Evaluating and Improving Indoor Thermal Comfort on the Top Floors of Multilevel Energy-Efficient Dwellings

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(Master of Architecture)



Submitted in fulfilment of requirements for the degree of Doctor of Philosophy

UniSA STEM

University of South Australia

June 2021

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Nomenclature

AAF = area adjustment factor
CFA = conditioned floor area (m^2)
CL = total annual cooling load (i.e. the sum of the sensible and latent cooling loads) (MJ/annum)
C_o = coefficient in Equation 2.4 (-)
DH = degree hours (degree-hrs)
EL = total annual energy load per conditioned floor area (MJ/m^2/annum)
h_{ey}= time in hour when $\Delta T = y$ (h)
h_c = convective heat transfer coefficient in Equation 2.7 (-)
h_r = radiative heat transfer coefficient (-)
HL = total annual heating load (MJ/annum)
clo = clothing insulation, 1 clo = 0.155 Km^2/W
met = activity level or metabolic rate in (W/m^2)
p_a = vapour pressure (kPa)
T = number of days in the month under study in Equation 7.1 (-)
t_a = air temperature (°C)
T_c = constant temperature (°C)
T_{core} = Core temperature (°C)
T_{db} = indoor air (dry bulb) temperature
T_h = acceptable maximum divergence from neutral temperature (°C)
T_n = neutral operative temperature (°C)
T_{NL} = neutral line temperature for adaptive thermal comfort (°C)
T_{mr} = indoor mean radiant temperature (°C)
T_o = outdoor temperature (°C)
T_{od-1} = daily mean outdoor temperature for one day before the day in question (°C)
T_{od-2} = mean daily outdoor temperature for two days before the day in question (°C)
T_{rm} =running mean outdoor temperature (°C)
T_{skin} = Skin temperature (°C)
v = relative air speed (m/s)
wf (weighting factor) = 0 if $\Delta T \leq 0$, otherwise wf = ΔT
y = running mean outdoor temperature for day t before retrofitting (°C)
z = running mean outdoor temperature for day t after retrofitting (°C)
λ = adaptive coefficient (-)

Abbreviations

aPMV	Adaptive predicted mean vote
AMV	Actual mean vote
ASHRAE	American Society of Heating, Refrigerating, and Air conditioning Engineering
ATG	Adaptieve temperatuur grenswaarde (in Dutch), Adaptive temperature limit
BASIX	Building Sustainability Index, a method used for rating dwellings in New South Wales
BCA	Building Code of Australia
CIBSE	Chartered Institution of Building Services Engineers
CSIRO	Commonwealth Scientific and Industrial Research Organization
EN	European Standards
MM	Mixed mode
NatHERS	Nationwide House Energy Rating Scheme
nPMV	New Predicted Mean Vote
PCM	Phase Change Material
PMV	Predicted Mean Vote
PMVe	Extended Predicted Mean Vote
SET	Standard effective temperature
SPAVF	Electrical/Solar-Power Attic Ventilation Fan
TMY	Typical Meteorological Year
WEHs	Weighted Exceedance Hours

Glossary

AccuRate	A thermal simulation and airflow software developed by CSIRO for rating the energy efficiency of dwellings
Air change per hour	The number of building space volumes that air is replaced in a building during an hour
Climate change	A change of climate, which is directly or indirectly attributed to human activity that changes the composition of the global atmosphere and is in addition to natural climate variability over comparable time periods (Nations 1992)
clo	A unit to measure the average of human clothing thermal resistance
Climate zone	The climate characteristic of air such as temperature, humidity, pressure in a specific zone
Double glazing	A form of glazing by two panes of glass separated by air, other gas or vacuumed
Emissivity	A measure of how well a material surface emits thermal radiation
Energy	The capacity to perform work
EnergyPlus	A building energy simulation program licenced by the US Department of Energy
Standard effective temperature	"The temperature of an imaginary environment at 50% relative humidity, <0.1 m/s air, mean radiant temperature equal to air temperature, in which the total heat loss from the skin of an occupant with the activity level of 1.0 met and clothing level of 0.6 clo is the same as that from a person in the actual environment, with actual clothing and activity level" (ASHRAE 2017)
Heat	A form of energy that transfers by the temperature difference
Heatwaves	For Adelaide, a heatwave is defined five consecutive days with maximum temperature at or above 35°C or three consecutive days at or above 40°C.
Infiltration	Uncontrolled air leakage through the building fabric
Kilowatt-hour	A unit for measuring the quantity of energy consumed during an hour
mean radiant temperature	"The uniform temperature of an enclosure in which the radiant heat transfer from the human body is equal to the radiant heat transfer in the actual nonuniform enclosure" (ISO 2001)
Low-e	Low emissivity materials that for glazing reflect infrared radiation and does not reduce visible light transmission.
Natural ventilation	The flow of outside air due to wind and pressures difference through intentional openings in the building shell
Nocturnal ventilation	Natural ventilation during the night
Operative temperature	"The uniform temperature of an enclosure in which an occupant would exchange the same amount of heat by radiant and convection as in the actual nonuniform environment" (ASHRAE 2017; ISO 2001, 2005a)
Passive house	A low-energy house that meets the passive house five core principals
R-Value	The thermal resistance of a material
Rock wool	Mineral wool produced from molten rock
Roof space	The space between a roof and ceiling
Solar heat gain	Amount of solar energy entering a building by radiation
Thermal mass	Potential of a given material to store heat energy
Thermal resistance	The resistance to heat flow, the reciprocal of thermal conductivity
Typical Meteorology Year	Selected hourly weather data for a specific location for one year period
U-value	The number of Watts per second that pass through $1m^2$ of an object when subjected to a temperature difference of 1 °C
Ventilation	Supply/ removal of air
Weighted Exceedance Hours	The sum of hourly temperatures which exceed a defined limit for given hours

Abstract

Increasing the energy efficiency in dwellings has been internationally at the forefront of efforts to reduce the carbon footprint of the housing sector. In Australia, compulsory minimum residential energy efficiency for dwellings was introduced by the National Construction Code in 2003, with higher requirements in 2006 and 2010. The focus of these regulations has been to limit the heating and cooling energy demand. While this is anticipated to improve thermal comfort as a by-product, this has not been the main aim.

Global evidence has demonstrated increasing overheating in energy-efficient dwellings during summer in both cooling and heating-dominated climates. The energy efficiency does not necessarily result in year-round thermal comfort.

Using the long-term temperature and energy use monitoring data of Lochiel Park Green Village in Adelaide, alongside the responses of a survey in the Adelaide metropolitan area, this research investigates the occurrence of overheating in energy-efficient multilevel dwellings with a focus on their top floors and proposes criteria for evaluating long-term thermal comfort and limiting overheating.

This research has found that overheating generally exists on the top floors of multilevel dwellings. Based on data analysis, criteria for evaluating overheating for the South Australian climate are proposed. The research also introduces a numerical scale for thermal comfort evaluation that can predict the thermal comfort perception of residents. The research examines possible approaches for improving thermal comfort and provides effective combinations of measures to decrease overheating. Also, it was found that the combination of measures need optimization. The research showed that this optimization could be achieved by simulation.

Applying the suggested criteria for overheating through simulation has demonstrated that the use of these criteria can eliminate the high temperature in the rooms which have the potential for overheating. The research demonstrates that the application of the overheating criteria in the Nationwide House Energy Rating Scheme software would enhance thermal comfort and other associated benefits to residents in Australian dwellings.

Declaration

I certify that this research is carried out by myself and contains no material that has been submitted for the award of any other degree. I certify that no part of this thesis will be used in my name for any other degree. To the best of my knowledge, this research contains no previous-published material by another person except where due reference is made in the text. All contributions by others to the thesis are clearly acknowledged and the copyright of published works in this thesis resides with copyright holders.

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Sormeh Sharifi

Date: June 30, 2021

Acknowledgement

This project would be impossible without the help of my family.

I am deeply thankful for the supervision, support, advice, feedback, guidance, inspiration and encouragement from my principal supervisor Professor Wasim Saman from the year he accepted me as an adjunct to the end of my PhD. His belief in me rebuilt my confidence after migration. Thank you for being so kind to me. I have learnt a great deal from you. This thesis has benefited enormously from your patience and critiques. I would like to express my special thanks to my first co-supervisor Dr Alemu Alemu for his perfect understanding of my situation and for assistance. Your expertise and generous interactions have shaped this research. I am thankful to my second co-supervisor Dr Martin Belusko for his comments and energetic character.

I am also greatly indebted to Professor John Boland for his supportive engagement in mathematical calculations and support as a co-author of research papers drawn from this thesis. I appreciate your pleasing approach, patience and willingness to teach.

I acknowledge Dr Stephen Berry for helping me to start this research. Also, I thank Dr David Whaley for providing the Lochiel Park monitoring data.

Further guidance, advice and comments from Professor Richard De Dear and Professor Mattheiaos Santamouris helped me to develop the method of this research. Their expertise and passion for the subject of this thesis provided fundamental critiques. Special thanks to Professor Richard de Dear for the essential manual and references.

I am incredibly grateful to Dr Dong Chen for his generous support in simulation. It was impossible to carry out the simulations correctly without his help.

I especially appreciate Dr Monica Behrend for her constructive professional comments on research writing. I learnt a new approach to thinking from her.

Special thanks to Dr Nick Langsford, Dr Heather Nimmo and Dr John Pockett for their time and precious advice about my writing practice.

I am indebted to the residents of Lochiel Park, who responded to the survey. I would also like to recognise the industry experts, Jim Woolcock and Andrew Bishop, who generously gave their time and provided various documents.

I acknowledge the University of South Australia and CRC Low Carbon Living to cover all my tuition fees and providing my living expenses for three and a half years.

My husband Mehdy; you are unique. Thank you, darling, for your continuous support, grounding, encouragement and patience. Without your help and drive, I could not complete my PhD. Thank you for making me and our child, Som, happy.

Thank you, my mother, back home. You always have encouraged me to study and learn.

Associated publications from this thesis

1- Sharifi, S, Saman, W & Alemu, A 2019, 'Identification of overheating in the top floors of energy-efficient multilevel dwellings', *Energy and Buildings*, vol. 204, Dec, pp. 1-37

2- Sharifi, S, Saman, W, Alemu, A & Boland, J 2020, 'A proposed long-term thermal comfort scale', *Building Research & Information*, 30 Oct, 1-18.

3- Sharifi, S, Saman, W, Alemu, Chen, D 2021 'Overheating in energy-efficient dwellings in Adelaide metropolitan during summer: a survey', *Building Research & Information,* Under preparation.

4- Sharifi, S, Saman, W, 2021 'Effect of roof shape on top floor overheating in energy-efficient multilevel houses in Adelaide', *Energy and Environment,* Under preparation.

1 Introduction

Thermal comfort is important for maintaining good health, satisfactory living conditions for people, once controlling energy use as well as suggesting and setting standards (Humphreys 2005). Providing thermal comfort results in controlling the indoor environment and improving the Indoor Air Quality (IAQ) for people, saving energy and reducing the harm to the environment (Raw & Oseland 1994). Research into thermal comfort is generally focused on offices and residential buildings. A considerable number of dwellings do not maintain thermally comfortable conditions for their occupants (Dengel & Swainson 2012; Khalifa 2013), although they are constructed according to thermal regulation codes (McLeod, Hopfe & Kwan 2013; Saman et al. 2013; Sharifi, Saman & Alemu 2019). The literature provides many examples of energy-efficient residential buildings in Australia, Canada, Denmark, the United Kingdom and the United States which do not achieve thermal comfort during summer (Berry et al. 2014; Gupta & Kapsali 2015; Oropeza-Perez & Østergaard 2014; Saman et al. 2013; Sehizadeh & Ge 2015; Willand, Ridley & Pears 2016). Increasing evidence indicates that improved energy-efficiency standards and building regulations have not entirely solved overheating (elevated air temperature above thermal comfort threshold in a building) in dwellings (Dodoo & Gustavsson 2016; Gupta & Gregg 2013; Gupta & Kapsali 2015; Manua et al. 2016; McLeod, Hopfe & Kwan 2013; Sehizadeh & Ge 2015; Tabatabaei Sameni et al. 2015). This is mainly the case on the top floors of multilevel houses (Sharifi, Saman & Alemu 2019), top floor units of high-rises buildings and top floors of apartments (Abdullah et al. 2009; Taylor et al. 2016). Exploring the best way of reducing the impact of heatwaves on the top floor temperature of dwellings is the object of the risk management model framework of Australia 'Planning, Prevention, Preparedness, Response, Recovery' (PPPRR) in the "prevention" section (Commonwealth Governments 2011; Council of Australian Governments 2011; Queensland Government 2016).

Overheating of dwellings can have a range of negative health effects on people, ranging from discomfort and reduced performance to serious health issues. Its most documented impact is the potential to degrade individuals' physical and psychological health (Alam et al. 2016; Dengel & Swainson 2012; Hatvani-Kovacs et al. 2016b). Another impact of overheating is the increased electricity demand to cool the house (Pechan & Eisenack 2015; Saman et al. 2013; Willand, Ridley & Pears 2016). The increase in electricity consumption can result in increasing the peak electricity demand on generators and transmission system, which leads to higher infrastructure costs (Pechan & Eisenack 2015), raising Green House Gas (GHG) emissions (Alexis, Ange & Ne 2012), increasing energy supply cost (Pechan & Eisenack 2015) and higher electricity bills (AEMO 2016).

The criteria of Australian energy rating schemes and building codes have reduced householders' annual energy usage for heating and cooling and improved the level of thermal comfort over the years. However, they have not necessarily maintained thermal comfort, especially during heat events (Ren, Wang & Chen 2014; Sharifi, Saman & Alemu 2019) which can happen several times in a year in Australia (BCA Australia 2012a; 2012, 2016; Livable Housing Design 2012). The proliferation of dwellings can cause the multiplication of thermally discomfort spaces, highlighting the importance of setting a limit for thermal discomfort and finding methods of improving thermal comfort.

1.1 Background

Thermal discomfort has been investigated in studies through surveys, monitoring and simulation or a combination of those. The following paragraphs categorize these results based on surveys, monitoring or simulations in dwellings, particularly in the bedrooms. Additionally, some factors are noted as possible reasons for overheating.

Prevalence of overheating is reported through different surveys as follow. In Adelaide, Australia, overheating during summer high temperatures was reported by 92% of the residents in 25 energy-efficient dwellings (Berry et al. 2014). In Sweden, nine of 18 surveyed dwellings had overheating (Samuelsson & Lüddeckens 2009). In the UK overheating was recorded in 100% of 575 dwellings (190 of which were insulated) (Humphreys, Rijal & Nicol 2013), 38-75% of 145 insulated units (Adekunle & Nikolopoulou 2016) and 35% of 70 insulated dwellings (Vellei et al. 2016a). The government of the UK admitted that all new buildings were prone to overheating

(environmentanalyst 2018). The gap between predicted and actual thermal performance in buildings can be very significant (IPEEC 2019).

Monitoring the indoor temperature has revealed overheating worldwide. In Adelaide, Australia, all eight energy-efficient houses that have been monitored for eight years recorded overheating (Sharifi, Saman & Alemu 2019). In another Australian study of two-story townhouses, the temperature of the top floor reached over 39 ºC during a four-day heatwave (Saman et al. 2013). In Estonia, overheating was observed in 31.7% of 100 new units (Maivel, Kurnitski & Kalamees 2014). In New Zealand, 36% of 17 houses recorded overheating (Birchmore et al. 2017). In the UK many examples of overheating are reported: all of a four-story group (Gupta & Gregg 2020), 56% of a 55-dwelling group (Vellei et al. 2016b), 25% of a 25-dwelling group (Tabatabaei Sameni et al. 2015), 81% of a 122-dwelling group (Pathan et al. 2017), and all 268-dwelling group (Lomas & Kane 2013) had overheating. Four out of six 94–146 m^2 two to three-story detached townhouses having mechanical cooling and complying with level 4 and 5 of the 'Code for Sustainable Homes' also suffered from overheating (Gupta & Kapsali 2015). In Oxley Wood and Bridport (UK), 67% of spaces from nine units had overheating (Adekunle & Nikolopoulou 2016). For a typical attached UK townhouse with completely closed windows during summer, the bedrooms on the top floors were warmer than the ground floor, with a peak temperature of 30.9 C (Roberts et al. 2019). In Detroit, USA, the measured maximum indoor temperatures for 30 homes using a combination of air-conditioned (AC) and naturally ventilated (NV) modes were 13.8 °C higher than the average maximum outdoor temp from 1 July to 1 Sep 2009 (Jalonne L et al. 2012). Overheating can get more severe in the afternoon as the indoor air becomes very hot due to the joint effect of the afternoon sun on façades and higher outdoor temperature (Humphreys, Nicol & Roaf 2015).

Overheating has been demonstrated in simulations too. Simulation of a typical single-story house in Australia under various design scenarios for Adelaide found significant overheating for a typical minimum energy-efficiency compliant house during summer (Hatvani-Kovacs et al. 2016a). The simulated 'Passive House' in Quebec, Canada, climate showed overheating for 10–31.4% of the year (Sehizadeh & Ge 2015). For two-story units of an apartment in Lisbon, Portugal, the simulation showed overheating for more than half of the occupied hours (Barbosa, Vicente & Santos 2015). In the Netherland, 9216 dwellings were simulated to examine the impact of the current

global warming scenario for 2100. The simulation showed that the summer indoor air temperatures would increase by 1 to 7 ºC in most resilient dwellings and least resilient dwellings respectively (Hamdy et al. 2017). In this study, a resilient dwelling is a dwelling with a minimum temperature variance in summer. Three semidetached and mid/end typical terrace houses in Bristol, Oxford and Stockport, UK, showed a 90% probability of overheating for each dwelling in summer (Gupta & Gregg 2013). Two semidetached and detached townhouses with 84.4 and 129.6 m2 floor areas in York, the UK, found a 50–100% probability of summer overheating for each house (Gupta & Gregg 2018). A unit in London was simulated and presented a 26–60% probability of overheating in summer (Mavrogianni, A et al. 2015).

Bedrooms are generally more at risk of overheating in both apartments and houses. Studies in multilevel houses have not indicated the level on which bedrooms were located. Based on the typology of multilevel houses, it is likely that the bedrooms were in top floors in many of the studies. In Adelaide, Australia, for 18 single or two-story houses designed and built according to passive principles, where living rooms and bedrooms do not have air conditioners, bedrooms are on average 2.7 °C warmer than the living rooms. If both living rooms and bedrooms have air conditioning, this number reduces to 0.5 º C (Saman et al. 2013). In Melbourne regulation-compliant homes tended to be warmer than lower-rated homes in summer unless they were actively cooled (Willand, Ridley & Pears 2016). The apartments in Adelaide with air conditioner (AC) in living rooms had bedrooms well above the ASHRAE 55 adaptive thermal comfort upper threshold and some residents had to move to the living room during hot nights (Saman et al. 2013). In the same city, it was observed that in two multilevel townhouses with bedrooms on the top floors, after retrofitting for energy efficiency, the temperature of the top floor during a four-day heatwave was over 41.9 ºC whilst for the ground floor, the maximum was 39 ºC (Table 1.1) (Saman et al. 2013). For 30 cases in Sydney, Australia, the dining room temperature was about 2 °C cooler than the other rooms. The same phenomenon was found in Spain, where the top floor under the roof was found to be one of the overheating factors for dwellings, especially for bedrooms (Monge-Barrio & Sánchez-Ostiz Gutiérrez 2018). The simulations of three dwelling types showed that the solar load provokes overheating in top floors (Pisello, Goretti & Cotana 2012). Three cities in the UK showed overheating particularly in the bedrooms. From 111 dwellings in Leicester, 63% of bedrooms were overheated in more than 5% of the occupied hours

(Lomas & Kane 2013). The monitoring of 268 houses in the same city revealed that 100% of the bedrooms had overheating, whilst for the living rooms, it was 78% (Lomas & Kane 2013). Amongst 122 dwellings in London, the overheating hours of bedrooms were 2-13% more than the overheating hours of living rooms (Pathan et al. 2017). In three mid-terrace houses in Torquay, UK, the bedrooms were at increased risk of overheating. In six monitored townhouses located in the South-East of the UK, bedrooms were overheated more than living rooms (Gupta & Kapsali 2015). In this area, large bedrooms exceeded the overheating limit by up to 11 hours daily (Ozarisoy & Elsharkwy 2019). It is predicted that in all areas of the UK, the bedroom temperatures will be over 30 °C and overheating will increase by 40% during July to August peak summer 2080 compared with that of 2010 (Patidar et al. 2014). Thermal equilibrium between bedrooms and living/ dining rooms in single and multilevel homes happens rarely (Saman et al. 2013).

Table 1.1 Temperature of two townhouses in Adelaide before and after thermal retrofitting during a four-day heatwave (Saman et al. 2013)

Number of bedrooms on the top floor, Total area	Function	Max temperature before retrofitting ºC	Max temperature after retrofitting ºC
3, 189 m2	Living/Din/Kitchen	37.9	35.6
	Master Bedroom (top floor)	43.4	40.5
2,159 m2	Living/Din/Kitchen	39	37.7
	Master Bedroom (top floor)	41.9	39.2

The overheating risk of dwellings is rising globally in the future due to climate change (Psomas et al. 2016). Central and Western Australia are projected to potentially experience 50 °C for many days by 2050 (Perkins, Pitman & Sisson 2013). Most of the houses that are now constructed according to the minimum energy rating standards will still be in use in 2030 and most likely in 2050 (Saman et al. 2013). In Adelaide, the number of days with a daily maximum higher than 30 °C will rise from 13 in 2013 to 29 in 2070. Similarly, the number of days with a daily maximum higher than 35 °C will increase from one in 2013 to seven in 2070 (Saman et al. 2013). The overheating level may be even worse than the predicted values through simulation as the actual built performance does not necessarily match the predictions and is often worse (Gupta & Kapsali 2015).

Overheating happens particularly for houses with no capability for cross ventilation (windows or vents placed at opposite sides of the building) (Dengel & Swainson 2012;

Vellei et al. 2016b). Some of the buildings that predominately rely on NV mode will experience overheating during the summer season (Oropeza-Perez & Østergaard 2014) because natural cross ventilation might not happen. The items that prevent natural cross ventilation can be environmental temperature increasing, heat waves, urban heat islands (UHI), deep-urban location, single-sided properties and closed windows due to noise, pollution or security concerns. It may be easy to use NV mode in rural and suburban areas, especially at nights (Dengel & Swainson 2012) because the difference between urban and rural night-time temperatures is, on average, around 2 °C (Mavrogianni, A et al. 2015). The prevalence of terraces in urban dwellings can make them vulnerable to overheating (Jonathon Taylora 2016).

Improved standards for energy-efficiency have in some instances caused overheating in new dwellings (Dodoo & Gustavsson 2016; Tabatabaei Sameni et al. 2015) and energy retrofitted dwellings (Manua et al. 2016; Sehizadeh & Ge 2015). Two cities in Australia have presented the same result. In Adelaide, the simulation showed that overheating in some of the buildings with 6 stars or above was higher than in traditional homes with only 2.6 stars. The same simulation showed three homes with 6, 7 and 8 stars even reached indoor temperatures above 35 °C (Hatvani-Kovacs et al. 2016a). In Melbourne, monitoring found that from 107 dwellings, the minimum regulation-compliant ones tended to be warmer than the lower-rated homes in summer, unless they were actively cooled. In the UK, passive houses and super-insulated dwellings are at risk of overheating (McLeod, Hopfe & Kwan 2013). In addition, among six multilevel detached houses which were designed and built to comply with level 4 and 5 of the 'Code for Sustainable Homes', four householders complained of high indoor summer temperatures of more than 28 °C (Gupta & Kapsali 2015).

1.2 Impacts of overheating

1.2.1 Overheating impacts on health

The range of health issues caused by overheating varies from discomfort and reduced human performance to death. Overheating is a real threat to residents' health and wellbeing (CIBSE 2018) particularly for certain vulnerable populations such as the elderly, children, infants, chronically ill and socially deprived members of the population (Moon, Horne & Hauck 2007; Mylona et al. 2015; Rohde et al. 2013). If these groups occupy homes during the hottest part of the day, excess heat can significantly impact

health (Dengel & Swainson 2012). Most at risk are the elderly, especially women over 75 years of age; those living alone or the socially isolated; those with chronic or severe illnesses; individuals who cannot take adaptive measures to keep cool, e.g. the bed-bound, those with Alzheimer's disease, or babies and the very young; and those living in urban areas and in sun-facing top floor flats (Lomas & Kane 2013). Although the health effects of exposure to excessive heat can be mild and if left untreated, symptoms have the potential to develop quickly into severe, often fatal heat illness (Dengel & Swainson 2012).

Heat-related morbidity includes illnesses resulting from the body's inability to cope with excess heat exposure (Mylona et al. 2015). Dehydration is a problem primarily for the elderly and the very young, as it causes an increase in thermal stress, following by increasing cardiovascular strain and trauma and strokes (DCLG 2006). The most documented impact of heat events is their potential to degrade individuals' physical and psychological health and wellbeing within communities (Dengel & Swainson 2012). The intense heatwaves with long-duration caused a significant increase in infants' hospital admissions (Xu, Z et al. 2017). Sleep quantity and quality decrease by overheating. The sleep interruption and total sleep time reduction are part of overheating effects (Pannell 2015).

The heat-related mortality affected by indoor temperature during the heat periods is more than that caused by increased outdoor temperature (Santamouris 2019) and is more likely to occur in homes or nursing homes (Jean-François et al. 2004; MS, A & Joel 2003). Apparently, mortality increases in temperatures over 25 °C in the UK (DCLG 2006). The consequence of future major heatwaves for human health, including death rates, is expected to be more severe than the death toll in more recent heatwaves such as those in Chicago in 1995, Europe in 2003 and Russia in 2010 (Schar 2016). The heatwaves that occurred in northern France in August 2003 for a period of three weeks resulted in 15,000 additional deaths (Argaud et al. 2007; Dengel & Swainson 2012). Recent heatwaves in Australia were associated with mortality increases in Sydney and Melbourne (Xu, Z & Tong 2017). In the UK, yearly heath-related death due to heatwaves is approximately 2000 persons (Pannell 2015). There is a significant positive association between ambient temperature during one month before death or two weeks before death and infant mortality (Son, Lee & Bell 2017). Overheating is one of the known risk factors for Sudden Infant Death Syndrome (SIDS) (Martin, Fanaroff & Walsh 2014) as the stress-responsive genes are highly influenced by thermal stress and two of these genes are the most affected

in SIDS cases (Rohde et al. 2013). Overall, exposure to high air temperature is identified as a major contributing factor for predicting human thermal risk (Chong et al. 2019).

The heat-related mortality is predicted to increase significantly in the future. In the UK, the heat-related deaths are expected to rise three-fold compared with 2003 and reach approximately 7,000 by the 2050s (Environmental Audit Committee 2018). In Australia, it is predicted that there will be more than 2500 heat-related fatalities in the year 2050 compared with 2011 (Australian Associated Press 2013). More intense heatwaves will increase (Barentt et al. 2012) or even double (Alam et al. 2016) in the future. Therefore, the heat-related mortality is expected to double if no steps are taken to upgrade the energy rating of existing housing (Alam et al. 2016).

Although the predictions above show increased mortality, they do not account for human body adaptation. Some studies found that overall, heat-related mortality will not change by 2050 compared to 2006 in some locations such as the southern and western USA due to acclimatisation (Wang, Yan et al. 2018). The upper limit of thermal comfort for the heat climate zone in China is found to be 2.1 °C higher than what was declared in ASHRAE 55 (Daokun et al. 2019). Ignoring adaptation in projections could substantially overestimate the projected heatwaves-related mortality by 277–747% in 2050 (Wang, Yan et al. 2018).

If the bedroom temperature exceeds 26 °C for more than 2–4 hours during the night, it reduces sleep by one hour. If it exceedance continues for more than 4 hours, it reduces sleep by two hours (AECOM 2019). Additionally, if the bedroom temperature exceeds 29 °C for more than 1–2 hours during the night, it reduces sleep by one hour and if exceedance continues for more than 2 hours, it reduces sleep by two hours (AECOM 2019).

The high indoor temperature not only causes physical and mental health problems but also reduces productivity. An experimental study showed that in Doha, Qatar, the effect of temperature is more significant than other indoor environment quality (IEQ) factors(Kaushik et al. 2020). Temperatures above 28 °C for offices located in Tokyo, Japan, ended up reducing staff productivity by 6.6% (Tanabe et al. 2013).

By no means can the overheating impacts on resident's health be ignored due to the wide range of users' ages and physical abilities and the increasing intensity and frequency of heatwaves (Jalonne L et al. 2012; Patidar et al. 2014).

1.2.2 Peak cooling demand and energy use increase

Overheating increases the cooling demand period, which is the period that people need to make themselves cool inside their home. This period generally occurs in summer and particularly during heatwaves. It is predicted that the cooling demand increases worldwide. Table 1.2 shows that even in the warming-dominant countries such as Sweden and Germany, the cooling demand is expected to rise by at least 25% in 2031. For Adelaide, the cooling demand will rise by 18% in 2030. The number of days in an Adelaide typical meteorology year (TMY) with a daily maximum higher than 30 ºC and 35 ºC will rise respectively from 13 and one in 2013 to 29 and seven in 2070 (Saman et al. 2013). Given that in Australia, more than 80% of people rely on mechanical heating and cooling when the outdoor temperature is below 22 ºC and above 28 ºC (Kim, J et al. 2016), the cooling demand will continue rising in Adelaide by 2070.

Table 1.2 Predicted increase in cooling demand in some countries

Country	City	Increase in annual cooling demand (%)	Reference climate year	Target year	Reference
Australia	Alice Springs, Darwin, Hobart, Melbourne, Sydney	90-462	1990	2100	(Wang, X, Chen & Ren 2010)
	Adelaide	18		2030	(Saman et al. 2013)
Germany	All the country	25-59	1960-1990	2031-2060	(Olonscheck, Holsten & Kropp 2011)
Greece		250		2100	
Sweden	Stockholm	100-500	2011	2100	(Nik & Kalagasidis 2013)
	Gothenburg	47	1991-2000	2100	
Mediterranean	Venice, Marseille, Podgorica, Istanbul, Naples, Valencia, Izmir, Athens, Tunis	137	1990	2080	(Rodrigues & Fernandes 2020)
USA and		20-35	2011	2100	(Zhou, Eom & Clarke 2013)
China		37-41			
USA	California	50	1991-2005	2070	(Xu, P et al. 2009)
	Miami	63-93	2004	2089	(Wang, X, Chen & Ren 2010)
	Chicago, San Di ego Minneapolis, Miami	50-270	1991-2005	2080	(Wang, H & Chen 2014)

The high penetration of AC, which has resulted in a substantial increase in electricity consumption, is one of the consequences of overheating (Pechan & Eisenack 2015; Saman et al. 2013; Santamouris 2019; Willand, Ridley & Pears 2016). The air-

conditioners are operated with the highest capacity for long hours in heat events. Thus, the need for high-capacity electricity generating plants rises, while the electricity transmission system is vulnerable to high temperature (Zuo et al. 2015). Therefore, the demand rises and generation and transmission efficiency fall simultaneously. Hence, demand and supply are adversely affected by the increase in temperature. Two-story houses with no eaves are one of the determinants for electricity consumption rate growth (Australia Productivity Commission 2013). Providing thermal comfort contributes to a high percentage of residential energy use. It is anticipated that by 2030 a current typical house in Adelaide will have an increase of 18% of installed cooling system capacity and 32% increase in electricity usage for cooling to provide thermal comfort (Saman et al. 2013). Furthermore, during peak demand in South Australia, New South Wales, and Queensland, residential air conditioning was 38% of the total energy usage in 2008 (Saman et al. 2013). Australian electricity usage is predicted to increase by 9.5% by 2025 compared to 2015 (AEMO 2015) and 29% by 2050 compared to 2019 (Brinsmead, Hayward & Graham 2014), which indicates the potential for needing more high capacity electricity consumption plants (Figure 1.1).

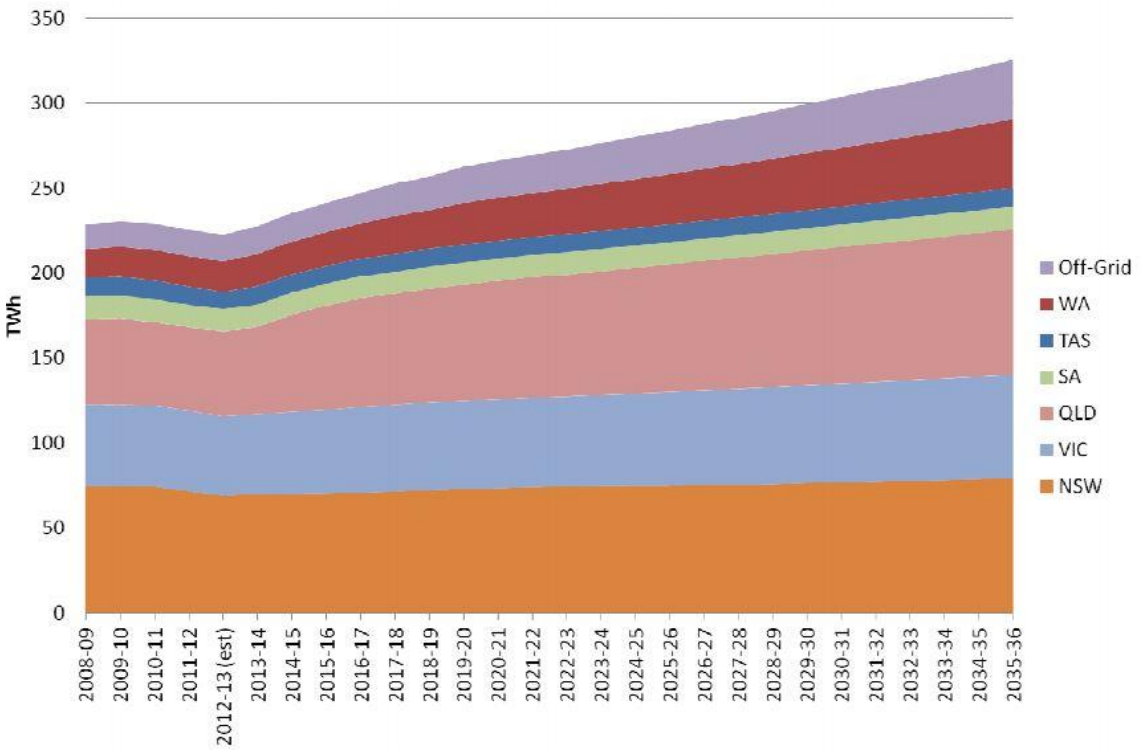


Figure 1.1 Anticipated national electricity demand profile (AEMO 2015)

The increased electricity demand results in increased Greenhouse Gas (GHG) emissions, carbon footprint and energy supply cost (Pechan & Eisenack 2015) due to the decrease in

the efficiency of power plants (Santamouris 2019). The residential electricity prices in Australia have increased by 80–90% over 2008–2018 (asbec 2018).

Multilevel detached/attached houses have been in demand in Australia due to the reduced area of allotments to create affordable housing (Australian Bureau of Statistics 2017; National Housing Supply Council 2012, 2013; Rudin 2014; Worthington & Higgs 2013). The proliferation of multilevel houses means a multiplication of discomfort spaces in homes. This situation highlights the importance of improving thermal comfort in these types of dwellings.

1.3 Overheating criteria and measurement

There should be a reasonable limit on how much warmer the indoor dwelling temperature can be than summer outdoor temperature (CIBSE 2017) and for how long it can continue. The method for identifying overheating in previous studies are not the same. Most studies provide a set temperature as an upper threshold and temperatures exceeding that are considered overheating. The literature represented here shows that three organizations have suggested an overheating limit; these are the CIBSE, Commonwealth Scientific and Industrial Research Organization (CSIRO) and Good Homes Alliance (GHA). The criterion proposed by CIBSE is based on the European climate and is not expected to be appropriate for Australia. The GHA's criterion is for the England climate and is not as accurate as the other two organizations. The criterion proposed by CSIRO towards the end of this research is based on the Australian climate. A part of the method to develop the CSIRO criteria was a modification of the CIBSE criteria.

1.4 The scope of this research

A limit for overheating does not provide a safe temperature for vulnerable people. Rather, through a standard, it levels up buildings' thermal performance by 1) reducing overheating as much as possible and 2) making a balance between energy efficiency and thermal comfort.

Overheating assessment is based on adaptation as overheating is a phenomenon with a temperature above the thermal comfort threshold. Some studies criticize the CIBSE overheating criteria because they are based on the upper limit of thermal comfort and can cause serious health problems for vulnerable groups (Dengel & Swainson 2012). As overheating is about the existing heat above the upper threshold, it is not safe for

vulnerable individuals as their acceptable temperature differs from ordinary people. For instance, healthy children might tolerate a low temperature similar to an adult, but for high temperature, their safe threshold is significantly lower than adults (Rupp, Ricardo Forgiarini, Vásquez & Lamberts 2015; Telia et al. 2017). Thus, the scope of this research includes healthy residents who can adapt to a temperature higher than the upper thermal comfort threshold. The healthy residents who cannot adapt to high temperatures, such as infants, children, or elders, are not the overheating assessment subjects.

During the sleeping time, thermal adaptation is hard for individuals (Patidar et al. 2011) and apparently, the comfort temperature for sleeping hours is higher than the waking state. Besides, thermal comfort during sleeping time is related to both operative temperature and bedding temperature (Lin & Deng 2008; Song et al. 2015; Wang, Yingying et al. 2015). Therefore, the overheating of sleeping time is not included in this study. Bedrooms are considered a 24/7 occupied space as is assumed in CIBSE TM 59 (CIBSE 2018) because a home is potentially a 24/7 occupied place and the type of families and substantially the occupied hours of each space for the lifetime of a home is unpredictable. However, Australia's NatHERS does not consider bedrooms as 24/7 spaces. The CIBSE TM 59 has provided some tolerance for occupied hours of bedrooms, but from May to September, the bedrooms are necessarily considered in 24/7 use.

1.5 Aims, objectives and research questions

The study aims to control overheating and improve thermal comfort on the top floors of multilevel energy-efficient dwellings in Adelaide.

The key objectives to meet the aim are:

1. *To address overheating as an extreme issue on the top floor of energy-efficient dwellings*
2. *To identify the adaptive thermal comfort neutral and upper threshold for Adelaide*
3. *To define criteria for analysing overheating risk in naturally ventilated rooms of dwellings during summer*
4. *To propose a numerical thermal comfort perception scale*
5. *To investigate the effect of the combination of passive energy efficiency measure on thermal comfort on the top floors of a multilevel dwelling.*

The following questions have been developed in response to the mentioned issues:

1. *How severe is the overheating on the top floors of multilevel dwellings in South Australia?*
2. *How can the thermal comfort level be validated?*
3. *Can the ASHRAE 7-point scale be used for the South Australia climate zone?*
4. *How can the level of thermal comfort during heat events be evaluated?*
5. *What passive building measures/ techniques can be employed to achieve thermal comfort in Australian homes during heatwaves and how effective are they?*

1.6 Thesis outline

This thesis is presented in seven chapters. The methodologies used in the chapters are summarized in Table 1.3

Chapter 2 is an extensive literature review on the acceptable thermal condition for the human body, thermal comfort assessment approaches and their models. The drawbacks and advantages of the Steady-State approach and Field-State approach models are discussed. Thermal comfort perception scales, their various expressions and similarities to pain perception are studied. The evaluation of long-term thermal discomfort for static and dynamic approaches besides the overheating limits are studied. Methods of achieving thermal comfort are reviewed through four categories. The measures that were shown to be successful in other studies to reduce overheating are explained and prioritized. The energy rating schemes for residential buildings in Australia and their accredited software is reviewed. At the end of this chapter, the knowledge gap about overheating and the necessity of having indices for that in the energy use software is presented.

Chapter 3 presents an extensive household survey's methodology and outcomes to determine the household perceptions of thermal comfort and overheating.

Chapter 4 presents the analysis of the eight-year temperature monitoring data of nine energy-efficient houses in Adelaide. This analysis identifies the main zones for overheating, the adaptive thermal comfort regression line for Adelaide. Based on the results, three metric indices for measuring overheating are introduced. Also, this chapter evaluates the proposed criteria by comparing them with the two available criteria in CIBSE and CIBSE TM 52. The comparison was conducted by applying criteria for eight summers in three high-performance energy-efficient houses in Adelaide.

Chapter 5 proposes a long-term thermal comfort perception numerical scale by relying on a combination of the monitoring and survey outcomes. This scale is based on the biological similarities between pain and thermal perceptions and has borrowed the concept of long-term pain perception numerical scale.

Chapter 6 presents overheating in a house before and after retrofitting based on the suggested criteria. It compares monitored temperatures with simulated temperatures during two summers before and after retrofitting. Also, this chapter presents an investigation of the measures to reduce overheating on the top floors by simulation and suggest the most effective combinations.

Chapter 7 summarises the major research findings and contributions in this study. Also, some recommendations for future research are proposed.

Table 1.3 summary of the method used in this research

Chapter Number	Chapter Inputs	Methods	Deliverables	RO	RQ
3	Thermal Comfort Threshold →	**Overheating Existence and Location** →	Overheating Location	1	1
	Thermal Comfort Scale →	Survey Excel	Thermal Comfort Range		2
	Thermal Comfort Questionnaires →	Numerical Scale Verbal Scale	Thermal Comfort Scales		2
4	Running Mean Outdoor Temperature →	**Metric Model to Assess Overheating** →	Adaptive thermal comfort threshold	2	2
	Thermal Comfort Upper Threshold →	Dynamic Threshold Modes of AccuRate →	NV mode	2	2
	Safe High Air Temperature →	Static Threshold Excel →	Model to assess overheating	3	3
	8-year monitored data →	Static Threshold Calibration →	Finalise the criteria	3	4
5	Monitoring and Survey Results →	**Numerical long-term thermal comfort perception**			
	Drawing →	Finalised criteria Excel →	Numerical thermal comfort perception scale	4	4
6	8-year monitored data →	**Evaluation of the Metrics**			
	Overheating Limits →	Finalised criteria Excel →	Finalised metrics	3	4
7	Finalised Method →	**Application of the Metrics**			
	Drawing →	DesignBuilder AccuRate Excel →	Most Effective Technique	5	5
	Measures to Reduce Overheating →	Nocturnal ventilation, Shading, Insulation, Day ventilation, Light colour roofs and walls, Double glased,….			

1.7 Contributions of the thesis

This research develops and presents a process and a metric for identifying the level of overheating perception. This work also develops a new numerical scale to assess thermal comfort perception, which provides an unambiguous method to enable households to characterise their thermal perceptions.

This study also examines available measures to improve thermal comfort and determines which combinations of measures are most effective. Based on simulation outcomes, new guidelines to improve thermal comfort on the top floors in both the early and final stages of the dwelling design process are presented.

The methodology developed can be integrated into the next generation of house energy assessment software to ensure that the house thermal simulation results in a thermally comfortable and energy-efficient dwelling throughout its living/sleeping spaces.

While the proposed novel methodologies for characterising and limiting overheating in dwellings are general and can be applied in other climatic regions, the results of this research are focusing on one specific temperate climate of Adelaide, South Australia. Other limitations of the research include the data size of the monitored top floor temperatures in bedrooms, population number for the survey reported in Chapter 5, lack of some data in Chapter 4 and some fixed defaults of software in chapter 6.

2 Thermal comfort, overheating measurements and limits: A Literature review

This chapter studies the measurement and limits of thermal comfort and overheating with a particular focus on natural ventilation. First, a short historical perspective of thermal comfort presents how understanding this area has developed and led to changes in the standards. The approaches for thermal comfort and acceptable ranges for parameters of short-term thermal comfort equation are investigated. Also, long-term thermal discomfort and overheating limits are reviewed. The second part of this chapter discusses methods to achieve thermal comfort, measures to reduce overheating and energy rating schemes in Australia and their shortfalls.

Evaluating thermal comfort has been important for many reasons, such as providing satisfactory conditions for people, controlling energy use, developing and setting standards (Humphreys 2005; Raw & Oseland 1994; Taleghani et al. 2013). Equation 2.1 highlights the importance of thermal comfort. In this equation, "*I*" is the index of overall comfort and has a linear correlation with various aspects of overall physiological comfort (Humphreys 2005):

I= 1.2 + (0.39 ×Satisfaction Code for Warmth) + (0.16 ×Satisfaction Code for Air Movement) + (0.12 ×Satisfaction Code for Humidity) + (0.05 ×Satisfaction Code for Light) + (0.13 ×Satisfaction Code for Noise) + (0.36 ×Satisfaction Code Air Quality)

(Equation 2.1)

In this equation, warmth with the biggest coefficient of 0.39, is the most crucial factor. The physiological interpretation of thermal comfort is the thermal equilibrium at one's normal body temperature with the minimum amount of bodily thermal regulation (Nicol, Humphreys & Roaf 2012). Thermal comfort is defined as 'that condition of mind that expresses satisfaction with the thermal environment' (ASHRAE 2017). Thermal comfort is one aspect of indoor air quality (IAQ) and the provision of good indoor air quality is a significant parameter in determining the energy use of buildings. A good indoor environmental quality can improve overall health, work satisfaction, productivity and learning performance.

The first method to evaluate and predict thermal comfort was a graphical chart named psychometric chart which was released in 1904. This chart shows thermal comfort based on seven parameters (Donald 2004). Empirical studies about thermal comfort in industry started in England in 1932 (Andris & Steven 2007). The first thermal comfort equation proposed in 1936 included air temperature, radiant temperature, humidity, vapour pressure, and airspeed (Bedford 1936). This measurement, named the Bedford scale of 1 to 7, was the best standard for 30 years (Humphreys, Nicol & Roaf 2015). Two more factors, metabolism and clothes insulation, were added in 1970 by Fanger (Fanger 1970) in a new equation known as the Physiology Heat Balance Equation (Parsons 2014). This equation was a new step for thermal comfort in air conditioning mode, named predicted mean vote, and became the basis for ISO 7730-1984 and ASHRAE 55-1992 (Taleghani et al. 2013). The first equation for adaptive thermal comfort appropriate for natural ventilation mode was developed in 1978 (Humphreys 2008), was modified many times up to 2004 when it was published as a standard (ASHRAE 2004; de Dear & Brager 1998; Humphreys & Nicol 2000; Nicol et al. 1995; Nicol et al. 1999). Humphrey's monthly average 'mean outdoor temperature' proposed in 1978 was changed to 'prevailing mean outdoor temperature' (Humphreys 2008; Humphreys, Nicol & Roaf 2015). The important modification of the adaptive thermal comfort equation was that in 2002 Fanger added the thermal expectation (of temperature change) item to the measuring factors (Fanger & Toftum 2002). The thermal factors still can include more parameters such as beliefs, values and aspirations (Shove et al. 2008). Any thermal environment has a descriptive/evaluable part (sensation) and an unmeasurable part (pleasure, comfort). While the descriptive part remains unchanged, the affective part is unclear and depends on a stimulus's ability to help the body feel comfort (Mishra, Loomans & Hensen 2016). Adaptive thermal comfort was suggested for the natural ventilation mode in the first place, but research has been developing this model for other modes too.

2.1 Defining acceptable thermal conditions in indoor occupied spaces

Two approaches exist to determine the acceptable thermal comfort conditions in occupied spaces:

1- Steady-State Study; This approach measures the thermal comfort of a person while in an enclosure, namely a climatic chamber with controlled environmental conditions. The three methods that follow the steady-state study approach are Graphic Comfort

Zone, Predicted Mean Vote (PMV) and Elevated Air. Due to the nature of the steady-state study, the results are predictable, accurate and can be carefully controlled, but this study has limits on daily life. Because environmental factors constantly change in the real world. The steady-state approach is discussed further in section 2.1.1.

2- Field-State Study; This approach measures the thermal comfort of a person while they are in an actual site and is closer to real day-to-day living. The three methods that statistically follow field-state study approach are the extended Predicted Mean Vote (PMVe), Adaptive Predicted Mean Vote (aPMV) and Adaptive Thermal Comfort. Field-State research is best suited for assessing the potential impacts of behavioural or psychological factors as they occur in realistic settings (de Dear & Brager 1998).

2.1.1 Steady-state approaches

2.1.1.1 Graphic comfort zone

This is a graphical representation of thermal comfort conditions based on operative temperature and humidity (Pellegrino, Simonetti & Chiesa 2016). Most of the graphic comfort zone model applications are for determining comfort in air-conditioned spaces, particularly for humidity adjustment (Kodama et al. 2001). The factors of this model are listed in Table 2.1.

2.1.1.2 Analytical comfort zone/ PMV model

The PMV was initiated in 1960 (Fanger & Toftum 2002). It is based on empirical studies on heat balance and skin temperature. The PMV has a numerical value that predicts the average thermal comfort voting of a group of healthy European subjects for a particular combination of air temperature, mean radiant temperature, relative humidity, airspeed, metabolic rate, and clothing insulation (Fanger 1970). The thermal comfort voting in PMV is thermal sensation vote (TSV) which includes seven scales (Hot, Warm, Slightly Warm, Neutral, Slightly Cool, Cool, Cold), that correspond to +3, +2, +1, 0, -1, -2 and -3, respectively (ASHRAE 2017). PMV model predicts TSV in buildings with a Heating, Ventilating, Air Conditioning (HVAC) system by the combination of six parameters (Carlucci 2013; Fanger & Toftum 2002; Parson 2019; Yau & Chew 2014) (Equation 2.2).

$$PMV = f(t_a, t_{mrt}, v, p_a, M, I_{cl}) \qquad \text{(Equation 2.2)}$$

Where**:**

t_a= air temperature (°C)

t_{mrt}= mean radiant temperature (°C)

v = relative air speed in m/s

p_a = vapour pressure (kPa)

M= activity level or metabolic rate (W/m^2)

I_{cl}= clothing insulation

Inevitably some of the occupants are not thermally satisfied due to being too hot/cold; the proportion of this group can be predicted via the predicted percentage of dissatisfied (PPD), which is calculated by the equation below (Yau & Chew 2014).

$$PPD = 100 - 95 \times exp(-0.03353 \times PMV^4 - 0.219 \times PMV^2) \quad \text{(Equation 2.3)}$$

Where:

exp= exponential function

The recommended limit for PPD in ASHRAE 55 is (PPD <10). An additional 10% PPD is considered for local discomfort. So, a PMV of ± 0.5 predicts 90% of the population is satisfied.

