use patterns and behaviours (which are a reflection of occupants' lifestyle choices) is more likely to predict energy use that closely matches the actual energy use and which will not result in disadvantaging them by imposing unnecessary design requirements.

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Learning from thermal mavericks in Australia: comfort studies in Melbourne and Darwin

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