In comparison with the graphic comfort zone, PMV considers a wider range of physical factors (Yao, Li & Liu 2009). Immediately after a step-up change of temperature, the PMV model predicts well the thermal sensation (de Dear, Ring & Fanger 1993). However, for a down-step temperature change, it takes around 20 minutes for a typical human to get to the predicted rate by PMV (de Dear, Ring & Fanger 1993). In warm climate air-conditioned buildings, PMV overestimates the sensation of warmth in comparison with the average of occupants' actual votes, namely Actual Mean Vote (AMV) (de Dear & Brager 1998; Fanger & Toftum 2002; Humphreys 2008; Humphreys & Nicol 1998; Taleghani et al. 2013) because it does not reflect human acclimatization (Humphreys & Nicol 1998; Kwong, Adam & Sahari 2014).

To reduce the deviation between PMV and AMV, the new Predicted Mean Vote (nPMV) was formed by changing some coefficients (Humphreys & Nicol 2002). Making PMV compatible with people acclimatisation and applicable for naturally ventilated buildings, aPMV was later proposed to include adaptive coefficients (Kim, JT et al. 2015; Yao, Li & Liu 2009). A comparison of factors for PMV with nPMV and aPMV is shown in Table 2.1.

It was believed that PMV followed a static model (de Dear & Brager 1998). However, Fanger explained that PMV was not a static model, as a static model predicts one constant temperature while PMV predicts a range around the neutral temperature between 10 and 35 °C (Fanger & Toftum 2002). The neutral temperature is when occupants feel thermally neutral. Despite the basic assumptions of PMV mode, the physiological acclimatization for heat exposure has been documented (de Dear & Brager 1998). For different types of mental work, occupants would prefer different room temperatures (Humphreys, Nicol & Roaf 2015). The indices of PMV and PPD have a weak correlation with thermal satisfaction (Li, P et al. 2020). The PMV is still used in research for determining comfort in air-conditioned spaces.

Table 2.1 Thermal comfort parameter and their limits for steady-state study

	Graphic Comfort zone	Analytical Comfort Zone, Predict Mean Vote (PMV)	New Predicted Mean Vote (nPMV)	Elevated Air (Occupants Control)	Elevated Air (Without Occupants Control)
Metabolic Rate (met)	1–1.3	*1–2 **0.8–4	***,*1–2 **0.8–4	1–1.3 **1.2	1–1.3 ***1–2
Clothing Rate (clo)	0.5–1	***0.5–1 **0–2	***0.5–1 **0-2	0.5–1.5 **0.5 ***0–1.5	0–1.5
Air speed (m/s)	<0.2	**<0.2	**<0.2	0.2–1.2 **0.2–1.5	0.2–0.8 ***0.15–0.8
Humidity Ratio	<0.21	Any	Any	0.01 ***Any	0.01
Relative Humidity (%)	<81	* ✓ **40–60	* ✓ **40–60		
Mean Radiant Temp. (℃)	Any	**10–40	**10–40		
Wet Bulb Temp. (℃)	12–20.5				
Indoor Air Temp. (℃)	21.5–28.3	*10–30	*10–30	**<26	
Indoor Operative Temp. (℃)		**18–27	**18–27	20.5–30.8	22.5–30.2
Water Vapour partial Pressure (Pa)	1910	*<2700			
Dew-Point Temp. (℃)	16.8				
Effective Mechanical Power (W/m²)		* Any	* Any		
Clothing Surface Area		* Any	* Any		
Clothing Surface Temp. (℃)		* Any	* Any		

(ASHRAE 2017), *=(Fanger & Toftum 2002), **=(NSAI 2007), ***=(ASHRAE 2016)

2.1.2 Field-state approaches

The field-state approach is based on the fact that the human body is not passive to the thermal environment but actively acclimatizes through a self-regulating system to achieve thermal comfort. Individuals perceive the same thermal environment differently and a sudden ambient temperature change affects their thermal sensation (Asita Kumar & Ramgopal 2013; de Dear & Brager 1998; Humphreys, Nicol & Roaf 2015). Table 2.2 summarizes the measuring parameters and limits used in field studies. Increasing research evidence has proved that the thermal regulation system is an incorporation of the psychological, physiological and behavioural responses. Some of the studies that have documented human acclimatization, include four groups of men in the Arctic and Antarctica, have shown remarkable ability to tolerate cold weather (Folk 1981). A survey of 12 mechanically ventilated office with 877 staff in Quebec showed that the acceptable range for summer and winter was much wider than both the ASHRAE and ANSI standards (Donnini et al. 1997). About forty years of research and 21,000 sets of raw data collected from Athens, America, Australia, Bangkok, Canada, Greece, England, Pakistan, Singapore and Thailand presented a high range of temperature for thermal comfort, which formed the adaptive thermal comfort equation basis (de Dear & Brager 1998; Humphreys, Nicol & Roaf 2015). Surveying 1520 volunteers from different climatic regions in Thailand showed that higher educated subjects were accustomed to a lower temperature during summer (Yamtraipat, Khedari & Hirunlabh 2005). Investigating 30 rural and 28 urban residents for NV mode in China found that the rural residents had greater tolerance to the same climatic conditions and demonstrated more thermal comfort than their urban counterparts (Han et al. 2009). Monitoring and surveying a 15-story office building in China for one year in AC, NV and mixed of them (MM) modes found that the actual thermal sensation and the acceptance of thermal conditions varied for AC and NV modes (Luo et al. 2015). A longitude survey of 11,500 individuals in Australia suggested that occupant thermal sensitivity varied by building typologies and ventilation mode. This survey found that participants were about half as sensitive to temperature in NV mode compared with AC mode (Rupp, Ricardo Forgiarini et al. 2019). Another survey in South Korea of 54 occupants revealed that the occupants of residential buildings were less sensitive to indoor temperature changes compared to the occupants of other buildings (Ryu et al. 2020). A survey of 3,452 university students showed that the long-term thermal

history influenced the subjects' comfort temperature, thermal comfort zone, thermal sensation, acceptability and preference (Jowkar, de Dear & Brusey 2020).

Table 2.2 Main and combined measuring parameters of thermal comfort and their limits used in field-state studies

Parameters	Extended Predict Mean Vote (PMVe)	Analytical Comfort Zone, Adaptive Predict Mean Vote (aPMV)	Adaptive Thermal Comfort
Metabolic Rate (m)	*1	*1– 2 **0.8< <4	1–1.3
Clothing Rate (clo)	*0.5		*****Any (at least 0.5< <1)
AirSpeed (m/s)	*0.3	**<0.2	0.3–1.2 *****Any
Relative Humidity (%)	*70% **40–60	* ✓ **40–60	
Mean Radiant Temperature (℃)		**10–40	✓
Indoor Air Temp. (℃)	*<30.5	*10–30	<32
Indoor Operative Temp. (℃)		**18–27	17.5≤ ≤24.2
Water Vapour partial Pressure (Pa)	*<2700	*<2700	
Effective Mechanical Power (W/m^2)	*✓	✓*	
Clothing Surface Area	*Any	*Any	
Clothing Surface Temp. (℃)	*Any	*Any	
Expectation	****0.5≤ ≤1 (Adaptive Coefficient)		Through a prevailing mean outdoor temp
Mean Outdoor Temp. (℃) (Monthly or Prevailing/Running)			***** 10–33.5 Monthly is used if Prevailing is not available ***15< <30

(ASHRAE 2017), *=(Fanger & Toftum 2002), ** = (NSAI 2007), ***=(ISO 2005a), ****=(Yao, Li & Liu 2009), *****=(ASHRAE 2016)

2.1.2.1 Extended PMV (PMVe)

PMV in unconditioned spaces predicts a warmer thermal sensation than the AMV as this model is not based on physiological acclimatization (Fanger & Toftum 2002). The PMVe for unconditioned buildings in warm climates predicts the PMV well, as it combines the best of the PMV and adaptive models due to considering the thermal expectancy factor in the calculation (Fanger & Toftum 2002). The expectancy factor's range is 0.5–1 for low to high expectancy (Fanger & Toftum 2002). Only the upper temperature limit of the comfort zone is affected by the expectancy factor.

2.1.2.2 Adaptive PMV (aPMV)

The aPMV model is useful to apply rather than the PMV in NV mode as it incorporates the local climate, dynamic, heterogeneous or unsteady thermal conditions, cultural-social backgrounds, behaviour habits and lifestyle (Kim, JT et al. 2015; Wei, Xiangguang & Jun

2010; Yao, Li & Liu 2009). Research showed that the smaller PPD was attributed to aPMV, PMVe and PMV, respectively (Luo 2020). The equation for evaluating aPMV is:

$$aPMV = \frac{PMV}{1-\lambda \times PMV} \qquad \text{(Equation 2.4)}$$

Where: λ = adaptive coefficient

The λ reflects a human's adaptive functions such as behavioural and psychological adaptation, which differs for warm and cool conditions and can be found through field study. The λ connects a lab-based factor to actual conditions. Some studies have provided values for λ for warm and cool conditions in various cities. For Chongqing, the values suggested for λ in warm and cold conditions are -0.293 and 0.125, respectively (Yao, Li & Liu 2009). Beijing's corresponding values are -0.285 for and 0.136 (Wei, Xiangguang & Jun 2010). In the same country, -0.34 was obtained for Tibetan climate from 10.18 to 22.91 °C (Yu, W et al. 2017). The aPMV shows that occupants could feel less hot and less cool than that the PMV predicts. It is supposed that the aPMV model can be applicable for air-conditioned spaces (Mishra, Loomans & Hensen 2016).

2.1.2.3 Adaptive thermal comfort model

Adaptation is at the heart of all species in the ever-changing climates of our planet. People have strategies for dealing with daily and monthly climate changes and stay thermally comfortable by changing their environment or adapting themselves through activities, posture, clothing or physiology (Humphreys, Nicol & Roaf 2015). The adaptive thermal comfort is derived from office buildings' field measurements in NV mode and is applied to occupant-controlled NV spaces (ASHRAE 2017). During the last 30 years, various versions of the adaptive thermal comfort model have increasingly been accepted (de Dear et al. 2013).

By adapting to human acclimatization, desired indoor conditions are linked to the building's climatic context, which accounts for past thermal experiences and current thermal expectation (de Dear & Brager 1998; Humphreys & Hancock 2007; Humphreys & Nicol 1998, 2018). The relation between the indoor neutral temperature and outdoor temperature was proposed in 1992 and incorporated into ASHRAE database in 1998 (Humphreys & Nicol 2000). This model introduced a range of thermal comfort levels using regression equations that relate the neutral indoor temperature to the monthly average outdoor temperature in the first versions (ASHRAE 2004; Fanger & Toftum

2002) and running mean outdoor temperature in the subsequent versions (NSAI 2007). The running mean outdoor temperature is necessary for dynamic thermal comfort simulation, while the monthly mean temperature is valuable for initial design assessments (Humphreys, Rijal & Nicol 2013). The acceptable airspeed for this model is 0.3–1.2 m/s. The base equation that determines the neutral, upper and lower levels of thermal comfort is (ASHRAE 2017; CIBSE 2015; DIN 2012; ISSO 2014):

$$Tn = C_o \times T_{rm} + T_c + T_h \qquad \text{(Equation 2.5)}$$

Where:

T_n = Neutral operative temperature

C_o= Coefficient

T_{rm}=Running mean outdoor temperature

T_c= Constant temperature

T_h= Acceptable maximum divergence from neutral temperature

The value of 'C_o' and 'T_h' in equation 2.4 for ASHRAE 55 standard are higher than that from EN 15251 by 0.02 and 1°C. As a result, the 'T_n' of ASHRAE 55 is divergent from the rest of the standards and in higher outdoor temperature, their differences are more significant. The standard EN 15251 has separated the thermal comfort to Categories I, II and III for respectively high, normal and moderate thermal comfort expectations. By comparison, ASHRAE 55 groups the thermal comfort to 90% and 80% of occupants' acceptability, whilst ISSO 74 groups the thermal comfort to B, C and D for 90%, 80% and 75% thermal satisfaction, respectively. The difference between upper and lower limits for indoor comfort temperature for these groups ranges from 8 °C in Category III of EN 15251 to 4 °C in 90% acceptance of ASHRAE 55 (Nicol 1993) (Nicol 2017; Nicol & Humphreys 2002; Roaf, Nicol & de Dear 2013).

The running mean outdoor temperature is daily temperature weighted regressively according to their distance from the day understudy, for a minimum of 7 days and a maximum of 30 days outdoor temperatures. The 7-day running mean outdoor temperature is used an accepted by experts in Australia during the last 15 years (de Dear 2011; Deuble & de Dear 2012; Kim, J et al. 2016; Manua et al. 2016; Morgan, Craig & de Dear 2003; Saman et al. 2013). The formula of running mean outdoor temperature is (ASHRAE 2017):

T_{rm}= (1-α)(Tod-1+αTod-2+α2Tod-3+α3Tod-4+α4Tod-5+α5Tod-6+α6Tod-7)= (1-α)Tod-1+αT_{rm-1} (Equation 2.6)

Where:

T_{od-1} = daily mean outdoor temperature for one day before the day in question

T_{od-2} = daily mean outdoor temperature for two days before the day in question and so.

T_{rm-1} = the running mean outdoor temperature for one day before the day in question. If this temperature is not available, the mean outdoor temperature on the preceding day can be used.

α = a constant (0 < α < 1), which depends on how quick local people adapt to the running mean outdoor changes.

The α coefficient impacts the amplitude of acceptable indoor temperature responses to outdoor weather transients (BASIX 2017). The recommended α is from 0.6 to 0.9. The 0.6 is for the fastest response and appropriate for major dynamic day-to-day temperatures such as midlatitude, whilst the 0.9 is for the slowest response and appropriate for minor dynamic day-to-day temperature such as humid tropics (ASHRAE 2017). The T_n for ASHRAE with α = 0.6 is close to the 'T_n' for EN 15251. It is likely that the value of 0.6 be employed in this study, as the subject of research are healthy and active people and it is expected that they can adapt to the day-to-day temperature variation.

The 'T_c' in the equation 2.4 varies in standards and papers such as 13.8 °C (Humphreys, Rijal & Nicol 2013), 16.75 °C (Kim, J et al. 2016), 17.8 °C (ASHRAE 2017) and 18.8 °C (CIBSE 2015; ISSO 2014; NSAI 2007). The 'T_h' determines the upper and lower thresholds for the 'T_n' variation and is not bigger than 2.5 °C or smaller than -2.5 °C.

The Neutral temperature is related to the operative temperature and running mean outdoor temperature (Humphreys, Rijal & Nicol 2013) (Figures 2.1 and 2.2).

The operative temperature (T_{op}) is what humans experience thermally in space and is calculated by the equation below (ASHRAE 2016; Nicol & Brian 2013):

$$Top = Tdb\left(\frac{hc}{hc+hr}\right) + Tmr\left(1 - \left(\frac{hc}{hc+hr}\right)\right) \quad \text{(Equation 2.7)}$$

h_c = convective heat transfer coefficient

h_r = radiative heat transfer coefficient

T_{db}= indoor air (dry bulb) temperature

T_{mr} = indoor mean radiant temperature

The value of $\frac{hc}{hc+hr}$ is related to the airspeed and there is a minor diference in some references (Table 2.3).

Table 2.3 the impact of airspeed on one of the coefficients in the Equation 2.5

Airspeed (m/s)	≤0.1	<0.2		0.2> and <0.6	0.6> and<1
$\frac{hc}{hc+hr}$	0.5	0.57	0.5	0.6	0.7
Ref.	(Nicol & Brian 2013)	(Pellegrino, Simonetti & Chiesa 2016)			

The air temperature can substitute operative temperature if it meets the criteria listed in the ASHRAE 55 standard users' manual (ASHRAE 2016).

The chronological study of adaptive thermal comfort shows that although the concept of thermal acclimatization of humans was commenced as a worldwide condition, a unique equation is not applicable globally. Various equations are suggested based on the local climate by changing the coefficient and constant. Table 2.4 lists the equations for adaptive thermal comfort for specific areas.

Table 2.4 Development and localization of adaptive thermal comfort equation during the last 40 years

Year	Area	Equation	Ref.
1978	Worldwide	$T_n = 0.534*T_{out} +11.9$	(Humphreys 2008)
1995	Pakistan	$T_n = 0.38*T_{out} +17.0$	(Nicol et al. 1995)
1998	----	$T_n =0.255*T_{out} +18.9$	(de Dear & Brager 1998)
1999	Pakistan	$T_n = 0.36*T_{out} +18.5$	(Nicol et al. 1999)
2000	----	$T_n = 0.54*T_{out} +13.5$	(Humphreys & Nicol 2000)
2004	Tropical climates worldwide	$T_n= 0.534*T_{out} +12.9$	(Nicol 2004)
2004	America	Upper 80% or 90% acceptability limit = 0.31 T_{rm}+17.8+ 2.5 or 3.5 Lower 80% or 90% acceptability limit = 0.31 T_{rm} -2.5 or 3.5	(ASHRAE 2004)
2007	Europ	$T_{(upper\ limit\ theresholds)} = 0.33\ T_{rm} + 18.8 + 2$ or 3 or 4 $T_{(lower\ limit\ theresholds)} = 0.33\ T_{rm} + 18.8 - 2$ or 3 or 4 T_{rm} = (Tod-1 + 0.8Tod-2 + 0.6Tod-3 + 0.5Tod-4 + 0.4Tod-5 + 0.3Tod-6 + 0.2Tod-7) / 3.8	(NSAI 2007)
2010	America	Upper 80% or 90% acceptability limit = 0.31 T_{rm}+17.8+ 2.5 or 3.5 Lower 80% or 90% acceptability limit = 0.31 T_{rm}+17.8- 2.5 or 3.5	(ASHRAE 2010)
2010	Europ	$T_n = 0.33\ T_{rm} + 18.8$	(Nicol & Wilson 2011) (Nicol & Humphreys 2010)
2011	Worldwide	$T_n = 0.33\ T_{rm} + 18.8$ $T_{rm} =0.34T_{od-1} + 0.23T_{od-2} + 0.16T_{od-3} + 0.11T_{od-4} + 0.11T_{od-5}+ 0.11T_{od-6}+ 0.11T_{od-7}$	(de Dear 2011)
2013	Worldwide	$T_n = 0.053*\ T_{rm} +13.8$	(Humphreys, Rijal & Nicol 2013)
2014	Netherland	$T_{(upper\ limit\ theresholds)} = 0.33\ T_{rm} + 18.8 + 2$ or 3 or 4 $T_n = 0.26\ T_{rm}+ 21.4$	(ISSO 2014) (Indraganti et al. 2014)
2016	India	$T_n = 0.54\ T_{out} +12.83$ (NV) $T_n = 0.28\ T_{out} +17.87$ (MM)	Sanyogita Manua et al. 2016)
2016	Australia (Sydney-Wollongong)	$T_n =0.26*\ T_{rm} +16.75$ Upper 80% or 90% acceptability limit = T_n + 4.5 or 5.5 Lower 80% or 90% acceptability limit = T_n - 4.5 or 5.5	(Kim, J et al. 2016)
2017	America	Upper 80% or 90% acceptability limit = 0.31 T_{rm} +17.8+ 2.5 or 3.5 Lower 80% or 90% acceptability limit = 0.31 T_{rm} -2.5 or 3.5	(ASHRAE 2017)
2017	UK	$T_n =0.26*\ T_{rm} +18.2$	(Telia et al. 2017)
2019	Australia (South)	$T_n = 0.3\ T_{rm} + 19.2$	(Sharifi, Saman & Alemu 2019)
2020	Australia (Temprate climate)	$T_n = 0.26\ T_{rm}+ 15.9$ Upper 80% or 90% acceptability limit= 0.26 T_{rm}+ 15.9 +3.5 or 4.5 Lower 80% or 90% acceptability limit = 0.26 T_{rm}+ 15.9 -3.5 or 4.5	(Williamson, T & Daniel 2020)

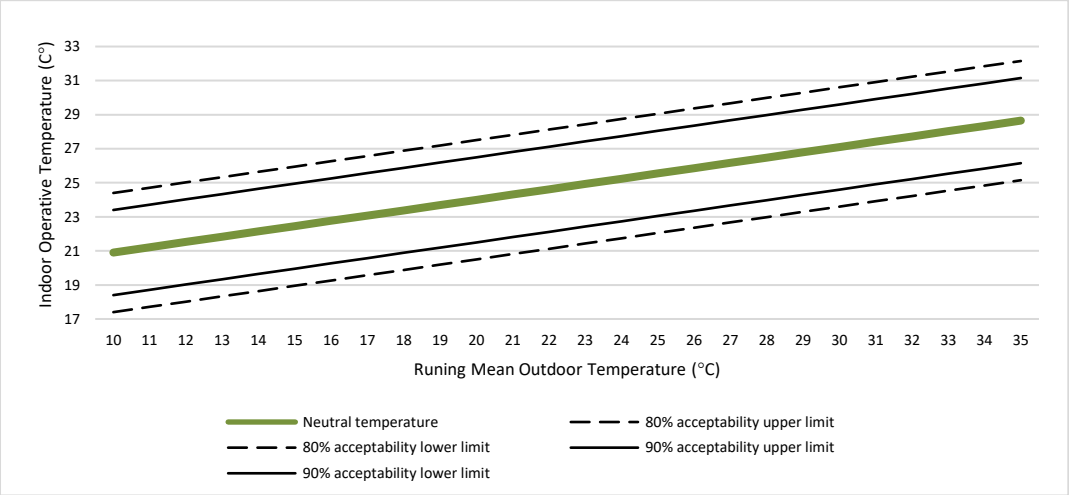


Figure 2.1 ASHRAE adaptive thermal comfort (ASHRAE 2017)

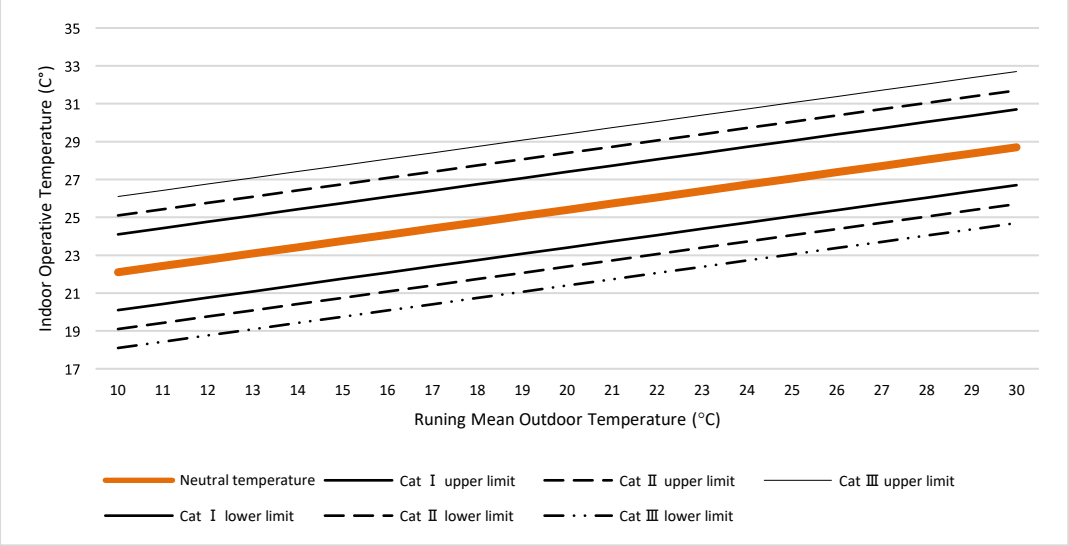


Figure 2.2 Adaptive thermal comfort of EN 15251 and CIBSE (CIBSE 2015; DIN 2012)

2.1.2.4 Adaptive Temperature Limit (ATG)

The ISSO 74: 2014 integrated adaptive and non-adaptive thermal comfort on the basis of ASHRAE 55: 2004 and 2010; En15251:2007, CIBSE TM 2013, Swiss guideline SN 180 and SIA: 2013 and the national standard of China GB/T 50758:2012. The ISSO 74:2014 categorizes buildings into α and β types (Boerstra, Hoof & Weele 2014). The β type, which refers to the summer situation and primarily relies on centrally controlled cooling, is irrelevant for this research. This guideline classifies the need for thermal comfort from A to D. A is a high level of thermal comfort expectation with a maximum of 5% PPD or a combination of B, the normal level of expectation with 10% PPD, and occupants

controlling local temperature within ±2ºC tolerance and airspeed between 0.2 and 1.5 m/s. The D class refers to the limited level of expectation with a maximum of 25% PPD. This guideline also considers upper and lower limits for cases with active heating or cooling systems (ISSO 2014). This model is applicable for T_{rm} from 10 to 25 °C. The formula for 'T_n' changes according to comfort bandwidths and dwelling zones. Classes B, C, and D upper limits for the intermediate and summer season (type α and β) are the same as Categories I, II and III upper limits presented in Annex A2 of EN 15251, respectively. The upper and lower limits for the heating season are equal to those specified for winter in ISO 7730 and EN 15251. The β upper limits for Classes A, B, and C for summer are also equal to those in ISO 7730 and (the non-adaptive part of) EN 15251(Boerstra, Hoof & Weele 2014; ISSO 2014).

The ATG will not be employed for this research because the equations of upper thresholds in this model are the same as the EN 15251 and EN 15251 is used for this study.

2.1.2.5 Comfort for mechanically conditioned buildings linked to the outdoor temperature

The indoor air of a building can be mechanically conditioned with the settings linked to the outdoor air temperature and human acclimatization. CIBSE presents an equation for mechanically cooled buildings but relating to the outdoor temperature, which is an updated formula originally suggested by Nicol, 2007. The CIBSE equation is potentially a benchmark to improve this method and can also be used for MM buildings (CIBSE 2015). The T_n is calculated as below (CIBSE 2015):

Upper threshold of thermal comfort= $0.09 * T_{rm} + 24.6$ (Equation 2.8)

2.1.2.6 Recently proposed equations

A recent 2-year monitoring program of 42 homes in Sydney and Wollongong (Kim, J et al. 2016) indicates that for these cities, the comfort zone range is 2 °C wider than that of ASHRAE 55 standard (Figure 2.3). The equation suggested by this research is in Table 2.4. Equation 2.9 shows that the upper thermal comfort threshold for the proposed T_n is 0.65-3 °C above the ASHRAE 55 adaptive thermal comfort upper threshold. As this spectrum is based on the case studies located in Australia's east, it is named the "Sydney-Wollongong" threshold in this thesis.

Upper threshold of thermal comfort= $0.26 * T_{rm} + 20.25$ (Equation 2.9)

Analysis of 8-year minute-by-minute monitoring program of 11 highly energy-efficient houses in Lochiel Park, Adelaide, Australia, alongside survey resulted in a T_n close to ASHRAE 55 (Figure 2.3) (Sharifi, Saman & Alemu 2019). The equation for T_n is listed in Table 2.4. The upper thermal comfort threshold of this proposed T_n is shown by Equation 2.10.

Upper threshold of thermal comfort = $0.27^* T_{rm} + 21.7$ (Equation 2.10)

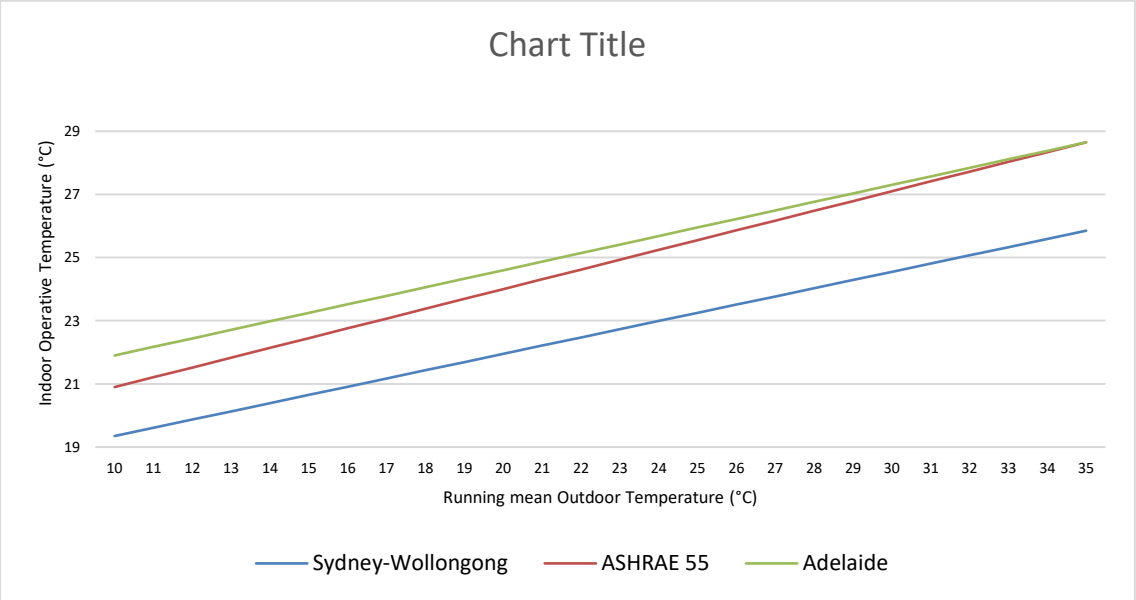


Figure 2.3 Adaptive thermal comfort of Sydney-Wollongong and Adelaide compared to ASHRAE 55 (ASHRAE 2017; Kim, J et al. 2016; Sharifi, Saman & Alemu 2019)

A breakthrough in the adaptive thermal comfort research is implementing qualitative factors, expectation and adaptation, in a quantitative equation. The adaptive thermal comfort model can predict occupants' thermal sensation better than that of PMV (Boerstra, Hoof & Weele 2014; Wagner et al. 2007). In well-insulated rooms away from direct sun radiation or from other high-temperature radiant sources, the difference between the air and the mean radiant temperature (and hence between the air and operative temperature) is small (CIBSE 2015). The adaptive thermal comfort model with just a slight penalty is usable for spaces with mechanical cooling/heating and substitute the PMV (Boerstra, Hoof & Weele 2014; Humphreys, Rijal & Nicol 2013; Nicol & Brian 2013; Nicol & Humphreys 2007; Yun, Lee & Steemers 2016).

Studies have found that the adaptive thermal comfort model can be used for spaces with mechanical cooling/heating (Boerstra, Hoof & Weele 2014; Humphreys, Rijal & Nicol 2013; Yun, Lee & Steemers 2016) and MM buildings (Kim, J et al. 2019). However, one other investigation concluded that this model could not be employed in hybrid ventilation

or MM buildings (Hitchings 2018). The adaptive thermal comfort is the most cost-effective model, as it can predict the thermal sensation of occupants better than that of PMV (Wagner et al. 2007) and is more insightful for assessing thermal comfort in homes (Lomas & Kane 2013). Research has shown that adaptive thermal comfort for mechanically conditioned buildings can substitute for PMV (Boerstra, Hoof & Weele 2014; Humphreys, Rijal & Nicol 2013; Nicol & Humphreys 2007; Yun, Lee & Steemers 2016). Luo confirmed that the adaptive model was more applicable to MM condition (Luo et al. 2015). A comparison of five regulatory standards that employ the adaptive thermal comfort (ASHRAE 55, EN 15251, prEN 16798-1, ISSO 74 and GB/T 50784) in Amsterdam, Beijing, Palermo, San Francisco and Shanghai, showed that despite some differences, there were clear similarities between the results. This reinforces the robustness of the adaptive thermal comfort model (Hitchings 2018).

The adaptive thermal comfort model's applicability is empowered by some data that show it is possible to design buildings to operate in the free-running mode to be comfortable when the prevailing mean outdoor temperature lies within the range 10-30 °C (Lomas & Giridharan 2012). A free-running building uses no energy for heating or cooling but just fans to increase air movement (Nicol & Humphreys 2010).

The majority of adaptive thermal comfort studies have been undertaken in commercial buildings (Saman et al. 2013), with little work done on residential buildings. Drawbacks of the adaptive thermal comfort model include not considering humidity and clothing. The metabolic rate inclusion of adaptive thermal comfort is more limited than that in the analytical comfort zone. This model is applicable for local people, so people who travel or move to a new climate cannot adapt in one week or one month (Jowkar, de Dear & Brusey 2020).

2.1.3 Discussion

The literature review about acceptable thermal comfort condition has demonstrated that field studies on thermal conditions can be more holistic than the steady-state approach. The field-study can cover contextual factors alongside the physiological and psychological aspects of individuals. Amongst the field-study models, the adaptive thermal comfort is considered most appropriate for this research, as it can be applied flexibly for NV, MM and perhaps AC modes. The adaptive thermal comfort has been

employed for various climates and resulted in just minor equation changes, but its concept and methodology were entirely acceptable for the studied cases.

2.2 Thermal comfort perception scales

Questionnaires are generally used to assess individuals' short-term and long-term thermal comfort perception. The American Society of Heating, Refrigerating and Air-Conditioning Engineers, and ASHRAE 55 standard has provided the verbal 7-point thermal sensation vote (TSV) scale to assess short-term thermal sensation in natural ventilation (NV) mode and a visual scale to evaluate long-term thermal comfort satisfaction (ASHRAE 2017). The literature shows that the TSV scale is widely used for presenting thermal sensation, short-term and long-term thermal comfort assessment in the questionnaires. Apparently, the ASHRAE 55 standard long-term thermal comfort satisfaction scale has not been employed. Rather it has been substituted with the TSV verbal scale (Heidari & Sharples 2002; Saman et al. 2013; Vellei et al. 2016a).

The TSV scale has been challenged by several studies which have raised issues such as the following matters. The scale scores are not perceived as equidistant, the comfortable (acceptable) range varies significantly among various subjects (Schweiker et al. 2016) and that the type of scale used to relate thermal sensation and the operative temperature can change the relationship (Schweiker et al. 2016). Also, as the understanding of the scale words could differ from person to person and require interpretation (Koelblen et al. 2016; Traci Lynne 2008), the meaning of each descriptor (score) may be ambiguous (Humphreys & Hancock 2007). Moreover, the preferred thermal sensation tends to increase with room temperature (Humphreys & Nicol 2004). The rationale for scaling would lead people to attribute the last point of the scale to the best or worst condition regardless of the verbal description for that point (Koelblen et al. 2016), the relation between temperature and TSV is non-linear and most people do not perceive the scale points as equidistant (Schweiker et al. 2020; Schweiker et al. 2016). Furthermore, the verbal scores cannot indicate whether the thermal condition was pleasant, comfortable, acceptable, preferred or tolerable (ISO 2005a; MS, A & Joel 2003); and thermal expectation influence the TSV (Schweiker, Rissetto & Wagner 2020).

Although TSV is a voting method to evaluate individuals' thermal 'sensation', it is based on the individuals' thermal 'perception' (ASHRAE 2017; Humphreys & Nicol 2002; Koelblen et al. 2016) as it is designed for people to report only their short-term thermal

perception (Ebner & Kaas 2015; Krantz 2012; Waldman 2009). Thus, TSV is a verbal scale that does not measure the sensation, rather shows the perception.

The thermal sensation could be estimated by the Mean body temperature (MBT). The MBT can be calculated by core and mean skin temperatures (MST) using the following equation (Bligh 2001; Burton 1935; Liu et al. 2011; Mitchell & Wyndham 1969).

$MBT = 0.64\ T_{core} + 0.36\ T_{skin}$ (Equation 2.11)

Some studies have modified equation 2.11 as below (Bligh 2001):

In cold environments: $MBT = 0.6\ T_{core} + 0.4 T_{skin}$ (Equation 2.12)

In warm environments: $MBT = 0.8\ T_{core} + 0.2 T_{skin}$ (Equation 2.13)

Where:

T_{core} = Core temperature

T_{skin} = Skin temperature

The core temperature is determined by a few measurements and is assumed constant. Skin temperature is determined through weighted tissue temperature (Liu et al. 2011). Measurements are made at head, hands, trunk and feet; or chest, arms, thighs, and legs. A coverage surface area coefficient is assigned to each segment as below (Liu et al. 2011; Mitchell & Wyndham 1969).

$T_{skin} = c_1T_1 + c_2T_2 + \ldots + c_nT_n$ (Equation 2.14)

The skin is not equally sensitive in all areas. For example, the neck is highly sensitive to heat and cold, whilst the lower leg appears less sensitive (Law 2013). There is a need to differentiate between the weighting by skin coverage versus weighting by skin sensitivity (Law 2013). Studies have suggested equations to correlate T_{skin} and thermal comfort (Liu et al. 2011), TSV (Takada, Matsumoto & Matsushita 2013) and overall thermal sensation (Choi, Joon-Ho & Vivian 2012). Previous research has proposed an equation by which the TSV can be predicted through T_{skin} if the temperatures of skin for all body segments increase or decrease simultaneously (Takada, Matsumoto & Matsushita 2013). Also, the thermal sensation could be measured through skin temperature and heart rate (Choi, Joon-Ho & Dongwoo 2019; Choi, Joon-Ho , Loftness & Lee 2012; Choi, Joon-Ho & Vivian 2012; Choi, Joon-Ho & Yeom 2017). Thermal sensation has a negative correlation with

heart rate and a significant correlation with the forehead, arm, wrist, chest and belly temperatures (Choi, Joon-Ho & Dongwoo 2019).

The thermal sensation is converted to thermal perception after processing in the brain (Mishra, Loomans & Hensen 2016; Stanley 2012). The perception nature of TSV of thermal comfort has extended the use of the TSV scale as an indicator for voters' long-term thermal comfort perception. To measure perception, the respondents are asked to report their conscious reasoning or sensation (Traci Lynne 2008). Perception is subjective and is made through the process of interpreting and organizing objective sensory information (Traci Lynne 2008). Other human perceptions, such as pain (Conti 2001; Fanger 1970; Jensen, MP, Karoly & Braver 1986; Jensen, PM et al. 1989), effort (Lampropoulou & Nowicky 2012) and taste (Pannell 2015) are assessed and predicted through numerical scales. For instance, the numerical rating of 0-10 is used for the perception of pain (Turk & Melzack 2014) and effort (Lampropoulou & Nowicky 2012), while a scale of 1-5 is used just for the perception of effort (Paschoarelli, Santos & Bruno 2012). The scales are the same for the perception of chronic (long-term) pain and the short-term pain (Turk & Melzack 2014). The assessment of a subjective experience related to an objective stimulus is significantly relevant in pain research (Schweiker et al. 2016). A previous study has proposed a thermal perception scale by a numerical thermal preference scale. This scale showed the preferred temperature by sliders graduated from -10 to 10. The results outperformed the TSV (Jazizadeh, Marin & Becerik-Gerber 2013).

The numerical scale for predicting short-term thermal comfort during AC mode was introduced in 1970 (Fanger & Toftum 2002) for steady-state, which is PMV. The PMV scores are convertible to the TSV scores. This conversion is used to compare the practicality of the adaptive thermal comfort model with a steady-state model for AC and MM (Kim, J et al. 2019). Although the PMV is used for short-term thermal comfort, some studies have used it to assess long-term thermal comfort (Hawila et al. 2018; Kim, J et al. 2019; Soutullo et al. 2014). PMV scale has been employed for developing new tools to control thermal comfort (Ruz, Garrido & Vázquez 2018); however, it has been shown to overestimate the sensation of warmth in the warm climate (de Dear & Brager 1998; Fanger & Toftum 2002; Humphreys 2008; Humphreys & Nicol 1998; Taleghani et al. 2013) as it does not reflect human acclimatization (Humphreys & Nicol 1998; Kwong, Adam & Sahari 2014; Nairn, J & Fawcett 2012). PMV cannot be used as a tool for surveying occupants' perception.

2.2.1 Expression of thermal comfort perception

The ASHRAE 55 standard specifies one verbal and one numerical scale to measure short-term thermal comfort and one visual scale to measure long-term thermal comfort as follows (ASHRAE 2017). The standard also provides methods for converting the scales to numerical values.

- TSV for Short-term/Point-in-time/Right-now thermal comfort. This scale scores are 'Cold', 'Cool', 'Slightly Cool', 'Neutral', 'Slightly Warm', 'Warm', and 'Hot'. This scale's correspondence with the predicted mean vote (PMV) scale is shown in Table 2.5. The acceptable range for this scale with a 0.5-unit resolution is from −1.5 to +1.5 on the PMV scale, which corresponds to the region above 'Cool' and below 'Warm' on the TSV. With one-unit resolution, the acceptable range is from -2 to +2 by the PMV scale, which corresponds to 'Cool' to 'Warm' on the TSV scale. The accuracy of PMV is low (Cheung, Schiavon & Parkinson 2019; Humphreys & Nicol 2002), about 40–60% (Schweiker et al. 2016), but the PMV scale is the only scale correlated to TSV which can convert the verbal ranges to numerical values.

- Long-term thermal comfort. This visual scale is appropriate for determining thermal comfort for a period such as a season. The ASHRAE 55 standard equates 'Very satisfied' to +3, 'Very dissatisfied' to -3, and the middle position to 'neutral' (Figure 2.4). Thus, the seven points range from -3 to +3 with a one-unit resolution. The acceptable range is from zero to +3. This scale is applied visually on questionnaires and is later converted to numbers by interviewers. There is no correlation between the ASHARE 55 standard long-term thermal comfort and any short-term thermal comfort scales.



Figure 2.4 Visual long term thermal comfort scale of ASHRAE 55

Table 2.5 Correlation between two ASHRAE short term thermal comfort scale (TSV) and PMV (ASHRAE 2017)

	TSV	PMV
Short-Term Thermal Comfort	Hot	+3
	Warm	+2
	Slightly warm	+1
	Neutral	0
	Slightly cool	-1

Acceptable Range	Cool	-2
	Cold	-3

Some studies have used the TSV for long-term thermal comfort rating by repeating the survey; however, the ASHRAE 55 standard provides no justification to convert the short-term thermal comfort to long-term thermal comfort. The long-term thermal comfort of social housing occupants in the UK was investigated through TSV in two consecutive summers to assess overheating (Vellei et al. 2016a). The thermal comfort of occupants was investigated by the TSV scale in three cities of Australia through surveying the occupants fortnightly for about six months (Saman et al. 2013). The TSV was used to assess the thermal comfort of 30 residents in Iran each of whom used TSV to provide the rating for an average of 100 times during two separate 28-day and 14-day periods (Heidari & Sharples 2002). The occupants of a gym in Canada were asked to rate their thermal comfort at any time for six months by the TSV scale, with the two extreme votes omitted, so it was a five-point scale (Berquist, O'Brien & Ouf 2020). In three groups of buildings in the UK, 65 residents' thermal comfort was evaluated by rating through TSV three times a day for two months (Adekunle & Nikolopoulou 2016). Some research has employed PMV as a long-term thermal comfort scale (Carlucci & Pagliano 2012; Silva, Ghisi & Lamberts 2016). The long-term thermal comfort numerical scale does not appear to have been applied in any previous study.

2.2.2 Similarities between thermal and pain perception scales

There are many similarities between long-term thermal comfort perception and long-term pain perception (Schweiker et al. 2016). Both have two independent parts. The first is the sensation that is constant and measurable; the sensation detects external or internal stimulation (Mishra, Loomans & Hensen 2016; Stanley 2012). The thermal and pain sensitivities of individuals are related to their cortical thickness (Erpelding, Moayedi & Davis 2012). The perception also changes depending on the stimuli, such as pleasure or comfort; the perception is about understanding or describing the stimulation (Mishra, Loomans & Hensen 2016; Stanley 2012). The sensation is processed simultaneously in different parts of the brain to produce the perception (Grabenhorst & Rolls 2009; Rolls, Grabenhorst & Parris 2008).

Both temperature and pain are felt through the skin and share common physiology (Krantz 2012). Both have receptive fields that cover large areas of the skin with sensory receptors

connected to free nerve endings (Krantz 2012). Both receptors are categorized as somatic sensory nerves in the Peripheral Nervous System (PNS), which is outside the brain and spinal cord (Marieb & Hoehn 2015) associated with conscious perceptions (Canavero & Vincenzo 2013; Ebner & Kaas 2015; Waldman 2009). Two groups of somatic sensory nerves, thermoreceptors and nociceptors conduct the impulses of temperature and pain, respectively, from the receptors to the Central Nervous System (CNS) (Cuevas 2015; Hees & Gybels 1981; Marieb & Hoehn 2015; Ochoa & Torebjork 1989; Waldman 2009). Both types of impulses are transmitted to the tissue outside of the brain (Apkarian et al. 2005; Ebner & Kaas 2015; Karl H 2011) by lateral parts of the spinothalamic tract ascending pathway of the spinal cord (KENHUB 2018; Krantz 2012; Rea 2015). Temperature and pain are processed for perception in different columns of the somatosensory cortex (Krantz 2012; Oi et al. 2017). The final output is a perception of the senses. Due to the similarities of thermal perception and pain perception in terms of their receiving, transmitting portals and processing, it is rational to consider the currently accepted use of the long-term pain reporting method for characterising long-term thermal comfort perception.

A few methods have been used to report or evaluate the intensity and average pain perception; however, there is no single agreed method for evaluating pain (Turk & Melzack 2014). The four commonly used methods are the numerical rating scale (NRS), visual analogue scale (VAS), verbal rating scale (VRS), and McGill pain questionnaire with the NRS, VAS, and VRS being used to assess pain intensity (Jensen, PM et al. 1989). The NRS has 11 points from no pain (0) to the highest pain (10) (Jensen, MP, Karoly & Braver 1986). The NRS method is retrospective, easy to understand, quick, and practical for verbal assessment, specifically for chronic pains (Jensen, PM et al. 1989; Williamson, A & Hoggart 2005). Compared to the other scales, the NRS has been reported as the only one that maintained its mean values during a period while no treatment was initiated (Conti 2001) and is a suggested scale by medical research (Fanger 1970). The drawback of the NRS methods is that it is challenging to use after an operative procedure (Jensen, PM et al. 1989). The VAS method uses a 100 mm long ribbon labelled ‘no pain’ and ‘worst pain possible’ at the ends; another version of this ribbon has a numerical scale of 0–100 (Cardiff University 2014; Turk & Melzack 2014). Compared with other scales, the VAS method is more sensitive, harder to understand, more time consuming, involves more steps and therefore more prone to error (Cardiff University 2014; Turk & Melzack

2014). The VRS method uses a verbal list describing pain from 'no pain' to 'extremely intense pain'. The VRS can show the intensively of pain (Jensen Hjermstad et al. 2011; Jensen, MP, Karoly & Braver 1986; Jensen, PM et al. 1989), and it assumes equal intervals between the markers, although it is unlikely that respondents perceive these intervals as equal (Turk & Melzack 2014). The VRS method responses are neither reliable nor accurate as patients have to become familiar with the terms before choosing the appropriate rating for their pain (Cardiff University 2014), whilst they have a cognitive understanding of numbers (Trujillo Valencia 2007). For all the mentioned methods, the level of pain at the time of responding can influence the average rating of the pain.

Given the advantages and convenience of NRS, a modified version of this method is proposed as a convenient numerical scale for evaluating long-term thermal comfort in this research. Zero was taken out of the NRS scale as occupants who are exposed to long-term outside weather conditions are afforded some measure of thermal comfort inside any building. Thus, zero is being assumed as a baseline reflecting no thermal comfort during uncomfortable weather conditions outside a building. Accordingly, the proposed scale has 10 points from one to 10, indicating minimum to maximum indoor thermal comfort perception, respectively.

2.3 Long-term thermal discomfort limits

The thermal discomfort limit is generally defined for three groups of AC, MM and MM/NV modes in the standards. The methods for identifying or predicting the thermal discomfort limits are listed in Table 2.5 for these modes. Long term thermal discomfort limit standards aim to define the maximum period that a person can tolerate thermal discomfort.

2.3.1 Static approach thresholds

Some research and standards consider 29 °C as a safe upper thermal threshold for both infants and elderly occupants. There is a three-fold increased risk of sudden infant death syndrome (SIDS) on days that indoor temperature is equal to or higher than 29 °C compared to 20°C days during the summer (Jhun et al. 2017). As a result, the maximum acceptable temperature to assess overheating should be less than 29 °C. The maximum setpoint for a thermostat to maintain the temperature for a dwelling with forced-air movement is 29 °C (American Public Health Association 2014). Also, Fanger had

considered 29 °C for the upper thermal comfort threshold (Fanger 1970). 28 °C was the highest temperature suggested for living rooms (CIBSE 2006), at which occupants voted 'Neutral' for NV mode In Adelaide (Saman et al. 2013). In the Netherland, 26 °C is the highest thermal comfort threshold in 'Mechanically conditioned buildings unlinked to the outdoor temperature' for 80% satisfied people (ISSO 2014). 26 °C was the maximum acceptable temperature as a thermal discomfort indicator for cooling bedrooms and living rooms in CIBSE TM 59 and CIBSE Guide A (CIBSE 2006, 2015; Nicol 2013; NSAI 2007) and all buildings in EN 15251 (DIN 2012). In offices located in South Korea, if the indoor temperature was 26 °C or less, the percentage of occupant acceptance of the indoor temperature was more than 89% and this percentage decreased as the indoor temperature rose above 26 °C (Yun, Lee & Steemers 2016). The recommended nursery temperature for infants' thermal comfort should be kept at 22-26 °C (Kliegman et al. 2015). The maximum recommended setpoint temperature for babies' rooms by the Environmental Health of Government of New South Wales is 26 °C (NSW Government 2015). The sleep quality may be somewhat compromised at 24–26 °C, but not more than 26 °C is recommended (CIBSE 2015). In London dwellings, the indoor temperature over 25 ºC increases mortality (DCLG 2006) and stroke, while temperature below 24 ºC provides minimal risk to sedentary people's health (WHO 1987).

There are problems using a fixed temperature or period as the national or international threshold (Nicol 2013). Local thresholds are more realistic as they are based on acclimatization. EN 15251 emphasizes using its generic criteria for acceptable deviation of indoor environmental factors only if no national or local criteria for deviation are available (NSAI 2007). Besides, the static approach cannot reasonably account for climate change in assessing the thermal comfort implications of NV mode buildings due to the adaptation of people to the higher ambient temperatures (Lomas & Giridharan 2012), which has already happened (Daokun et al. 2019).

2.3.2 Dynamic approach

The thermal discomfort for AC mode can be defined by a number of methods listed in Table 2.6 and could be grouped as below:

a) specific value for PMV or PPD (CIBSE 2015)
b) weighted exceedance hours (WEH) (ASHRAE 2017; ISO 2005a; NSAI 2007)
c) the percentage of occupied hours (ASHRAE 2016; DIN 2012).

The WEH evaluates the extent of exceedance time beyond a baseline of occupied hours. For the AC mode, the WEH is a function of PMV or PPD and the related standard has no threshold for it (ASHRAE 2017; ISO 2005a; NSAI 2007). Thermal discomfort is defined by EN 15251 (DIN 2012) as the percentage of occupied hours when the temperature is 2 °C above the upper threshold, which is more specific than that provided by ASHRAE 55 (ASHRAE 2016). ASHRAE 55 does not have any limit for the highest temperature during the thermal discomfort period (ASHRAE 2016, 2017) (Table 2.5). Due to the 1% exceedance probability, the selected AC is oversized while it can meet lower loads (ASHRAE 2016). The ISO 7730 results in less energy use for the AC mode than 'EN 15251' or ASHRAE 55 models, as it relies more on acclimatisation (Attia & Carlucci 2015).

The thermal discomfort for MM is defined by WEH that is a function of operative temperature, the upper temperature limit and optimal temperature (ISO 2005a) but has no prescribed limit (Table 2.5). For MM/NV modes, WEH (CIBSE 2015) or the percentage of occupied hours (NSAI 2007) define thermal discomfort. No limit is prescribed for WEH. The percentage of occupied hours shows the time limit for discomfort, but there is still a need for introducing a limit for maximum temperature.

The characterization of long-term thermal discomfort needs insight into how the human body might acclimatize to warmer temperatures (Lomas & Giridharan 2012) (Daokun et al. 2019) as people in offices and dwellings have been reported to be thermally comfortable with a 2 °C higher set point for AC (Kwong, Adam & Sahari 2014).

Studies show the WEH by "W_e" in formulas (Nicol 2013). The same method is followed in this research.

Table 2.6 Available methods of identifying (I) and predicting (P) thermal discomfort

	Standard/ Guide	Mode	Variable	Ref.
Identification	EN1 5251 Iso 7730	AC	WEH= $\sum (H_d (\frac{PPD\ of\ acctual\ PMV}{PPD\ of\ PMV\ limit}))$ $H_{d\ =}$=Hours of discomfort	(ISO 2005a; NSAI 2007)
	EN 15251	AC	1% of occupied hours 2 °C outside the limit	(DIN 2012)
	CIBSE TM 52, CIBSE Guide A	AC	PMV available: PMV≤0.5 (PPD=10%)	(CIBSE 2015)
			PMV not available: 26 °C with 0.5≤clo≤1.2 and 0.9≤met≤1.5	(Nicol 2013) (CIBSE 2015)
	ASHRAE 55, Users' manual	AC	1% of occupied hours.	(ASHRAE 2016)
	ASHRAE55	AC	WEH= $\sum (H_d (\|PMV\| - 0.5))$ $H_{d\ =}$=Hours of discomfort	(ASHRAE 2017)
	ISO 7730	MM	WEH= $\sum (H_d (1+ \frac{\|Toperative - Tupper\ limit\|}{\|Toptimal - Tupper\ limit\|}))$ $T_{optimal}$ is on Annex A of ISO 7730	(ISO 2005a)
	CIBSE Guide A	MM	Living area: 28 °C (1% of occupied hours) Bedrooms: 26 °C (1% of occupied hours)	(CIBSE 2006)
	EN 15251	MM/ NV	3-5% of occupied hours outside the limit: Minute/ day; Hours/ week; Hours/ month; Hours/ year Working hours: 15-24; 1-2.6; 5-9; 61-108 Total hours: 43-72; 5-8.4; 22-36; 259-438 The maximum temperature above the criteria can be 108 hours during a year if it is not more than 24 minutes during a day and 2 hours during a week.	(NSAI 2007)
	EN 15251	MM/ NV	1.2<met<1.5 clo=0.5 26 °C	(DIN 2012)
	ASHRAE55	MM/ NV	WEH= $\sum (H >_{upper} (T_{operative} - T_{upper\ limit}) + H <_{lower} (T_{lower\ limit} - T_{operative}))$	(ASHRAE 2017)
Prediction	CIBSE Guide A	AC	Indoor air temperature should not exceed the tabulated values in EN 15251 (23-26° for cooling bedroom and living room in category II with clo~0.5) for more than 3% of occupied hours. An operative temperature 2 °C away from the optimum corresponds to about 0.6 units of PMV or 12% of PPD.	(CIBSE 2015)

2.4 Overheating limits

There are many guides and papers that outline the factors which impact overheating risk assessment such as 1) regional climate, urban or rural, neighbourhood factors; 2) building characteristics, internal design; 3) occupants behaviour (Pannell 2015). However, there are only a few standards which provide a specific limit for overheating inside dwellings.

"Overheating is the existing heat, as degree hour unit, above the thermal comfort upper threshold in a building during a given span of time" (Sharifi, Saman & Alemu 2019). Another definition of overheating is *"successive and continuous indoor heat events that*

occur daily over at least a prescribed number of hours during daytime and trigger physiological responses of human subjects" (Laouadi, Bartko & Lacasse 2020).

One way to define overheating is to identify a particular temperature above which a given proportion of people in a building, say 20%, vote +2 (Warm) or +3 (Hot) on the ASHRAE scale (Nicol 2013). From 2006 to 2013, a few static limits for overheating have been introduced by the following organizations CIBSE Guide A, Department for Education and Skills School of UK; and Health Technical Memorandum of UK. From 2013 to 2020 dynamic methods of overheating have been suggested by CIBSE TM 52, CIBSE TM 59, CSIRO, National Research Council Canada and other papers (Sharifi, Saman & Alemu 2019). It is found that the static method shows a higher occurrence of overheating than the dynamic method (Gupta & Gregg 2020).

The suggested limits for hospitals (Department of Health 2007) and other types of buildings, including dwellings, are summarized in Table 2.7 (Chen & Ren 2019; CIBSE 2006, 2017; Laouadi, Bartko & Lacasse 2020; Nicol 2013; Skills 2006). The limit of overheating provided through the Health Technical Memorandum for hospitals (Department of Health 2007) has not changed and has been employed in research (Fifield et al. 2018; Lomas & Giridharan 2012), but the overheating limit for other types of buildings has been modified many times. Table 2.7 lists three versions of overheating criteria published by CIBSE, the criteria suggested by the Department for Education and Skills School in the UK, two criteria suggested through papers (Chen 2019; Sharifi, Saman & Alemu 2019) and the criteria proposed by the National Research Council of Canada. The study of the National Research Council of Canada has offered a range of limits for WEH. In this method, temperatures are based on SET. Also, the upper thermal comfort thresholds are static temperatures that vary for average age adults, older people, with adaptation, without adaptation, waking hours and sleeping hours (Laouadi, Bartko & Lacasse 2020). These static temperatures are the maximum SET for given ages in which the body water loss was acceptable and more than that would be dangerous. The process of calculating WEH is the same as ASHRAE 55 2017, which is listed in Table 2.4 (Laouadi, Bartko & Lacasse 2020). The approach of this research is also suggested in a publication that suggests the current energy load should be substituted by comfort criteria as a building performance indicator (Daniel, Williamson & Soebarto 2017).

Overheating is a dynamic phenomenon and requires a dynamic approach to assess (CIBSE 2018), as in a given climate, an overheating event in autumn or winter could be an acceptable condition in summer. Thus, the more frequently overheating is measured, the better. However, there should be a balance between the measurements period and the necessary accuracy for assessing overheating. The current shortest time for assessing overheating in the standards is one day suggested by CIBSE TM 52 (Table 2.7) (CIBSE 2015). There is an extensive list of overheating limits from 2006 to 2020 in Table 2.7.

Criterion 2 of CIBSE TM 52 does not cover excess temperatures less than 1 °C; while the weighted exceedance of temperatures less than 1 °C for 24 hours could result in more than 6. For example, if the temperature exceeds 0.5 °C for 16 hours, the weighted exceedance will be 0.5×16, which equals 8 (Table 2.7). In addition, ignoring the temperature of less than 1 °C lets the thermal comfort upper threshold be shifted up by close to 1 °C. Apparently, meeting Criterion 3 is easy as a simulation of 52 units showed that dwellings met Criterion 3, 2 and 1 in EN 15251 Categories II by 100%, 17.3% and 21.2%, respectively, whilst just 13.5 % met the Passivehus criteria (Tabatabaei Sameni et al. 2015). The same study suggests that although the CIBSE TM 52 limits can help to identify the overheated spaces, it is relatively weak in determining the frequency, intensity and severity of overheating. The CSIRO suggests limits for overheating in three categories by defining the frequency of occurrence of overheating during sleeping time and non-sleeping time.

The criteria of CIBSE TM 59 and CSIRO are focused specifically on dwellings' NV mode (Table 2.7). The questionable criterion in these guides is the overheating of sleeping hours that is a percentage of a whole year, while overheating is expected to occur mostly in summer. The CIBSE TM 59 and CSIRO Category C are investigated in this research as their defaults (building type and mode) match the buildings targeted in this research.

The strong point of the criteria suggested by the National Research Council of Canada is being based on the physiological response. However, there are a few concerns about it. Overheating impacts many human systems of organizations and it is not clear that dehydration is the most important one. As one of the indices, the' Intensity' is the average of exceeded temperatures rather than the actual maximum temperature of overheating. As a result, the maximum exceeded temperature that is a crucial factor in health is ignored. Although this method is for NV mode and free-running buildings, the acceptable

maximum and minimum operative temperatures are fixed and do not follow the adaptive thermal comfort approach. Furthermore, a limit for overheating means adapting a temperature over the upper threshold of thermal comfort and considering this situation, a vulnerable person could be at high risk.

The criteria of overheating need to be modified for different climates as they are based on the adaptive thermal comfort upper threshold, which should be localized (Indraganti et al. 2014; Kim, J et al. 2016; Telia et al. 2017).

The available standards for long-term thermal discomfort addressed the necessity of an upper limit for thermal discomfort. It is possible to convert dynamic simulation of hourly resolutions to probable overheating (Banfill et al. 2013). The current overheating limits showed that at least three indices are needed to define the overheating limit: WEH, frequency of times that temperature exceeds the upper thermal comfort threshold and the maximum acceptable temperature for discomfort. The users' manual for standard ASHRAE 55 highlights that if attention were paid to the WEH mismatch, the buildings would be designed with a balanced exceedance equally on both the warm and cool sides of the comfort zone (ASHRAE 2016). Although finding the overheating upper limit needs an adaptive (dynamic) approach, there should be a maximum temperature limit to ensure invulnerable individuals' health and safety. Both CIBSE TM 59 and CSIRO Category C, match with the characters of this research. The appropriateness of their limits for this research is investigated in section 5.2.

Table 2.7 Overheating limits

Guide/Paper Building Type	Mode	Upper Thermal Comfort Threshold	Location	Criteria	Ref.
CIBSE Guide A Office, School, Dwelling	MM	Living area: 28 °C Bedrooms: 26 °C	UK	1% of occupied hours over comfort temperature	(CIBSE 2006)
Department for Education and Skills School	MM	28 °C		Maximum hours above 28 °C =120 during occupied hours from May to September Maximum temperature= 32 °C	(Skills 2006)
Health Technical Memorandum	MM	28 °C	UK	The number of yearly hours exceeded the threshold should be less than 50.	(2007)
CIBSE TM 52 All Types	MM	EN 15251 Category II by default, EN 15251 Category I for vulnerable	UK	**Criterion 1** (frequency of overheating): The number of hours exceeds 1 °C or more than the threshold defined in EN15251 should not be more than 3% of occupied hours during May to September. **Criterion 2** (severity of overheating): daily weighed exceedance is calculated by below formula and should be less than or equal to 6. WEH= $W_e = \Sigma h_e \times wf = (h_{e0} \times 0) + (h_{e1} \times 1) + (h_{e2} \times 2) + (h_{e3} \times 3)$ Where: wf (weighting factor)= 0 if $\Delta T \leq 0$, otherwise wf = ΔT h_{ey}= time in hour when $\Delta T = y$ The unit for W_e depending on the simulation/monitor interval can be, say, degree hours or degree half an hour **Criterion 3** (upper-temperature limit): The absolute maximum daily temperature of a room during occupied or monitored hours shall not exceed more than 4°C of category II of EN15251 upper limit.	(Nicol 2013)
CIBSE TM 59 Dwellings	NV	EN 15251 Category II by default, EN 15251 Category I for vulnerable	UK	**Non-sleeping hours:** The number of hours exceeds the 'adaptive thermal comfort threshold defined in EN15251+1' should not be more than 3% of occupied hours during May-Sep=67.5 hours **Sleeping hours (bedrooms only):** The number of annual hours from 10pm–7am exceed 26°C should not be more than 1% of annual hours between 10pm–7am= 32.4 hours	(CIBSE 2017)
CSIRO Dwellings	NV	EN 15251 Neutral Regression Line	Australia – Category A	**Non-sleeping hours (7.00-21.00):** The number of hours exceeds the 'adaptive thermal comfort threshold defined in EN15251+2.5' should not be more than 3% of occupied hours during Nov-Mar=67.5 hours **Sleeping hours (21.00-7.00 and bedrooms only):):** Static 26 °C	(Chen & Ren 2019)
			Australia – Category B	**Non-sleeping hours (7.00-21.00):** The number of hours exceeds the 'adaptive thermal comfort threshold defined in EN15251+3.5' should not be more than 3% of occupied hours during Nov-Mar=67.5 hours **Sleeping hours (21.00-7.00 and bedrooms only):** Static 26 °C	
			Australia – Category C	**Non-sleeping hours(7.00-21.00):** The number of hours exceeds the 'adaptive thermal comfort threshold defined in EN15251+4.5' should not be more than 3% of occupied hours during Nov-Mar=67.5 **Sleeping hours (21.00-7.00 and bedrooms only):** The number of annual hours from 10pm–7am exceed the 'adaptive thermal comfort threshold defined in EN15251+2.5' (but not less than 26°C) should not be more than 1% of annual hours between 10pm–7am= 32.4 hours	
Paper Dwellings	NV	Adaptive thermal comfort modified for Adelaide	Australia	**Integrity** ≤ 250 degree-hours, **Frequency**≤ 243 h, **Intensity**≤ 3.5 h The integrity, frequency and intensity are calculated based on adaptive thermal comfort for Adealaide as below: Indoor temperature = 0.27 T_{rm} + 19.2 Where: T_{rm} = Running mean outdoor temperature	(Sharifi, Saman & Alemu 2019)
National Research Council Canada Dwellings	NV Free Running		Canada	Severity index/ magnitude of overheating (SETH) for raverage adult= 230±42 degree-hrs Severity index/ magnitude of overheating (SETH) for healthy old people= 117±31 degree-hrs or 3.8±0.2 °C	(Laouadi, Bartko & Lacasse 2020)

2.5 Documented overheating events

Despite the improved energy-efficiency standards of refurbished or newly-built dwellings that have drastically reduced the demand for heating in recent years, the addition of more insulation, reducing air infiltration or other features have created new problems on top floors for a high percentage of multilevel houses. This phenomenon, overheating, is reported in dwellings during periods of hot weather in many countries, including Australia (Hatvani-Kovacs et al. 2016b; Willand, Ridley & Pears 2016), Canada (Sehizadeh & Ge 2015), Denmark (Larsen & Jensen 2011), Estonia (Maivel, Kurnitski & Kalamees 2014), New Zealand (Birchmore et al. 2017), the Netherlands (Hamdy et al. 2017), Portugal (Barbosa, Vicente & Santos 2015) Scotland (Nicol & Brian 2013), Sweden (Dodoo & Gustavsson 2016; Samuelsson & Lüddeckens 2009) and UK (Beizaee, Lomas & Firth 2013; Lomas & Kane 2013; Pathan et al. 2017; Vellei et al. 2016b). The methods and results of these studies are listed in table 2.8. The research methods employed were monitoring, surveys and simulations. The overheating reported in the various publications is not directly comparable, as the studies have not employed the same limit. Some studies used static limits (Dengel & Swainson 2012; Larsen & Jensen 2011; Nicol & Brian 2013; Samuelsson & Lüddeckens 2009; Sehizadeh & Ge 2015; Willand, Ridley & Pears 2016) and the rest used dynamic limits. Simulation results indicate that overheating happens even in heating-dominated countries like the Netherlands and Canada (Hamdy et al. 2017; Nicol & Brian 2013; Sehizadeh & Ge 2015). The differences in the percentages of overheated houses obtained from simulations can be attributed to differences in overheating indicators, software and case study specifications, weather scenarios, and the reference year used. Regardless of the differences in the results obtained, the significant point is that all these studies have identified overheating. In particular, these studies have found that overheating can happen in NV mode (Adekunle & Nikolopoulou 2016; Birchmore et al. 2017; Lomas & Kane 2013; Vellei et al. 2016b), AC mode (Gupta & Kapsali 2015) or mixed mode (Dodoo & Gustavsson 2016; Maivel, Kurnitski & Kalamees 2014; Pathan et al. 2017; Pyrgou et al. 2017; Symonds et al. 2017; Tabatabaei Sameni et al. 2015). In addition, Table 2.8 lists the assessment methods for identifying overheating in studies. This list assists in shaping this research method.

Table 2.8 Summary of overheating investigations in residential buildings

Country	Number of Dwellings Studied	Study Method	Assessment Scheme	Percentage Overheated	Ref.
Australia	107	Monitoring	25 °C as overheating threshold	20–63% of dwellings	(Willand, Ridley & Pears 2016)
	2	Simulation	Excess heat factor+ adaptive thermal comfort (ATC)	100% of dwellings	(Hatvani-Kovacs et al. 2016b)
Brazil	5	Monitoring	CIBSE TM59 EN15251 and ASHRAE 55	20% of dwellings	(Gamero-Salinas, Monge-Barrio & Sanchez-Ostiz 2020)
Canada	1	Simulation	26 °C as overheating threshold	10–31.4% of the year	(Sehizadeh & Ge 2015)
Cyprus	4	Simulation	28 °C as overheating threshold	50% of dwellings	(Pyrgou et al. 2017)
Denmark	1	Simulation	26 °C as overheating threshold	30% of the summer	(Larsen & Jensen 2011)
Estonia	100	Monitoring	EN 15251 Cat II and III	31.7% of dwellings	(Maivel, Kurnitski & Kalamees 2014)
Netherland	36864	Simulation	CIBSE Guide A, ISSO74, Class B	6–38% of dwellings	(Hamdy et al. 2017)
New Zealand	17	Monitoring	EN 15251 Cat I, II and III CIBSE TM52	37% of dwellings	(Birchmore et al. 2017)
Scotland	5	Monitoring Survey	25 °C as overheating threshold	80% of dwellings	(Nicol & Brian 2013)
Portugal	2	Simulation	EN 15251 Cat III	10–23% of study time	(Barbosa, Vicente & Santos 2015)
	1	Monitoring Simulation	EN 15251 Cat II	13-43% of summer	(Figueiredo, Kämpf & Vicente 2016)
Sweden	18	Survey	29 °C as overheating threshold	50% of dwellings	(Samuelsson & Lüddeckens 2009)
	3	Simulation	CIBSE Guide A, SNBHW	100% of dwellings	(Dodoo & Gustavsson 2016)
UK	269	Monitoring Survey	EN 15251 Cat II and III	100% of dwellings	(Lomas & Kane 2013)
	233	Monitoring Survey	CIBSE Guide A CIBSE TM52, ASHRAE 55	12–25% of dwellings	(Pathan et al. 2017)
	207	Monitoring	CIBSE Guide A, EN 15251	55% of dwellings	(Beizaee, Lomas & Firth 2013)
	55	Monitoring Survey	EN 15251 Cat I, II and III CIBSE TM52	11.6% of dwellings	(Vellei et al. 2016b)
	23	Monitoring	CIBSE Guide A, CIBSE TM52	72% of dwellings	(Tabatabaei Sameni et al. 2015)
	9	Monitoring Survey Simulation	EN 15251 Cat I, II and III CIBSE Guide A	67% of dwellings	(Adekunle & Nikolopoulou 2016)
	6	Monitoring	EN 15251, CIBSE Guide A, CIBSE TM52	100% of dwellings	(Gupta & Kapsali 2015)
	8	Monitoring Simulation	EN 15251, CIBSE Guide A	10% of dwellings 24–60% of occupied hours	(Mavrogianni, A et al. 2015)
	2	Simulation	EN 15251	50–100% probability for each dwelling	(Gupta & Gregg 2018)
	3	Simulation	EN 15251	90% probability for each dwelling	(Gupta & Gregg 2013)
	2	Monitoring Simulation	EN 15251, CIBSE TM52	100% of dwellings during heatwaves	(Ozarisoy & Elsharkwy 2019)
	4	Monitoring	CIBSE Guide A, CIBSE TM52	100% of dwellings during summer	(Gupta & Gregg 2020)

Overheating has been more recently reported in energy-efficient dwellings (Adekunle & Nikolopoulou 2016; Gupta & Kapsali 2015; Saman et al. 2013; Vellei et al. 2016a) (Birchmore et al. 2017; Gupta & Gregg 2020; Hamdy et al. 2017; Hatvani-Kovacs et al. 2016b; Hatvani-Kovacs et al. 2016a), old and refurbished homes (Lomas & Kane 2013; Pathan et al. 2017; Vellei et al. 2016b), as well as older ones without refurbishment (Barbosa, Vicente & Santos 2015; Beizaee, Lomas & Firth 2013). However, the new or refurbished dwellings in various British cities that comply with tighter energy efficiency regulations appear to be at a higher risk of overheating (Beizaee, Lomas & Firth 2013; Hamdy et al. 2017). This includes new apartments which have been reported to be approximately 1 ºC warmer than older ones (Maivel, Kurnitski & Kalamees 2014). For the cases listed in Table 2.8, overheating was more acute on the top-floor (roof-exposed rooms) (Adekunle & Nikolopoulou 2016; Beizaee, Lomas & Firth 2013; Birchmore et al. 2017; Hamdy et al. 2017; Pathan et al. 2017; Symonds et al. 2017; Vellei et al. 2016b). A survey and monitoring study conducted in India found that the top floors of apartment buildings needed to use fans or AC, while the lower floors of the same building could use adaptive cooling methods (Indraganti 2011). In a survey carried out in Australia, 23 out of 25 households (92%) reported that the upstairs areas were uncomfortable during periods of high summer temperatures, and some of the residents had to sleep on the ground floor on summer nights to maintain a tolerable thermal condition (Berry et al. 2014). Bedrooms are known to be at high risk of overheating (Hatvani-Kovacs et al. 2016a; Lomas & Kane 2013; Pathan et al. 2017; Saman et al. 2013). In Sydney, monitoring has shown that bedrooms were 2 °C warmer than living/dining rooms, on average (Saman et al. 2013). In general, no thermal equilibrium exists between bedrooms and living or dining rooms in single and multilevel homes (Saman et al. 2013).

A review of global and Australian case studies has found that energy-efficient dwellings are not necessarily thermally comfortable during extreme weather conditions (Hatvani-Kovacs et al. 2016b). Another study provided evidence of energy-efficient dwellings with overheated top floors and differences in temperature between the top floor and other floors during summer (Monge-Barrio & Sánchez-Ostiz Gutiérrez 2018).

Climate change is adding to the risk of overheating in dwellings (Psomas et al. 2016), and consequently, cooling demand is increasing globally. The predicted percentage of increased cooling demand varies by country from 25% by 2060 in Germany to 460% by 2100 in Sweden (Dodoo & Gustavsson 2016; Karimpour et al. 2015; Nik & Kalagasidis

2013; Olonscheck, Holsten & Kropp 2011; Wang, H & Chen 2014; Wang, X, Chen & Ren 2010; Xu, P et al. 2009; Zhou, Eom & Clarke 2013; Zuo et al. 2015). By 2100, Dutch dwellings' average summer indoor air temperatures might increase by 1 ºC for the most resilient to 7 ºC for the worst building variants, respectively (Hamdy et al. 2017). It is anticipated that by 2030, a typical house in Adelaide will need an 18% increase in cooling system capacity and a 32% increase in electricity usage for cooling (NSAI 2007). As a result of climate change, it is predicted that bedroom temperatures in London's cavity-wall houses will increase from 25 to 30 ºC by 2080 (Patidar et al. 2014). The future risk of overheating in dwellings currently under construction might be relatively high for two reasons: first, asbuilt performances do not often match the modelling predictions (Gupta & Kapsali 2015), and second, houses currently under construction adhering to the compulsory energy rating standards will most likely still be in use by 2050 and beyond (McLeod, Hopfe & Kwan 2013; Saman et al. 2013).

2.6 Methods of achieving thermal comfort

This part categorizes the methods of achieving thermal comfort using passive design, active systems, hybrid design and behavioural adaptation. The focus is on passive design measures as one of the objectives of this thesis is searching for the lowest energy-consuming methods for eliminating or limiting overheating and passive design is the option that should be first considered to meet this objective. The addition of active elements should be considered as complementary to the passive systems to achieve a hybrid design that provides thermal comfort.

2.6.1 Passive design

The passive design takes advantage of building elements, materials and climate to maintain a comfortable temperature range in a building (Caitlin McGee 2013). This strategy does not use mechanical devices that consume energy. Design is an essential consideration in relation to climate change and heatwaves both in terms of mitigation and adaptation (Zuo et al. 2015). This research focuses on passive design measures to reduce or eliminate overheating as this method consumes no energy and is more close to the aim of energy-efficient buildings.

A wide range of solutions has been considered and used in new or traditional buildings to provide summer thermal comfort. These can be grouped in less solar radiation, low-e,

high thermal resistance, high thermal capacity, natural ventilation and thermal regulation. These groups are explained below in more details. Table 2.10 shows a list of the mentioned measures based on the building characters and the major mechanism that the measure is based on. Study shows that to reduce or eliminate overheating, a combination of measures had the best result (AECOM 2019; Eskander et al. 2017; Grussa et al. 2019; Jamil et al. 2016; Khalifa 2013; Lapisa et al. 2013; Mavrogianni, A. et al. 2014; Piselli et al. 2020; Porritt et al. 2012; Psomas et al. 2016; Sougkakis 2017; Yew et al. 2013; Yu, J et al. 2013). The research found that some passive design measures have been more successful in reducing overheating than others (Table 2.11). These results were achieved more through simulation and partly by monitoring.

2.6.1.1 Less solar radiation

Up to 78% of heat gain in a home is through glazing due to solar radiation (Caitlin McGee 2013; Lapisa et al. 2013). The exceeded maximum indoor temperature above maximum outdoor temperature could be due to the solar heat gain of the envelope and inside the building (Hamdy et al. 2017; Willand, Ridley & Pears 2016). Some of the design strategies to reduce direct summer radiation are shading (Friess & Rakhshan 2017; ISO 2005b), electrochromic windows that vary the transmittance of visible and infrared solar energy, double external glazing, optimization of the glazing area (Carletti, Sciurpi & Pierangioli 2014; Virk et al. 2015), limiting the glazing to floor ratio (Eskander et al. 2017; Friess & Rakhshan 2017), low solar heat gain coefficient (SHGC) (Carletti, Sciurpi & Pierangioli 2014; Friess & Rakhshan 2017) and optimized orientation to allow direct sunlight in winter and avoid it in summer (Rodriguez-Ubinas et al. 2014). Reduction of cloud cover in all regions is predicted, which will increase global direct radiation (Saman et al. 2013) and prove the need for sunlight protection inside and outside the buildings.

Shadings are essential for reducing overheating in dwellings and should be included in regulations that are recommended in climates with severe summers (Monge-Barrio & Sánchez-Ostiz Gutiérrez 2018). The most effective measure to reduce the level of overheating in the UK are external moveable or fixed shadings (Gupta & Gregg 2013) and these are more effective than internal ones for Copenhagen, London, Marseille, and Vienna (Psomas et al. 2016). Solar shading is the most effective measure that causes the minimum net primary energy use (Australia Productivity Commission 2013).

To prevent overheating, besides solar heat gain, low U-value and appropriate glazing-to-floor ratio, a sufficient daylight transmittance for given-oriented room is necessary (Monghasemi & Vadiee 2018). Permanent solar shading such as low-SHG-coated glazing is a cost-effective, user-friendly way to reduce overheating in direct-sun-oriented rooms for Denmark (Monghasemi & Vadiee 2018).

Light colours absorb less infrared radiation, so using light coloured roofs and walls is a method for reducing heat gain too, which is based on less solar-radiation (ISO 2019). For a double skin school roof in India, changing the external roof from grey to white caused a reduction in monitored indoor air temperature by an average and peak of 2.1 °C and 5 °C, respectively (Garg et al. 2016). The light colour should not be categorised in the low emissivity group, as light colour is based on less absorbance rather than emissivity.

2.6.1.2 Low emissivity

Reducing the solar heat gain is more effective than reducing conduction through external walls (Sanga, Panb Wei & Kumaraswamyb 2014). The poorly insulated buildings in hot climates can have improved thermal conditions if the envelope materials have solar reflectance values up to 0.8 (Costanzo 2016). Increasing the total solar reflectance by adding reflective foils or anti-glare coatings provide other options for reducing the solar radiation gain (Saman et al. 2013).

Roofs are an effective strategy for reducing overheating (Costanzo 2016). Monitoring of a house in Townsville, Australia showed that an acrylic coating for the roof that increased the solar reflectance and infrared emittance could reduce the roofspace temperature by 2 to 10 °C (Miller, Crompton & Bell 2015). In Sicily, Italy, monitoring showed that the roof temperature was maximum 48 °C higher than the air temperature and low-e coating reduced it to 26 °C. The same building simulation showed a 2.3 °C decrease for indoor temperature (Romeo & Zini 2013).

2.6.1.3 High thermal resistance

The high U-value envelope reduces both heating and cooling loads in a building. Higher insulation levels tend to be advantageous during the summer cooling period (Costa-Carrapiço, Raslan & González 2020). A wide range of insulation could be applied in buildings such as traditional cellulose, nano-vacuum insulation (Romeo & Zini 2013) and cork (Sierra-Pérez et al. 2016). The use of additional high U-value materials reduces overheating up to 85% in simulations (Sougkakis 2017). The same simulations found that

the timber frame and modern masonry walls had very similar performance, with reduced overheating for modern masonry up to 12% in the UK.

The location of insulation is critical to achieving the highest efficiency of the insulation in various archetypes. For instance, although the roof surface generally drives the heat flow into the building, the impact of heat transfer through roofs was slight in impacting the energy performance of the whole building in simulated high-rise dwellings in China (Yu, J et al. 2013). The evidence suggests the need for appropriate insulation according to the climate (Schiavoni et al. 2016).

Architectural design strategies can increase the thermal resistance, such as a double skin façade (Environmental Audit Committee 2018; Ghaffarianhoseini et al. 2016; Rodriguez-Ubinas et al. 2014), reduced area of the envelope (thermal transmission area), green roof (Shafique, Kim & Rafiq 2018), green walls, unconditioned internal zones as thermal buffer/filter (Palmer et al. 2012; Palmer et al. 2013b; Saman et al. 2013) and cool retreat (Palmer et al. 2013a; Saman et al. 2013; Saman et al. 2014; Zuo et al. 2015).

Green roofs provided higher energy savings than highly insulated standard roofs as shown by simulation for Catania, Italy (Gagliano et al. 2015). The same simulation showed an extensive and moderately insulated green roof is the most effective technique to reduce significantly Mediterranean buildings' cooling energy needs. Higher level insulation is crucial in the ceilings, particularly in high star rated energy-efficient dwellings, in saving energy (Karimpour et al. 2015). The level and location of insulation influence significantly overheating. For instance, omitting floors' thermal insulation at the ground level of homes decreases the indoor air temperature because the ground behaves as a heat sink (Psomas et al. 2016). The value for decrement for indoor temperature due to floor insulation omitting is approximately 4 °C during heatwaves, but the average floor surface temperature increased just 0.5 °C (Staszczuk, Wojciech & Kuczynski 2017).

2.6.1.4 High thermal capacity

Thermal energy can be stored in three ways based on the underlying physical principles of the storage technique: sensible and/or latent storage and thermochemical energy storage. Phase change materials (PCM)s are widely used for thermal energy storage as they involve the use of latent heat in the transition from liquid to solid phases (Akeiber et al. 2016; Banfill et al. 2013; Osterman et al. 2012; Waqas & Ud Din 2013).

PCMs have been demonstrated to be more responsive than conventional plasterboard in terms of reducing overheating (Osterman et al. 2012; Sougkakis 2017). The incorporation of a phase change layer in the walls/roof decreases the variations of indoor air temperature as shown by both experimental and simulation studies (Osterman et al. 2012; Sougkakis 2017); shifts the peak energy use for heating and cooling of buildings by several hours and decreases energy use for maintaining comfortable temperature levels in buildings (Akeiber et al. 2016; Banfill et al. 2013; Osterman et al. 2012). The basic mechanism of phase change materials makes them highly applicable for reducing overheating inside buildings (Alizadeh & Sadrameli 2016). The best location of PCMs is inside the west and equator-facing external walls on the indoor side (Lee et al. 2015; Saman, Bruno & Halawa 2005).

PCMs could be used in a wide range of buildings applications such as construction elements (Banfill et al. 2013), floor, ceiling and wall (Akeiber et al. 2016; Alizadeh & Sadrameli 2016; Osterman et al. 2012; Saman, Bruno & Halawa 2005). An experimental study showed that using PCMs in ceilings reduces the day temperature and thermal discomfort hours by 1.1 °C and 34%, respectively (Jamil et al. 2016). Adding experimentally a condensed PCM layer to a traditional cellulose roof insulation resulted in a 30% reduction of the heat flow rates during the peak-hour time (Kośny et al. 2014). Simulating showed that the inside layer of PMC added to the wallboard was 2 °C cooler than that without the PMC (Shilei, Neng & Guohui 2006). The maximum and average indoor air temperatures in a PCM room were 1.9 °C and 0.6 °C lower than in an experimental reference room in summer 2017 (Zhu et al. 2019). An experimental study found that PCM blinds can minimize the façade temperature (Li, Y, Darkwa & Kokogiannakis 2017). The PCM reduced the indoor air and wall temperatures by 1.4 °C and 2.7 °C, respectively, in another experimental-numerical study (Barilelo Nghana 2016).

Adding thermal mass absorbs the heat the same way as PCMs, but with much lower storage capacity. Simulations have revealed that heavier thermal mass results in more energy savings for summer and winter in Phoenix, Fresno and Denver, in the USA (Yoon et al. 2020). This negative impact of thermal mass is most tangible at night during prolonged heatwaves and coincides with increased adverse health problems (Hatvani-Kovacs et al. 2016b; Hatvani-Kovacs et al. 2016a). Rejecting heat from PCMs during the night is not tangible.

The following points should be considered before employing PCMs for a building. Firstly, if the nocturnal cooling temperature in the summertime is not low enough, the PCM will not reduce the building overheating during the daytime (Khalifa 2013; Osterman et al. 2012). Secondly, if the building is well insulated, the heat transfer into the building would have a minimal effect (Osterman et al. 2012). Thirdly, condensation on the PCMs containers is an effect if the building is not well designed in terms of ventilation and humidity.

High thermal capacity, thermal mass/PCMs, reduces the intensity and frequency of overheating, as they postpone the heat transfer. Masonry construction reduced overheating up to 12% (Sougkakis 2017). The PMCs can prevent overheating for buildings in Wuhan, China (Zhu et al. 2019) or act as latent heat and widely reduce overheating, particularly with the UK lightweight construction (Khalifa 2013).

2.6.1.5 Natural ventilation

Natural air movement is an effective means to improve thermal comfort in buildings (Monge-Barrio & Sánchez-Ostiz Gutiérrez 2018). Newly developed software (Grasshopper plug-in, Ladybug and honeybee) (Grasshopper 2021) imported weather data to the building simulating software, EnergyPlus, for simulating a house in California and Arizona (Yoon et al. 2020). This simulation showed that by having a good understanding of design parameters and the climate potential of natural ventilation, the natural ventilation cooling effect is significant and more airflow brings higher building performance. An optimum combination of ventilation and insulation leads to a decrease in the internal temperature (Barbosa, Vicente & Santos 2015). A ventilation rate of 0.5 air change per hour (ACH) is a minimum standard in most European countries and less than that causes impaired air quality (Psomas et al. 2016). In Sydney, Brisbane and Adelaide, the residents of double-level, and split-level apartment units preferred to adapt their residential indoor air high temperature by ventilation (Saman et al. 2013). The window area, orientation and operation, as well as the internal walls and partitions, significantly affect the natural ventilation of buildings (Nguyen & Reiter 2014; Rodriguez-Ubinas et al. 2014; Sorgato, Melo & Lamberts 2016). The location and orientation of windows have a significant effect on natural ventilation as monitored data in Australia showed that the cross ventilation and single-side ventilation could provide thermal comfort for 70% and 1% of the time, respectively (Omrani et al. 2017).

Attics can also be ventilated by various methods such as soffit vents, ridge vents, gable vents, goose-neck vents, and roof turbines (Al-Obaidi, Ismail & Abdul Rahman 2014; Yu, O-Y & Moore 2015). The turbine ventilators are of three types: straight vane turbine with curved sides, a straight vane turbine, curved vane turbine (Al-Obaidi, Ismail & Abdul Rahman 2014). An experimental study has shown that this method reduces the attic temperature by 2.9 °C (Basrawi, Ibrahim & Rzaki 2019).

However, natural ventilation, particularly natural cross-ventilation, does not happen easily and may not be effective with increasing outside temperatures and the urban heat island effect (UHI). The causes can be the deep-urban location, single-sided properties and closed windows due to space limits, noise, pollution or security concerns (Dengel & Swainson 2012). As a result, natural ventilation is much easier to achieve in rural and suburban locations than in urban and deep-urban locations (Dengel & Swainson 2012). The single-sided properties where cross ventilation is not possible are at risk of overheating more than other buildings (Dengel & Swainson 2012).

Some of the architectural design strategies used to increase the natural ventilation for cooling are wind catchers (Haghighi, Pakdel & Jafari 2016; Jomehzadeh et al. 2017), solar chimneys (Monghasemi & Vadiee 2018), courtyard, cross ventilation, buoyancy ventilation (Guillén-Lambea, Rodríguez-Soria & Marín 2016; Yang, X et al. 2015) and layout of windows and internal walls and doors (Chu et al. 2015). Some strategies are also employed to reduce outside air infiltration and prevent high ACH, such as door stops and window air leakage, particularly during the heating season (Palmer et al. 2012)(Saman et al. 2013).

The NV in buildings may decrease the peak indoor temperature of the next day up to 3 °C in Europe (Santtamouris & Kolokotsa 2016). The cooling effect of nocturnal ventilation is greater than that of other ventilation strategies (Grussa et al. 2019). The simulation showed that the nocturnal ventilation kept the indoor temperature 21–23 °C during summer nights in Madrid (Grussa et al. 2019). Applying optimized nocturnal ventilation caused an average reduction of 1.4 ◦C for the indoor air temperature (Fokaides et al. 2016). For effective nocturnal ventilation, most of the following conditions should be satisfied (Tamura & Yoshie 2016):

• Day temperature minus night temperature >10 °C

• Internal heat gains <30 W/m^2

• High thermal mass for construction

• High ventilation rates at night.

2.6.1.6 Nocturnal ventilation

The cold night air can cool down the thermal mass and improve indoor thermal comfort during the daytime without mechanical cooling. Nocturnal ventilation is one of the effective strategies to cool the building during the night for a hot and dry climate (Soong & Costantinou 2014). The effectiveness of nocturnal ventilation depends on the prevailing climate, relative humidity and the wind, microclimate, location, outdoor temperature, and the building characteristics (Santtamouris & Kolokotsa 2016). Infield studies showed that the nocturnal ventilation could reduce the degree hours by up to 60% in India (Pellegrino, Simonetti & Chiesa 2016) and decrease the cooling load by up to 40 kWh/m^2 per year in Mediterranean residential buildings (Santtamouris & Kolokotsa 2016). Field experiments found that nocturnal ventilation provides better thermal comfort and operative temperature for Malaysian terraced houses than other ventilation strategies (Kubota, Chyee & Ahmad 2009).

A significant risk factor is the night-time temperature. The ability to cool dwellings down overnight is limited in urban locations and property types (Dengel & Swainson 2012) and can only be effective in locations of high diurnal temperature differences and the period of the heat event. The difference between day and night-time temperatures is around 2 °C in London but can reach up to 9 °C (Mavrogianni et al. 2015), which affects cooling the thermal mass. The TMY of Adelaide shows that nights are cooler than days on average by 5.1, 4.6 and 6.2 °C in December, January and February (Table 2.9). However, as TM is based on typical means, the actual diurnal difference would be higher than this.

Table 2.9 Average of the night (9 pm by 7am) and day (7 am by 9 pm) temperatures

Month	Night (°C)	Day (°C)
Jan	19.8	24.4
Feb	20.2	26.4
Dec	17.7	22.8

2.6.1.7 Combination of measures

There is considerable practical evidence which suggests that overheating can be avoided by using a combination of passive measures. An experimental study indicated that incorporating light-colour-roof and opened-attic-inlet reduced the attic temperature by

13 °C (Yew et al. 2013). The following combined measures are based on simulations. The combination of shading and increased ventilation reduces the number of overheating hours in Sweden's light-frame buildings (Dodoo & Gustavsson 2016). The combination of nocturnal ventilation and closed shading during the day provide a significant increase in thermal comfort (Grussa et al. 2019). PCM shows the highest efficiency in reducing overheating when combined with nocturnal ventilation for Melbourne, Australia (Jamil et al. 2016) and all six climate zones in Italy (Piselli et al. 2020). With other passive technologies, this material could mitigate overheating in highly insulated dwellings in the UK (Sougkakis 2017). The conjunction of Micronal PCM (MPCM) with nocturnal ventilation reduces the overheating period by about 50% (Khalifa 2013). For High-rise residentials in China, the wall heat transfer coefficient and the window-to-wall ratio are the most sensitive factors for energy usage reduction (Yu, J et al. 2013). The combination of low-e roof, ventilation and high thermal capacity of the building can be adequate to cause a 99.8% drop in DH above the discomfort temperature in the Mediterranean buildings during summer (Lapisa et al. 2013). Shading and/or nocturnal ventilation could modify overheating significantly in the UK (Mavrogianni, A. et al. 2014). The conjunction of high insulation with other solar controls (Porritt et al. 2012), particularly low-e and low SHG glazing, contribute to year-long energy neutrality in the UK as well as cooling (Bilbao, Spain) and heating_dominated (Berlin, Germany) regions (Eskander et al. 2017). Omitting the insulation of the floor and decreasing the airtightness are the most effective measures for significant reduction of overheating in Austria, Denmark, France and the U.K. (Psomas et al. 2016). The risk mitigation packages suggest the following measures for the UK arranged on cost: internal blinds, low SHGC glazing, reduced glazing ratio in flats, fixed external shading, inward-opening window, additional openable windows and high thermal mass (AECOM 2019).

Table 2.10 Passive design methods to provide thermal comfort during summer

Major Mechanism		Outside	Envelope					Inside
			Roof	Wall	Window		Floor	
					Glazing	Frame		
Conduction	High thermal resistance		Insulation Green roof	Green wall Double skin façade Optimized envelope and thermal bridge	Optimize the area Glazing to floor ratio of glass Balanced U-value, Double external glaze	Insulation		Utilized unconditioned internal zones as thermal buffer/filter Insulated cool spaces Below/sub-grade as a summer room Walls and windows layout
	High thermal capacity		PCM	PCM		PCM		
Convection	Ventilate							Attic ventilation Courtyard Cross-natural ventilation, high-low-natural ventilation Earth/ground-air cooling The layout of internal walls and doors Nocturnal ventilation Solar chimney Windcatcher
	Airtight							Stop door and window air leakage
Radiation	Less SHG	Shading	Shape	Orientation	Glazing to floor ratio of glazing Orientation			
	Low-e		Solar coat	Solar coat	Solar coat	Solar coat		

Table 2.11 Measures to reduce overheating (A to C shows the most to the medium effect of measures in their allocated study)

Building Element	Outside		Envelope							Inside		Ref.	Country
	Shading/ Blind		Roof		Ceiling	Wall		Window		Rooms			
Major Mechanism	Radiation	Conduction	Conduction	Radiation	Conduction	Conduction	Radiation	Conduction+ Radiation	Radiation	Convection			
	Emissivity	Insulation, Thermal mass	Insulation, Thermal mass	Emissivity	Insulation, Thermal mass	Insulation, Thermal mass	Emissivity	Window to floor ratio	Emissivity SCGH	Day	Nigh		
			A		A					A		(Jamil et al. 2016)	Australia
				A						A	A	(Willand, Ridley & Pears 2016)	
					A							(Karimpour et al. 2015)	
		A	A			A						(Zhu et al. 2019)	China
			A					A				(Yu, J et al. 2013)	
							A	A				(Monghasemi & Vadiee 2018)	Denmark
				A								(Garg et al. 2016)	India
			A									(Gagliano et al. 2015)	Italy
	A										A	(Mavrogianni, A. et al. 2014)	
				A								(Romeo & Zini 2013)	
										A	A	(Yew et al. 2013)	Malaysia
	A									C	B	(Monge-Barrio & Sánchez-Ostiz Gutiérrez 2018)	Mediterranean
			A	A		A				A		(Lapisa et al. 2013)	
	A									A		(Hamdy et al. 2017)	Netherland
	A										A	(Grussa et al. 2019)	Spain
	A									A	A	(Dodoo & Gustavsson 2016)	Sweden
	A											(CIBSE 2017)	UK
								A	A	C	C	(Ministry of Housing Communities & Local Government 2013)	
										A	A	(Gupta & Kapsali 2015)	
	A											(Gupta & Gregg 2013)	
			A								A	(Khalifa 2013)	
									A			(Porritt et al. 2012)	
	B		A			A			A	B	A	(Eskander et al. 2017)	Germany, Spain
	B					A				B	A	(Psomas et al. 2016)	Germany, Austria, France, UK
			A		A	A						(Alizadeh & Sadrameli 2016)	Global

Nocturnal ventilation was suggested as being the most effective solution to eliminating overheating by half of the references, following by shading. The highly insulated roof and day ventilation were seen to be equally effective in the literature review. Australia's suggested measures were first, nocturnal ventilation with high ceiling insulation and, secondly, shading, high level of roof insulation with day ventilation. Therefore, nocturnal ventilation and shading are the first and second measures for Australia and other countries.

2.6.2 Active systems

Active systems rely on mechanical systems powered by fossil fuel or green energy sources such as air conditioners, fans (attic, ceiling, desk, personal) (Guillén-Lambea, Rodríguez-Soria & Marín 2016) and mechanical ventilation (Cao et al. 2014; Makhoul, Ghali & Ghaddar 2013; Pasut et al. 2014). The use of active systems is out of the scope of this research.

2.6.3 Hybrid design

The hybrid design is a combination of active and passive strategies. Some examples for hybrid cooling designs include active solar shading (Konstantoglou & Tsangrassoulis 2016), electrical/Solar-powered attic ventilation fans (SPAVFs) (Yu, O-Y & Moore 2015), ground-coupled heat exchanges (Soni, Pandey & Bartaria 2016), evaporative cooling (Cuce & Riffat 2016), forced ventilation (Al-Obaidi, Ismail & Abdul Rahman 2014; Alizadeh & Sadrameli 2016) and solar cooling (Drosou, Kosmopoulos & Papadopoulos 2016).

Achieving forced ventilation requires energy supply only for the fan operation. It can be applied to floors, ceilings and walls. There are technical limitations for free ventilation, such as climatic conditions, security requirements, and architectural restrictions. However, this system provides a significant economic benefit because of shifting the peak load time of electricity usage and reducing domestic electric energy use during peak load periods (Alizadeh & Sadrameli 2016).). It is possible to provide thermal comfort by free ventilation techniques if the prevailing mean outdoor temperature stays within 10-30 °C (Humphreys, Rijal & Nicol 2013). In Adelaide, ceiling fans are the most frequent hybrid strategy to achieve thermal comfort during summer (Saman et al. 2013). The maximum acceptable airspeed in the ASHRAE 55 is 1.2 m/s (ASHRAE 2017) and in CIBSE is

1.5 m/s (CIBSE 2015). The hybrid design is not the subject of this research and will not be investigated.

2.6.4 Behavioural adaptation

This strategy refers to the individuals' behaviour to provide thermal comfort for themselves. There are three categories of thermal adaptation: behavioural, physiological and psychological (de Dear & Brager 1998). The individual thermal adaptive behaviour is normally due to contextual conditions (e.g. cost implications, availability of products, energy supplier and price, infrastructure), attitudes (specific predisposition), habits and experiences (e.g. daily household routines, occupants heating patterns and lifestyle) (Kumar et al. 2016; Pothitou et al. 2016). Individuals adapt by personal adjustment (e.g. change clothes, drink cold water and reduce activity) and/or physical environment adjustment (e.g. control on the fan, AC and windows (Gupta & Kapsali 2015), live in cooler places (Saman et al. 2013) and change furniture layout. For example, a survey in Jaipur, India, found that adjusting clothing and window opening and relying on air movement were preferred for providing thermal comfort (Kumar et al. 2016). This behavioural adaptation is beyond the scope of this study.

The impact of occupancy and design appear to be as significant as location and climate on overheating. Thus, even identical buildings have performed very differently due to different occupancy patterns, control and behaviour (Morgan, C et al. 2017). Meeting the passive construction and occupancy control on those is a socio-technical matter that sometimes could be an issue (Gupta & Kapsali 2015). Occupants correct engagement in energy-efficient dwellings can mitigate overheating (Dengel & Swainson 2012). Occupants with an opportunity to regulate thermal conditions by opening and closing the windows could accept a higher temperature than those predicted by PMV (ISO 2005a). Regulating the thermal state can extend the thermal comfort range. Lowering acceptable thermal comfort upper threshold from 90% to 70% saves the cooling energy use by 40% for heavyweight and combination of constructions in Australia regions with hot summers for current and future climates (Ren & Chen 2018). The objectives of this research are not related to behavioural adaptation, so this part is not considered further.

2.7 Main reasons for overheating

There are a variety of reasons for overheating in buildings. In some cases, a dominant factor is noticeable, while other cases demonstrate a lack of consideration for a number of passive measures. Low R-Value insulation without appropriate ventilation has been shown to expose the building to overheating in summer (CIBSE 2018). Dwellings with high roof exposure and low R-Value roof were found to be overheated more in South America (Gamero-Salinas, Monge-Barrio & Sanchez-Ostiz 2020). The high external temperatures cause overheating in the United Arab Emirates (Haggag, Hassan & Elmasry 2014). In well-insulated and fully air-tight dwelling in the UK, the lack of sufficient ventilation through the living spaces and excessive heat gains through the composite cladding material have caused overheating (Ozarisoy & Elsharkwy 2019). Factors that increase the risk of overheating in London are identified as site context, urban heat island, orientation, building design, thermal mass, service design, restricted ventilation (Richards Partington Architects 2012). The orientation that admits late solar gain in windows is another reason for overheating in the UK (Gupta & Gregg 2012). Other research in 2016 found that the reasons for overheating in the UK comprise solar gain on the exterior surfaces, dark surfaces, penetrating glazing, skylights, internal heat gains, rooms in the roof space, inability to ventilate and single aspect units on top floors (Vellei et al. 2016a). A report showed that overheating in the UK dwellings happens particularly for houses with incapability of cross ventilation (Dengel & Swainson 2012; Vellei et al. 2016b). West oriented windows in London increased the level of overheating by almost 50% (Virk et al. 2015). The French building characteristics that mainly contributed to the risk factors of deaths during 2003 heatwaves were bedrooms under an uninsulated roof and the number of hours that bedrooms received sunlight (Vandentorren et al. 2006). Lack of shading and lack of natural ventilation has been specified as design factors that significantly impact overheating (Gupta & Gregg 2020). Some of the buildings that rely on natural ventilation predominately could experience overheating during the summer season (Oropeza-Perez & Østergaard 2014). Natural cross-ventilation might not happen due to environmental temperature increasing, heat waves, urban heat islands (UHI), location in urban and deep-urban, single-sided properties and closed windows according to obligation or selection. Internal heat gains, a high proportion of windows-to-floor area, occupancy schedule and dwelling's size are other known reasons.

2.8 Energy rating schemes and associated software for dwellings in Australia

A wide range of schemes are used globally to evaluate, model, assess, compare and rate, the energy usage of homes to provide the required thermal conditions. For example, Australia uses the Nationwide House Energy Rating Scheme (NatHERS), Building Sustainability Index (BASIX) and Deemed-to-Satisfy (DTS) provisions to rank and control energy efficiency (Australia 2012b, 2012a; BCA 2012; NatHERS 2015a). The United Kingdom follows the Energy Performance Certification (EPC) to meet the requirement of the European Energy Performance of Buildings Directive (DCLG 2006). The USA uses Leadership in Energy and Environmental Design (LEED) rating or Energy Star rating schemes (Green Building Council 2020). As this research is focusing on Australian dwellings, this section reviews the Australian accredited schemes.

2.8.1 NatHERS

The NatHERS scheme administrated by the Department of Industry, Science, Energy and Resources (NatHERS 2021) is a star rating (0–10) to display home typica energy demand. NatHERS models a thermal heating and cooling load based on house properties, climate zone TMY data, and assumed occupancy profiles (NatHERS 2021). NatHERS, accepted in all states except New South Wales, is used to demonstrate compliance with the mandatory energy efficiency requirement, which operates its regulatory framework, namely BASIX. Each star band indicates a maximum annual energy use per unit area (MJ/m^2) which differs in various climate zones and are separate for heating and cooling loads (Australian Government Department of the Environment and Energy 2019; Department of Planning Transport and Infrastructure 2020). For example, the heating and cooling loads for the conditioned areas in a 6-star rating home in Adelaide are 139 MJ/m^2 and 20 MJ/m^2 per year, respectively (Territories 2019). The higher star rating means less energy use and the 10-star dwellings assumed to require no mechanical heating/cooling.

This scheme has accredited three software tools for energy use assessment: AccuRate, BERS Pro and FirstRate5, all of which use the same engine which is Cheenath. The first minimum energy-efficiency standards for residential dwellings were incorporated into the BCA in 2003 and the provisions for 4-star rating were implemented (BCA 2012, 2016). New buildings, extensions, additions, alterations, and renovations must comply with DTS provisions in the same year. On 1 May 2006, these provisions were increased to require

a minimum 5-stars for all new houses and from 1 September 2010 the level changed to 6-star (BCA 2012). The DTS provisions for energy efficiency are contained in Part 3.12 of the BCA and permit compliance with either: a) The 6-star prescriptive requirements (fabric, glazing and shading, sealing and air movement); or b) Heating and cooling loads evaluation, which requires the building to demonstrate (class 1 buildings in BCA).

Despite the positive impact of the energy rating tools as they evaluate the energy requirements to achieve preset comfort temperatures, there is no direct emphasis on thermal comfort either in the star rating tools or in the BCA. NatHERS aims to evaluate and reduce energy use for the conditioned spaces, not to evaluate thermal comfort. The thermal comfort is not reflected in the Performance Requirements or DTS provisions (Verification Using a Reference Building (VURB) and energy rating). Making houses inherently comfortable is a by-product of the overall BCA energy efficiency, performance requirement/DTS (BCA 2016). However, none of them describes their acceptable range of thermal comfort. The Australian Standards address the ISO 7730 and ASHRAE 55 for thermal comfort conditions for the use of ventilation and air conditioning in buildings (Australia 2012b). The necessary data for calculating the cooling effect and air movement are not currently outputs of the released versions of the NatHERS' accredited software (Daniel, Williamson & Soebarto 2017).

2.8.1.1 AccuRate

AccuRate models measure and compare the energy efficiency of dwellings. This program has been developed by the CSIRO over many years and accredited by NatHERS is the benchmark software for housing rating in Australia. NatHERS can assess the energy rating of a house in 69 different climate zones in Australia (AFRC 2013; CSIRO 2016; Energy Inspection Pty Ltd 2016). It uses climate data for a typical year. This software's climate data consists of 27 inputs, 14 of which are significant for thermal performance simulation, such as dry and wet bulb temperature, Mean Radiant Temperature (MRT) and wind factors.

The relevant inputs are month number, day number, hour number, dry bulb (air) temperature (°C), moisture contents (tenths of g/k), atmospheric air pressure (kPa), wind (tenths of m/s), wind direction (0–16), cloud cover (0–8), global solar radiation (Wh/m^2), diffuse solar radiation (Wh/m^2), direct normal solar radiation (Wh/m^2), solar altitude (0–90) and solar azimuth (degree), building orientation, floors and ceilings areas, thickness,

insulations, ventilation, conditioning types; walls areas, layers materials; window areas, materials shading; zone and occupancy pattern (Dewsbury 2015; Kingspan Insulation Australia 2011; NatHERS 2015b, 2016). The outputs of AccuRate are hourly temperatures for every zone, hourly energy requirements for lighting, cooling and heating air/water for every zone, annual thermal performance loads MJ/m^2 and the energy rating of the house in decimal format.

The total annual Energy Load is adjusted using the equation below and be reported using the Star Band Criteria in which it falls.

EL = ((HL+CL)/CFA)*AAF (Equation 2.15)

Where:

EL = Total Energy Load (MJ/m^2 conditioned floor area.annum)

HL = Total heating load (MJ/.annum)

CL = Total cooling load (i.e. the sum of sensible and latent cooling loads) (MJ/annum)

CFA = Conditioned Floor Area (m^2)

AAF = Area Adjustment Factor

The AAF increases the EL for large CFA and reduces the EL for small CFA. The value of AAF is related to the total building surface area to floor area ratios in the given climate zone. Since heat transfer through the building fabric is proportional to the total building surface area, an AAF is required to ensure that smaller dwellings (with less building surface area, however, larger surface area to floor area ratio) are compared with larger houses fairly and therefore rated based on adjusted energy loads (NatHERS National Administrator 2012). Accurate has two modes: regulation (for energy rating) and non-regulation (for plain calculations). For regulation mode, the energy ratings must be based on EL.

2.8.1.2 FirstRate5

"FirstRate5" is Victoria's leading residential thermal performance assessment software. It generates the energy rating for a home by tracing over floor plans. Similar to AccuRate, it can be used to rate an existing design or as an interactive tool to optimize the design. The inputs and outputs are similar to AccuRate (FirstRate house energy rating software 2016).

2.8.2 BASIX

BASIX was introduced in 2004 and aims to deliver equitable, effective water and greenhouse gas (GHG) reduction across New South Wales. This web-based scheme targets are up to 40% reduction in potable water consumption, up to 40% reduction in GHG emissions and minimum performance level for the thermal comfort in dwellings (BASIX 2013). In this scheme, the minimum thermal comfort means thermal comfort for dwelling occupants appropriate to climate and season, good building design, appropriate construction materials, managed peak demand for energy required for cooling and heating. Acceptable software for BASIX is AccuRate, FirstRate5 and BERS Pro version.

Unlike other rating tools, BASIX relies on a checklist and requires the following input data: occupation level, the market penetration rate of technology, climate properties, location, orientation, landscape and site area, adjacent buildings, trees and vegetation, building construction and details, ground reflectance, various insulations, sealing, sub-floor ventilation, floor covering, internal layout and zoning; windows size, frame, type and shading; curtains, pelmets, internal windows/glazed door, roof /wall type and colour; skylight size and location; heating/cooling appliance properties, ventilation or air conditioner properties (Department of Planing and Environment 2015). The outputs of BASIX include yearly total energy use, water consumption and energy rating.

This scheme will not be employed in this research as the case study homes are in South Australia and it is preferred to assess the energy use and thermal comfort by full simulation.

2.8.3 Discussion

Energy Efficiency Provisions for the BCA are not directly related to occupant comfort, but if the house design and construction keep conditions inside the house comfortable for the occupants, they will be less likely to use heating or cooling services; thereby reducing energy demand and greenhouse gas emissions. The AccuRate rating tool calculates the energy use within a house for cooling and heating separately, but some zones are completely outside the thermal comfort range during heat events. That is why in Adelaide the difference between measured energy demand and predicted energy demand from NatHERS had been found to diverge in some spaces on peak cooling days (Saman et al. 2013).

2.9 Knowledge gap and contribution

The literature review demonstrates that many energy regulated buildings have overheating issues. Furthermore, the literature review shows that while a wide range of techniques are proposed and applied to provide thermal comfort, there is no specific design strategy or guidelines to assess and ensure thermal comfort, particularly for the top floors of multilevel dwellings.

There is a significant need to develop a globally accepted definition for overheating in dwellings (Dengel & Swainson 2012). Assessing overheating, coupled with the regulatory focus on reducing energy use, could result in controlling overheating to an acceptable level.

The literature review has demonstrated that the AccuRate rating software outputs include hourly temperatures, which can be used for assessing the thermal comfort and overheating during the NV mode. Therefore, overheating indices could be added to NatHERS to evaluate the discomfort periods and zones in NV mode. ASHRAE 55 and EN 15251 mention WEH as a factor to assess overheating, but they do not suggest any daily, monthly or seasonal limit for WEH. The CIBSE 2016 introduces daily limits for WEH in NV mode and provides some criteria. The dwelling's thermal performance for each season should be evaluated separately (Willand, Ridley & Pears 2016). There should be some limits on the maximum temperature necessary to maintain health and wellbeing and to assess daily, monthly or seasonal overheating.

Through the literature review, it was found that the aims of current Australian energy rating schemes and the BCA are to raise energy efficiency and it is expected that thermal comfort is a by-product of energy efficiency. Therefore, the schemes are not designed to indicate the likelihood of thermal discomfort during extreme weather events. As a result, there is no method to point out the hottest part in a home during heat events. Overheating risk is addressed neither in the Australian Building Code nor in the building regulations. As a result, one of the key human health risks associated with the warming climate is not seriously considered in the early stages of dwellings design.

This research aims to commence work to redress this situation. Through the steps below, it aims to contribute to the body of knowledge and fill some of the gaps using case studies in South Australia.

- Identify overheating perception through a household survey
- Identify overheating through the examination of extensive temperature monitoring data available in a low energy housing development
- Define a threshold for overheating and evaluate its relevance and appropriateness
- Evaluate the viability of available techniques and measures to prevent overheating.

2.10 Summary

This literature review had critically reviewed relevant available literature in nine sections to provide the necessary background for the subsequent chapters. It covered the problem definitions (2.1), overheating scales (2.2) and limits (2.3 and 2.4), methods used in similar studies (2.5) and possible solutions (2.6), reasons for overheating (2.7) and available software in use (2.8). It concluded with a summary of the research gap (2.9). Table 2.12 shows the relevance of the sections of the literature review to subsequent chapters and sections.

Table 2.12 The application of Chapter 2 sections

Literature Review sections	Sections that have used particular Literature Review section
2.1 Defining acceptable thermal conditions in indoor occupied spaces	3.2.2, 4.3.3, 5.2.3
2.2 Thermal comfort perception scales	5.1, 5.2.1, 5.2.3
2.3 Long-term thermal discomfort limits	5.1, 5.2.1, 5.2.3, 4.2.2, 4.3.3, 6.2
2.4 Overheating limits	4.2.2, 4.2.3, 4.3.4
2.5 Documented overheating events	4.2.1, 4.2.2, 4.2.3, 4.4
2.6 Methods of achieving thermal comfort	6.3.1
2.7 Main reasons for overheating	6.2.1
2.8 Energy rating schemes and associated software for dwellings in Australia	6.3.1
2.9 Knowledge gap and contribution	4.2.2, 4.2.3, 4.3.4, 6.3.1

3 Surveying thermal comfort and overheating in energy-efficient dwellings in Adelaide during summer

3.1 Introduction

This chapter demonstrates the occurrence of overheating through a field survey study on energy-efficient multilevel dwellings located in Adelaide, Australia, during NV operation mode in summer. Previous studies have shown that a high percentage of energy-efficient dwellings have prevalent overheating during NV mode according to thermal comfort building standards, even in heating dominate climate (Table 3.1). Overheating in dwellings has been the focus of considerable research during the last decade (Chen 2019).

Although a number of studies have been carried out on overheating in residential buildings in Adelaide (Berry et al. 2014; Saman et al. 2013; Sharifi et al. 2020), the extent of overheating in recently built energy-efficient dwellings is still not well understood. Through surveying households' experiences, the research aims to identify the current status of overheating in energy-efficient dwellings, specifically at their top floors and thus to provide empirical evidence for characterising the overheating issue with the aim of improving building regulations in the future to avoid the onset of overheating.

Table 3.1 Summary of results on overheating investigations in energy-efficient dwellings for NV mode

Country	Study Method	Year of Built	Ref.
Australia	Monitoring	2010 onward	(Sharifi, Saman & Alemu 2019)
	Simulation	2010 onward	(Hatvani-Kovacs et al. 2016b)
	Survey	2010 onward	(Berry et al. 2014)
	Simulation	2010 onward	(Ren, Wang & Chen 2014)
Italy	Simulation	2006	(Pyrgou et al. 2017)
Cyprus	Monitoring	2014 Passive house	(Fokaides et al. 2016)
	Simulation	2014-15 NZE house	
Netherland	Simulation	2013	(Hamdy et al. 2017)
New Zealand	Monitoring	2004	(Birchmore et al. 2017)
Sweden	Survey	2009	(Samuelsson & Lüddeckens 2009)
UK	Monitoring	1990 Retrofitted for energy-efficency	(Summerfield & Lowe 2007)
	Simulation	2016-17	(Gupta & Gregg 2018)

3.2 Method

The survey focuses on overheating and thermal comfort during NV operation mode. The AC mode is excluded, as overheating during the AC mode can be attributed to inappropriate cooling capacity or arrangement of the air conditioning system outside the scope of this study. Considering that the top floors of dwellings perform the worst in terms of overheating (Sharifi, Saman & Alemu 2019), only energy-efficient dwellings were surveyed with a focus on top floors regardless of the dwelling archetype. The target was to survey at least 1% of the energy-efficient dwellings built in Adelaide after 2010. In order to have an in-depth insight into participants' thermal comfort perceptions and allow for annual variations, the average daily temperatures of the surveyed summer months were compared with those of six summers before and one summer after the summer during which the survey was carried out.

3.2.1 Suburbs and dwelling types

The selection criteria for dwellings were detached/attached townhouses or top floor apartments built during or after 2010, as this was the year that newly built houses had to meet the Australian Nationwide House Energy Rating Scheme (NatHERS) minimum performance requirement of 6-star (NatHERS National Administrator 2012). Table 3.1 shows the typical construction materials of the surveyed houses. Figure 3.1 presents typical plans and features of these houses. Dwellings that met the survey criteria are spread all around suburban Adelaide. The survey was conducted within 13 suburbs, 5 of which had more energy-efficient houses than other suburbs (Figure 3.2). All dwellings were rated at least 6-stars with a cluster of houses located in Lochiel Park that had 7.5-stars rating.

This survey was conducted in the autumn of 2017 to report the participants' experiences during the target summer season (December 2016 to February 2017) in their dwellings as overheating in Adelaide often extends to days in March and April. This is in contrast to some studies which have carried out post-occupancy surveys before the end of summer (Adekunle & Nikolopoulou 2016; Symonds et al. 2017; Vellei et al. 2016a). Each householder replied to the questionnaire once and their ratings reflected the overall impressions of their dwellings during the summer season in question.

The survey was conducted through distributing the survey questionnaire by email or as a paper version through mailbox delivery. Of the 243 questionnaires sent by email, 45 completed questionnaires were returned. The email recipients were asked to answer the

questionnaires only if they had spent the last summer in their respective dwellings. Of the 652 hard copies distributed through mailboxes, 133 completed questionnaires were returned. The hard copies were distributed across five suburbs with high proportions of energy-efficient dwellings.

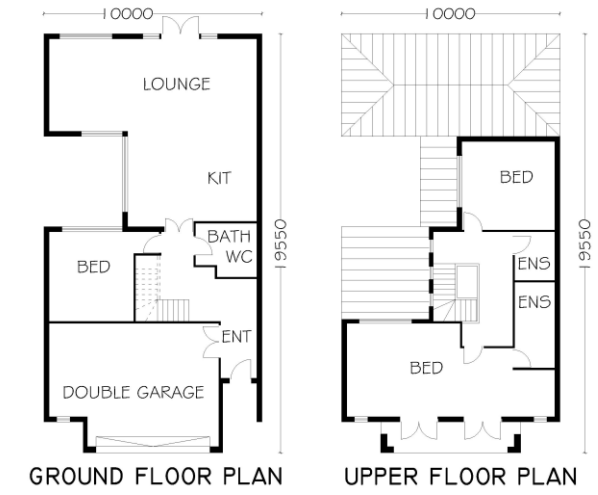




Figure 3.1 typical plans and features of the surveyed houses

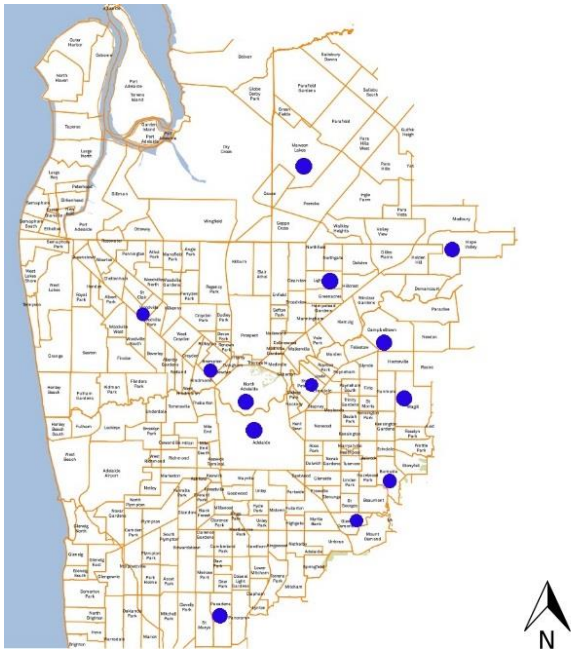


Figure 3.2 Locations of suburbs surveyed in Adelaide

Table 3.2 Properties of typical construction elements in the surveyed houses

Construction Elements	Materials
External wall	Rock wool batt Plaster Brickwork or Fibre-cement sheet/Weatherboard or Aerated autoclaved concrete block
Window	Single or double Glazing Thermal break frame
Entrance door	Timber Crete Timber hardwood
Ceiling/ Floor	Rock wool batt or Glass fibre batt Plasterboard Concrete slab Timber Crete Carpet or Ceramic or Parket
Internal wall	Rock wool batt Plasterboard Brickwork
Pitched/Hip Roof	Cellulose fibre batt or Rock wool batt Plasterboard Steel

3.2.2 Questionnaire details

A summary of the survey questions is listed in Table 3.3. Appendix B shows the complete questionnaire that was distributed. Also, Appendix B presents the participants' information sheet. The participants were asked if they suffered any physical issue associated with heat stress and if the answer was yes, the questionnaire was ruled out. The age was grouped by ten-year intervals. The last question about the participants profile

was their gender. Respondents needed to point out the type of dwelling they were residing in. If they were in an apartment block, the total number of floors of the building and their unit level had to be recorded. The 24-hour periods in the questionnaire started at 7 am, the daytime start hour in the NatHERS accredited energy rating software. AccuRate divides the 24 hours to 7 am–12 pm, 12 pm–17 pm, 17 pm–21 pm, 21 pm–24 pm, 0 am–4 am and 4 am–7 am. The occupancy of the living and sleeping areas is listed in Table 3.4. The participants were asked in which periods they were generally in their homes. The space that respondents had spent most of their days and nights was asked to review their judgments' accuracy. The daily duration of using cooking appliances use were requested to have a better insight into their judgment about overheating and thermal comfort and if the heat generated from cooking could have affected their comfort. The clothes insulation (clo) and metabolic rate (met) scales were based on ASHRAE 55 and Nicol 2012 scales (ASHRAE 2017; Nicol, Humphreys & Roaf 2012). Answers to the clothes insulation and metabolic rate were useful to correlate their thermal comfort rating or overheating to their personal condition. Although the questionnaire focus was NV mode, the AC setpoint and the level of setpoint change during heat events were requested to have a better insight into of residents thermal comfort range. Also, this information helped to conduct a cross-comparison between star ratings. The questions about overheating were information about the floor level, location, time and approximate duration of overheating. The questions regarding thermal comfort were a quantitative, qualitative modified version of a questionnaire initially developed by ASHRAE 55 and EN 15251. Participants were asked to rate their thermal comfort in the ground floor, top floor, and in the whole house, separately if they lived in a multilevel dwelling. They were asked to provide one rating for the whole dwelling if they lived in an apartment or one more rating for an overheated room. Two types of thermal comfort scales were applied: The TSV scale presented by ASHRAE 55 and an alternative numerical 10-point scale where a score of one is for the minimum thermal comfort and 10 is for the best thermal comfort sensation. Chapter 5 explains extensively the 10-point scale, the reason for using it and the results. At the end of the questionnaire, participants were asked to add comments, notes, or suggestions, which helped to interpret their ratings. The survey results were analysed using Excel.

Table 3.3 Summary of summer thermal comfort questionnaire structure and scales

Questionnaire item	Measuring scale
Hours at home: On which hours were you usually at home during weekdays and weekends?	7 am–12 pm 12 pm–17 pm 17 pm–21 pm 21 pm–24 pm 24 am–4 am 4 am–7 am
Location at home: Where did you spend most of your day/night?	Living room Dining room Kitchen Bedroom Open plan spaces Other spaces
Switched on oven/stovetop: How many minutes daily were you using your oven/stovetop?	30–60 60–90 90–120
Clothing insulation (clo): Which items did you generally wear?	17 items of clothing were listed
Activity level: What was your major activity?	Resting Light manual work Continuous arm work Intense arm work Very intense activity
AC setpoint (ºC): What were the major air conditioner set-points in summer and during heat events separately	16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30
Was there any overheating while AC was off?	Which floor Which room Approximate duration of overheating Any shade/curtain Any addition cooling device
Thermal comfort rating (numerical) 1 is the worst and 10 is the best: What is the thermal comfort rating for the below spaces by natural ventilation during summer or heat events? - Top floor - Ground floor - Whole of the house	1, 2, 3, 4, 5, 6, 7, 8, 9, 10
Thermal comfort sensation rating (TSV): How do you describe the thermal comfort of below spaces by natural ventilation during summer or heat events? - Top floor - Ground floor - Whole the house	Hot Warm Slightly warm Neutral Slightly cool Cool Cold

Table 3.4 Day and nighttime periods in the AccuRate software

Zone type	Assumptions and comments
Living	Conditioned from 07.00 - 2400 Daytime occupancy. No cooking heat gains
Bedroom	Conditioned from 16.00 – 09.00 Night-time occupancy
Living/Kitchen	Conditioned from 07.00 – 24.00 Daytime occupancy. Cooking heat gains included.

3.2.3 Number of surveyed dwellings

The target number of surveyed dwellings was at least 1% of detached/attached townhouses and top floor of apartments built in Adelaide from Jan 2010 (after the 6-star energy-efficiency became compulsory) to Mar 2017. During this period, a total of 13964 dwellings were built in Adelaide (Australian Bureau of Statistics 2017). The archetypes of these dwellings are semi-detached, row or terraced houses, townhouses with two or more stories, units or apartments in one up to four-story blocks (Table 3.5). In order to estimate the number of multilevel dwellings as well as the top floor apartments in 2017, the numbers of units in three or four-story blocks were divided respectively by three and four, and the number of units in a one or two-story blocks remained the same to estimate the maximum possible number of dwellings (Table 3.5). The outcome of the estimation was 9,178 homes and at least 1% of this number was considered necessary for the survey to provide some statistical credibility, which is 92 dwellings.

Table 3.5 Categorised number of Multilevel energy-regulated dwellings approved to build in Adelaide from January 2010 to March 2017 (Australian Bureau of Statistics 2017)

Type of Dwelling	Number of Approved	Estimated Current Number of Multilevel and Top-floor Dwellings
Semi-detached, row or terrace houses, townhouses, Two or more storys	5,481	5481
Units of apartments, In a one or two-story block	1,998	1,998
Units of apartments, In a three-story block	941	313
Units of apartments, In a four or more-story block	5,544	1,386
Total	13,964	9,178

3.2.4 Summer daily temperatures

The monitored average daily temperature of eight summers (December to February) for Adelaide was collected from the Bureau of Meteorology for Kent town, station 23090. To compare the annual variations of eight summers, a threshold of 30 °C was used as the baseline for evaluating the total summer deg hours.

3.3 Results

In total, 178 completed questionnaires were collected from households in 13 suburbs in Adelaide (1.93% of estimated new dwellings with potential overheating issues); of these,

10 were ruled out because of incomplete answers. The hard copy questionnaires made up 74.4% of the total received responses (Table 3.6). The suburb of Lochiel Park and Mawson Lakes had the highest percentage of completed questionnaires (29.8% and 23%, respectively) (Table 3.7). Lochiel Park houses were being monitored during the survey period and the results of the survey from this suburb will be used again in Chapters 4, 5 and 6.

Table 3.6 Questionnaire distribution information

Distribution Method	Name of Sites or Places	Number of Questionnaires Sent	Group Total	Number of Questionnaires Returned
Email	Individual	43		
	University of South Australia			
	School of Engineering	70	243	45
	School of Nature and Built Environment	70		
	University of Adelaide, School of Architecture and Build Environment	60		
Hard copy	Lochiel Park Residents and community	86		
	Bowden	87	652	133
	Adelaide CBD	110		
	Mawson Lakes	299		
	Lightsview	70		
	Total	895		178
	Ruled out			10
	Usable			168

Table 3.7 Collected questionnaires information

Suburbs	Number
CBD	35
Bowden	12
Burnside	3
Gilles Plaines	1
Hope Valley	2
Lightsview	15
Lochiel Park	53
Magill	2
Mawson Lakes	41
North Adelaide	1
Pasadena	1
St Peters	1
Woodville	1
Ruled out	10
Total Collected	178

The average value of the outdoor daily maximum, daily minimum and daily average temperatures in the Adelaide metropolitan area were 33.7 °C, 15.3 °C, and 22.5 °C, respectively, during the summer of 2016–2017. The average daily temperatures over eight summers (six summers before the survey and one summer after the survey) are plotted in Figure 3.3 and show that the surveyed summer was not atypical in terms of heat severity.

Comparing the WEH with the threshold of 30 °C shows that the summer of the survey was on the cool side, having one of the lowest DH, as shown in Figure 3.4.

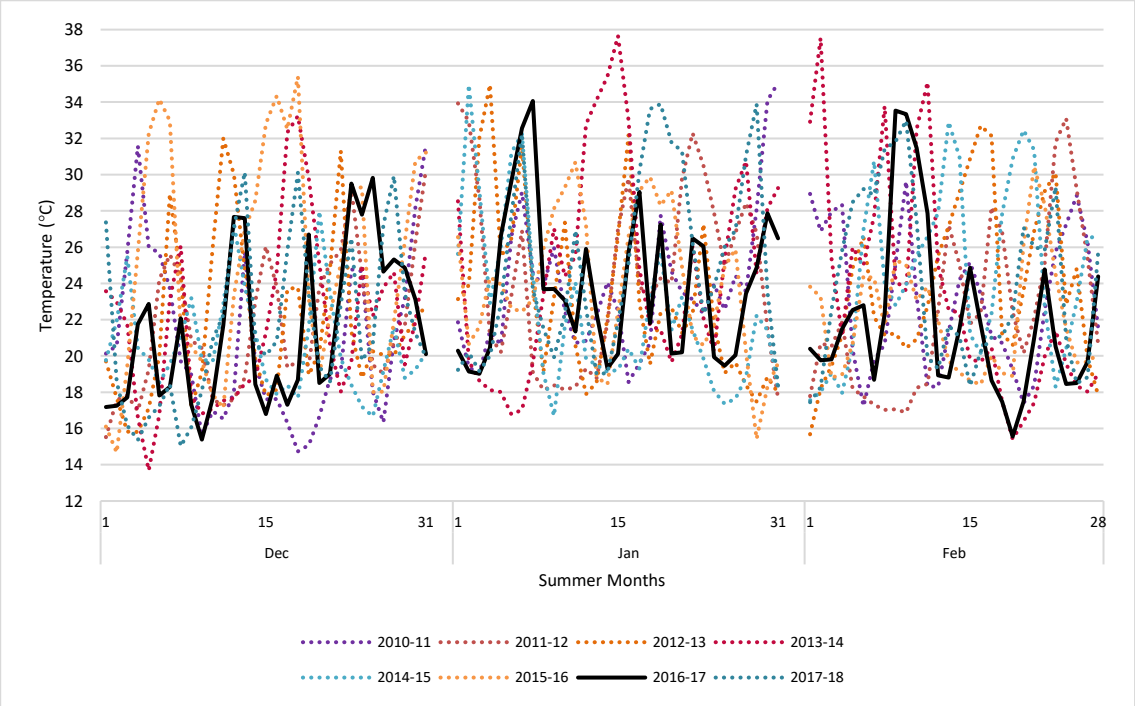


Figure 3.3 Average daily temperature of the eight summers from Dec 2010 to Feb 2018

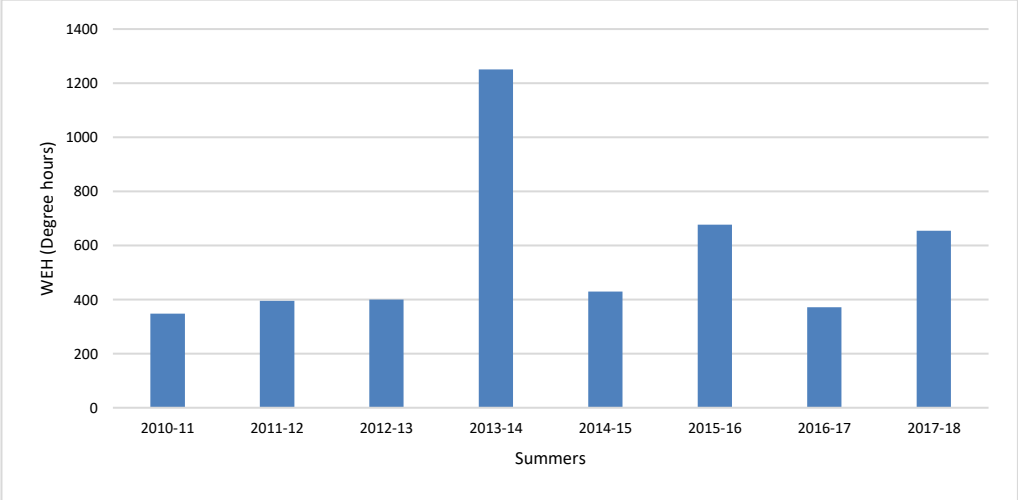


Figure 3.4 WEH above 30 °C for eight recent summers

he completed questionnaires were analysed in detail in two groups (with and without overheating) in Appendix C, Tables C1 and C2. Of the total respondents, 47.3% were male and 52.7% were female. Figure 3.5 shows the age distribution of participants in the survey. The highest percentage of respondents were between 50 to 60 years old.

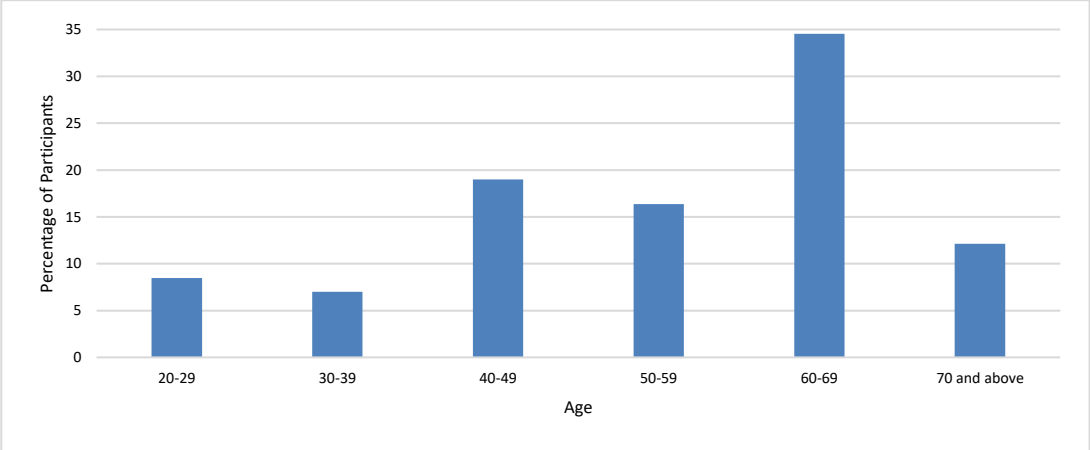


Figure 3.5 Percentage of participants by age

All the participants had lived in their respective dwellings during the preceding summer. More than 35% of participants had spent 16 hours of their summer days at home for and more than 30% had been at home all days (Figure 3.6). The high number of occupancy hours at home supports the accuracy of judgments for 65% of participants. Close to 47% of respondents used to spend their home hours in open-plan space, 43% of them had been in either an open-plan space or a bedroom and close to 10% were generally in the bedroom (Figure 3.7). These percentages reflect that judgments about open-plan spaces could be more accurate compared to that of bedrooms.

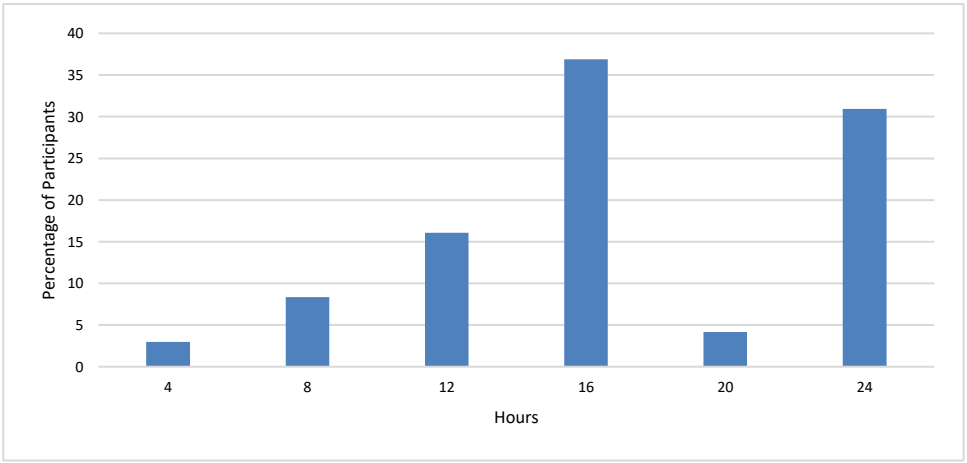


Figure 3.6 Daily hours spent by respondents at home

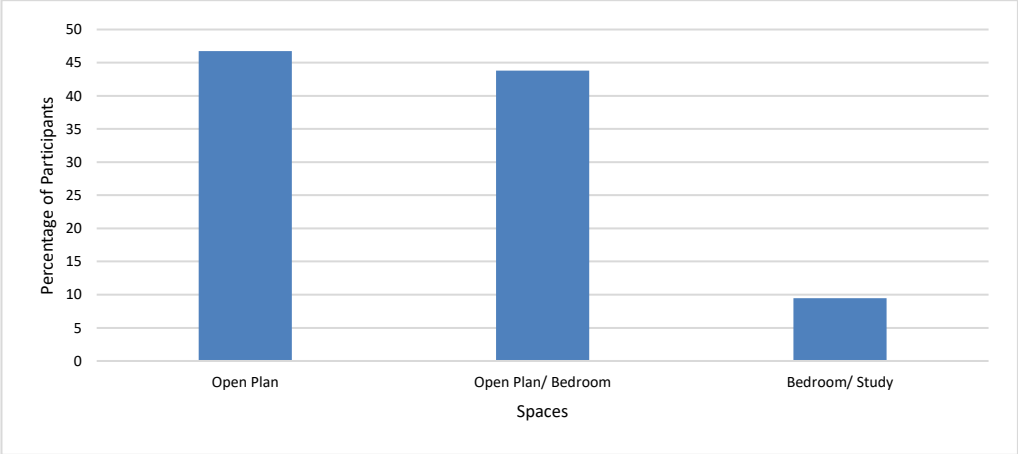


Figure 3.7 Spaces that respondents spent most of the surveyed summer in

About 65% of respondents had clothing thermal insulation (*clo*) of 0.3 (Figure 3.8). The average *clo* was about 0.35, less than normal summer light clothing, which indicates that participants' clothing did not exaggerate their perception of the indoor thermal condition. Figure 3.9 shows the percentage of participants by the metabolic rate (met). The average metabolic rate was 1.0. This value is below ASHRAE 55 that demonstrates the prevailing activity level in dwellings to be 1.3 met (ASHRAE 2017). The *met* value matched the seated, quiet range and could not negatively influence the residents' thermal comfort rating.

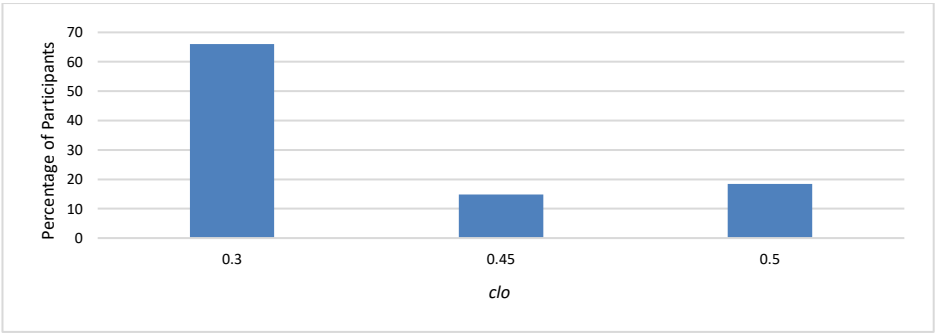


Figure 3.8 Participants' clothes thermal insulation

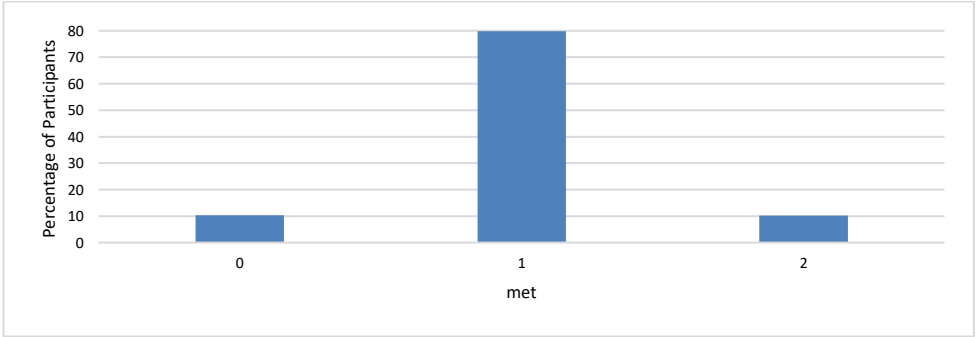


Figure 3.9 Participants' metabolic rate

About 40% of the residents used their stovetops for less than 30 minutes, and more than 41% used those for 30–60 minutes. These two groups, totalling 81%, represented a common pattern of stovetop usage as an internal heat source for less than one hour per day. There was no report on other significant internal heat sources. As expected, these dwellings had fridges and TV, but the heat these devices produced was little. Given that kitchens were located on the ground floor and the stovetops were used for an average of one hour daily, it is unlikely that the stovetops had a serious impact on the residents' long-term perception of thermal comfort, particularly on the top floors.

The completed questionnaires were analysed in three groups of dwellings: 7.5-star multilevel detached/attached dwellings (located in Lochiel Park), 6-star multilevel detached/attached dwellings (located in 12 suburbs of the Adelaide metropolitan area, excluding Lochiel Park), and top floor apartments (located in Adelaide CBD, Bowden, and Mawson Lakes). Figure 3.10 compares the total number of dwellings in the three groups.

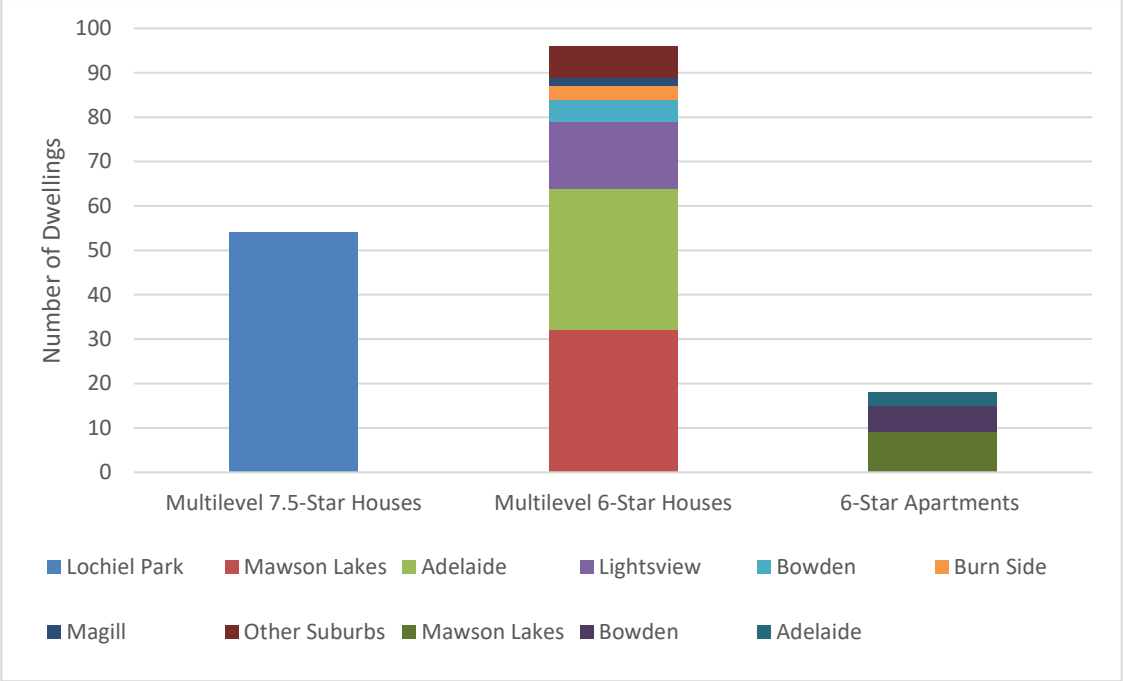


Figure 3.10 Number of dwellings in each group by suburbs

The majority of completed questionnaires, 88.7%, were from multilevel houses (Table 3.8). Of the 149 participants living in multilevel detached/attached houses, 61.1% reported overheating on the top floors based on the numerical scale. Similarly, of the 19 participants that lived in top floor apartments, 52.6% reported overheating. The average of the 149 ratings given for the whole floors according to the TSV scale was 'Slightly

Warm'. About 54.2% of the entire surveyed households reported some overheating during the summer in question.

Table 3.8 Summary of surveyed dwelling characteristics and results

Dwelling Type	Star Rating	Number Surveyed	With overheating on top floor		Without overheating on top floor	
			Number	%	Number	%
Multilevel Houses	6	96	51	53.1	45	46.9
	7.5	53	40	75.5	13	24.5
Apartment	6	19	10	52.6	9	47.4

3.3.1 The 7.5-star houses

The questionnaires for 7.5-star houses were analysed in detail in two groups (with and without overheating) in Appendix C, Tables C3 and C4. For the 53 surveyed households with 7.5-star rated houses in Lochiel Park, 62% had spent all day at home during summer. This reflects that the majority of households in this suburb are either families with young children or senior retirees. The setpoint of ACs in summer was between 23 °C and 26 °C for 67.5% of the residents, and 58% of the residents did not change the air conditioner setpoints during heat events (Table 3.9). The setpoint temperatures were within the 'Neutral' to 'Slightly Warm' range for Adelaide (22.7 °C to 26.7 °C) as suggested by Saman (Saman et al. 2013). Only 17% of the residents reduced the setpoint by 1 °C or 2 °C during heatwaves (Table 3.9). Overheating on the top floors and stairwells was reported in 75.5% of the surveyed households based on the numerical scale. Notably, more than one-third of the remaining resident (approximately 8%), who had not experienced overheating on the top floors were at home only at night. Their experience is not as reliable as residents who occupied their dwellings during the daytime, because the residents who stay at home all day experienced overheating more than twice as often as those who only occupied their homes at night (ASHRAE 2017). The reported overheating in this survey (75.5%) was less than the overheating reported in a previous survey conducted in Lochiel Park (Berry et al. 2014), which reported 92% overheating. Regardless of the difference between the previous and the current survey results, they confirm that the top floors were overheated. Specifically, overheating was noted for the north and west-facing spaces for a duration ranging from 30 minutes to 24 hours a day during heatwaves (Figure 3.11). The afternoon was reported as the main period of overheating. The results also revealed that some of the participants slept on the ground floor during summer nights due to uncomfortable top floor temperatures. Similar reports

were received in the previous study (Berry et al. 2014). Some participants also highlighted the following issues:

- High heat transfers from the ceilings and walls on top floors
- Lack of cross ventilation
- Inability to use patios due to spiders
- Inability to use evaporative cooling systems at night due to noise disturbance
- The garage acts as a heat collector, particularly if facing North or West. Thermal insulation is needed between rooms and garage walls and roof. The garages should be ventilated. North or west-facing garage doors need thermal insulation.
- Some have installed interior block blinds for all west-facing windows and heat reduction films on glazing, but they were not very effective.
- Some have installed external blinds on the west-facing windows and insulation on the garage door. These changes helped to reduce the top floor temperature.

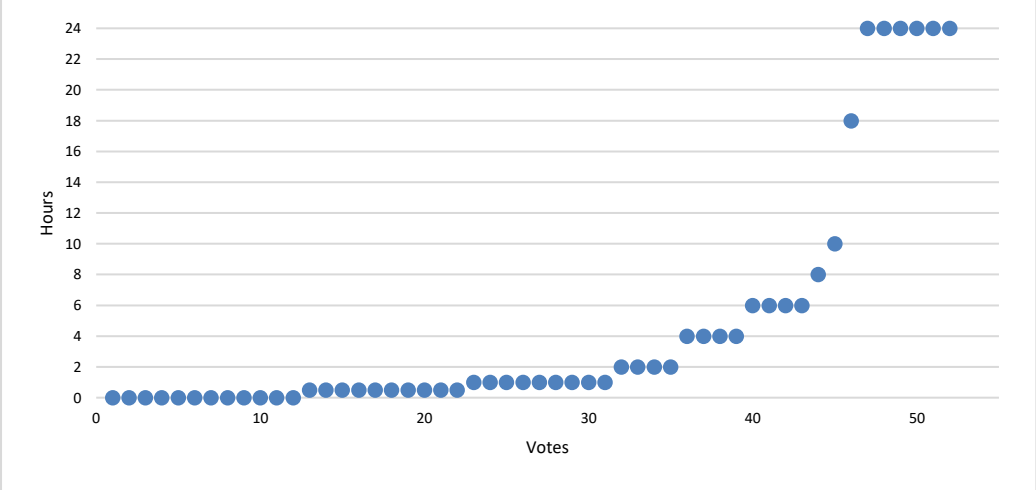


Figure 3.11 Duration of overheating for the 7.5-Star houses during heatwave days

In a previous survey in Lochiel Park, the residents were concerned about the lack of shading, the location of fixed shading, the location and width of openable apertures, the inability to close off the stairwell (zoning) to prevent heat transfer between floors, lack of building material choices offered by the builders and failure to gain adequate cross ventilation (Berry et al. 2014).

Of the respondents who reported overheating, 75% rated the thermal comfort of the ground floor at six or more, based on the numerical scale. The average thermal comfort of the houses with overheating issues was 5.3, while the ground and top floors were rated 7.4 and 3.1, respectively. More than 62% of these participants rated the thermal comfort of the top floors between 4–8 points less than that of the ground floors. The average

thermal comfort of the whole dwellings for those with overheating issues during summer was marked outside the acceptable range of the TSV scale, 'Hot', by 13% of the participants and within the acceptable range by 87% of them.

3.3.2 The 6-star dwellings

The questionnaires for 6-star houses were analysed in detail in two groups (with and without overheating) in Appendix C, Tables C5 and C6. Most of the residents in 96 6-star houses surveyed were full time working adults; two thirds (67.7%) occupied their homes only at night after working hours. The AC main setpoint was between 22 °C and 24 °C for 68.7% of the respondents, which is within the temperature range rated as 'Neutral' to 'Slightly Warm' for Adelaide (22.7 °C to 26.7 °C) by Saman (Saman et al. 2013). About 62% of the participants reported reducing the AC setpoint during heat events, and three-quarters of them had decreased the setpoint by 2–5 °C. Overheating on the top floors was reported in 53% of the questionnaires based on the numerical scale (Table 3.9). Overheating was reported by residents in the north-facing bedrooms on the top floors, followed by those facing west and then those facing east. The overheating duration varied from 30 minutes to the entire day during heatwaves (Figure 3.10), with the worst conditions experienced in the afternoons. Like the 7.5-star households, in some cases, occupants spent the night on the ground floors to avoid overheated bedrooms. To cool down the overheated rooms, 37.3% of residents used ceiling fans, portable fans, or increased the fan of the AC. About 8% of residents adopted other means such as installing shades on north-facing windows on the top floors, tinting windows, changing the dark colours of the outside walls to white, or night cross-ventilation. Generally, the participants were dissatisfied with the cost of providing thermal comfort on the top floors, while their dwellings were 6-star energy rated. In the overheated dwellings cohort, 74.4% rated the top floor thermal comfort less than five on the numerical scale, and 55% rated the ground floor at more than five. Based on the same scale for the houses with overheating, the average thermal comfort of the whole house, top floor, and ground floor was found to be 4.4, 3.2, and 5.6, respectively (Table 3.9). In the overheated houses group, 55.8% rated the ground floor thermal comfort at 1–3 points higher than that of the top floors. The same difference was noted between the two levels in dwellings that experienced no overheating. For the houses that experienced overheating during the summer, 25.5% of residents marked the average thermal comfort outside the acceptable range of the TSV scale, 'Hot', and 74.5% marked it within the TSV scale acceptable range. The average of the ratings,

according to the TSV scale was ‘Slightly Warm’ and ‘Warm’. The participants in this group also provided the following remarks:

- Regardless of keeping the blinds and curtains closed, the top floor was extremely hot most of the time during summer.
- Using a ceiling fan can reduce the need for AC
- The use of cross-ventilation at nights improved thermal comfort.

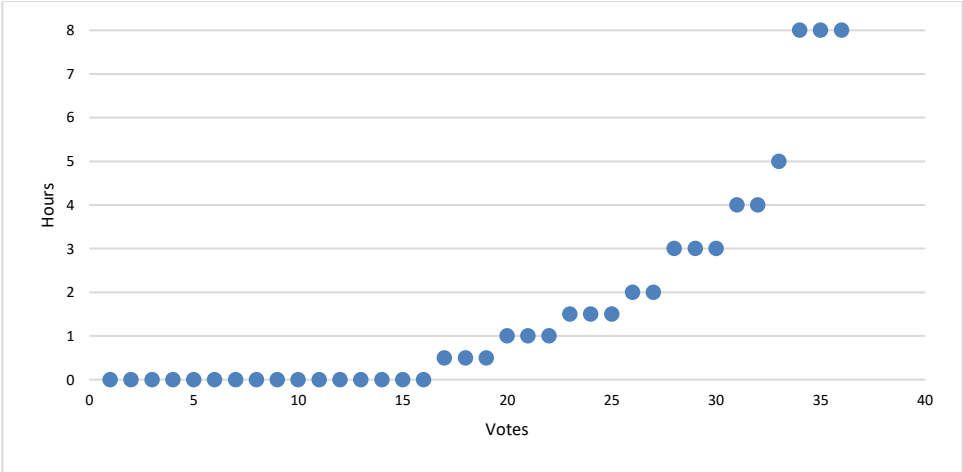


Figure 3.12 Duration of overheating for the 6-Star houses during heatwave days

3.3.3 The floor of 6-star top floor apartments

The responses from the 19 apartment units, all located within one suburb, were analysed. In this group, 63.1% of residents were at home after working hours. The setpoint of the AC was constant for summer and heat events for 50% of the participants, but the other 50% reduced the setpoint by 2–3 °C (Table 3.9). Overheating was reported by 52.6% of residents, mainly in the bedrooms (Table 3.9). This result agrees that bedroom temperatures in Adelaide apartments were higher than living room temperatures (Saman et al. 2013). Overheating was most severe in the north-facing rooms, even when the blinds and curtains were shut. The duration of overheating varied from 30 minutes to 24 hours in a day (Figure 3.11). Although some residents had ACs, most used portable fans to cool the occupied spaces. The average thermal comfort rating in the apartments with overheating was 3.1 based on the numerical scale which is equal to thermal comfort rate for the top floors of 6 and 7.5-star houses. All the participants in this group reported that the thermal comfort of their dwellings was outside the acceptable range of the TSV scale during summer. Half of the ratings was ‘Warm’ and the other half was ‘Hot’. In Table 3.9, the TSV rates are converted to numbers as follows: ‘Hot’= +3, ‘Warm’= +2, ‘Slightly warm’= +1, ‘Neutral’=0, ‘Slightly cool’= –1, ‘Cool’= –2, ‘Cold’= –3.

More than half of the residents that reported no overheating gave thermal comfort rating that were contradictory between the TSV scale and the numerical scale. Using the TSV scale, they chose 'Warm', but they rated their apartments more than five on the numerical scale. This conflict may indicate that respondents were able to withstand the warm conditions and did not consider overheating as an issue. Table 3.9 shows that the top floors of apartments had more overheating than the two other groups followed by the 7.5-star and 6-star dwellings, respectively. The extreme overheating in the units located on top floors could be associated with their roofs exposed to direct solar radiation (Department of Energy and Climate Change 2015).

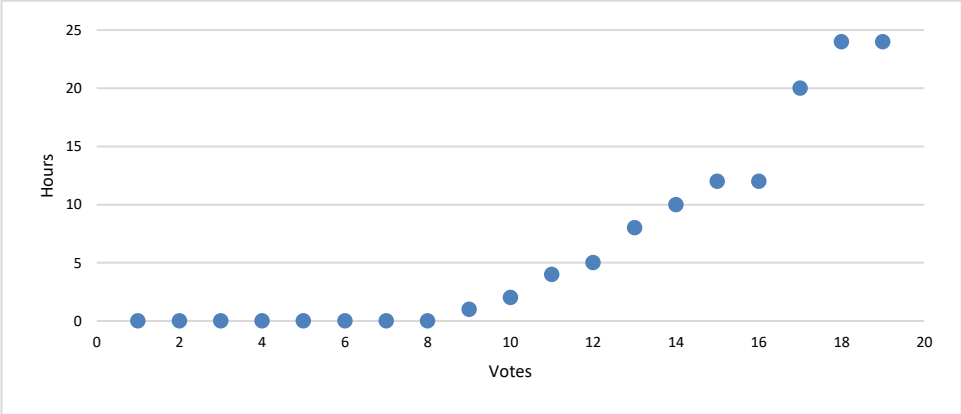


Figure 3.13 Duration of overheating for the 6-Star apartments during heatwave days

Table 3.9 Summary of surveyed dwellings with overheating

Surveyed items		7.5-star house		6-star houses		Apartments (top floor units)	
		Dominant proportion	%	Dominant proportion	%	Dominant proportion	%
Time spent at home		24 hours	65	Nighttime	67	Nighttime	63.1
Setpoint in summer		23–26 °C	64.2	22–24 °C	68	21–24 °C	66.7
Constant set-point in heat events			58.8		38		50
Decreased setpoint during heat events (°C)		1–2 °C	41.2	2–6 °C	49	2-3 °C	50
Average Thermal comfort rating by the numerical scale in	Whole dwelling	5.3		4.4		3.1	
	Top floor	3.1		3.2			
	Ground floor	7.4		5.6			
Thermal comfort rating by PMV for top floors		+2 ≤	13	+2≤	25.5	+2≤	100
Average Thermal comfort of the whole dwelling by TSV and PMV		Slightly Warm (+1)		Slightly Warm (+1)		Warm and Hot (+2,+3)	

3.4 Discussion

Using a survey questionnaire, this research has evaluated the occurrence and severity of overheating on the top floors of energy-efficient multilevel dwellings by providing indicative empirical evidence based on residents' thermal perceptions. About 1.3% of the households of energy-efficient dwellings built after the introducing of minimum

mandatory 6-star NatHRS rating between 2010–2017 in Adelaide (168 dwellings), were surveyed. In addition to overheating, the thermal comfort rating was evaluated by two scales, verbal and numerical.

The summer under question was one of the coolest summers between six summers before and one summer after it. Therefore, the overheating reported in this survey could be more extreme for the next summers. This survey covered all age ranges from 20 to above 70, so it can indicate a strong idea about thermal comfort. The judgment of participants on overheating had an acceptable accuracy due to the high number of hours they had spent at home, particularly in an open space. The participants' clothes were appropriate for summer, and the met value was low. So, the *clo* and *met* values are unlikely to have affected the perception of the indoor thermal comfort. The internal heat source for less than one hour on the ground floor is unlikely to impact on thermal comfort rating.

The occupancy patterns varied between the surveyed 7.5-star and 6-star houses. In the 7.5-star dwellings, 62% of participants were usually at home for 24 hours, while in 6-star houses, 67% of respondents were outside the house during the day and were home at night. This discrepancy reflects the demographics of the different groups as other research has shown that the 7.5-star suburb residents included more retirees who are generally more sensitive to heat (Berry et al. 2014). The discrepancy also indicates that the responses from the 7.5-star households were more reflective of conditions during daytime hours, while daytime overheating was less noticeable in the 6-star homes. More than 54.2% of surveyed houses reported overheating during summer. In the dwellings with overheating, the average occupancy duration was 17.7 hours of a summer day. The overheating duration varied from 30 minutes to the whole 24 hours, with an average of about eight hours (11:00–19:00). Thus, on the overheated days, the overheating period was on average 43.5% of the occupied hours which is similar to the result from monitored houses in Adelaide (Sharifi, Saman & Alemu 2019). This percentage is well above the acceptable discomfort period specified in the standards. The EN 15251 limits the thermal discomfort hours to 3–5% of the occupied hours for mixed mode (Nicol 2013) and CIBSE limits overheating to 1% of occupied hours for mixed mode (CIBSE 2006). The high frequency overheating on the top floors in this group coincides with the assumption of CIBSE TM 55 that top floors are likely to be at risk of overheating (CIBSE 2017).

The average AC setpoint in the 7.5-star and 6-star houses were 24.5 °C and 23 °C, respectively, which generally indicates that the 6-star houses need more cooling than the 7.5-star houses at least during the heatwaves. The 7.5-star houses setpoint matches exactly with ISSO 74 recommendations for summer (ISSO 2014). In the 7.5-star dwellings, approximately 90% of participants held AC setpoint constant during heat events, while the others decreased it by 1–2 °C. In the 6-star houses, 38% of residents kept AC setpoints constant and 62% reduced by 2–5 °C. The difference between the 7.5-star and 6-star houses in terms of constant setpoint percentage and the amount of reduction suggests that the whole of the 6-star houses are likely to be more affected by heatwaves than 7.5-star houses (which are quite comfortable on the ground floor) and consequently contribute more to raising the peak electricity demand (Yang, L, Yan & Lam 2014). However, 50% of participants in the 7.5-star houses had their bedrooms on the ground floor and spent little time on the top floors. Subsequently, this group did not need to adjust the AC setpoint. Overall, the higher star energy-efficient houses had cooler ground floors during summer.

The average thermal comfort rating for the ground floors in the 7.5-star and 6-star houses was six or higher on the numerical scale. The proportion with this rating range in the 7.5-star houses was 32% higher than those in the 6-star residences. The severity of overheating on the top floors of the 7.5-star houses was more acute and more noticeable in the 7.5-star rated dwellings, as 67.8% of the occupants rated the thermal comfort of the top floors 4–8 units less than that of the ground floors. This difference for the 6-star houses was only one or two units. The top floor rating was four or less in the 7.5-star and 6-star dwellings by the numerical scale, which indicates that energy-efficient houses tend to have a larger difference in thermal comfort between the top and ground floors. These results suggest that the higher star energy-efficient households experienced hotter top floors during summer. This finding is consistent with some simulation studies (Birchmore et al. 2017; Hamdy et al. 2017) and monitoring studies (Indraganti 2011; Summerfield & Lowe 2007) that demonstrate in the studied climates energy-efficient dwellings are at higher risk of overheating than non or less energy-efficient dwellings. The extreme overheating monitored on the top floors of energy-efficient multilevel houses in Adelaide (Sharifi, Saman & Alemu 2019) confirms the outcome of this survey. Although the whole 7.5-star house thermal comfort rating is approximately equal to that of 6-star houses, the 7.5-star houses residents appeared to be more thermally comfortable on the ground floor

and less satisfied with the top floor thermal comfort compared with those in 6-star houses. The top floor overheating in 7.5-star dwellings is more extreme or less acceptable for occupants as the temperature variation between the ground and top floor is remarkably higher.

The whole-house thermal comfort ratings were in the ASHRAE 55 acceptable range, 'Slightly Warm', for 57% of the 7.5-star residents and 53% of the residents of 6-star houses. However, it is important to note that more than half of the 7.5-star residents used the ground floor more often because their master bedrooms were on the ground floor, and the top floors were allocated as guest rooms. As a result, it is more likely that their thermal comfort ratings were unintentionally based on their ground floors judgments. Therefore, the whole-house thermal comfort was similar in both cohorts. The top floor apartment thermal comfort was generally rated 'Hot', which is outside the ASHRAE 55 acceptable range and coincide with other investigations in NV and mixed mode for apartments (CIBSE 2017; GHA 2019; Indraganti 2011). Having no lower floor to move into during periods of overheating could be one reason for the lowest thermal comfort ratings reported on top floor apartments. Other reasons that make units more prone to overheating than houses are their smaller size and higher density, providing lower opportunities for cross ventilation and preventing heat dissipation from communal areas (GHA 2019).

On the whole, the 6 and 7.5-star dwellings had better TSV and higher numerical thermal comfort ratings than those of the top floor units. This result is in contrast with a simulation study that found higher energy-rated dwellings having higher indoor air temperatures (Willand, Ridley & Pears 2016). Given that the top floors of houses and apartments had similar numerical thermal comfort rating, the correlation between energy-efficiency of dwellings and their indoor air temperature should be studied for each level separately.

Residents were more satisfied with 'Cool' and 'Slightly Cool' conditions, while the 'Warm' was the lowest acceptable level (Table 3.10). The most satisfaction was associated with the 'Cool' condition in the TSV scale. Similar results have been reported in other Australian cities. In Melbourne, people chose 'Neutral' at a lower temperature than that of the PMV model (Daniel, Williamson & Soebarto 2016). For dwellings in Sydney and Wollongong, the neutral temperature was 2 °C lower and the comfort zone for 80% acceptability was 2 °C wider than that of ASHRAE 55 (Kim, J et al. 2016). Other studies also note that acclimatisation tolerances should be considered in thermal comfort

descriptions. For example, the thermal acceptability of Indian occupants is higher than that of ASHRAE's (Dhaka et al. 2015). The Cameroon locals are acclimatised to the weather (Alexis, Ange & Ne 2012). Due to the acclimatization, the neutral temperature is lowest in cool climates and highest in sub-tropical climates (Rijal, Yoshida & Umemiya 2010). The current thermal comfort model does not encompass the conditions acceptable for occupants (Daniel, Williamson & Soebarto 2016) and it is apparent that people do not equate the 'Neutral' on the TSV scale with a complete thermal comfort (Baizhan et al. 2010; Humphreys & Hancock 2007; Humphreys & Nicol 2004; Tweed et al. 2014).

As the surveyed summer had lower DH than the summers before and after, the overheating results are on the conservative side. More thermal discomfort is anticipated in the future as a result of climate change due to the increase in heatwaves frequency and intensity associated with climate change.

Table 3.10 Correlation of TSV and numerical scale based on a survey of 168 households

Sample size	TSV (ASHRAE 2017)		Acceptable PMV thermal comfort for long-term (ASHRAE 2017)	Numerical scale
	Describes	PMV		
24	Hot	+3		2.3
30	Warm	+2	acceptable	5.5
54	Slightly warm	+1	acceptable	6.3
34	Neutral	0	acceptable	6.9
10	Slightly cool	-1	acceptable	7.6
16	Cool	-2	acceptable	8.3
0	Cold	-3		------

3.5 Summary of main findings

This chapter analysed empirical evidence of overheating on the top floors of multilevel energy-efficient dwellings by surveying a sample of Adelaide metropolitan households. The investigation was focused on the NV mode for overheating and thermal comfort. For this investigation, two thermal comfort scales were applied. Questionnaires were analysed in three cohorts based on their star ratings and number of floors inside the family dwelling. The three cohorts were also cross-compared.

The results demonstrate that the ground floors of energy-efficient dwellings had acceptable thermal comfort conditions during summer, including heat events. More than 50% of 6 and 7.5-star dwellings experienced overheating in their top floor during summer,

based on the numerical scale. The average period of overheating was about 43.5% of occupied hours. The top floors of apartments experienced most overheating, followed by the 7.5-star and 6-star houses.

The cross-comparison of the three groups found that the 6-star houses are impacted by heatwaves more than the 7.5-star houses and this would cause an increase in the magnitude and duration of the peak summer electricity demand. The 7.5-star energy-efficient houses had cooler ground floors during summer. The overheating on the top floors of these houses was noticeable by households, possibly due to significant temperature variation between the ground and top floors in these houses. The overheating was more common in rooms facing north and west. The top floor units in the 6-star apartments had a lower score in thermal comfort compared to the average thermal comfort score of the 6 and 7.5-star multilevel houses. The result of the surveyed summer may be generalized to other summers with the expectation of more overheating. As the survey covered almost a fifth of newly constructed energy-efficient Adelaide dwellings, its findings are anticipated to be applicable to other houses in Adelaide.

The results demonstrate the need for thermal comfort evaluation of all floor levels and occupied spaces in dwellings.

In addition, it was found that the point ‘Cool’ in the TSV scale was the most desirable for the participants, whilst it is the last acceptable point by ASHRAE 55.

This study calls for: a) Indices to be added in residential building regulations such as the Building Code of Australia (BCA) to determine and regulate the level of acceptable overheating in dwellings and b) Further evaluation of the practicality of TSV for thermal comfort acceptability evaluation.

This chapter finding, particularly for 7.5-star houses, support Chapters 4, 5 and 6 in terms of analysis overheating and thermal comfort perception.

4 Identification of overheating on the top floor of energy-efficient multilevel dwellings through monitoring

4.1 Introduction

This chapter investigates summer indoor temperatures in energy-efficient multilevel houses built since 2010 in Adelaide to identify and define overheating during summer months. The work relies on a comprehensive monitoring program on houses in the Lochiel Park Green Village, Adelaide. The analysis employs three steps:

1) calculating the number of days with top floor maximum daily air temperature above 32 °C during four summers (December-February of 2011–2015);

2) calculating the frequency, WEH and amplitude of outdoor air temperature above 35 °C, calculating the frequency, WEH and amplitude for top-floor temperature when it exceeded ground floor temperature in NV mode during eight summers (December-February of 2011–2018);

3) correlation between ground floor temperature and outdoor temperature during sunshine hours, correlation between ground floor temperature and running mean outdoor temperature for NV mode during eight summers (December-February of 2011–2018).

The outcome of these three steps is investigating possible criteria for characterising overheating by applying these parameters for houses and comparing them with other available criteria.

4.2 Method

4.2.1 Monitoring program

The study focussed on eight houses that were monitored in detail in the Lochiel Park Green Village in Adelaide, Australia. Lochiel Park is located eight kilometres northeast of the Adelaide CBD at latitude 34.886 °S and longitude 138.65 °E. This ecologically sustainable village includes 80 houses that are rated by Australian Nationwide House Energy Rating

The outcomes of this chapter have been published in a paper "Identification of overheating in the top floors of energy-efficient multilevel dwellings" Sharifi, S, Saman, W, Alemu, 2019, *Energy and Buildings*, vol. 204, Dec, pp. 1-37

Scheme (NatHERS) to a minimum of 7.5-star, which corresponds to a predicted required annual heating and cooling energy use of 58 MJ/m^2 per annum for each dwelling (NatHERS National Administrator 2012). A map depicting the location of these houses is shown in Figure 4.2-1. Eleven of the 80 houses have been monitored in detail since 2010. This included household electrical energy, water and gas consumption, major electrical appliances (including reverse-cycle air conditioners), internal temperature, and relative humidity (Saman et al. 2013). The temperature and humidity were monitored at one-minute intervals by analogue sensors installed approximately 180 cm above the floor on each level and in a maximum of three rooms and 30–650 cm from windows. All sensors were shielded from direct solar radiation. The technical specifications of the sensors are listed in Table 4.1. The sensor temperature resolution was 0.1 ºC (0–50 °C) with an accuracy of ±0.4 ºC. The sensor relative humidity resolution was 0.1% with an accuracy of ±2.95% (Saman et al. 2011). Household data were recorded and stored separately for each house. All data were automatically uploaded to a server within the development and subsequently were retrieved remotely by the University of South Australia team (Saman et al. 2011). Separate data on the setpoints and durations of operation of ACs in individual houses were not available. Thus, the ACs' electricity consumption pattern data showed only the operation duration.

Three of the eleven monitored houses were eliminated because two of the houses had no data for a few summers and one was constructed in 2014, so they had four years less data than the others. Thus, the final case study included eight houses from which temperature and humidity data were collected from eight living rooms, eight master bedrooms, seven other bedrooms, and one studio. All the living rooms and four master bedrooms were located on the ground floors. The other four master bedrooms, six bedrooms, and one studio were on the top floors, as shown in Table 4.2. Typical features and plans of the Lochiel Park houses are presented in Figures 4.1 and 4.2. For more detailed drawings, please refer to Appendix E, which presents the plan of six houses in Lochiel Park. The construction characteristics of houses are listed in Table 4.3. Appendix F lists the construction elements in detail with their specifications.

On the top floors of houses B, C, D, E, G and J the large windows and balconies faced East or West, due to the shape of their lots. On the top floors of houses A and K the big windows and balconies faced North or South. Table 4.4 lists the orientations of windows, their associated shading devices and reports summer ventilation pattern of houses. A blind is installed outside the east-facing balcony on the top floor of house B. All houses have blinds

inside for all windows except house C with no blinds or shade for the north-facing windows on the top floor.

Table 4.1: Technical specification of analogue sensors (KIMO, TH100) used for the temperature and humidity in Lochiel Park detailed monitored houses and ASHRAE acceptable range

Specifications	**Values**(Saman et al. 2011)	**ASHRAE 2016 acceptable values** (ASHRAE 2016)
Temperature measurement resolution	0.1°C	
Temperature accuracy	± 0.4°C(0 - 50°C)	± 0.2°C
Relative Humidity measurement resolution	0.1%	
Humidity accuracy	± 2.95% (18 - 28°C)	± 5%

Table 4.2 Characteristic of the eight monitored houses in Lochiel Park (TS4 Architecture 2014)

House	Air conditioning System	Number of outdoor units	Location of sensors	
			Ground floor	Top floor
A	Ducted Reverse-Cycle	1	Living room	Master Bedroom, Bedroom
B	Ducted Reverse-Cycle	1	Living room, Master Bedroom	Bedroom
C	Ducted Reverse-Cycle	1	Living room	Master Bedroom, Bedroom
D	Split Reverse-Cycle (Mitsubishi MXZ-4A80VA)	1	Living room, Master Bedroom	Bedroom
E	Ducted Reverse-Cycle	1	Living room	Master Bedroom
G	Ducted Evaporative	1	Living room, Master Bedroom	Bedroom
J	Ducted Evaporative	1	Living room	Master Bedroom, Bedroom
K	Split Reverse-Cycle (Mitsubishi MXZ-4A71VA)	2	Living room, Master Bedroom	Studio



Figure 4.1 Lochiel Park site, showing locations of the detailed-monitored houses marked in boxes. The shaded boxes are used in this study

Table 4.3 Properties of typical construction elements in Lochiel Park houses (TS4 Architecture 2014)

Construction Elements	Materials		Thickness (mm)	Construction Elements R-Value (m^2K/W)	Solar Absorptance of External Walls and Roof (%)	Solar Heat Gain Coefficient (SHGC) of glazing
External wall	Rock wool batt		83–99	3.17–3.86		
	Plaster/Plasterboard		5–26			
	Alternative outermost layers	Brickwork	110		23, 30, 50, 75, 80	
		Fibre-cement sheet/ Weatherboard	6			
		Aerated autoclaved concrete block	75			
Window	Glass		4	0.33–0.32		0.26, 0.27, 0.48, 0.49
	Air gap		12			
	Aluminium (thermally broken)		5			
Entrance door	Timber Crete		50	0.47–0.78		
	Timber hardwood		100			
Ceiling/Floor	Alternative thermal insulations	Rock wool batt	0.23–4.24			
		Glass fibre batt	88			
	Plasterboard		10–22			
	Timber Crete		6–19			
	Concrete block lightweight core-filled		100			
	Alternative floorings	Ceramic tile	8			
		Carpet	20			
Internal wall	Rock wool batt		50–99	0.44–3.28		
	Alternative internal layers	Plasterboard	10–13			
		Brickwork	110			
Pitched/Hip Roof	Alternative thermal insulations	Cellulose fibre batt	0.35–4.95	0.35–4.95	30, 50, 85	
		Rock wool batt				
	Plasterboard					
	Steel					



Figure 4.2 Photographs of some monitored houses

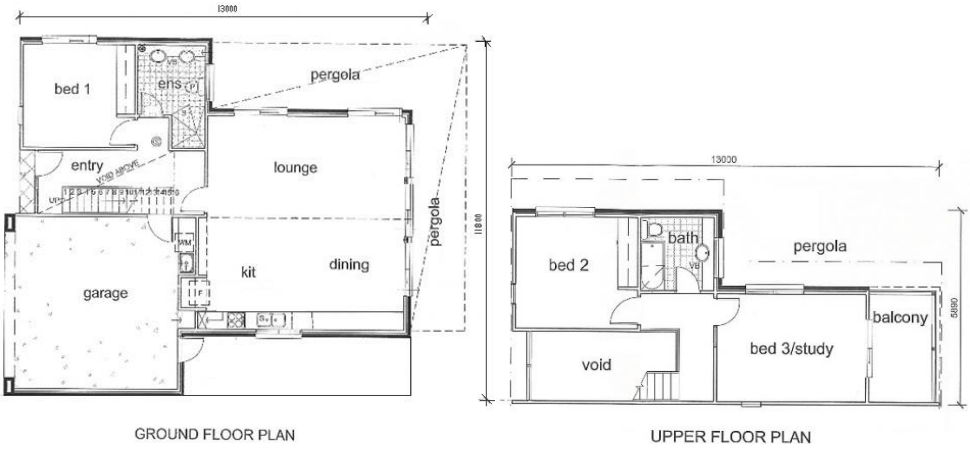


Figure 4.3 Typical ground-floor and top-floor plans of the monitored houses

Table 4.4 Shading of windows and the pattern of summer ventilation in houses (GF=ground floor, TF=top floor)

Houses		Window orientation				Ventilation pattern based on the survey
		North	East	South	West	
A	TF		Timber slat shading	Eave/ balcony shading	Eave shading	Nighttime
	GF	Eave shading		No shading	No shading	Nighttime
B	TF		Balcony roof/no shading	No shading	Balcony roof and external shade	Day time
	GF		No shading/porch roof	Eave shading	Eave shading	Nighttime
C	TF		Balcony roof/eave shading		Balcony roof and light bulkhead	Nighttime
	GF	Eave shading	Porch roof		Timber slat shading	Day time
D	TF	No shading	Balcony roof			----------
	GF	No shading	Porch roof		No shading	All day
E	TF		Balcony roof and eave shading		Eave shading	Nighttime
	GF	No shading			No shading	Day time
G	TF	Eave shading	Balcony roof		Shading	----------
	GF	Pergola	Pergola			Nighttime
J	TF	Balcony/eave roof		Balcony roof	No/ metal shading	Nigh time
	GF	No shading/ porch roof		No shading	Timber slat shading	Day time
K	TF	Eave shading	Timber/eave slat shading	No shading	Timber/eave slat shading	----------
	GF		Timber slat shading		Timber slat shading	All day

4.2.2 Thermal comfort and overheating threshold

The first step to identify overheating used the CIBSE definition for daily overheating, which is 'when the temperature in the building is too high for occupants to be comfortable' (CIBSE 2015). Based on this definition, a thermal comfort upper threshold should be considered. As this study investigates the NV mode, the upper threshold of adaptive thermal comfort is used. The literature summarised in Chapter 2 showed that the thermal comfort upper thresholds for NV/MM modes are based on adaptive thermal comfort versions described in ASHRAE 55, EN 15251, CIBSE Guide A, CIBSE TM52, CIBSE TM59 and ISSO 74.

Table 2.7 showed that for measuring overheating in NV and MM modes, three criteria are presented by CIBSE (CIBSE 2017; Nicol 2013) for buildings located in Europe; however, they might not be suitable for Adelaide due to different climate characteristics. Thus, for the first part of this study, the highest temperature from the upper threshold of adaptive thermal comfort was selected as an indicator of overheating in NV mode during summer. The specified upper thresholds of adaptive thermal comfort are shown in Figure 4.4. On the basis of ASHRAE 55, the upper threshold for adaptive thermal comfort is defined as follows:

Upper 80% acceptability limit:

Operative temperature = $0.31 \times T_{rm} + 21.3$ (if the airspeed ≤ 0.3 m/s) (Equation 4.1)

Where:

T_{rm} is defined in equation 2.6

Adelaide and South Australia can be considered in the midlatitude group; subsequently, 0.6 is used for α in this research with the starting date of 1 Jan 2009. Consequently, the equation for T_{rm} in this study is:

$0.4\ Tod\text{-}1 + 0.6\ T_{rm\ of\ one\ day\ before}$ (Equation 4.2)

For EN 15251 Category II, CIBSE Guide A, and ISS O74 Class C, the upper thermal comfort threshold is defined as follows (CIBSE 2015; ISSO 2014; NSAI 2007):

Upper 80% acceptability limit:

Operative temperature = $0.33 \times T_{rm} + 21.8$ (if the airspeed ≤ 0.3 m/s) *(Equation 4.3)*

where:

T_{rm} is calculated using Equation 4.2.

The upper thermal comfort threshold for EN 15251 Category II, CIBSE Guide A, and ISS O74 Class C is higher than that for ASHRAE 55 (Figure 4.4), but it covers the running mean outdoor temperature up to 30 °C, while ASHRAE 55 covers the running mean outdoor temperature up to 32 °C. Therefore, the maximum indoor temperature for ASHRAE 55 is higher than EN 15251 and meets the definition of overheating which is selected for the first step of this research.

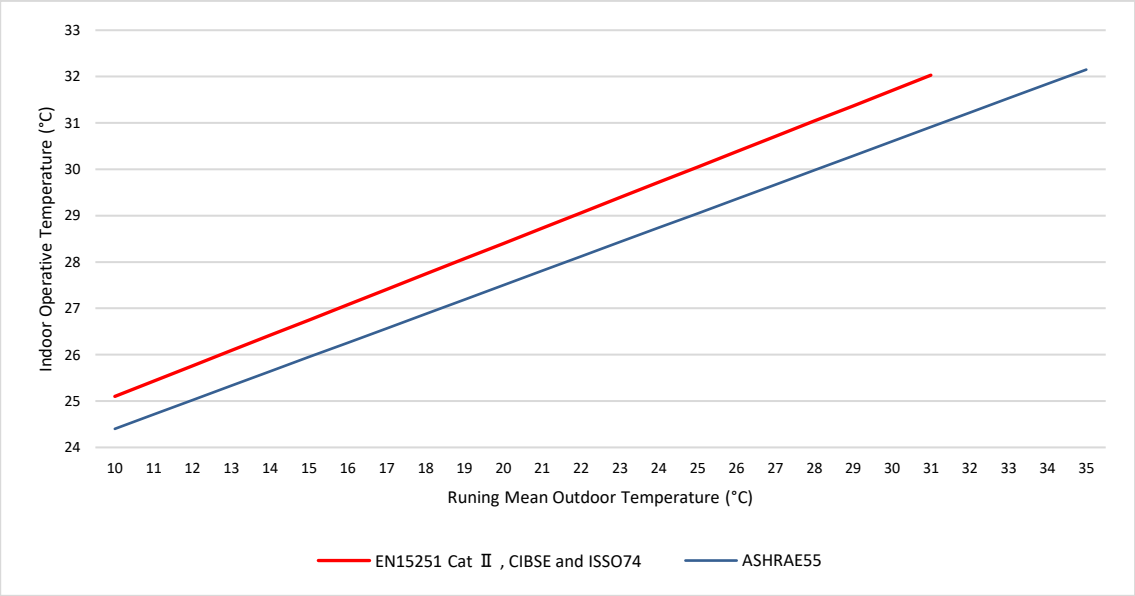


Figure 4.4 Upper thresholds of adaptive thermal comfort according to four standards

Some researchers have substituted the 'Indoor temperature' for 'Operative temperature'. This substitution is considered appropriate when none of the walls of the room is a heating source such as Trombe or glazed walls (Kim, J et al. 2016; Manua et al. 2016; Saman et al. 2013). The highest acceptable operative temperature is 32.15 °C based on ASHRAE 55 and 33.35 °C based on EN 15251, CIBSE, and ISSO 74 for the running mean outdoor temperature of 35 °C. The upper 80% acceptable threshold specified in ASHRAE 55 has been identified as suitable for adaptive thermal comfort in Adelaide, Brisbane, and Sydney (Saman et al. 2013), and this threshold has been applied in the assessment of reference buildings in Melbourne and Darwin (Daniel, Williamson & Soebarto 2017). Thus, for this research, the highest temperature of ASHRAE 55 was chosen as the overheating threshold. The maximum temperature in ASHRAE 55 was rounded down to 32 °C to simplify the analysis.

4.2.3 Overheating identification and criteria

The calculation and analysis were conducted in four steps (Table 4.5) as follows.

- Step 1 was a general screening for all houses in NV and AC mode to confirm the existence of overheating.
- Step 2 was metadata screening for all houses, including assessing the heat severity of outdoor temperature, comparing the ground floor temperatures with ASHRAE 55 adaptive thermal comfort range, and comparing the top floor temperatures with the ground floor temperatures in NV mode.
- Step 3 was a detailed screening for the high-performance houses in NV mode.
- Step 4 was a comparison of the proposed overheating criteria with the current criteria in NV mode.

Steps 1 and 2 assess the thermal conditions based on the current definitions of overheating (CIBSE 2015); adaptive thermal comfort range and upper threshold (ASHRAE 2016); and heatwaves (Nairn, J & Fawcett 2012; Nairn, JR, Fawcett & Day 2013). Step 3 develops a local definition for overheating and proposes a method that can be employed globally. Three parameters are examined in this research; namely frequency, amplitude and weighted exceedance temperatures (WEH). Descriptions of the three main terms in Table 4.5 are as below.

Frequency means the number of times that the hourly temperatures of a given item (outdoor air temperature/ ground floor/ top floor temperatures) exceed the relevant threshold during a year/ summer/ month (the period for calculation is noted on top of each cell in the table).

Amplitude means the maximum exceedance that the hourly temperatures of a given item (outdoor air temperature/ ground floor/ top floor temperatures) exceeds the related threshold during a year/ summer/ month (the period for calculation is noted on top of each cell in the table).

WEH means the total degree hours of the exceeded hourly temperatures of a given item (outdoor air temperature/ ground floor/ top floor temperatures) above the related threshold during a year/ summer/ month (the period for calculation is noted on top of each cell in the table).

Steps 1–4 are extensively explained in this section.

Table 4.5 Steps for overheating identification

Steps	Period	Mode	Criteria	Calculated parameters
1 General screening	December-February of 2011–2015	MM	32 °C for indoor temperature based on CIBSE 2015 definition of overheating and ASHRAE 55 highest acceptable temperature	**Yearly and during summer** Frequency of days with top floor maximum daily air temperature above criterion (overheating identification)
2 Metadata screening	December-February of 2011–2018	NV	35 °C for outdoor temperature based on heatwaves definition	**Monthly** Frequency, WEH and amplitude of outdoor air temperature
			ASHRAE 55 adaptive thermal comfort range	Correlation between ground floor temperature and running mean outdoor temperature for NV mode during eight summers
			Ground floor temperature during NV mode	**Monthly** Frequency, WEH and amplitude for top floor temperature (overheating criteria)
3 Detailed screening	December-February of 2011–2018	NV		**Monthly** Difference between ground floor temperature and outdoor temperature during sunshine hours
				Correlation between ground floor temperature and running mean outdoor temperature for NV mode of high-performance houses during eight summers
4 Criteria comparing			Suggested in Step 2, Suggested by CSIRO, CIBSE TM 52	**Monthly** Frequency, WEH and amplitude

<u>Step 1</u> includes the below process:

- Clean the available minute-by-minute data by deleting extra days of some February months which had more than 28 recorded days.
- Select the summers that have usable data based on the availability of data for all summer days. Summers 2011–12 and 2017–18 are deleted for houses K and B, respectively (Table 4.6) as a result of this stage.
- Convert the minute-by-minute data to hourly for AC electricity usage, ground floor (dining room) temperatures and top-floor (bedroom) temperature.

- Calculate the maximum daily temperature, the number of days when the maximum top floor air temperature exceeded 32 °C for each house in each year and each summer, separately.

- Calculate the T_{rm} based on equation 4.2

As the houses were not built at the same time, their monitoring did not commence simultaneously. Table 4.6 shows the months of available data for each house. In total, data of 64 months were processed.

The results of Step 1 showed the frequency of days with the top floor temperature higher than 32 °C for five years and four summers.

Table 4.6 Summer months processed for each house

Summer	Months	A	B	C	D	E	F	G	J	K
2011	2010 12	*		*	*		*	*		*
	2011 01	*		*	*		*	*		*
	2011 02	*		*	*		*	*		*
2012	2011 12	*		*	*	*	*	*	*	
	2012 01	*		*	*	*	*	*	*	
	2012 02	*		*	*	*	*	*	*	
2013	2012 12	*	*	*	*	*	*	*	*	*
	2013 01	*	*	*	*	*	*	*	*	*
	2013 02	*	*	*	*	*	*	*	*	*
2014	2013 12	*	*	*	*	*	*	*	*	*
	2014 01	*	*	*	*	*	*	*	*	*
	2014 02	*	*	*	*	*	*	*	*	*
2015	2014 12	*	*	*	*	*	*	*	*	*
	2015 01	*	*	*	*	*	*	*	*	*
	2015 02	*	*	*	*	*	*	*	*	*
2016	2015 12	*	*	*	*	*	*		*	*
	2016 01	*	*	*	*	*	*		*	*
	2016 02	*	*	*	*	*	*		*	*
2017	2016 12	*	*	*	*	*	*		*	*
	2017 01	*	*	*	*	*	*		*	*
	2017 02	*	*	*	*	*	*		*	*
2018	2017 12	*	*		*	*	*		*	
	2018 01	*	*		*	*	*		*	
	2018 02	*	*		*	*	*		*	
Number of Summers for Each House		8	6	7	8	7	8	5	7	6
Number of Months for Each House		24	18	21	24	21	24	15	21	18
Total Months					216					

Step 2 (metadata screening) involved all houses over eight consecutive summers focused on the NV mode during a longer period of monitoring, December–February 2011–2018. The NV mode was investigated, as it was expected that in AC mode no overheating should occur. As there was no data about occupancy hours and window opening hours, there is

no information on how much natural ventilation was actually activated during the NV mode. Therefore, the measured overheating is likely to have been affected by opening or closing the windows during the period of investigation. The AC operative hours were identified through reviewing the electricity usage data for AC during each hour. The AC electricity usage minute-by-minute data shows that there was always a small amount of electricity consumption for all houses while the residents pointed they turned off the ACs. This electricity consumption is apparently due to the pulses of sensors connected to ACs or the refrigerant circulation in some units. AC consumed 0.075 kWh for all houses except house H with 0.12 kWh and house B with 0.06 kWh (Table 4.7). Table 4.6 shows these values and the minimum electricity consumed per hour by the sensor for each house, forming a threshold with any usage above it, indicating operating the AC. In addition, the target rooms for operating AC were found through room temperatures before and after starting the AC operation. If the given room was at least 1 ˚C cooler after one hour of operating the AC, that room was considered the target room/s for AC.

Table 4.7 The technical data of AC electricity usage and sensors

Houses	AC System	AC Electricity Usage (kWh)	Pulses Interval (minute)	Minimum Electricity Usage for Pulses (kWh)
A 10	Ducted RC	5.2–13.5 (ActroAair 2018)	7	0.075
B 14	Ducted RC	5.2–13.5 (ActroAair 2018)	1-48	0.06
C 36	Ducted RC	5.2–13.5 (ActroAair 2018)	7	0.075
D 37	Split RC	2.5–13 (Mitsubishi 2018)	1-5	0.075
E 51	Ducted RC	5.2–13.5 (ActroAair 2018)	7	0.075
F 57	Splits RC	2.5–13 (Mitsubishi 2018)	1-11	0.075
G 60	Ducted Evaporative Cooling	2.9–13 (Coolair 2012; Norman 2018)	7	0.075
J 67	Ducted Evaporative Cooling	2.9–13 (Coolair 2012; Norman 2018)	1-5	0.075
K 77	Split RC (2 Outdoor units)	2.5–13 (Mitsubishi 2018)	1-2	0.075

The operative temperature is substituted by the monitored average air temperature as used by many other studies (Kim, J et al. 2016; Manua et al. 2016; Saman et al. 2013). To use average air temperature instead of operative temperature, the following conditions have to be met. No radiant-related heating/cooling system, average R-Value higher than 3.3 m²K/W, envelope requirements of ASHRAE 90.1-2013 (window U-Value lower than 2.38 W/m²K, average R-Value for all walls in various orientations higher than 0.53 m²K/W) for building construction and the Window Solar Heat Gain Coefficients (SHGC)

less than 0.48 (ASHRAE 2016). The properties of houses in Lochiel park (Appendix D) shows that these houses met the conditions due to the following reasons. The only possible issue might be the ceilings might be hot and behave as a heating surface during high summer temperatures. However, their surface temperatures were not monitored.

Table 4.5 shows that Step 2 includes three groups of calculations based on three thresholds. The first group was calculating parameters for outdoor temperature, which were monthly frequency, WEH and amplitude of outdoor air temperature exceeding 35 °C (Table 4.5). This calculation provides an overview of heat loads during these periods. The second group was finding a correlation between ground floor temperature of all houses and running mean outdoor temperature during eight summers. This calculation reveals the general thermal condition of the ground floors in NV mode compared with ASHRAE 55 adaptive thermal comfort range. The third group was calculating parameters for the top floor temperature, which were monthly frequency, WEH and amplitude of outdoor air temperature exceeding ground floor temperature during eight summers.

The WEH for outdoor air temperature when it was higher than 35 °C was computed through the following formula:

$$\sum_{d=1}^{29\ or\ 31} \left(\sum_{h=1}^{24} T_{Oh} - 35\right)\mathrm{d} \qquad \text{(Equation 4.4)}$$

Where:

T_o = Outdoor temperature when it is higher than 35 °C

d = days in December, January or February

h = hours of one day

The WEH for the top floor when it was warmer than the ground floor was computed by the following equation:

$$\sum_{d=1}^{29\ or\ 31} \left(\sum_{h=1}^{24} T_{TFh} - T_{GFh}\right)\mathrm{d} \qquad \text{(Equation 4.5)}$$

Where

T_{TF} = top floor temperature when it is greater than ground floor temperature

T_{GF} = ground floor temperature

d = days in December, January or February

h = hours of one day

In order to assess the overheating on the top floor, the top floor temperatures were compared with those of the ground floor because:

1) the result of second group calculations of Step 2 showed that in NV mode, more than 88.4% of ground floors temperature were in ASHRAE 55adaptive thermal comfort range, so the ground floor temperatures could be used as a baseline;

2) there is no localised standard for the adaptive thermal comfort upper threshold;

3) Chapter 3 survey showed a high thermal comfort perception by households in the ground floor during summer NV mode and the low operating AC hours found by calculation confirmed the survey result; and

4) Step 1 (general screening) was a deductive approach with a reasonable highest threshold, while Step 2 (metadata screening) was an inductive approach which the aim of finding a local upper threshold for adaptive thermal comfort and overheating. The metadata screening focused on the NV mode (Table 4.5) and all other interferences such as periods of sunshine, AC mode and thermal emittance for the outside part of external walls were not considered.

The outputs of Step 2 are:

a) proposed criteria for overheating indices;

b) confirmed that the categorization of general screening was conducted correctly.

Step 3 (detailed screening for the highest-performance houses) involved calculations for eight consecutive summers focussing on NV mode during December–February of 2011–2018. The ground floor indoor NV mode temperatures were compared with the outdoor temperatures during sunshine periods and for the whole day, separately for eight summers. The ground floors were investigated as these floors were used as a baseline in the metadata screening. The sunshine period was focused on because the metadata analysis showed that the top floors exceeded 32 °C, generally during this period. The sunshine period is generally defined when the direct solar radiation equals or exceeds 120 W/m^2 (Meteorology 2012) and for the summers under consideration, it occurred from 7 am to 5 pm. A correlation was found between indoor NV mode temperature and running mean outdoor temperature. The weather data were collected from the Bureau of Meteorology weather station closest to the houses.

Step 3 evaluated the difference between ground floor temperatures and outdoor temperatures during sunshine hours, suggested an equation for a neutral line for adaptive thermal comfort that formed the baseline for overheating criteria, checked the overheating criteria proposed in Step 2.

Step 4 (criteria comparison) includes comparing the proposed method for overheating limit in Step 2 with methods suggested by CSIRO (Chen & Ren 2019) and CIBSE TM 52 (Nicol 2013) that are explained in Chapter 2 (Table 2.7). The CSIRO method is selected as proposes limits for Australia, but as this method separates the night and day limits, another method was selected. The second method to compare with the proposed method by this study is CIBSE TM 52 as it is the last version of method for Europ with no separation for night and day. The three groups of criteria were compared by applying them to the top floor of three energy-efficient houses for eight summers (Dec 2010–Feb 2018). These houses (B, G and J) were identified as high-performance in Chapter 3 (Sharifi, Saman & Alemu 2019). The periods of the available data varied for the houses understudy, as houses B, G and J were occupied in 2012, 2010 and 2011, respectively. In addition, the data is incomplete in three summers for house G and two summers for house J. According to the survey results, house B and J residents rated the thermal comfort of the top floor of their house 8 and 5 on a numerical 10-point scale, respectively. The residents of house G did not participate in the survey, but it appears that the residents were happy with the thermal comfort condition of NV mode as they had no recorded AC operation during summer months (Table 4.8), while their neighbours reported that the residents of house G were at home during those periods.

The adaptive thermal comfort upper threshold for the developed criteria that is similar to the ASHRAE 55 standard adaptive thermal comfort 80% acceptable upper threshold was set in Step 3 for 10–35 °C running mean outdoor temperature (Sharifi, Saman & Alemu 2019). All weighted exceedance hours are calculated based on the formula of Criterion 2 in Table 2.7. The adaptive thermal comfort upper threshold for the CSIRO criteria and CIBSE TM 52 is the EN 15251 Category II upper threshold for 10-30 °C running mean outdoor temperature. The overheating limits for the CSIRO and CIBSE TM 52 are listed in Table 2.7 and the calculation is conducted based on those.

In addition to the overheating indices for three selected criteria, the percentage of overheating was calculated in NV mode for each criterion of three groups through the available summers, separately.

Step 4 found evaluated the proposed criteria.

Table 4.8 Number of hours and days that AC was operating in a whole house (WH) and top floors (TF) during a month

Houses	**B**			**G**			**J**		
	Days	Hours		Days	Hours		Days	Hours	
Months	WH	WH	TF	WH	WH	TF	WH	WH	TF
2010-12				0	0	0			
2011-01				0	0	0			
2011-02				0	0	0			
2011-12				0	0	0	0	0	0
2012-01				0	0	0	0	0	0
2012-02				0	0	0	0	0	0
2012-12	0	0	0	0	0	0			
2013-01	1	1	0	0	0	0			
2013-02	19	128	1	0	0	0			
2013-12	4	9	0	0	0	0	0	0	0
2014-01	14	70	0	0	0	0	0	0	0
2014-02	9	49	1	0	0	0	0	0	0
2014-12	1	1	0	0	0	0	0	0	0
2015-01	3	7	0	0	0	0	0	0	0
2015-02	0	0	0	0	0	0	0	0	0
2015-12	8	37	0				0	0	0
2016-01	13	38	0				0	0	0
2016-02	3	6	0				0	0	0
2016-12	3	6	0				0	0	0
2017-01	10	36	0				2	7	0
2017-02	6	43	2				2	14	1
2017-12	2	4	0				0	0	0
2018-01	13	67	3				1	0	0
2018-02	9	58	2				0	0	0

4.3 Results

4.3.1 General screening

The top floor of houses D and K were not expected to be ventilated as the residents were retired couples with their master bedrooms on ground floors and it is generally assumed that people only open windows in occupied rooms. The households A, C, E and J might ventilate the top floors only during night-time when they use it. House B had a home office on the top floor which was used during the day and the ground floor bedroom was allocated for night sleep. The ground floor of house G could be ventilated at night as residents were a working couple with no children and used the ground floor master bedroom. In total, seven of the houses had just nocturnal ventilation for the top floor except house B. Houses G and J with 4.5 and 2 days overheating, respectively were nocturnally ventilated houses. All houses had west-facing windows on both levels, except

house D, with no west-facing window on the top floor. The south-facing windows were used the least in all houses. House, J and K had shading devices rather than eaves.

The monitoring data collected over a period of five years (January 2011–December 2015) for the seven houses in MM mode were analysed, including four consecutive summer seasons (December–February). The number of overheated days for each house during each summer is summarised in Table 4.8. The number of overheated days on the top floors varied from one in house B to 33 in house A. On average, the number of overheated days for the top floors was 19 (21% of the summer days). Three houses (A, C, D) had overheating for more than 30 summer days. The remaining houses (B, E, G, J, and K) had overheating for less than 27 summer days. Six houses operated their AC on average for less than 9% for the first four summers and only house K operated its AC for about 15% of the summer (see Table 4.9). Table 4.9 presents two averages for general screening (four summers) and metadata screening for all houses (eight summers). The yearly number of overheated days on the top floors increased for five houses (Figure 4.5) with overheating occurring in all years (72.5% during summer and 27.5% outside summer months). The number of yearly overheated days outside summer varied from 1 to 24 days across all the houses and was highest for houses A, C, D and K. Figure 4.6 indicates that in all houses, the top floor mean daily and maximum temperatures were greater than that of the ground floor during the summer months. Houses C, D and K had the highest difference in terms of maximum temperature, whilst houses G and J had the lowest difference in both daily and maximum temperatures between the top and ground floors. This shows that houses C, D and K were performing poorly compared with houses G and J.

Houses A, C and D had 30 to 33 days with maximum temperatures above 32 ˚C while having an operating AC 0.8-66 hours in a typical summer (Tables 4.8 and 4.9). These houses have significant low performance compared to buildings B, G and J with overheating from 2 to 5.3 days and operating AC for zero to 0.4 hours in a typical summer. Furthermore, house A shows a high number of overheated days in comparison with other houses regardless of operating AC. Similarly, the ground floor of house K has low performance too, as the AC was running for about 50% of the summer hours on the ground floor and it still had overheated days whilst other houses did not show the same proportion. The results for houses G and J (Figures 4.5 and 4.6) indicate that the top floors of these houses had the best thermal comfort compared with the other houses.

Table 4.9 Frequency of days with maximum temperature above 32 °C in top and ground floor during four summers MM mode; TF = Top Floor, GF = Ground Floor

	A		B		C		D		E		G		J		K	
Summer	TF	GF	TF	GF	TF	GF	TF	GF	TF	GF	TF	GF	TF	GF	TF	GF
2011-2	41	20	----	----	24	1	45	0	13	0	1	1	3	0	21	0
2012-3	33	23	1	0	40	3	33	0	12	0	2	3	4	0	27	2
2013-4	34	22	11	0	32	0	39	0	16	9	5	2	8	0	24	0
2014-5	24	22	9	0	24	0	16	0	11	0	1	0	3	0	16	5
Average	33	22	7	0	32	1	33	0	13	2	2	1.5	4.5	0	22	2
The average number of overheated days for all houses									TF= 19		GF= 4					

Table 4.10 Number of hours for operating AC during summer months for top floor and ground floor; TF = Top Floor, GF = Ground Floor

House	**A**		**B**		**C**		**D**		**E**		**G**		**J**		**K**	
Level	TF	GF	TF	GF	TF	GF	TF	GF	TF	GF	TF	GF	TF	GF	TF	GF
Average of 4 summers	0.8	19.9	0.1	29.3	1.9	87.2	65.7	63.1	5.2	170.2	0.0	0.0	0.0	0.0	2.6	419.5
Average of 8 summers	0.8	15.7	0.4	30.7	1.8	82.1	62.9	60.3	3.5	146.4	0.0	0.0	0.0	0.0	3	419.3

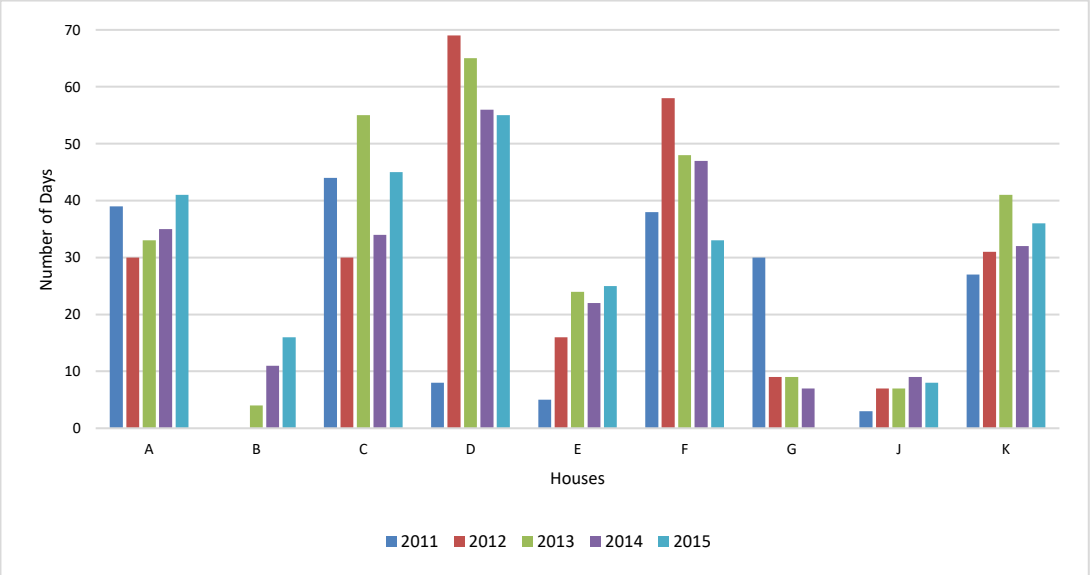


Figure 4.5 Number of days with maximum temperature on the top floors exceeding 32 °C for eight houses in Lochiel Park for five years

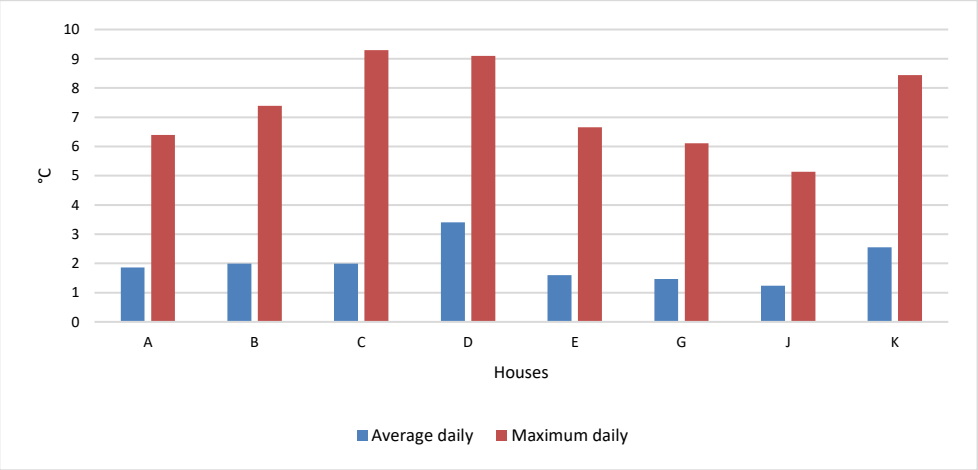


Figure 4.6 Difference in daily average and maximum temperatures between top and ground floors over four summers (December 2011 – February 2015)

4.3.2 Metadata screening for all houses

During the NV mode, only 3.6% and 11.6% of all eight houses' ground floor hourly temperatures were outside the ASHRAE 55 80% and 90% acceptability thresholds, respectively (Figure 4.7). The best fit linear equation for the neutral temperature was not far from that of ASHRAE 55.

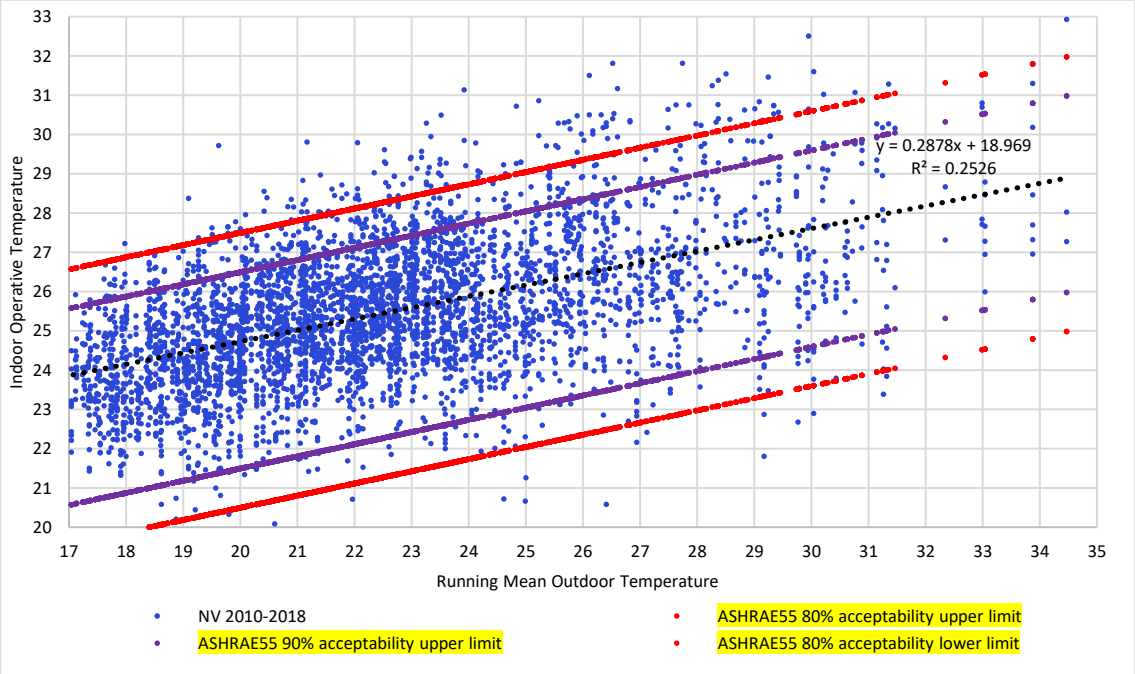
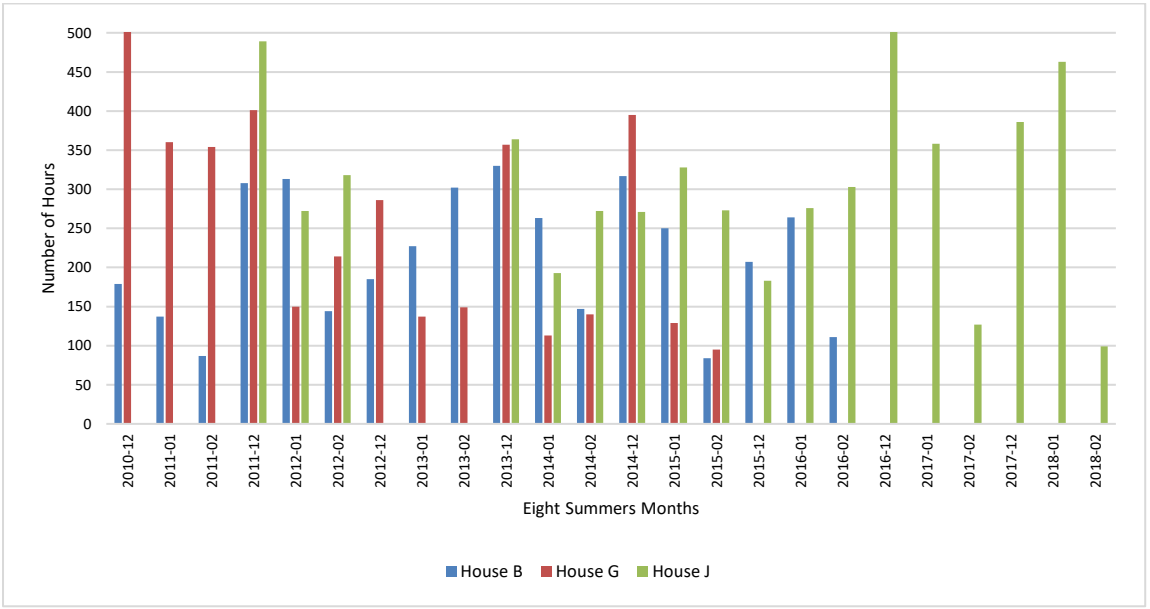


Figure 4.7 Ground floor temperatures plotted against running mean outdoor temperature compared to ASHRAE 55 80% and 90% acceptability limits for eight houses during eight summers

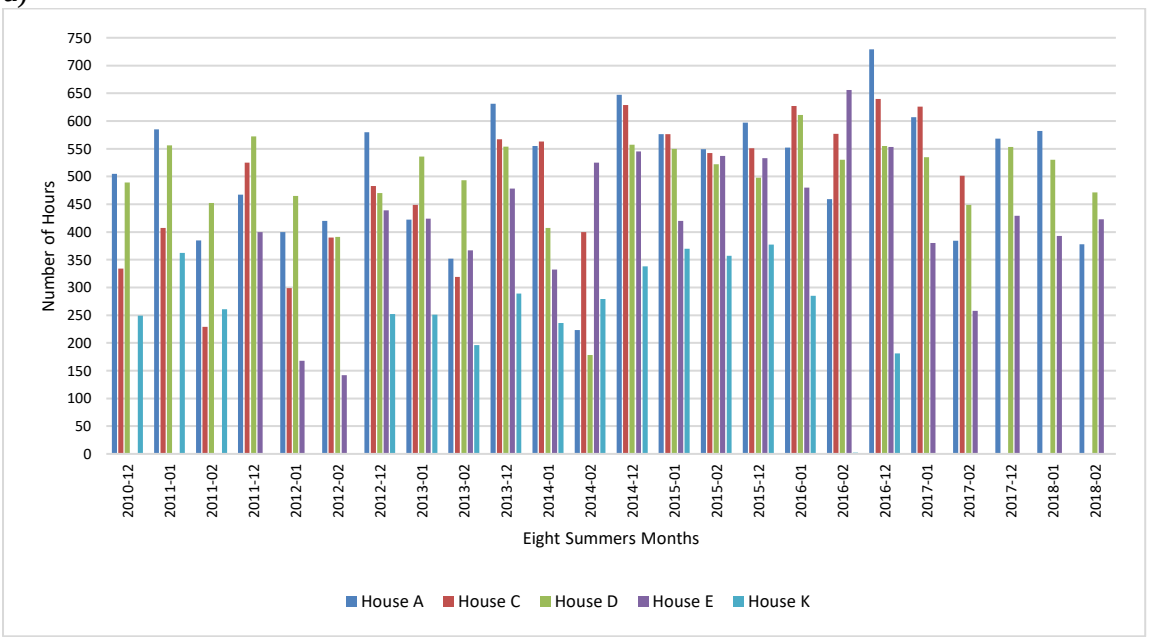
Based on the general screening of the houses, they were categorized as low-performance (A, C, D, E and K) and high-performance (B, G and J) in terms of overheating. The metadata screening for both categories involved analysing the monitored data collected over eight consecutive summers (December–February 2010–8) for the NV mode. The overheating on the top floor was measured through three indices: frequency, WEH and intensity of top floor temperature when exceeding ground floor temperatures.

Both the low and high-performance groups are close in their minima for the same indices. However, the maxima of the low-performance house indices are significantly higher than those of the high-performance house indices. The frequency parameter for the low-performance and high-performance houses was 125–730 and 75–500, respectively (Figure 4.9 and b). The WEH for the low-performance and high-performance is 100–1400 and 50–650 degree-hrs, respectively (Figure 4.10a and b). The amplitude parameter for

low-performance and high-performance was 2–10.7 ˚C and 2–9 ˚C, respectively (Figure 4.11a and b). Overall, the main difference between the two categories of house performance is the maximum of the frequency with 225 and the maximum of WEH with 750 degree-hrs.



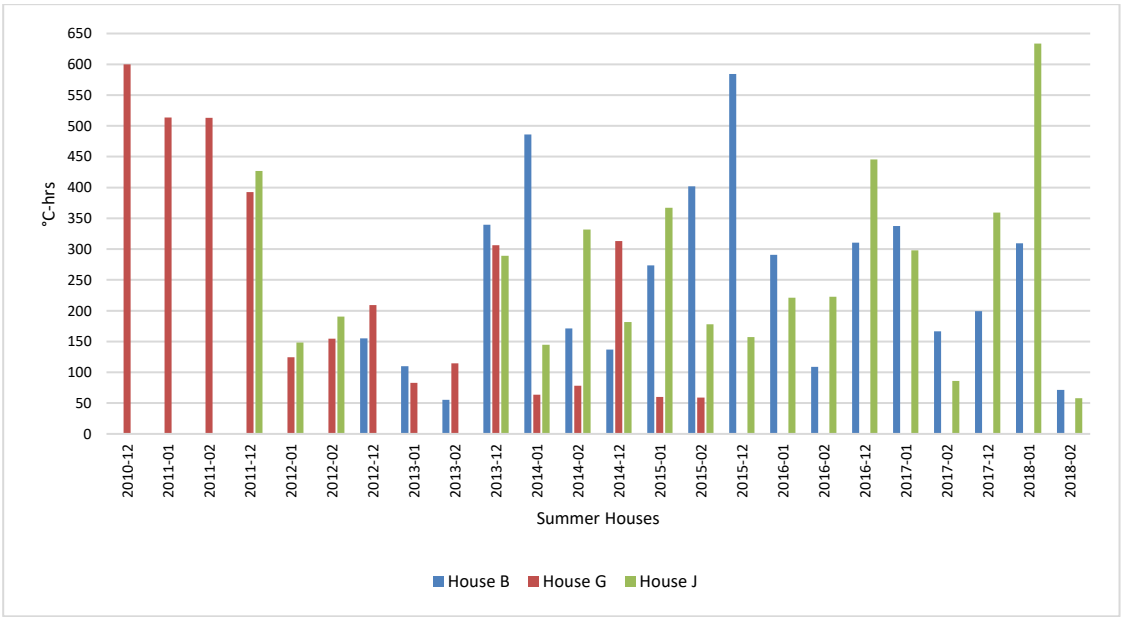
a)



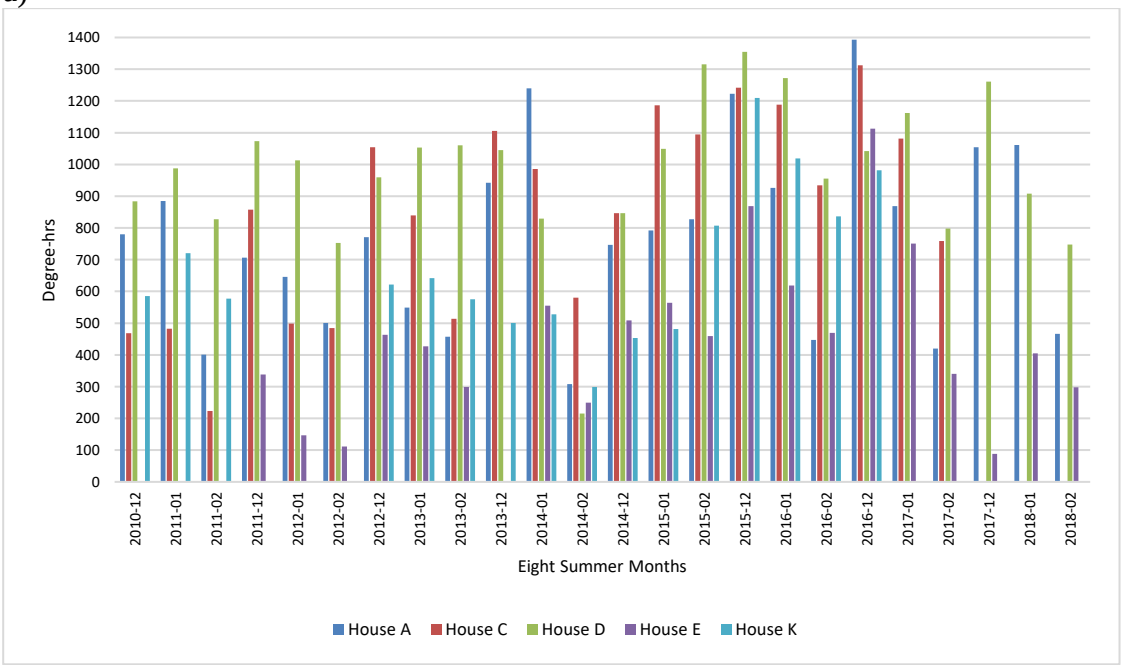
b)



Figure 4.8 Frequency of the top floor temperature exceeding ground floor temperature for seven houses in NV mode during eight summers: a) high-performance houses, b) low-performance houses



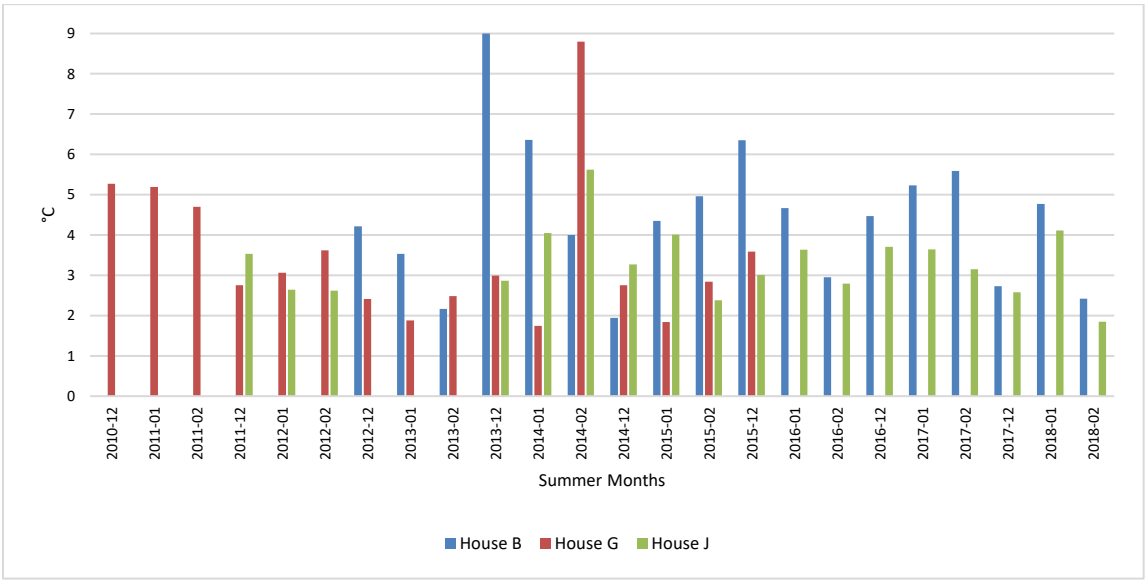
a)



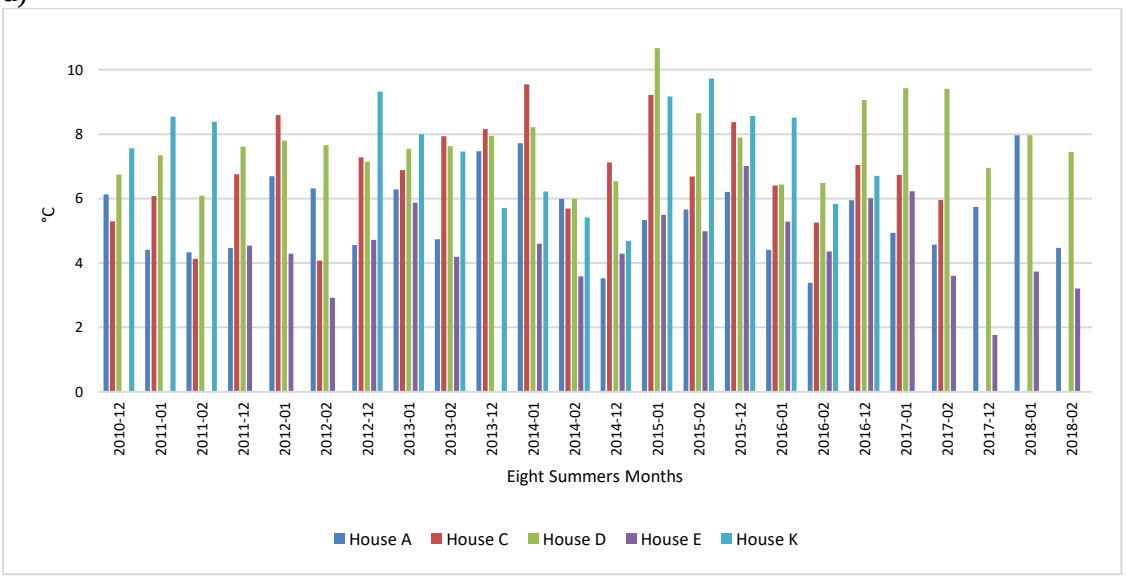
b)



Figure 4.9 WEH of top floor temperatures exceeding ground floor temperatures for eight houses in NV mode during eight summers a) high-performance houses, b) low-performance houses



a)



b)

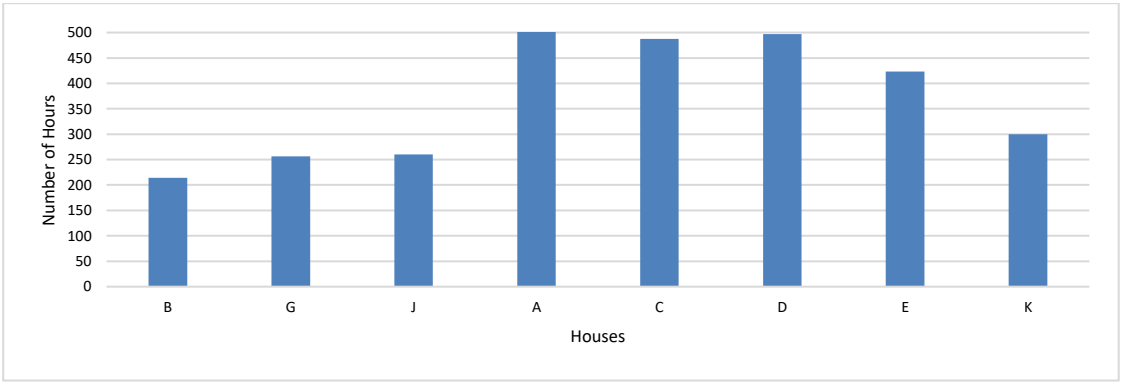


Figure 4.10 Amplitude of top floor temperature exceeding ground floor temperature for eight houses in NV mode for eight summers: a) high-performance houses, b) low-performance houses

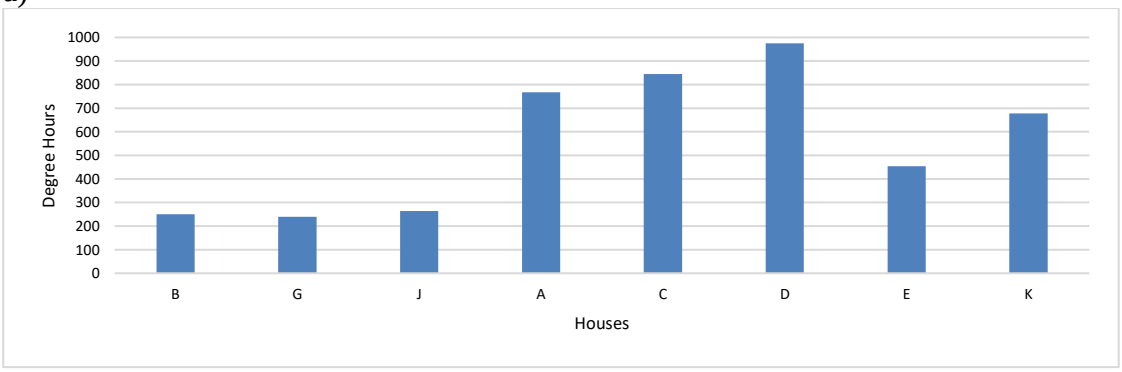
Figures 4.10 shows that the data for all houses are not covering the same period as some houses were built later or data for some houses were incomplete during some months. Although the data are not precisely for the same summers for all houses in the high-performance and low-performance cohorts, another way for comparing them is to compare the average of their indices. Figures 4.12a, b and c show the average of each

index for both groups and highlight a significant gap between the high-performance and low-performance houses, confirming that each house was allocated appropriately.

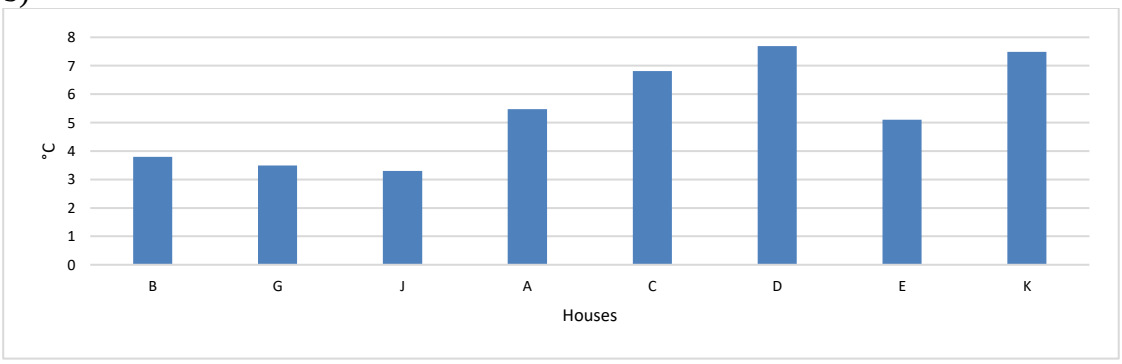
In all low-performance houses, the frequency trend was high, while the intensity was lower for three of them (A, E, and K) (Table 4.10). The decreased intensity trend is acceptable for houses A and K as their operating AC hours decreased in the ground floor of house A and increased on the top floor of house K. The decrease of intensity is not reasonable for house E, as the decrease of operating AC hours on the top floor was 19% more than that for the ground floor.



a)



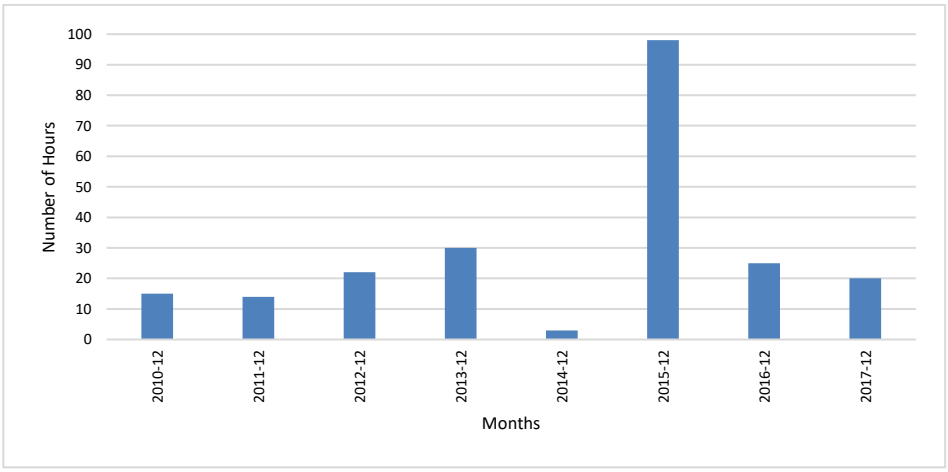
b)



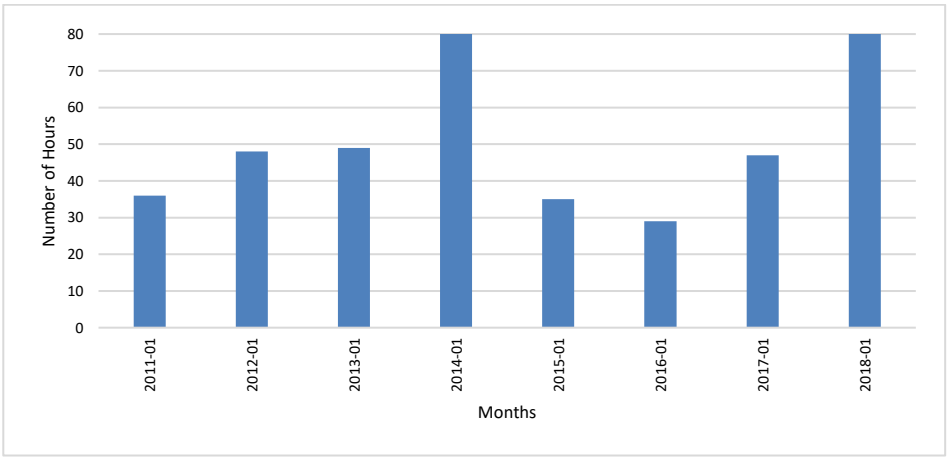
c)

Figure 4.11 Indices of top floor temperature exceeding ground floor temperature in eight houses average of eight summer months: a) frequency, b) WEH, c) amplitude

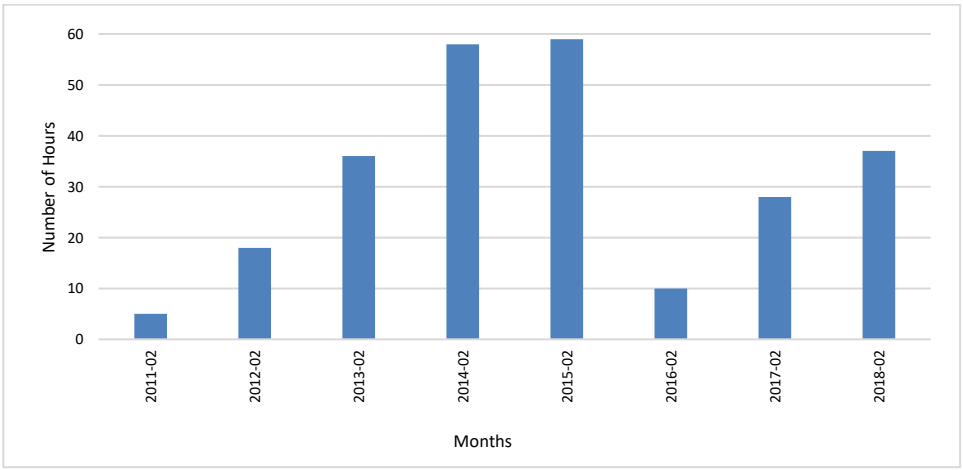
For the eight summers under study, the frequency of outdoor temperature exceeding 35 °C ranged from 3 hours for Dec 2014to 98 hours in Dec 2015 (Figure 4.12a). The figures show a general tendency of an increasing number of hours above 35 °C. (Figure 4.12a, b and c).



a)



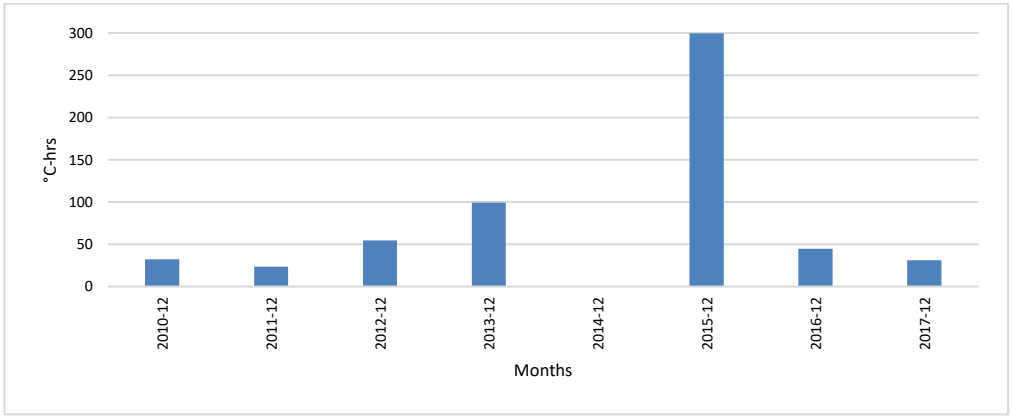
b)



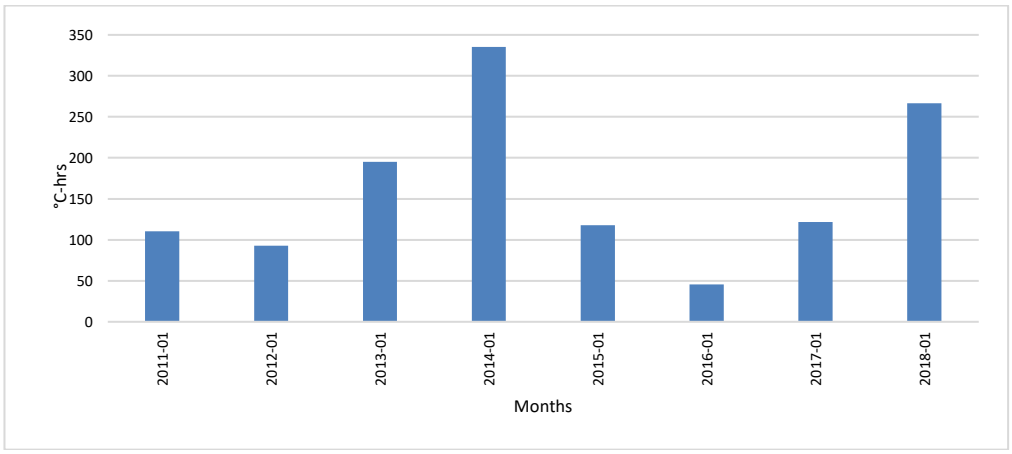
c)

Figure 4.12 Frequency of outdoor temperature exceeding 35 ° for eight summers: a) December months, b) January months, c) February months

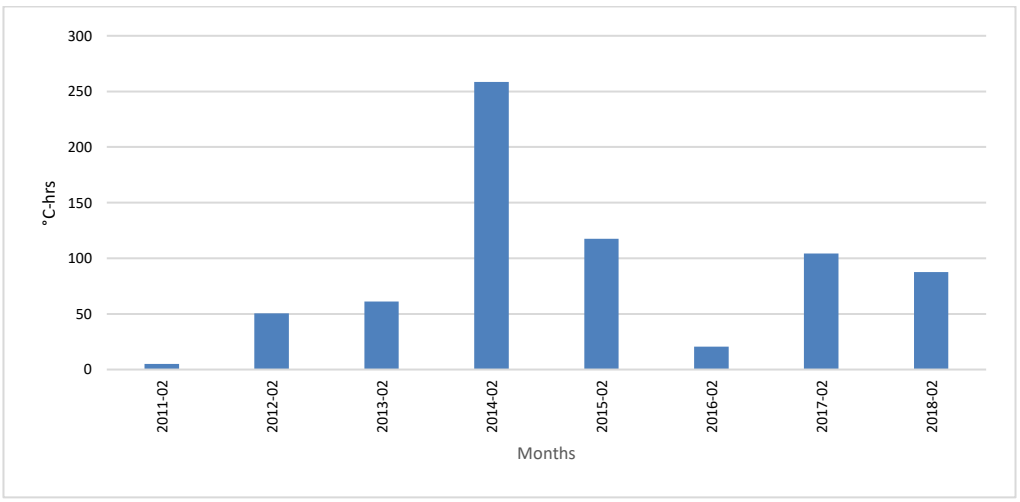
The WEH for months of the studied summers ranged from 0.5 degree-hrs in Dec 2014 to 335 degree-hrs in Feb 2014 (Figure 4.13a and b). The figures show a general tendency of an WEH of outdoor temperature exceeding 35 °C. (Figure 4.12a, b and c).



a)



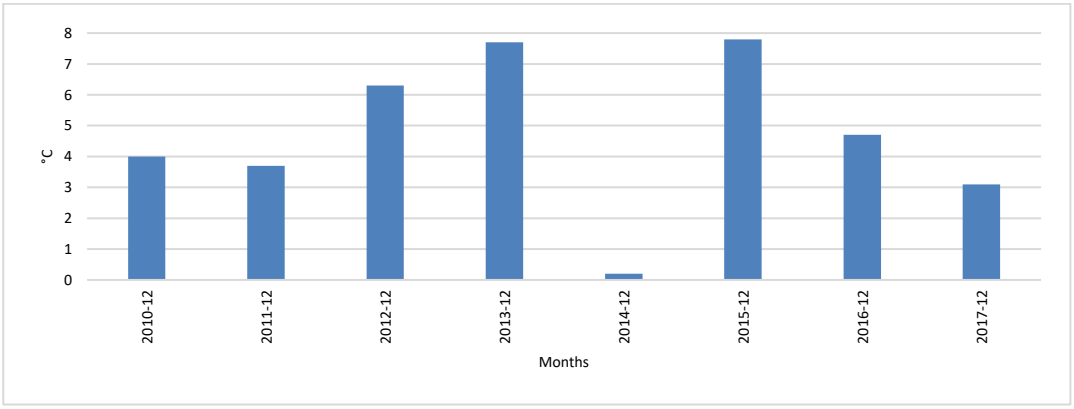
b)



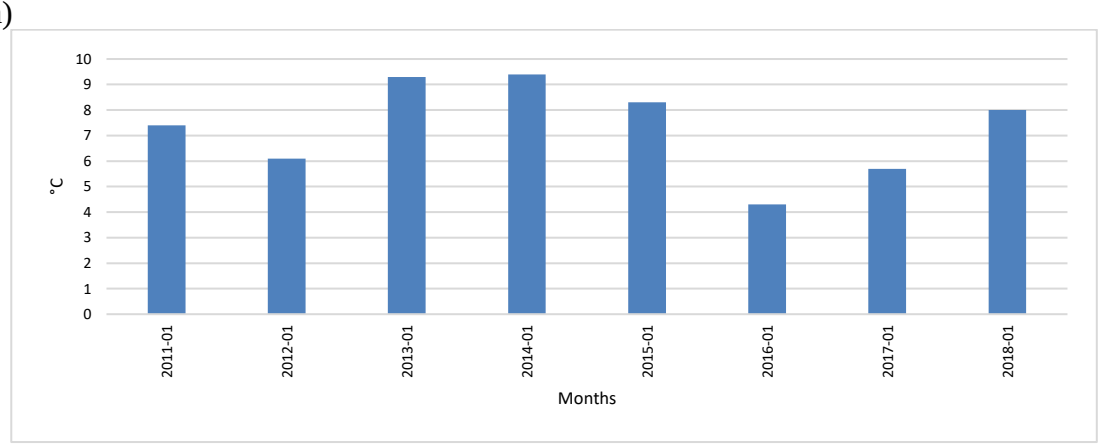
c)

Figure 4.13 WEH of outdoor temperature exceeding 35 ° for eight summers: a) December months, b) January months, c) February months

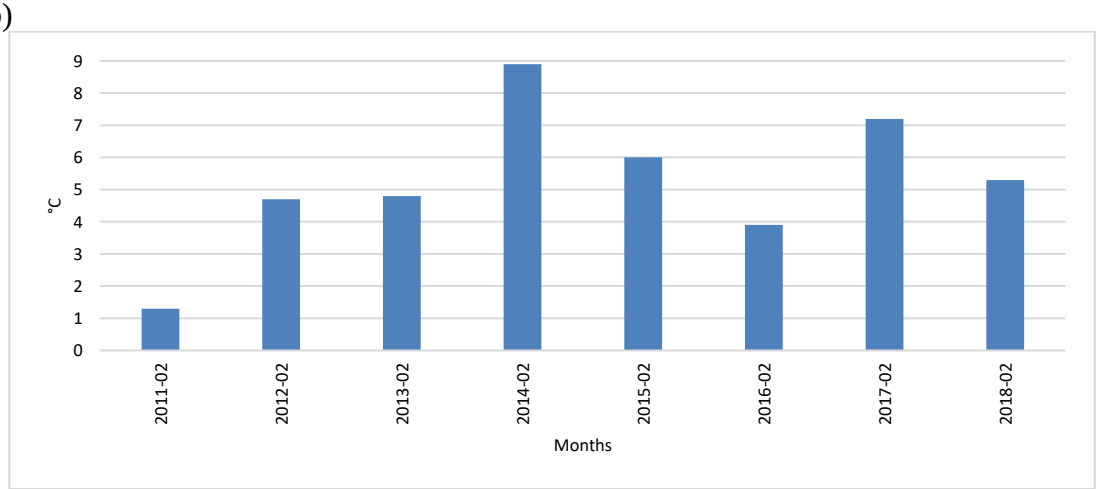
The amplitude of outdoor temperature exceeding 35 °C ranged from 0.2 °C in Dec 2014 to 9.5 °C in Jan 2014 (Figure 4.14a and b). There were many months where the temperatures approached the low and mid-forties C (Figure 4.14a, b and c).



a)



b)



c)

Figure 4.14 amplitude of outdoor temperature exceeding 35 ° for eight summers: a) December months, b) January months, c) February months

4.3.3 Detailed screening for high-performance houses

This section is based on general and metadata screening. The general screening categorized houses B, G and J as high-performance in terms of overheating and houses A, C, D, E and K as low-performance. The metadata screening confirms the general screening categorization. Thus, for detailed screening, houses B, G and J were investigated to find the correlation between these houses ground floor temperatures and the temperatures during sunshine hours as well as a running mean outdoor temperatures.

In NV mode, the ground floor temperatures were higher than the outdoor temperatures during sunshine for 28–83% of the hours, with the ground floor temperature cooler for the remaining hours (Figures 4.15). The maximum exceedance being 3.9 °C (Figure 4.16) and the largest reduction of 8.4 °C (Figure 4.17). On average, the ground floor temperatures are 3 °C warmer than outdoor during sunshine hours for 53% of NV mode and are 5 °C cooler than outdoor sunshine hours for 47% of NV mode. Therefore, these energy-efficient houses' ground floors can be labelled as being generally cooler than the outdoor during sunshine hours during the NV mode.

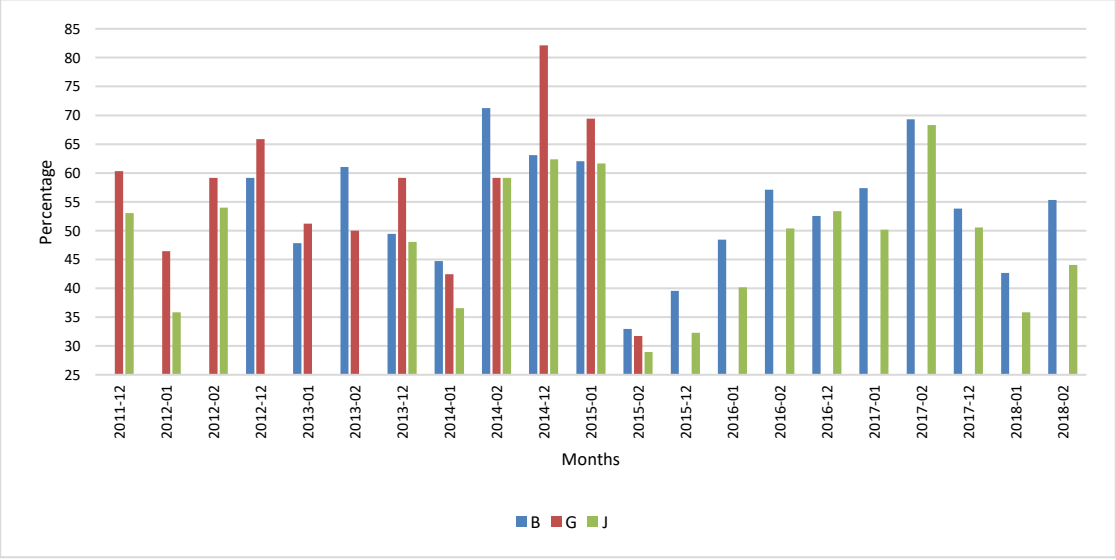


Figure 4.15 The percentage of hours when the ground floor in NV mode was warmer than the outdoor temperature during sunshine periods over eight summer months

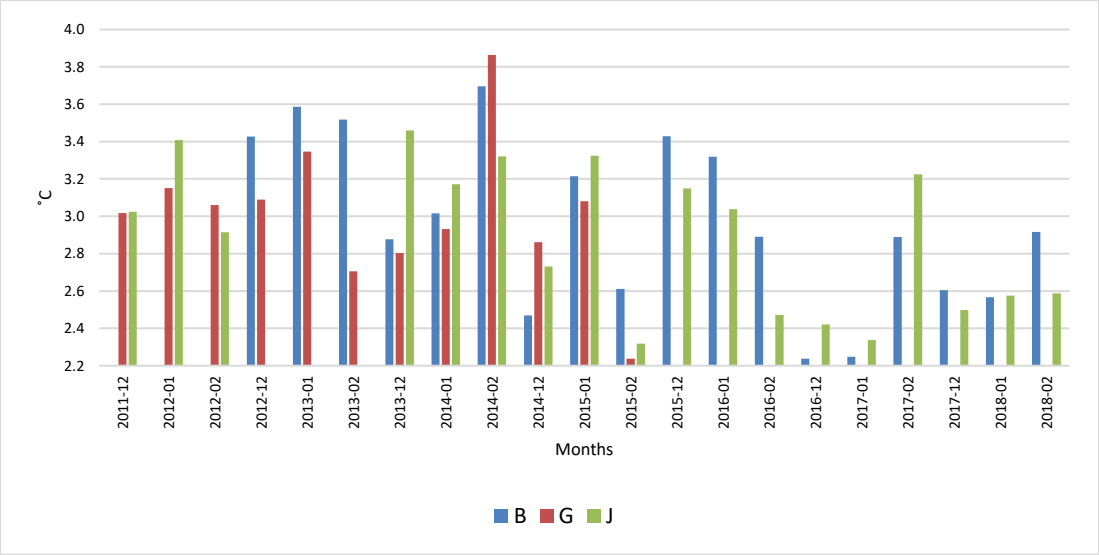


Figure 4.16 Monthly average ground floor temperatures exceedance of outdoor temperature during sunshine periods over eight summer months in NV mode.

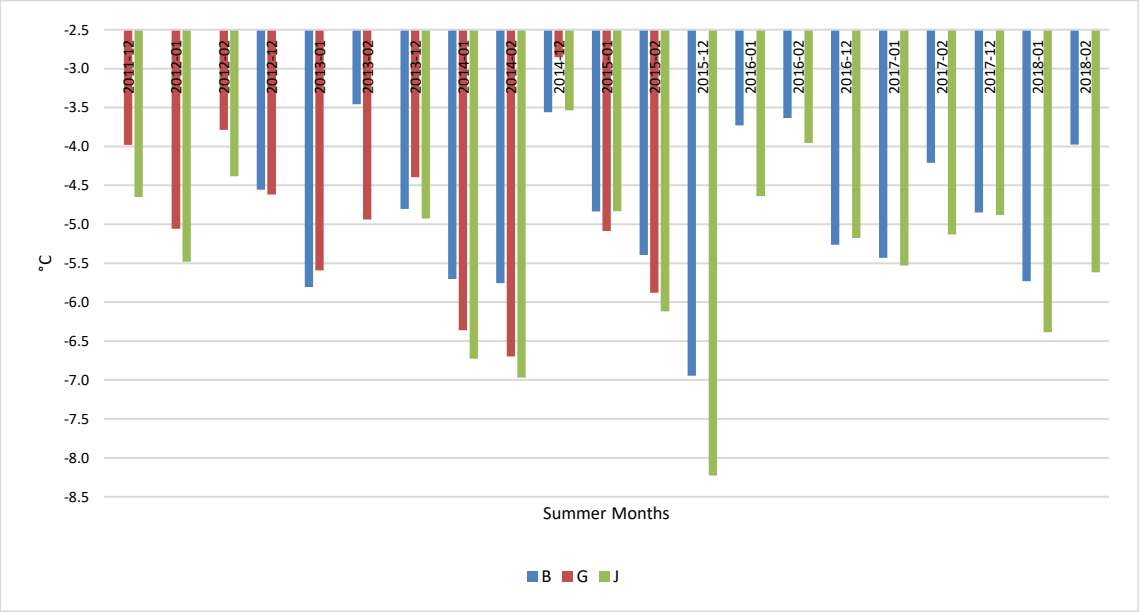


Figure 4.17 Monthly average temperatures in ground floors below outdoor temperature during sunshine periods over eight summer months for NV mode

The correlation between the ground floor indoor temperatures during NV mode and running mean outdoor temperature is plotted in Figure 4.18. The linear fitting equation (Indoor temperature = 0.27 T_{rm} + 19.2) is close to the ASHRAE 55 (ASHRAE 2017) adaptive thermal comfort equation (Indoor operative temperature = 0.31 T_{rm} + 17.8). This closeness confirms that the three houses were categorized correctly in the high-performance cohort and provides further support for the ASHRAE adaptive comfort equation.

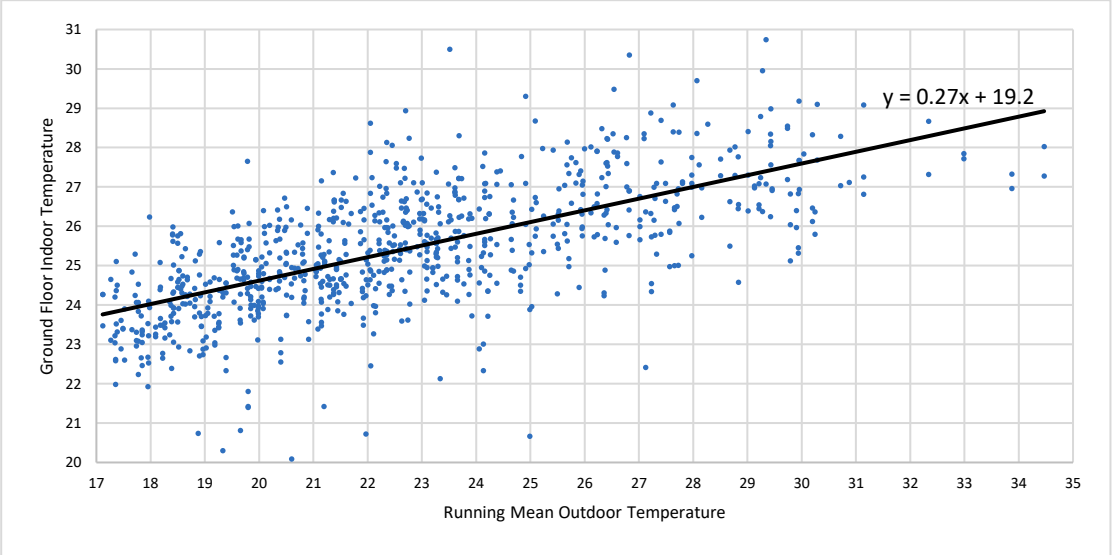


Figure 4.18 Correlation between running mean outdoor temperature and ground floor temperature for NV mode during eight summer months

4.3.4 Criteria comparison

The WEH of overheating for the top floors of houses B, G and J based on the developed criteria are 11%, 20% and 11% above the threshold (Table 4.12). The developed criteria found the amplitude of overheating for houses B, G and J to be 44%, 53% and 50% above the threshold, respectively (Table 4.12).

The criteria of CSIRO identified the minimum overheating in top floors for non-sleeping hours with 5% overheating for houses B and J and 20% overheating for house G (Table 4.12). The criteria of CSIRO showed overheating during sleeping hours on the top floor of houses B, G and J as 39%, 13% and 11%, respectively.

The criteria of CIBSE TM 52 identified overheating on top floors for non-sleeping and sleeping hours by 100% and 83% above the threshold, respectively. These percentages are far from the monitored performance and survey outcomes. Therefore, CIBSE TM 52 will not be used in the comparison and analysis.

There are agreements between the developed criteria' findings and those proposed by CSIRO (Tables 4.12 and 2.7). The overheating identified through the number of sleeping hours above the threshold of CSIRO criteria confirms the overheating identified by the developed criteria. The CSIRO sleeping hours agree with integrity by 90% and the intensity by 78% (Table 4.12).

Comparing with the proposed indices, two of the developed indices, WEH and amplitude, show some overheating for the three houses (Figures 4.19 and 4.20), the frequency index does not show overheating (Figure 4.21). The value for the proposed frequency index developed does not appear to be representative of overheating.

The results of the CSIRO criteria showed that the frequency of just one summer month could be close to or greater than the limit considered for five months or one year, as has happened in all three houses (Table 4.11). The frequency of overheating in sleeping hours in houses B and J showed a considerable overheating, which is not coincident with the survey as afternoons and evenings were pointed the main overheating hours in the questionnaires.

Table 4.11 Values of overheating indices for the developed criteria and the CSIRO criteria in houses B, G and J top floors (WEH=Weighted exceedance hours, Fr= Frequency, Am=Amplitude, Fr-n=Frequency of non-sleeping hours above the threshold, Fr s=Frequency of sleeping hours above threshold)

	House B					House G					House J				
	Developed Criteria			CSIRO Criteria		Developed Criteria			CSIRO Criteria		Developed Criteria			CSIRO Criteria	
	WEH	Fr	Am	Fr-n	Fr-s	WEH	Fr	Am	Fr-n	Fr-s	WEH	Fr	Am	Fr-n	Fr-s
Threshold	**250**	**243**	**3.8**	**67.5**	**32.4**	**250**	**243**	**3.8**	**67.5**	**32.4**	**250**	**243**	**3.8**	**67.5**	**32.4**
2010-12						413	218	6	107	53					
2011-01						370	196	6	107	19					
2011-02						522	232	7	111	50					
2011-12						94	77	3	38	6	82.2	67.0	3.8	32.0	11.0
2012-01						55	61	3	16	8	31.5	30.0	3.8	12.0	3.0
2012-02						92	86	4	40	1	23.4	36.0	2.7	12.0	0.0
2012-12	110.7	90.0	3.7	24.0	16.0	34	39	3	20	3					
2013-01	46.2	46.0	3.6	8.0	5.0	26	29	2	11	1					
2013-02	19.7	43.0	1.6	1.0	4.0	72	69	4	33	2					
2013-12	146.7	89.0	8.7	29.0	20.0	74	55	4	27	7	60.1	58.0	2.9	27.0	6.0
2014-01	199.0	141.0	4.9	38.0	45.0	20	21	2	9	1	53.9	49.0	4.2	23.0	1.0
2014-02	99.3	83.0	3.3	7.0	24.0	60	56	5	22	1	169.7	79.0	7.2	28.0	16.0
2014-12	54.2	56.0	2.6	13.0	9.0	117	103	4	51	3	57.7	47.0	4.5	23.0	4.0
2015-01	231.0	116.0	6.8	44.0	30.0	7	14	2	3	0	283.5	148.0	7.5	57.0	34.0
2015-02	302.3	192.0	4.8	61.0	55.0	17	21	3	6	0	34.7	42.0	2.4	16.0	0.0
2015-12	297.7	163.0	5.2	71.0	49.0						40	29	3	16	5
2016-01	210.6	192.0	3.6	32.0	46.0						75.8	74.0	3.8	28.0	2.0
2016-02	8.8	17.0	1.7	31.0	25.0						59.9	49.0	4.0	21.0	4.0
2016-12	123.0	84.0	3.7	27.0	25.0						80.2	56.0	4.2	36.0	4.0
2017-01	229.9	150.0	4.8	43.0	61.0						171.0	102.0	5.5	60.0	15.0
2017-02	156.1	66.0	6.1	15.0	34.0						77.3	59.0	4.3	32.0	1.0
2017-12	93.8	88.0	3.1	26.0	18.0						90.9	72.0	2.8	32.0	11.0
2018-01	218.1	142.0	4.8	33.0	40.0						347.1	139.0	6.8	72.0	39.0
2018-02	71.1	77.0	2.7	23.0	8.0						25.7	20.0	3.3	7.0	2.0
Above threshold (%)	11	0	44	5	39	20	0	53	20	13	11	0	50	5	11

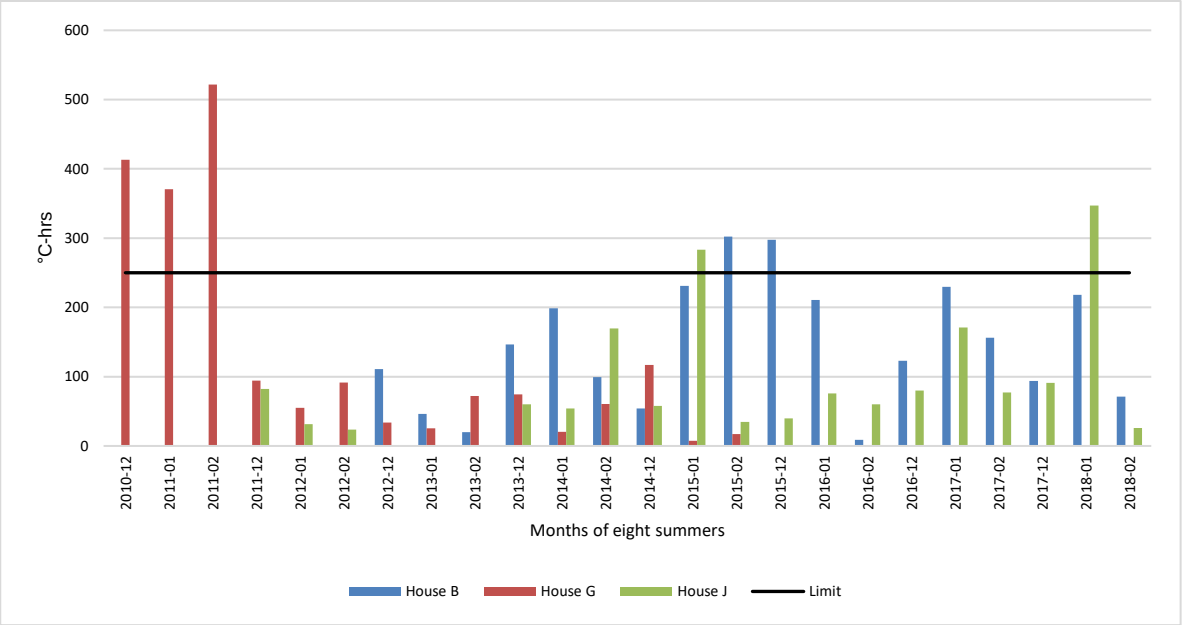


Figure 4.19 WEH index of overheated hours for houses B, G and J top floors during eight summers sing the proposed method

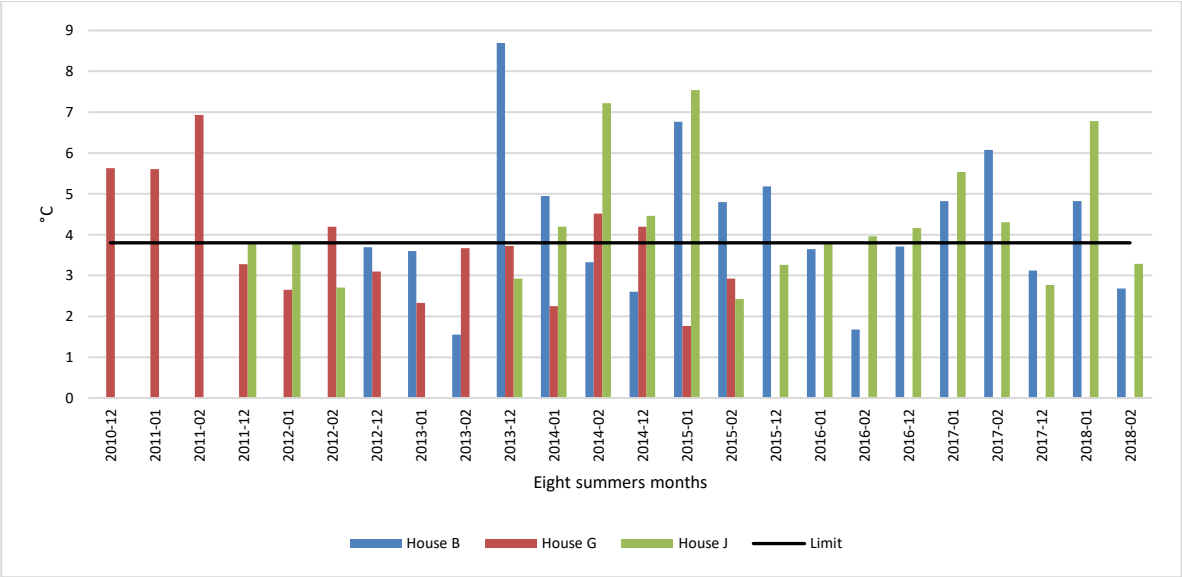


Figure 4.20 Amplitude index of overheated hours for houses B, G and J top floors during eight summers by the proposed method

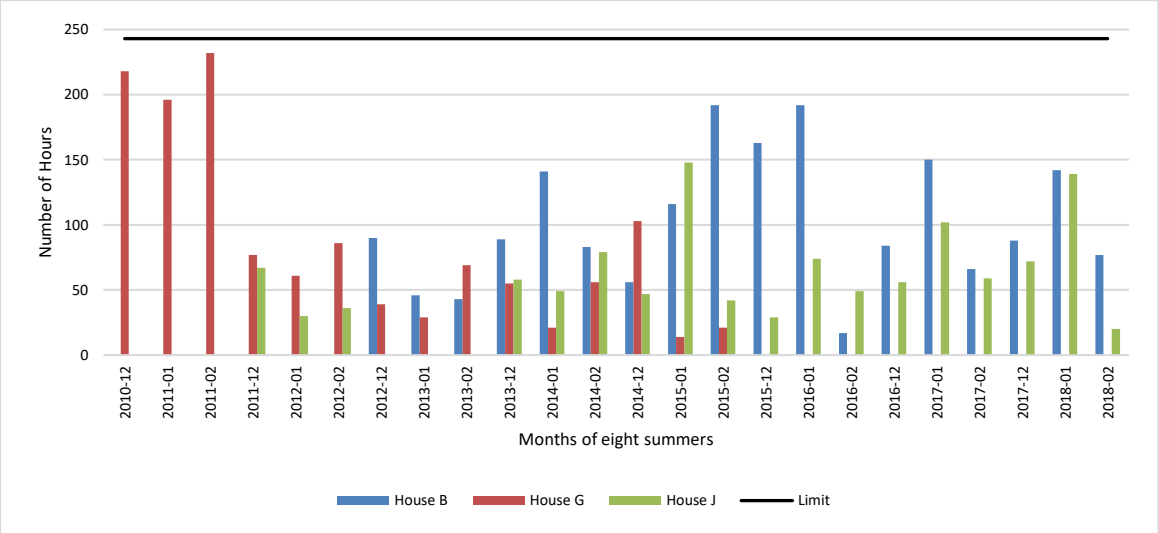


Figure 4.21 Frequency index of overheated hours for houses B, G and J top floors during eight summers based on the proposed method

4.4 Discussion

This research investigated characterising overheating in energy-efficient multilevel houses by pointing out the prevailing zones of overheating and identifying the magnitude and frequency of overheating through indices that indicate acceptable limits for overheating. The methods employed in this research is based on comfort levels of dwellings that have demonstrated thermal comfort through household perception surveys and monitored temperature results. The proposed indices have not been used in previous research, despite the prevalence of overheating in dwellings being reported in numerous studies around the world.

The general screening results showed that the temperature is not uniform in different levels of houses. During MM mode, the top floor temperatures increasd above 32 ºC for 21% of summer day hours (from 9 hours to 80 hours monthly). For the same period, the ground floors experienced air temperature exceeding 32 °C during only 4% of summer hours (0 to 17 hours monthly).

The metadata screening results showed that for the NV mode, the top floors were warmer than ground floors for 51% of the summer. On average, the top floors and ground floors were above 32 ºC by 61 and 8 hours monthly, respectively. The top floors were the main zones of overheating in all eight multilevel dwellings for MM and NV modes with their temperatures 1.7 °C to 10.7 °C warmer than ground floors during summer. This finding is aligned with other studies that noted the top floors were warmer than other levels (Gupta & Gregg 2020; Ozarisoy & Elsharkwy 2019; Pathan et al. 2017; Pellegrino, Simonetti &

Chiesa 2016; Symonds et al. 2017; Vellei et al. 2016a). While nocturnal ventilation was sufficient to prevent overheating for some houses (Pellegrino, Simonetti & Chiesa 2016), a more comprehensive study using other approaches such as shading, orientation and envelope materials is necessary. Most of the yearly overheating (72.5%) happen in summer and is increasing even outside the summer months which suggests the importance of the need for an indicator to predict the overheated rooms at the design stage.

In Adelaide, the outdoor air temperature exceeded 35 °C from 3 to 98 hours, by 0.5 to 335 degree-hrs and 0.1 to 4.5 °C during the summer month investigated. The proposed amplitude index trend in this study for outdoor and indoor temperatures appears to show overheating less clearly, with the frequency index trend being the clearest indicator. Thus, the duration of high summer temperature increased in the eight studied summers. The coefficient of the frequency trend equation of overheating on the top floor for low-performance houses was at least twice as great as for the high summer temperature. Therefore, the indoor overheating lasted longer than the high summer temperature.

The correlation of these indices with outdoor temperature showed that the high-performance houses showed a low correlation with the outdoor temperature when it exceeded 35 ºC. This indicates that the increased outdoor temperature did not impact these houses significantly. By contrast, the slopes of the trends for all indices in the low-performance houses were larger than those of outdoor temperature exceeding 35 ºC, which indicates the outdoor temperature impacted these houses more significantly. In houses C, E and K, the slopes of two indices were 1.5 to 16 those of the outdoor temperature presenting these houses' interior thermal performance during the years studied.

The average of operating AC hours for the eight houses was about 103 hours (14% of summer hours), nine hours (1%) of which was allocated to the top floor. This could show how little use was being made of the rooms on the top floor. For the top floor, the operating AC hours can be ignored, so the results of the top floor can be approximated as operating in the NV mode. The operating AC hours were low for seven houses during the eight summers, despite the increasing high summer temperature magnitude and frequency for five houses. The reduction of operating AC hours might be due to low hours of occupancy or occupant behaviour.

The high-performance houses that had their top floor temperatures close to the ground floor temperatures operated AC on average 10 hours on the ground floors and 8 minutes for the top floors per summer month. There was no data on occupied hours, so the low use of AC could be partly due to having no resident on the top floor. For the remaining hours, the occupants might have closed or opened the windows. During NV mode, top floors were warmer than ground floors for the average frequency of 243 hours with 250 degree-hrs and amplitude of 3.5 °C per month. These values could be considered limits for overheating in NV mode, as they were introduced through an inductive process. The proposed limits were closer to the actual condition than limits suggested by CSIRO and CIBSE TM 52, except the frequency, which needed a higher value. The limit for frequency in CSIRO limit underestimates thermal discomfit for high-performance energy-efficient houses in Adelaide. It appears that the limit for non-sleeping hours needs a review. The version of adaptive thermal comfort used for the CSIRO criteria covers up to 30 °C running mean outdoor temperature, whilst in Adelaide the actual running mean outdoor temperature has up to 34.3 °C. Thus EN 15251 needs to be extended close to the range of the ASHRAE 55 standard running mean outdoor temperature (10–35 °C) to cover the Adelaide conditions.

The adaptive thermal comfort equation for the ground floor of high-performance houses in NV mode confirms the equation of ASHRAE 55 adaptive thermal comfort. As the ground floor temperatures were used as the baseline for measuring overheating, its neutral operative temperature, the deduced equation presented below, is suggested to measure or predict overheating.

Neutral operative temperature = $0.27\ T_{rm} + 19.2$ (Equation 4.6)

Where:

T_{rm} = Running mean outdoor temperature

The proposed indices could show the building-performance in terms of overheating and energy-efficeincy. In addition, these indices could show the energy-consumption pick hours and highlight the rooms that need design revision in NV mode.

The results demonstrate that while the mandatory star rating of the Australian house energy rating schemes (NatHERS and Australian Building Code) has reduced annual heating and cooling energy usage and improved the average levels of thermal comfort.

However, this scheme has not necessarily succeeded in providing sufficient thermal comfort during heatwaves, which are likely to occur more frequently throughout Australia (ASHRAE 2017; Australia 2012a; BCA 2016; Livable Housing Design 2012; Saman et al. 2013).

The reasons for overheating on the top floors might be low thermal mass, lack of ventilation, roof space high temperature, lack of shading devices and external projections, the high number of west-facing windows, low number of south-facing windows and thermosiphon effect through the stairwell.

4.5 Summary

This chapter has presented results from extensive temperature monitoring of eight 7.5-star rated detached houses. The monitored data were investigated in three steps to identify and define overheating for summer months in Adelaide. The first step was general screening of four summers. The second step was metadata screening for all houses over eight summers. The last step was detailed screening for high-performance houses in the same eight summers. This research investigated: a) the main zone of overheating in multilevel dwellings for MM and NV modes; b) measurement of overheating through frequency, integral and intensity of higher temperature on overheated zones compared to the ground floor for NV modes; c) the relationship between trends of overheated zones and outdoor high summer temperature for NV mode; d) the relationship between ground floor NV mode temperature and outdoor sunshine period temperature; e) the relationship between ground floor NV mode temperature and running mean outdoor temperature; and f) limits for indices suggested to measure overheating.

Results found that 72.5% of the yearly overheating happened during summer (December-February), although the overheating is spreading outside this period. The findings highlight that an energy-efficient dwelling is not necessarily comfortable thermally, particularly on the top floors during the hot summer period. This study provides a comprehensive assessment of energy-efficient houses and finds that houses with the same energy-efficiency rating have significant thermal performance differences during summer. Moreover, the temperatures of ground floor high-performance houses for NV mode during summer are mostly in the ASHRAE 55 adaptive thermal comfort range. The highest difference between top floors and ground floors happened when both levels have their maximum daily temperature.

This chapter's main contribution is presenting new indices to quantify the level of overheating by WEH, frequency and amplitude indices based on the local adaptive thermal comfort acceptable range for the NV mode. The limit for WEH and amplitude in Adelaide were determined as 250 degree-hrs and 3.5 °C in each summer month. The analysis of the results demonstrated that the limit for frequency, 243 h, found that the attributed value was not useful in characterising overheating. This frequency index will be used for the rest of the research, but its limit is called into question.

The months that were identified as overheated by the developed criteria agreed with

the recently proposed CSIRO criteria by more than 78%. Further joint research may help provide improved overall criteria.

The study has provided evidence to show that special emphasis must be placed on distributing the temperature evenly in various levels and spaces in energy-efficient houses during summer.

The NatHERS and Australian Building Code need to develop new schemes to characterise and prevent overheating and provide even temperatures on all floors during heatwaves. By adding a suitable overheating index to home energy rating tools, rooms facing overheating risk can be identified during the design stage before starting the construction.

5 A proposed long-term thermal comfort scale

5.1 Introduction

This chapter proposes and trials an alternative 10-point numerical scale for assessing long-term thermal comfort perception all year round in NV mode for two reasons:

a) a similar scale to that used for long-term pain perception scale can be used for thermal comfort perception in NV mode because these two perceptions have many physiological similarities (Cuevas 2015; Erpelding, Moayedi & Davis 2012; Grabenhorst & Rolls 2009; Hees & Gybels 1981; KENHUB 2018; Krantz 2012; Marieb & Hoehn 2015; Mishra, Loomans & Hensen 2016; Ochoa & Torebjork 1989; Rea 2015; Rolls, Grabenhorst & Parris 2008; Schweiker et al. 2016) which have been extensively explained in 2.2.2 and b) the numerical assessment can present more accurate results for evaluating perceptions (Brunelli et al. 2010). The numerical thermal comfort perception scale is being proposed for both heating and cooling perception. However, the case study described below has only been carried out during the summer.

This chapter aims to propose a 10-point scale to assess long-term thermal comfort and to compare the performance of this proposed scale with that of TSV.

5.2 Method

The research is based on three steps: a) an extensive survey of 168 energy-efficient multilevel dwellings in 13 suburbs of Adelaide, Australia; b) analysing extensive monitored temperature data and comparing the survey results for the top and ground floors of five households, c) comparing the indices for the proposed numerical scale with the TSV verbal scale.

The dwellings were built after 2010 and had met the Australian Nationwide House Energy Rating Scheme (NatHERS) minimum performance requirement of 6 to 7.5-star which means that the maximum predicted energy requirement in these dwellings for heating and cooling was in the range of 96 MJ/m^2 and 58 MJ/m^2, respectively. From 168 surveyed

The outcomes of this chapter have been published in a paper "A proposed long-term thermal comfort scale" Sharifi, S, Saman, W, Alemu, A & Boland, J 2020, ', Building Research & Information, 30 Oct, p. 19.

dwellings, six 7.5-star rated houses located in one suburb (Lochiel Park) (NatHERS National Administrator 2012) had extensive temperature monitoring and the rest of the dwellings had no monitoring. Thus, the indices for the proposed scale was calculated for the monitored houses. The daily minimum, daily maximum and daily average temperature were obtained from the Bureau of Meteorology (BoM) station closest distance to Lochiel Park. The same data for the Adelaide metropolitan area was collected from the BoM reports.

5.2.1 Questionnaire

This survey was part of an extensive study of the residents' thermal comfort satisfaction in energy-efficient dwellings in Adelaide (Chapter 3). Thus, the questionnaire was composed of three parts. The first part included the demographic information of the respondents such as age, gender and type of dwelling. The second part recorded the hours spent at home, space used most of the time in, hours the appliances and AC were used, clothing thermal insulation (*clo*) and activity level (*met*). The third part of the questionnaire included the subjective rating of thermal comfort (thermal perception) in NV mode. Respondents were asked to provide a rating for each floor, separately, as well as the whole dwelling during the whole summer and heatwaves using the proposed numerical scale and the TSV verbal scale (Table 5.1). The NV mode was selected for the questionnaires as a) by default, it is expected that for AC mode, thermal comfort should be prevalent in most cases; b) in the 7.5-star houses, the AC mode hours are expected to be much less than NV hours. c) using AC can weaken the ability of thermal adaption of occupants (Kim, J et al. 2019; Wu et al. 2018), so rating the thermal comfort for the AC mode should be separated from other modes. At the end of the questionnaire, the participants were asked to add comments, notes, suggestions and any changes they have made in their home to prevent overheating or any adaptation method that they use. These notes helped to interpret their ratings. The survey results were analyzed using Excel.

Table 5.1 Questions of the survey which focus on thermal comfort

If 1 is the worst and 10 is the best thermal comfort condition: How do you rate the thermal comfort of your house by natural ventilation during the last summer and heatwaves in the a) Ground floor b) Top floor
Considering the seven below verbal descriptions: Hot, Warm, Slightly Warm, Neutral, Slightly Cool, Cool, Cold How do you describe the thermal comfort of your house by natural ventilation during the last summer and heatwaves in the a) Ground floor b) Top floor

5.2.2 Monitored houses

The targeted households for the case study were the residents of the six houses in Lochiel Park in Adelaide, Australia, who had completed the survey. However, only five households were used as the monitoring of one house was faulty (Figure 5.1). Typical materials and properties of these houses are listed in Chapter 4, Tables 4.3 and 4.4.



Figure 5.1 Locations of Chapter 5 case studies in the Lochiel Park

The process of monitoring and collecting data is explained in 4.2.1. To have a better insight, the location of sensors in this chapter case studies are listed in Table 5.2. The humidity is not taken into account for this chapter, as it is considered neither in TSV nor in adaptive thermal comfort. The trial of the proposed scale was conducted for summer, as the survey was carried out during the summer.

Table 5.2 Location of sensors in the case study houses for this chapter (LR= living room, BR= Bedroom, MRB=Master Bedroom)

House	Location of Sensors	
	Ground floor	Top floor
B	LR, MBR	BR
C	LR	MBR, BR
E	LR	MBR
F	LR, MBR	BR
J	LR	MBR, BR

5.2.3 Adaptive thermal comfort thresholds

Two versions of the adaptive thermal comfort criteria were selected for this research (Table 5.3). The first version is the adaptive thermal comfort criterion suggested for the Adelaide climate (Sharifi, Saman & Alemu 2019) (named Ad in this study). The second one is the AHRAE 55 (ASHRAE 2017), as Chapter 4 showed that AHRAE 55 is the most similar to the Ad version compared to the available standards (Figure 5.2).

Table 5.3 Thermal comfort thresholds used in this research

Version	Neutral Line Formula (threshold)	Ref.
Adelaide (Ad)	$0.27^{*}\ T_{rm} + 19.2$	(Sharifi, Saman & Alemu 2019)
ASHRAE 55	$0.31^{*}\ T_{rm} + 17.8$	(ASHRAE 2017)

$T_{rm} = (1-\alpha)\times(T_{od-1} + \alpha T_{od-2} + \alpha^2 T_{od-3} + \alpha^3 T_{od-4} + \alpha^4 T_{od-5} + \alpha^5 T_{od-6} + \alpha^6 T_{od-7}) = (1-\alpha)\times T_{od-1} + \alpha\ T_{rm\ of\ one\ day\ before\ the\ day\ in\ question}$

T_{od-1} is the daily mean outdoor temperature for the preceding day

The value for α ranges 0.6–0.9 for fastest to slowest response to day-to-day temperatures. 0.6 is employed in this study.

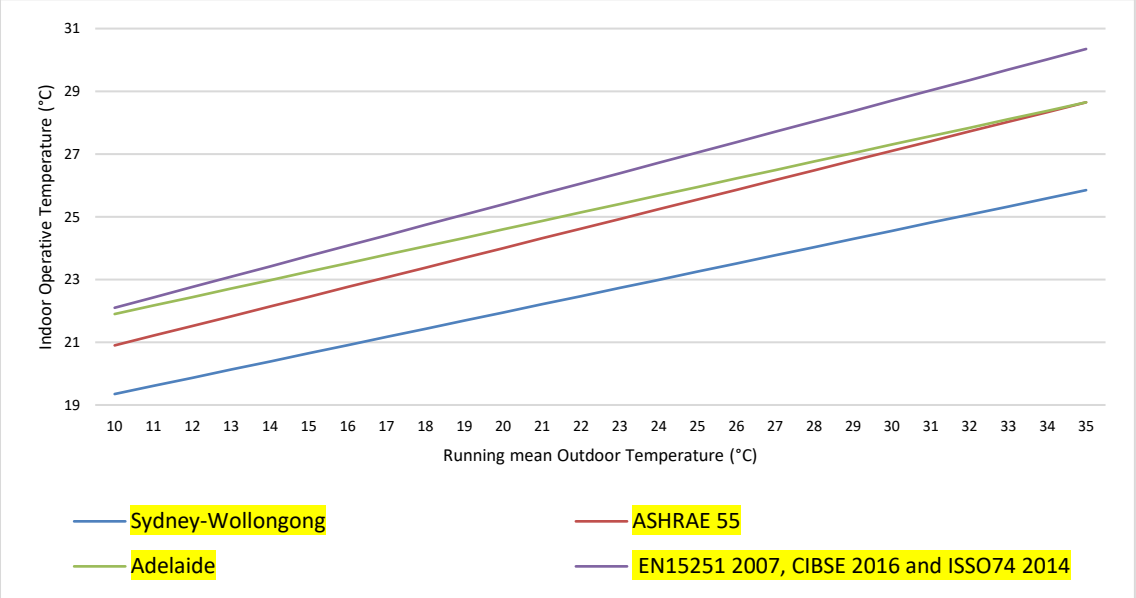


Figure 5.2 Neutral thresholds of adaptive thermal comfort for Ad and ASHRAE 55

5.2.4 Computed factors

Some of the analysis of the survey is related to thermal comfort rating and comprises binning the numerical scores that were rated with the same TSV scale in the questionnaires.

The parameters below were computed through the weather records of the Bureau of Meteorology (BoM) as well as the ground floor and top floor temperature monitored data in the five studied houses from December 2016 to February 2017:

1- Seven-day running mean outdoor temperatures

2- Neutral daily temperatures for Ad and ASHRAE 55 adaptive thermal comfort based on running mean outdoor temperature

3- Hourly indoor temperatures through averaging the minute-by-minute data

4- Hourly electricity usage of AC through averaging the minute-by-minute data

5- Daily DH for the ground floors and top floors for Ad and ASHRAE 55 standard using the neutral adaptive thermal comfort as the baseline. If two participants in one house had different numerical ratings, the average of their rating with a rounding-up was considered for each floor

6- The whole of summer DH for Ad and ASHRAE 55 standard

7- Bins of numerical and verbal TSV scales constituting the corresponding daily DH for each floor based on the questionnaire results were computed for thermal comfort thresholds. The following equation calculated the daily DH:

$$\sum_{h=1}^{24} \max\left((T_h - T_{NL}), 0\right) \qquad \text{(Equation 5.1)}$$

Where:

T_{NL} = Neutral line for adaptive thermal comfort threshold of the requested day (Two neutral limits are calculated based on Ad and SHRAE 55.)
T_h = Hourly measured air temperature

8- Average of daily DH and maximum daily degree hours for each bin

9- Frequency (Percentage of summer days with daily degree hours above the thresholds). Through calculating the proportion of days with degree hours greater than the threshold to all NV mode days in the studied summer.

10- Differences between two consecutive scores for each scale in terms of average daily degree hours, maximum daily degree hours and frequency

11- Association of numerical scale scores with total summer degree hours through regression coefficient (R^2) and possible value (P-vale) for two thermal comfort thresholds

The results of steps 6–9 demonstrate the clarity/ambiguity of the TSV scale scores for participants. The outcome of step 10 shows whether the differences between consecutive TSV scale scores are perceived as equal or not. Step 11 demonstrates the strength of the correlation between the numerical scale scores and the total summer degree hours.

5.3 Results

5.3.1 Outdoor summer conditions

In the Adelaide metropolitan area, the daily maximum temperature varied from 19.2 to 42.4 °C from December 2016 to February 2017 and the average daily temperatures ranged from 15.4 to 34.1 °C. The general climate condition in Lochiel Park showed an average daily temperature of from 15 to 32 °C with a daily maximum temperature of about 43 °C in February (Figure 5.2). The running mean outdoor temperature was 10–32 °C and was within the ranges in Ad and ASHRAE 55 standard ranges (Figure 5.3). The range of daily relative humidity (RH) was from 25 to 72%, with just one exception for 5th February of 87% (Figure 5.4). The wind was zero to 20 km/h with one exception for 6th February, 31 km/h (Figure 5.5).

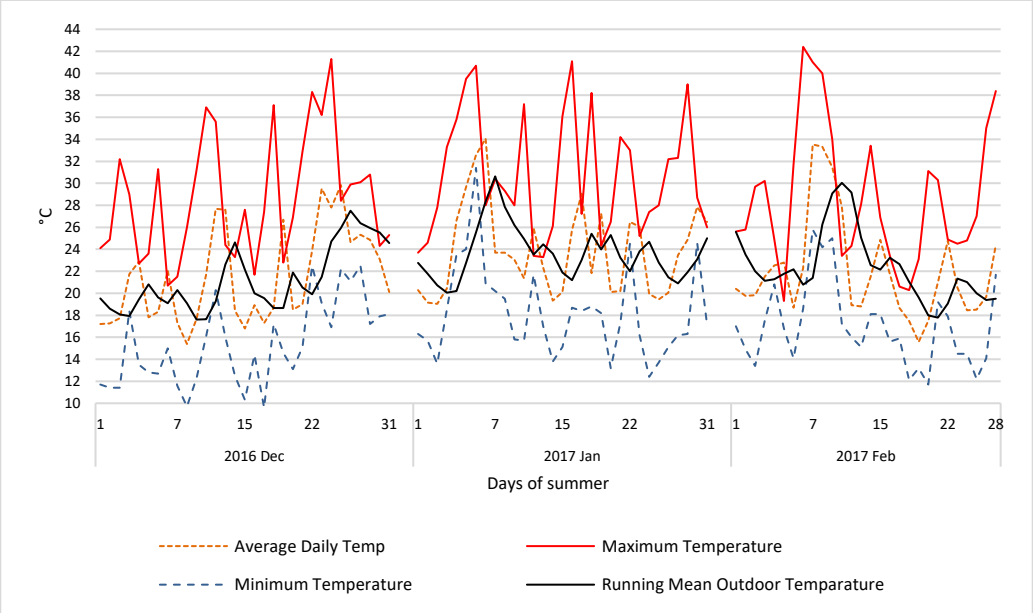


Figure 5.3 Outside temperatures in Lochiel Park, Adelaide during summer 2016-17

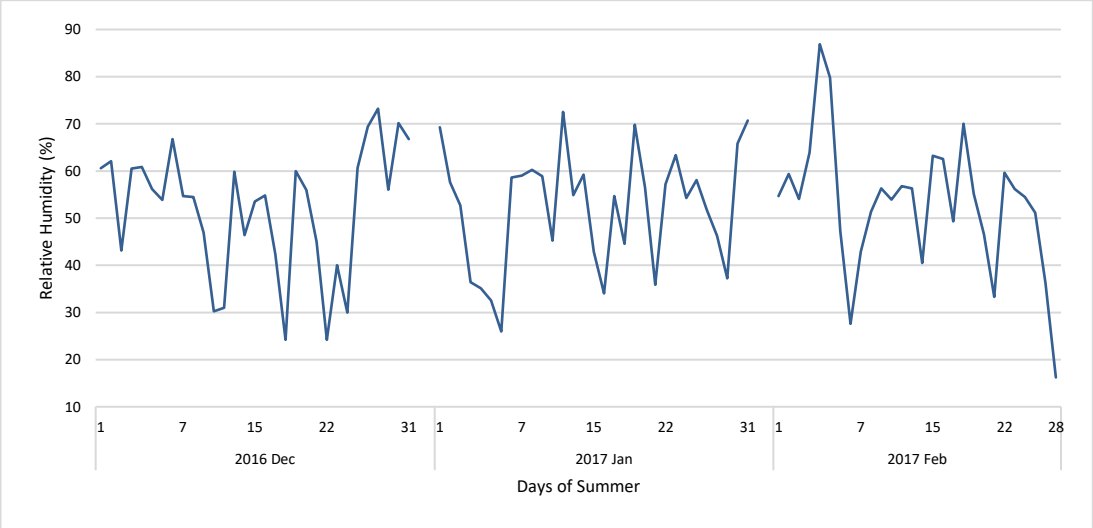


Figure 5.4 Daily relative humidity in Lochiel Park, Adelaide during summer 2016-17

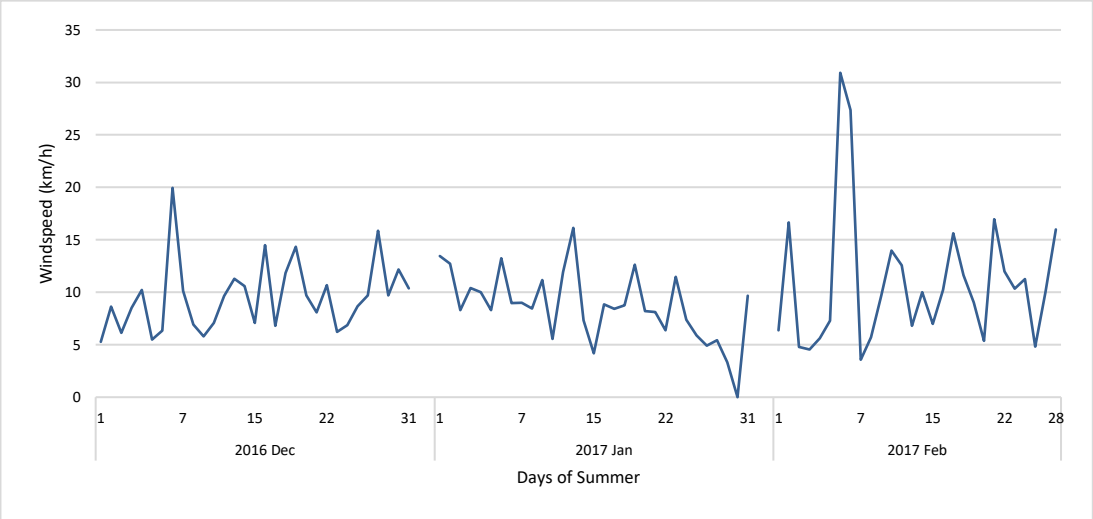


Figure 5.5 Daily windspeed in Lochiel Park, Adelaide during summer 2016-17

5.3.2 Indoor conditions

In total, 178 completed questionnaires were collected from households in 13 suburbs in Adelaide, ten of which were ruled out because of incomplete answers. The majority of completed questionnaires, 88.7%, were from multilevel houses (Table 5.4) and Appendix C.

Table 5.4 Summary of surveyed dwelling characteristics and results

Dwelling Type	Star Rating	Number Surveyed
Multilevel Houses	6	96
	7.5	53
Apartment	6	19

The average clothes thermal insulation (*clo*) was about 0.35 (less than normal summer light clothes), which indicates that participants' clothes did not exaggerate their perception of the indoor thermal condition. The metabolic rate (*met*) for all groups was 1.0 *met*. However, some studies consider the prevailing activity level dwellings to be 1.3 *met* (ASHRAE 2017). The participants were 22 to 70 years old. The *met* value matched the seated, quiet range and could not influence the residents' thermal comfort rating. More than 30% of participants noted their methods for adaptation during summer. These include: living downstairs, keeping blinds and curtains closed, particularly for the west-facing windows, low solar heat gain films, double glazing, cross ventilation, turning on the exhaust fan on the top floor, using a ceiling fan, insulating garage door, changing the external walls paints to white, adding shading on North-facing windows and planting trees and vines for shading.

Participants of the 168 surveyed dwellings rated a wide range of numerical scale scores for each TSV verbal scale score (Figure 5.6). The 'Hot', 'Warm', 'Slightly Warm', 'Neutral', 'Slightly Cool' and 'Cool' were attributed to the points 1-5, 2-9, 4-9, 4-10, 2-10 and 4-9, respectively. Therefore, each of the verbal scores corresponded to a wide range of numerical scales, which varied from three to eight values. On average, the middle of the numerical scale 5.5 was associated with the 'Warm' in the TSV verbal scale and higher ratings went for cooler thermal perceptions, as seen in (Table 5.5).

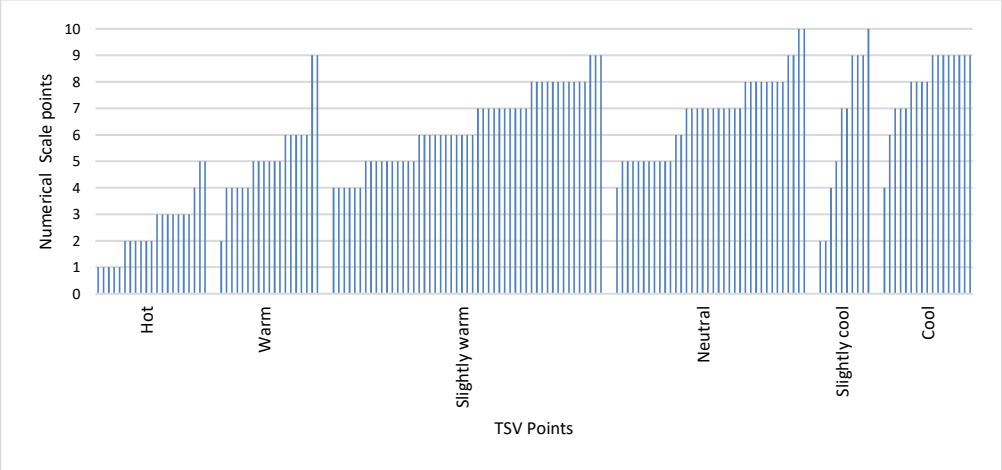


Figure 5.6 Correlation of the TSV and the numerical scale based on the survey of 168 households

Table 5.5 Average of correlation of TSV and numerical scale based on the survey of 168 households

Sample size	TSV (ASHRAE 2017)	Numerical scale
24	Hot	2.3
30	Warm	5.5
54	Slightly Warm	6.3
34	Neutral	6.9
10	Slightly Cool	7.6
16	Cool	8.3
0	Cold	------

5.3.3 Outcomes of the Lochiel Park survey

In total, ten residents of six houses participated in the survey of the case study houses. Two participants from houses C, E, F and J; and one participant each from houses B and K. All houses were owner-occupied and the participants had lived in their dwellings for at least the whole summer under question. Half of the respondents were males and half were females. The average *clo* and *met* for both genders were 0.35 and 1.4, respectively, which was equivalent to regular summer light clothing and in the seated, quiet range. About 50% of residents used their stovetops for 60-90 minutes, and 40% used them for less than 30 minutes daily. On average, the stovetops were used for about one hour daily, which is unlikely to have a major impact on the participants' ratings. Most of the participants (90%) used to spend their waking hours in the open-plan zone and 40% of them lived mostly on the ground floor as they were retired couples with the master bedrooms on the ground floor. For the studied summer, 80% of households had spent most of the 24 hours at home. The setpoint of AC was 24 °C to 26 °C for 80% of respondents. The residents of two houses reduced the setpoint by 2 °C during heatwaves while in three houses there was no change and in one house, residents turned on the AC just for cooling during heatwaves.

The residents in the same house selected the equal scores for TSV, but their numerical ratings were different except for houses E (Table 5.6). For houses F and C, the residents had different numerical ratings. Based on the residents' judgments, the 'Neutral', 'Slightly Warm', 'Warm' and 'Hot' refer to 7-9, 6-8, 5, 0.5-4 in the numerical scale, respectively. All the TSV verbal scale scores were used for rating, but in the numerical scale, the score 10 was not used and the score ranged between 0.5 and 9. The decimals were rounded up for analysis. None of the 10 participants had selected the score 6. The TSV verbal scale results for the ground floor were 80% 'Neutral' and 20% 'Slightly Warm', whilst for the top floor, just 10% of rates were 'Slightly Warm' with 50% 'Warm'

and 40% ‘Hot’ (Table 5.6). Participants reported overheating on top floors, particularly in the afternoons and during heatwaves inside north and west-facing spaces. The ‘overheating’ was not interpreted as numerical or verbal scale scores as there is no method for converting it.

Table 5.6 Numerical and verbal rating for long-term thermal comfort in ground floors and top floors during the studied summer (P1=Participant 1, P2=Participant 2, GF=Ground floor, TF=Top floor)

Houses		Numerical		Verbal	
		GF	TF	GF	TF
B	P1	9	8	Neutral	Slightly Warm
C	P1	9	1	Neutral	Hot
	P2	8.5	0.5	Neutral	Hot
E	P1	8	5	Neutral	Warm
	P2	8	5	Neutral	Warm
F	P1	6	3	Slightly Warm	Hot
	P2	8	4	Slightly Warm	Hot
J	P1	8	5	Neutral	Warm
	P2	7.5	5	Neutral	Warm
K	P1	7	5	Neutral	Warm

5.3.4 Monitoring outcome

The final case study was five houses as one house had faulty data. The data for houses B, E, F, J (ground floor and top floor) and K (just top floor as the ground floor had operating air conditioner for more than 90% of the summer) were analysed. This section presents the results of the process listed in ‘Computed parameters’ for these houses. The days with operating AC (Table 5.7) were ruled out and just the NV mode days were analysed. The participants of house F had two different numerical ratings for their house, so the average of their rating with a rounding-up was used for correlating with daily degree hours. Houses B, E, F, J and the top floor of K were in NV mode for 70%, 61%, 93%, 96% and 89% of the summer hours.

Table 5.7 Number of days with operating AC in five houses during summer 2016-17

Houses	**B**	**E**	**F**	**J**	**K (top floor only)**
December	3	7	2	0	1
January	10	19	1	2	2
February	6	9	3	2	4
Whole Summer	19	35	6	4	10

The values of summer degree hours corresponding to the survey responses on the proposed numerical scale and the TSV scale were calculated. The results are presented in Figure 9 for the floors of the houses using the thermal comfort thresholds. The value of degree hours associated with the scores 4, 5 and 8 of the numerical scale agreed very well with the 'Hot', 'Warm' and 'Slightly Warm' in the TSV verbal scale, respectively for both thresholds.

The numerical and verbal TSV scales were compared using two groups of parameters calculated as described a) decreasing trend for summer degree hour, intensity and frequency of daily degree hours; and b) the difference between two consecutive scores. It is expected that the value of parameters in group 'a' decrease as the thermal comfort changes from worst 1 or 'Hot' to the best 10 or 'Neutral'. The difference between two consecutive points in a scale can present the even distribution of the points.

As expected, the total summer degree hours demonstrated a general reduction as the value of the numerical scale increases (Figure 5.7). This trend is less pronounced for the verbal TSV scale, with a negligible difference between 'Slightly Warm' and 'Neutral'. The highest summer degree hours were associated with the ASHRAE threshold. The most significant difference of summer degree hours between two consecutive scores was for the TSV verbal scale between the 'Warm and 'Slightly Warm' results (Figure 5.8).

The maximum daily degree hours presented a decreasing trend for numerical and verbal TSV scales (Figure 5.9). The highest degree hours for all scores corresponded to ASHRAE. The greatest difference between two consecutive points was for 'Warm' and 'Slightly Warm' for both thresholds (Figure 5.10).

The frequency showed a decreasing trend for numerical and TSV scales by both thresholds (Figure 5.11). The highest percentage for each point corresponded to the ASHRAE scale. The most significant difference between two consecutive points was for 'Warm' and 'Hot' as well as '4' and '5' by Ad threshold. The second great difference was between 'Warm' and 'Slightly Warm' based on the ASHRAE thresholds (Fig. 5.12).

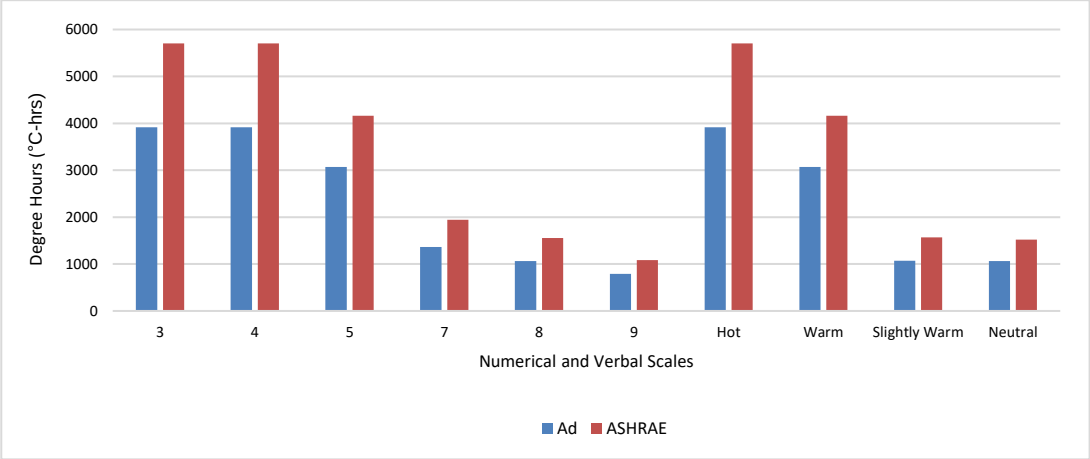


Figure 5.7 Total summer degree hours for numerical and verbal TSV scales based on two adaptive thermal comfort neutral threshold for summer 2016-2017

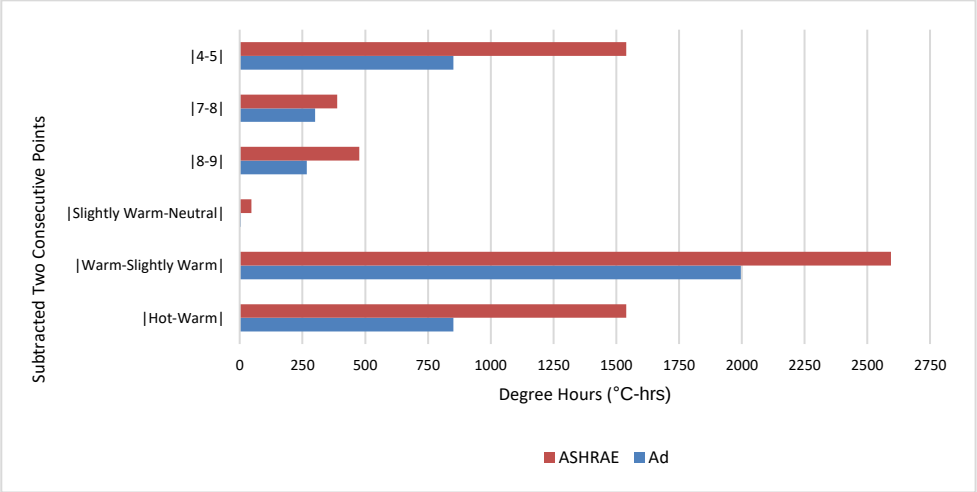


Figure 5.8 Absolute value of the difference between two consecutive points for each scale in terms of whole summer degree hours during summer 2016-17

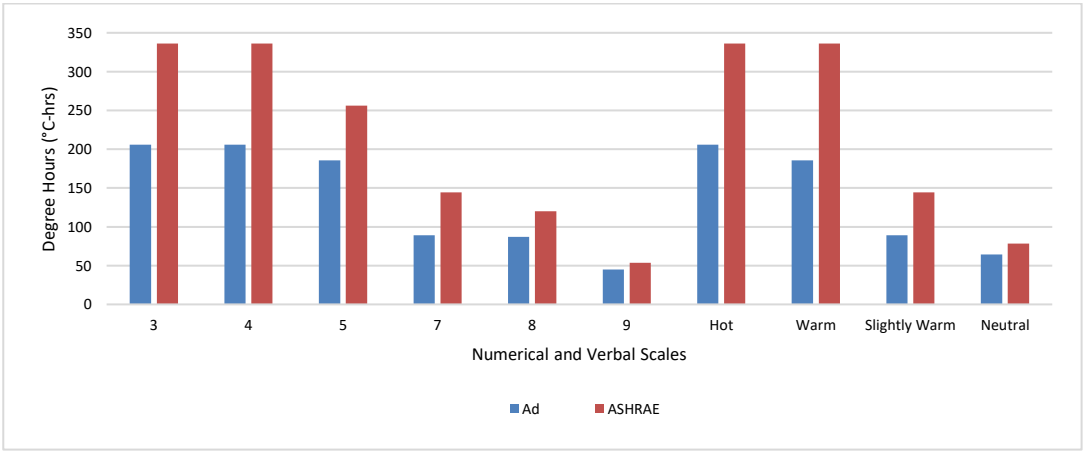


Figure 5.9 Intensity (maximum of daily degree hours for the numerical and verbal TSV scales) based on two adaptive thermal comforts for summer 2016-17

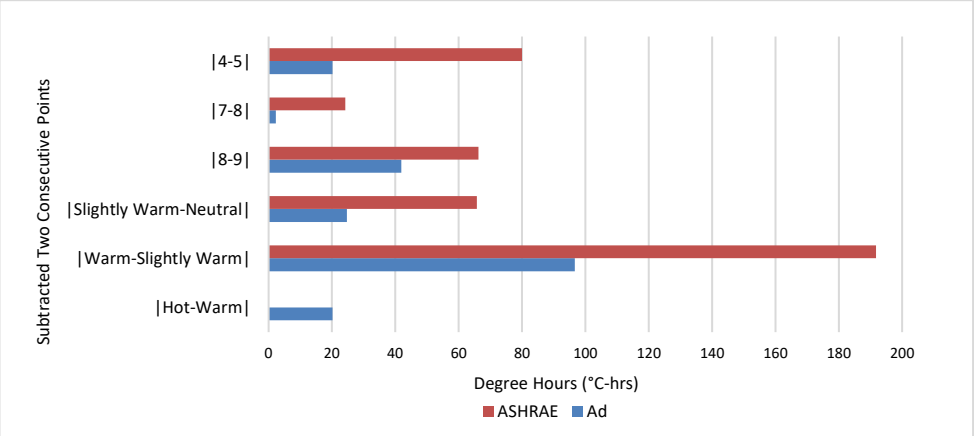


Figure 5.10 Absolute value of the difference between two points of numerical and verbal TSV scales in terms of maximum daily degree hours during summer 2016-17

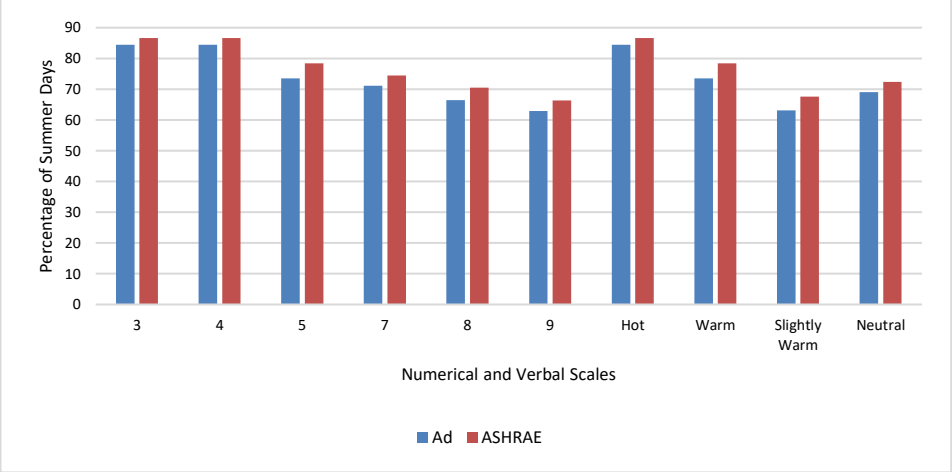


Figure 5.11 Percentage of frequency for numerical and verbal TSV scales based on two adaptive thermal comfort neutral thresholds for summer 2016-2017

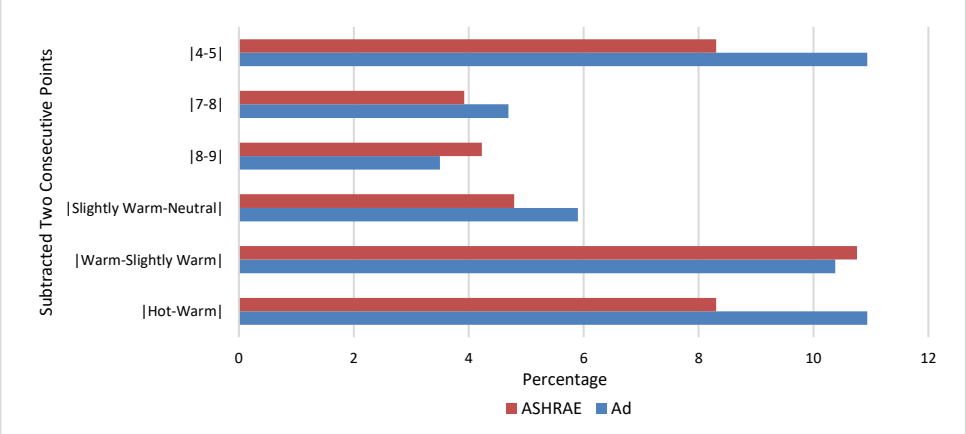


Figure 5.12 Absolute value of the difference between two consecutive points of numerical and verbal TSV scales in terms of percentage of daily degree hours greater than zero during summer 2016-17

When both numerical and verbal TSV points scales were converted to one unit (degree hour) as explained in the method, each verbal TSV scale scores corresponded to several numerical scale scores. When both scales were converted to total summer degree hours, the verbal scale scores, on average, equalled numerical scale scores. Some of the numerical scale numbers allocated to verbal scale are not whole as these numbers are the averages of ratings. The equalled numbers are Hot=4, Warm=5, 'Slightly Warm=7.5 and Neutral=7.5 (Table 5.8). Converted scales scores to average daily degree hours presented: Hot=4, Warm=5, Slightly Warm= 7.1 and 8.7; and Neutral=8.1 and 8 (Table 5.8). Finally, the average of converted scales scores for maximum daily degree hours resulted in: Hot=4, Warm=5, Slightly Warm=7 and Neutral=8.8 and 8 (Table 5.8).

The regression lines for numerical scale points versus summer degree hours presented a slope towards score 9 for both thermal comfort thresholds (Figure 5.13). The regression line coefficient for the numerical scale (Table 5.9) was 0.58 and 0.76 for Ad and ASHRAE, respectively. The P-values of the same correlations were 0.01 and 0.001 for Ad and ASHRAE, respectively. Both P-values are less than 0.05, making the coefficient of determination acceptable, particularly for ASHRAE 55 standard (Lhabitant 2013).

Table 5.8 The average of equalization for numerical and verbal TSV scale points in terms of three factors

Thresholds	**ASHRAE**			**Ad**		
Factors	Summer (DH)	Daily (DH)	Max (DH)	Summer (DH)	Daily (DH)	Max (DH)
Hot	4	4	4	4	4	4
Warm	5	5	5	5	5	5
Slighly Warm	7.5	7.1	7	7.5	8.7	7
Neutral	7.5	8.1	8.8	7.5	8	8.5

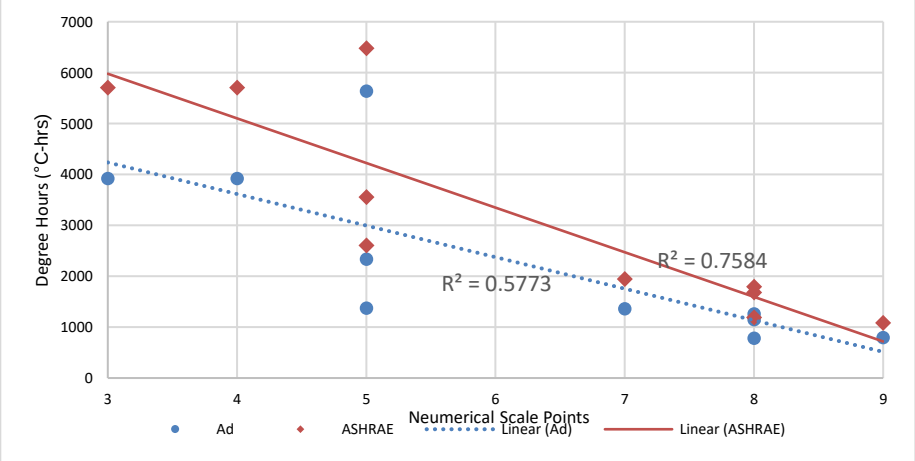


Figure 5.13 Correlation between the total degree hours and occupants long-term thermal comfort rating for using the numerical scale in NV mode based on two thresholds during summer 2016-1

Table 5.9 The regression line and coefficient of determination (R^2) for the regression line of numerical scale points versus summer degree hours

Thresholds		Regression Line	R^2
	Ad	-654.87x + 6342.8	0.53
	ASHRAE	-905.85x + 8800.9	0.71

5.4 Comparison between overheating indices of people's long-term thermal comfort rating

The data of the same houses in section 5.3.4 (B, E, F J and K) were used to find the correlation between overheating indices and the proposed numerical scale. The indices of the proposed overheating criteria were calculated for summer months on ground and top floors based on the Ad threshold. The correlation of values for each index with their corresponded thermal comfort numerical rate were investigated.

The available thermal comfort ratings for houses were from three to nine. The ratings three to eight corresponded to top floors and seven to nine were for ground floors. The strongest correlation with a coefficient determination of 0.87 was for amplitude (Figure 5.14), followed by the frequency with 0.65 (Figure 5.15) and WEH with 0.49 (Figure 5.16).

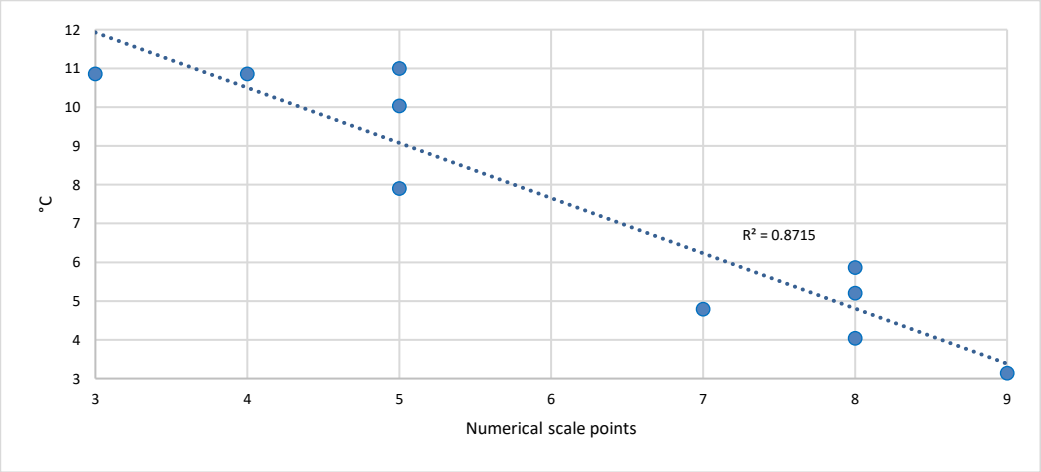


Figure 5.14 Correlation between the thermal comfort numerical rating and the amplitude of overheating

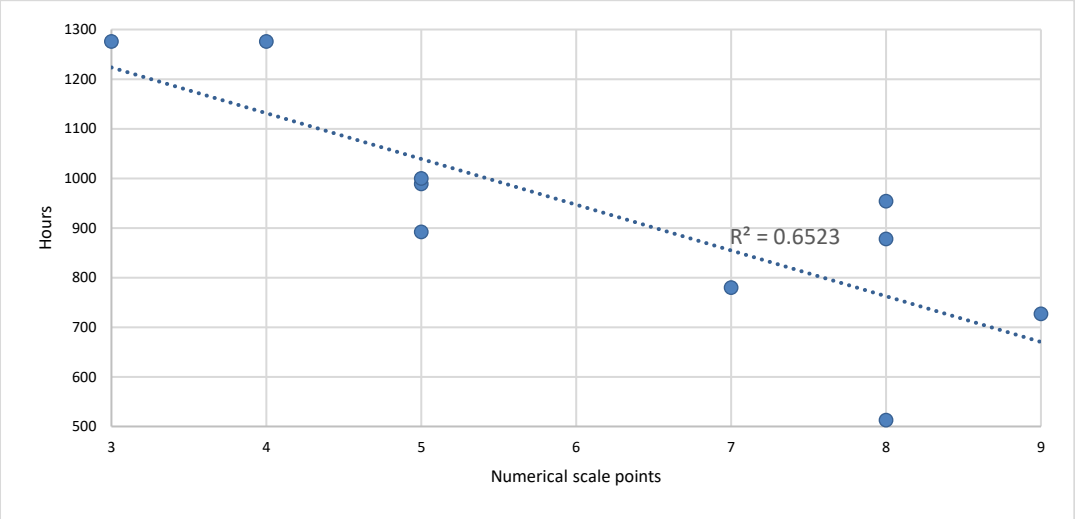


Figure 5.15 Correlation between the thermal comfort numerical rating and the Frequency of overheating

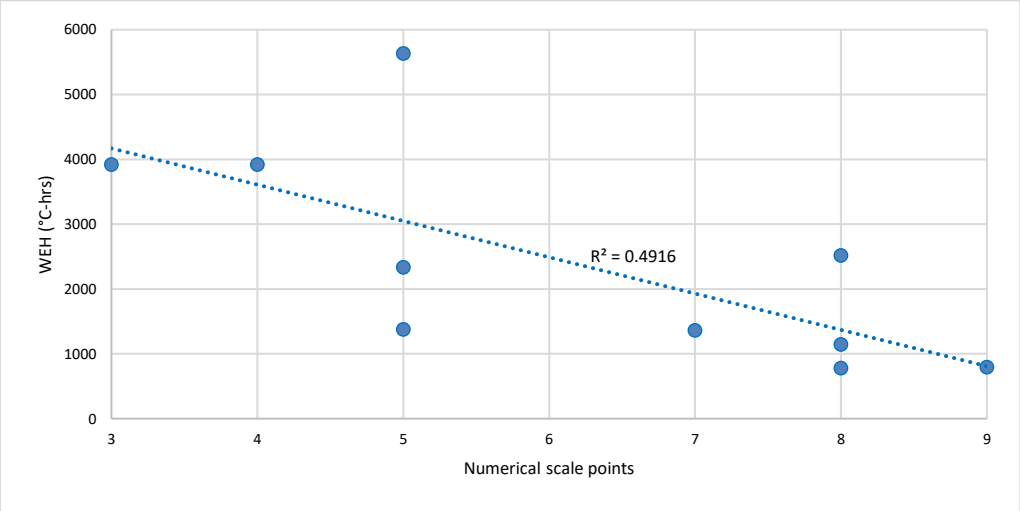


Figure 5.16 Correlation between the thermal comfort numerical rating and the WEH of overheating

The coefficient of determinations showed that the amplitude hasd a stronger correlation with the numerical thermal comfort ratings compared with the WEH and frequency. This outcome shows that the long-term thermal comfort rating is influenced the most by the amplitude of overheating. However, recent research on long-term thermal comfort indices suggested frequency as the strongest influencer (Li, P et al. 2020).

5.5 Discussion

The literature review found that the TSV scale can show the short-term thermal 'perception' rather than 'sensation'. This scale is used to indicate both short-term and long-term thermal comfort rating. However, the TSV has various issues due to its verbal scores (Humphreys & Hancock 2007; Humphreys & Nicol 2004; Koelblen et al. 2016; Schweiker et al. 2016; Traci Lynne 2008). Our extensive survey results have reinforced the results of the previous studies in terms of the uncertainties associated with the TSV scale as a long-term thermal comfort indicator. In the survey, each of the TSV verbal scores corresponded to five to seven scores on the numerical scale.

In particular, the survey results of 168 dwellings with residents in the age range of 22 to 70 showed that the discrepancy of the ratings 'Warm' and 'Slightly Cool' was significantly high. Thus, there was a wide range of thermal comfort expectation for each verbal score. Unexpectedly, the last acceptable score on the TSV scale, 'Cool' got the participants' highest numerical scale point. Thus, the 'Neutral' score did not correspond to a desirable condition for the participants.

Based on the concept of measuring long-term pain perception, biological similarities between pain perception and thermal perception and the subjective nature of perceptions, this research has investigated weather a numerical scale can evaluate long-term thermal comfort. This research uses two thermal comfort thresholds to compare the proposed numerical scale with the TSV verbal scale.

The climatic conditions in Adelaide and more locally in Lochiel Park show that the surveyed summer was similar to the typical summers in Adelaide. Respondents' clothing, activity, hours of using a stovetop and their hours spent at home did not affect their ratings. The monitoring showed that the houses were in NV mode on average for 80% of the studied summer duration. This percentage indicates that participants' responses were generally based on their perception during NV mode. The respondents who used the same verbal scale scores did not use the equivalent scores of the numerical scale. This demonstrates that the numerical scale provided more opportunities for them to point out their thermal perception levels. Some participants even added decimals which showed that they were aware of the higher resolution of their perception spectrum. This level of accuracy in a subjective question could, if quantified, minimize the error in survey statics.

The points ‘Hot’ and ‘Warm’ of the TSV verbal scale for all factors referred to the same degree hours that scores 4 and 5 of the numerical scale had referred. Therefore, there was no confilict between the numerical and verbal scale for rating the high temperature. However, the score ‘Slightly Warm’ was very close to ‘Neutral’ as indicated in the degree hours results. This outcome confirms the uncertainty of meanings for these verbal scale scores and isupports the accuracy of the numerical estimation participants (Park et al. 2015).

For the numerical scale, points from 4 to 9 were associated with decreasing intensity and frequency of degree hours in summer. In contrast, for the TSV verbal scale moving from ‘Hot’ to ‘Neutral’ was associated with decreasing degree hours only for the maximum degree hours. For frequency, a significant increase is resulted from ‘Slightly Warm’ to ‘Neutral’. Therefore, the numerical scale was significantly more representative.

The highest difference between the two scales always occurred for the verbal scale (‘Warm’ and ‘Slightly Warm’) that shows the uneven difference between points on the verbal TSV scale. Thus, the TSV scale scores are not perceived as equidistant (Schweiker et al. 2020; Schweiker et al. 2016).

The scores ‘Hot’ and ‘Warm’ equalled 4 and 5, respectively, on the numerical scale for various parameters in all thresholds. The ‘Slightly Warm’ referred to a wide range of 7–8.7, which shows an ambiguous interpretation of this scale for participants. The score ‘Neutral’ was on average equal to 7.5-8.5. The ‘Neutral’ was attributed to ‘7.5’ for summer degree hours, 8–8.1 for daily degree hours and 8.5–8.8. for maximum daily degree hours. This shows that even using the average could not match the various numerical scores that the ‘Neutral’ referred to. Besides, it was clear that for respondents, the point ‘Neutral’ did not necessarily correspond to the highest TSV. This supports evidence from previous research (Daniel, Williamson & Soebarto 2016; Humphreys & Hancock 2007; Humphreys & Nicol 2004; Sally et al. 2018). This result is not unexpected as the closest meaning to ‘Neutral’ in this context is: not engaged on either side (Merriam-Webster 2019) or belonging to neither kind (Dictionary.com 2019). Therefore, it is not to be expected that the interpretation of ‘Neutral’ indicates an ideal thermal comfort condition and the results confirm this. The ambiguous meaning of ‘Neutral’ in the verbal TSV scale outcomes could be misleading.

The regression analysis for the numerical scale scores versus summer degree hours presented an acceptable range for the coefficient of determination which confirms the success of the proposed numerical scale. The high value of 'coefficient of determination' for ASHRAE 55 standard shows that the numerical scale can be sensibly used to predict the perception of thermal comfort through exceeded degree hours. The predictive ability of the numerical scale makes this scale more applicable in calculations and research.

The comparison between overheating indices through the proposed numerical thermal comfort scale found that the long-term thermal comfort rating is influenced the most by amplitude.

While there is no doubt about the analysed data, it was difficult to judge the impact of house use parameters such as the hours of opening windows and their effect on the temperature as the operation of windows was not monitored. Another significant limitation of the research is that only six individuals responded to the case study questionnaires. The proposed scale should be tested more widely for larger numbers of participants in various longitudes and climates.

5.6 Summary

This chapter proposed a new numerical scale for expressing residents' long-term thermal comfort based on the similarity of pain perception to thermal comfort perception as biological 'perception' processes rather than a 'sensation'. We presented the result of an extensive survey in which a numerical 10-point scale was investigated as a potential means for determining residents long-term thermal comfort and compared this with a verbal TSV scale. The major survey showed that the TSV verbal scale could not clearly express the thermal comfort level of residents as each verbal score was associated with three to eight numerical values of 10-point scale.

In order to validate the proposed scale, a sample case study presented results from the survey combined with temperature monitoring of the surveyed houses. The monitoring was from December 2016 to February 2017 of five 7.5-star rated detached houses located in Lochiel Park, Adelaide. The long-term thermal comfort perception rates sought by numerical and verbal TSV through questionnaires were converted to degree hours from temperature monitoring data on the ground floor and top floor. The total summer degree hours, intensity and frequency of daily degree hours for each numerical and TSV verbal

scale scores were calculated. Also, the difference between the two consecutive scores was computed. The results demonstrated that the numerical scale provided better opportunities for individuals to express their thermal comfort satisfaction level more specifically than TSV verbal score.

Reviewing the results of both survey and monitoring outcomes support the claim that the meaning of TSV verbal scores, particularly the points 'Slightly Warm' and 'Neutral' does not have the same interpretation in different individuals. The findings showed that 'Neutral' in the TSV verbal scale did not represent 'ideal' thermal comfort for the studied group. It was found that the respondents associated each TSV verbal score with two to three numerical scores, particularly for 'Neutral'. In contrast, the numerical scale presented a more representative relationship between measured parameters and scale scores with an acceptable 'coefficient of determination' of 0.58 and 0.76. The case study, keeping in mind its limited sample size, has demonstrated that the numerical scale can predict people's thermal comfort perception by correlating their rating to the exceeded degree hours, while the TSV verbal scale cannot do that.

The results indicate that although the TSV indicates thermal perception, this scale showed less accuracy due to the verbal scale's descriptive nature and the high probability of different interpretations. The numerical scale in NV mode was accepted by more residents as it was more straightforward and easy to understand and apply.

Although both scales are subjective, the results support the hypothesis that the proposed numerical scale is a more representative scale for expressing long-term thermal comfort satisfaction. Amplitude was found the most effective index to affect occupants thermal comfort rating. Further studies are required to test the efficacy of the numerical scale using larger groups in different climates and various seasons.

6 The effectiveness of measures to reduce overheating on the top floors of dwellings

6.1 Introduction

This chapter is in two sections. The first part investigates house F which has been retrofitted to reduce overheating during the monitoring period. Monitored temperatures before and after retrofitting are compared. This section also compares the monitoring and simulation results to evaluate the impact of the retrofitting measures of house F on overheating. This section, also demonstrates the need for carrying out simulation at the design stage of any new dwelling or retrofitting. Section two uses the same house as an example to simulate the impacts of employing a range of passive building measures for reducing overheating, with the aim of finding the most effective elements to eliminate overheating. The measures are prioritized based on their effectiveness in reducing overheating on the top floor. Finally, employing a combination of measures are investigated.

6.2 Overheating before and after energy retrofitting: monitoring

This section investigates through monitoring the effectiveness of retrofitting measures to reduce overheating. The overheating indices are calculated for the top floor of house F before and after retrofitting. The overheating changes are compared between the most similar months.

6.2.1 Method

For house F the external walls, windows and fixed glass were improved by retrofitting (Table 6.1). The retrofitting was carried out in February 2014 and the detailed monitoring of the house continued before and after the retrofitting from 2010 to 2019.

Table 6.1 Improved elements in House F before and after retrofitting (GF=ground floor, TF=top floor, BR=bedroom) (TS4 Architecture 2014)

Element	Windows total U-Value (W/m^{2}K)		SHGC		Insulation R-Value (m^{2}K/W)	
	Before	After	Before	After	Before	After
Single window on West (TF, BR)	3	1.35	0.48	0.27		
Single window on North (TF, BR)	3	1.35	0.48	0.27		
Fixed glass on North (TF)	3	2.2	0.48	0.47		
Roof window (GF)	No roof window	2.5		0.21		
Northern Walls (TF)					2.5	5.2
Western Wall (TF)					2.5	5.2

Room temperatures were compared for the most similar outdoor temperatures. Two of the most similar months in terms of outdoor air temperature before and after retrofitting were selected to compare overheating on the top floor. As the indices of overheating measurement were based on T_{rm}, the similarity between the monthly values of two summers outdoor temperature was based on the similarity of T_{rm}. Three methods were nominated to find the most similar summer months: Frechet (Wards 1954), Kolmogorov-Smirnov (KS) test and the root mean square error (RMSE) (Devore & Berk 2012). The Frechet method and its new modifications (Tankov 2011) were too complicated for this case. The KS test focuses on distribution and goodness-of-fit but takes no account of the time component. RMSE calculates and weighs the differences so that large differences are magnified. Also, RMSE can compare the curves over time. Thus, for the purpose of this research, RMSE would seem the most suitable. Its equation is:

$$RMSE = \sqrt{\frac{\sum_{t=1}^{T}(y_t - z_t)^2}{T}} \qquad \text{(Equation 6.1)}$$

Where:

T= Days of months

y = T_{rm} before retrofitting of day t

z = T_{rm} after retrofitting of day t

day t = a given day in a given month

The Values of RMSE for outside temperature were computed for each month before retrofitting versus the same month after retrofitting. For example, RMSE was computed for December 2010 versus December months 2014, 2015, 2016 and 2017. Then RMSE was computed for December 2011 versus December months 2014, 2015, 2016 and 2017. The same was repeated for December months 2012 and 2013. This process was also conducted for the months of January and February. As a result, for each summer month, 16 RMSE values were calculated. The rows in Table 6.2 show the arrangement of calculations. The lowest RMSE amongst the December group indicated the most two similar December months from before and after retrofitting. The same was for the January and February groups.

The upper threshold of Adelaide adaptive thermal comfort (Ad) drived in Chapter 4 (Equation 4.6) was employed for the investigation. The data of the selected months were calculated for finding the indices below and factors in NV mode.

1. Hourly temperatures for top floors
2. Operating AC hours for the ground floor and top floor, separately
3. WEH, frequency and amplitude of exceeded temperatures above the threshold for each month
4. Time lag for daily indoor maximum and minimum temperatures
5. Maximum temperature and percentage of exceeded temperatures for each typical hour in one month

Furthermore, house F was simulated before and after retrofitting using AccuRate. This software is explained in section 2.8.1. For simulation, the weather data of the monitored years were employed. Also, the materials for simulation were exactly the same as built before and after retrofitting. Based on the simulations, two groups of comparisons were carried out:

a) overheating indices before and after retrofitting;

b) the top floor monitored temperatures with simulated temperatures for typical summer days and the hottest summer day before retrofitting (summer 2012–13) and after retrofitting (summer 2014–15). The typical summer day was selected on the basis of number of days with equal T_{rm}. The frequency of days with T_{rm} between 22 °C and 23 °C was the highest, with about 15 days during summer. The average for T_{rm} values was 22.4 °C. Therefore, the typical summer day was defined as a day with T_{rm}=22.4 °C. The hottest summer day was selected based on the highest $T_{rm,}$ which was 30.9 °C equally for simulation and monitored temperatures.

6.2.2 Results and discussion

Similar values for the lowest RMSEs from before and after retrofitting are found for Dec 2011 versus 2016, January 2011versus 2017 and February 2014 versus 2017 (Table 6.2). Table 6.2 shows that the lowest RMSE value for December months is attributed to December 2012 versus 2014. The lowest RMSE value for January months is equal for January 2011 versus 2017 and January 2013 versus 2015. The lowest RMSE for Februarys is associated with February 2013 versus February 2015. Between the two equal groups for January, the group 2013 versus 2015 was selected; because December and

February with the lowest RMSE values were in the same summer and carrying out all comparisons with one summer could increase the chance of accuracy.

Figure 6.1 demonstrates the similarity of T_{rm} between the three selected groups of the summer months. This Figure, alongside Table 6.2 shows that, in general, the January months were the most similar, followed by December and February, respectively.

Table 6.2 RMSE for summer months outdoor temperatures before retrofitting versus the same months after retrofitting

	Dec 2010 VS Dec				Dec 2011 VS Dec				Dec 2012 VS Dec				Dec 2013 VS Dec			
	2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017	2014	2015	2016	2017
RMSE	3.6	6.5	4.0	5.5	3.5	4.8	2.9	4.1	2.7	5.7	3.7	3.2	4.0	5.2	4.1	3.4
	Jan 2011 VS Jan				**Jan 2012 VS Jan**				**Jan 2013 VS Jan**				**Jan 2014 VS Jan**			
	2015	2016	2017	2018	2015	2016	2017	2018	2015	2016	2017	2018	2015	2016	2017	2018
RMSE	3.8	3.6	2.5	3.8	5.1	4.7	5.1	4.5	2.5	3.8	3.2	5.4	7.2	5.1	5.6	5.8
	Feb 2011 VS Feb				**Feb 2012 VS Feb**				**Feb 2013 VS Feb**				**Feb 2014 VS Feb**			
	2015	2016	2017	2018	2015	2016	2017	2018	2015	2016	2017	2018	2015	2016	2017	2018
RMSE	6.5	4.8	4.3	5.1	5.1	4.2	6.0	6.2	3.3	4.4	5.6	5.3	7.0	5.7	4.1	5.0

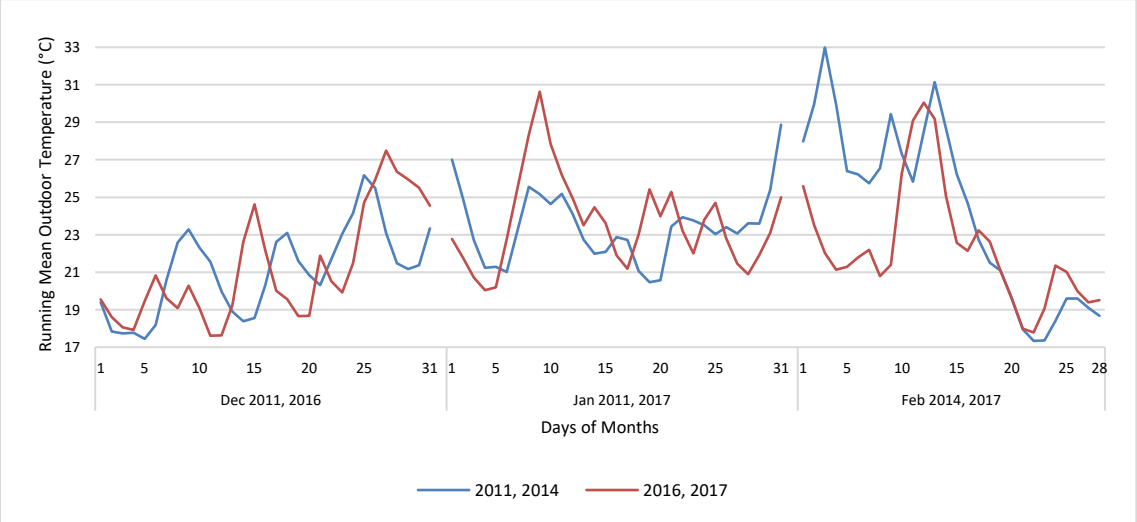


Figure 6.1 The running mean outdoor temperature of the two most similar months before and after retrofitting of house F

6.2.2.1 Indoor temperatures of similar months

The monitored indoor temperatures for a typical day of each month showed that, on average, retrofitting reduced the indoor temperature for all hours in similar months (Figure 6.2). The highest reduction for the indoor temperature for a typical day happened at 18:00 in December (by 0.9 °C), 19:00 in January (by 1.4 °C) and 13:00 in February (by 2 °C). The overheating indices of similar months are also plotted and demonstrate a reduction due to retrofitting (Table 6.3). The retrofitting on the top floor caused the largest

decrease for the WEH and frequency indices for December and January; however, some increase is observed in February. The WEH index reduced in December and January by 12.6 and 3.3, respectively. Also, the intensity reduced for December and January by 11% and 5%, respectively. The frequency index showed a decrease in December and January by 2.3% and 12.8%, whilst in February there was a 7.5% increase. Although most of the overheating indices dropped after retrofitting, they were still above the overheating limits.

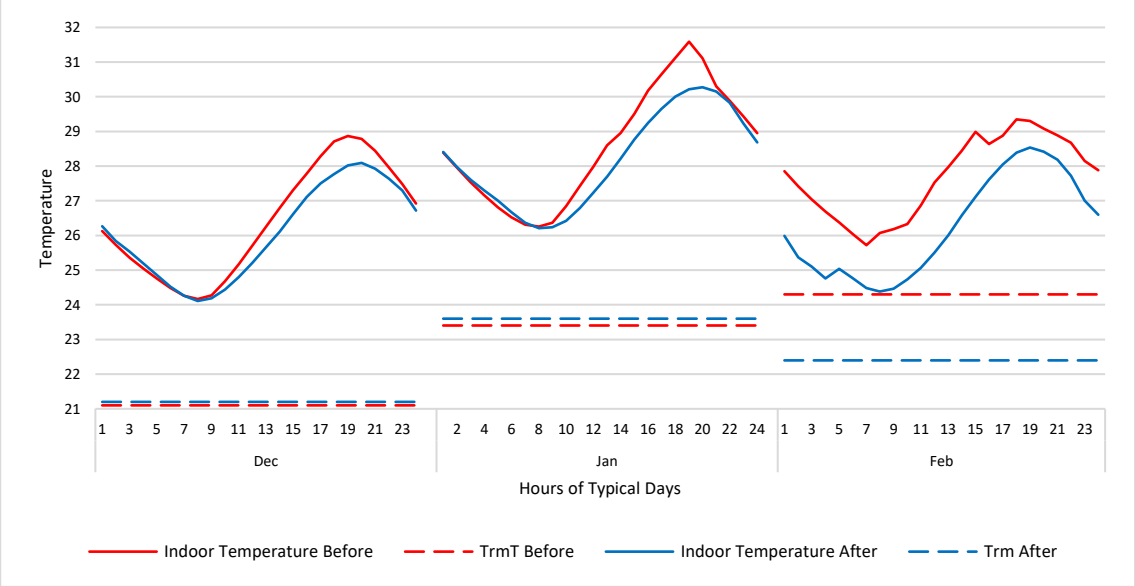


Figure 6.2 Indoor temperature of three typical days for similar summers

Table 6.3 Overheating indices before and after retrofitting in the most similar months

		WEH (degree hour)	Frequency (hour)	Amplitude (°C)	WEH Change (%)	Frequency Change (%)	Amplitude Change (%)
Limit		**250**	**245**	**3.5**			
Before	2011-12	508	222	8			
	2011-01	915	391	8.4			
	2014-02	471	202	8			
After	2016-12	444	217	9	-12.6	-2.3	-11
	2017-01	885	341	8	-3.3	-12.8	-5
	2017-02	509	202	8.6	+7.5	+7.5	0

For two similar months, about 50% of the overheating frequency index occurred during 1:00–15:00 and the other 50% was for 16:00–24:00 before retrofitting. After retrofitting, about 40% of overheating occurred between 1:00–15:00 and 60% of that was for 16.00–24.00 (Fig 6.3).

The amplitude index for each typical hour dropped by 0.1–1.3 °C after retrofitting, with the highest drop for 5:00 (Fig 6.4). This index dropped after retrofitting mostly in Jan with the highest decrease at 4:00–6:00, followed by February with the most significant drop at 24.00 and 4.00–5.00 (Fig 6.4).

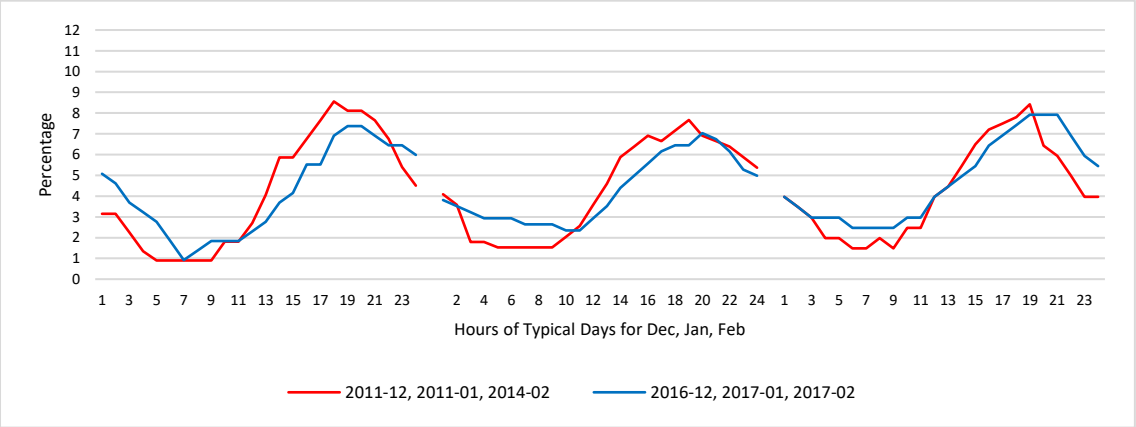


Figure 6.3 Percentage change of the frequency index for each typical hour in similar summers before and after retrofitting in houses F

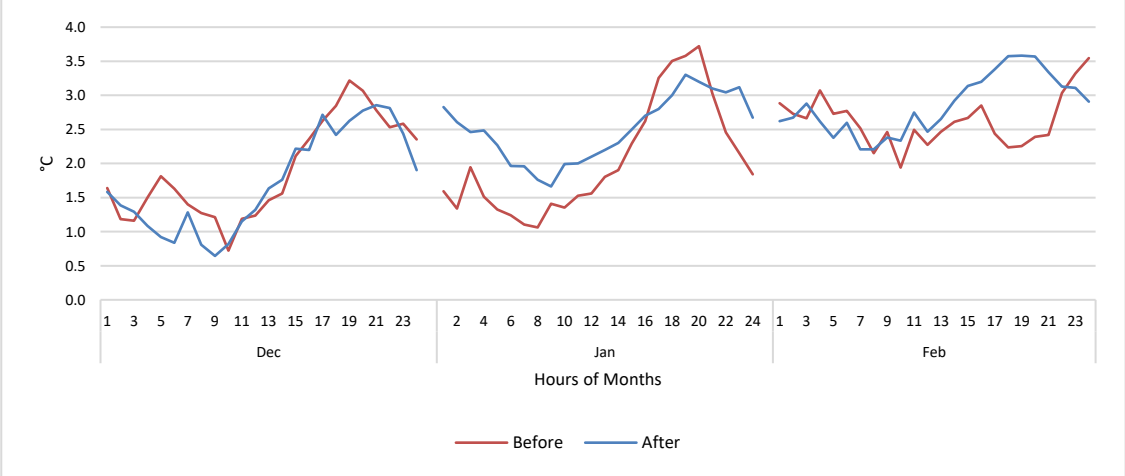


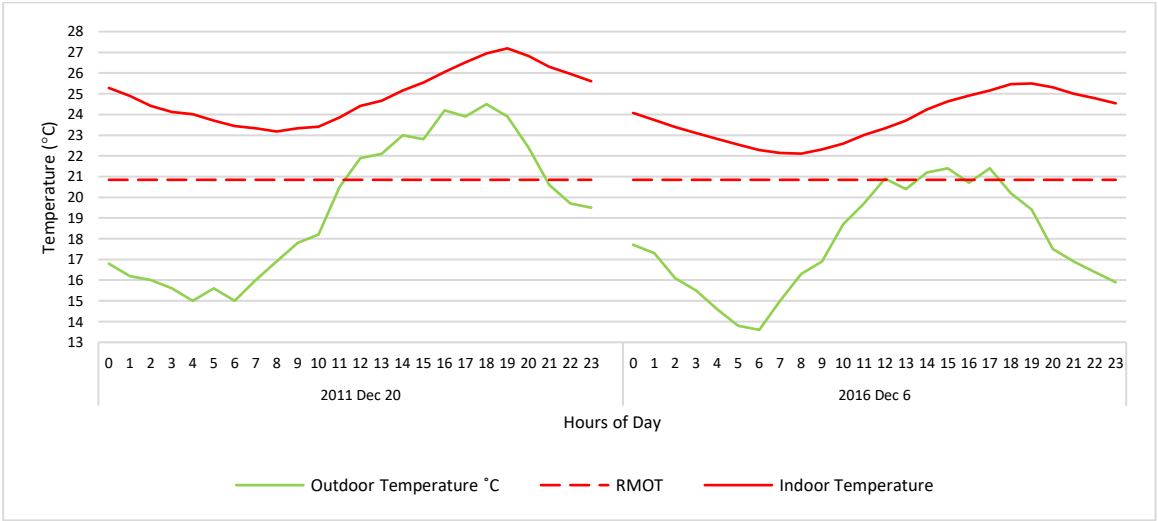
Figure 6.4 The amplitude index for each typical hour in similar months before and after retrofitting in house F

6.2.2.2 Indoor temperatures on similar days

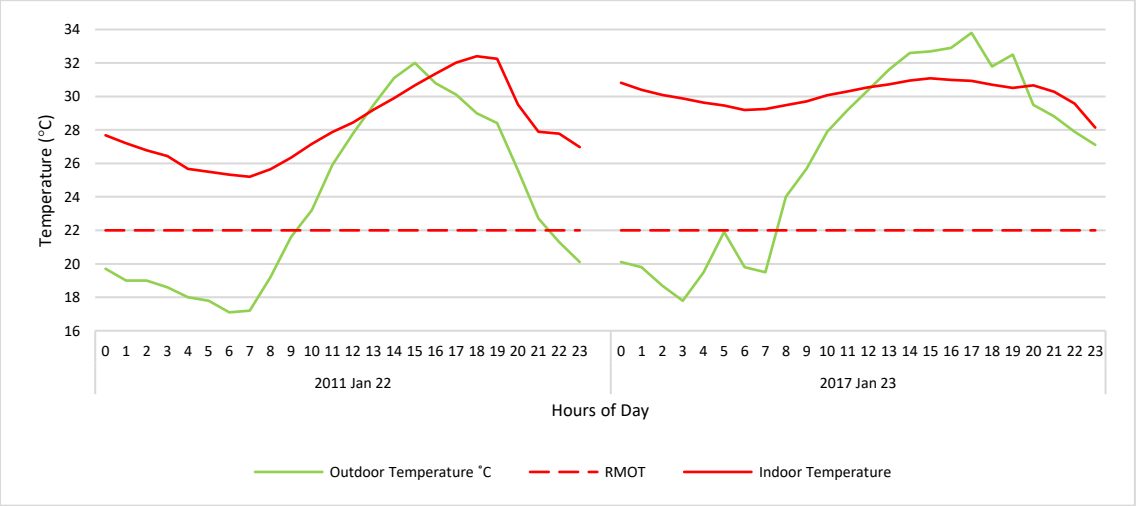
In view of the continuous variation of weather parameters, patterns of room occupancy and home use, no two days are similar. This chapter aims to find the most similar days, which is why the most similar months were found through computing RMSEs. In similar months, the days with equal T_{rm} should have the closest hourly temperatures. In the selected similar months, some days had equal T_{rm} as follows: eight days of December 2011 with five days of December 2016, 10 days of January 2011 with nine days of January 2017 and five days of February 2014 with five days of February 2017. However, most of

the days with equal T_{rm} did not have a similar hourly outdoor temperature. Figure 6.5 shows the outdoor hourly temperatures for the days found to be the most similar. The hourly outdoor temperatures were closest on 20th December 2011 and 6th December 2016 (Figure 6.5 a), 22nd January 2011 and 23 January 2017 (Figure 6.5 b), as well as 21 February 2014 and 21 February 2017 (Figure 6.5 c).

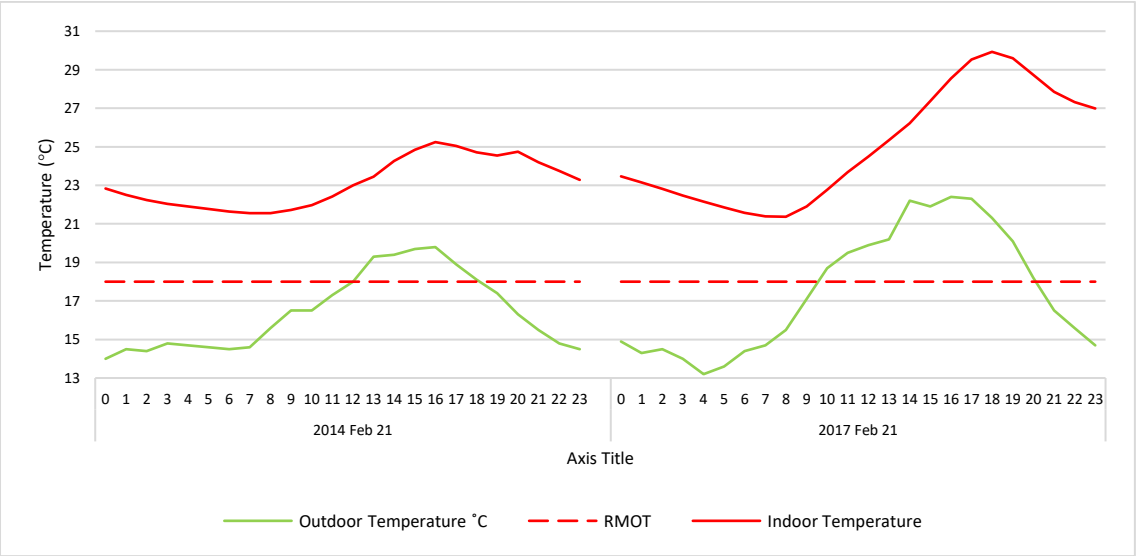
Although the selected days for comparison have equal T_{rm}, their hourly outdoor temperatures are not identical (Figure 6.5). For instance, the maximum daily outdoor temperatures for the three nominated pairs were different by 1.5 °C (Figure 6.5 a), 1 °C (Figure 6.5 b) and 5 °C (Figure 6.5 c). Also, the minimum daily outdoor temperatures for the three nominated pairs were different by 1.5 °C (Figure 6.5 a) and 1 °C (Figure 6.5 b). Therefore, comparing their indoor hourly temperatures could not be so justifiable. Thus, the time lag of each day is compared between similar days. The time lag of indoor daily maximum temperature was 1–3 hours after maximum outdoor temperature before retrofitting and extended to 2–3 hours after retrofitting (Table 6.4). The time lag for indoor daily minimum temperature was 2–7 hours before retrofitting and decreased to 2–4 hours after retrofitting (Table 6.4). The average indoor temperature was less than the average outdoor temperature before retrofitting. The average indoor temperature dropped approximately by 1 °C after retrofitting.



a) December T_{rm} =20.8



b) January T_{rm} = 22



c) February T_{rm} = 18

Figure 6.5 Daily temperature in two similar days before and after retrofitting

Table 6.4 Outdoor and maximum indoor temperatures and their happening hours (maximum outdoor temperature (OMaT), the hour when maximum outdoor temperature happened (HOMaT), maximum indoor temperature (IMaT), the hour when maximum indoor temperature happened (HIMaT)

Month, Day	Dec		Jan		Feb	
Year	**2011**	**2017**	**2011**	**2017**	**2014**	**2016**
OMaT	24.5	21.4	32	33.8	19.8	22.4
HOMaT	18.00	16.00	15.00	17.00	16.00	16.00
OMiT	15	13.6	19	19.5	14	13.2
HOMiT	6.00	6.00	1.00	7.00	0.00	4.00
IMaT	27.2	25.5	32.4	31	25.25	29.9
HIMaT	19.00	19.00	18.00	15.00	16	18.00
IMiT	23.2	22.1	25	28	21.6	21.4
HIMiT	8.00	8.00	7.00	23.00	7.00	8.00

6.2.2.3 Comparison of monitored temperatures with simulated temperatures

Comparing the house F simulations before and after retrofitting found that the retrofitting reduced both the WEH and amplitude indices on the top floor (Table 6.5). On the top floor, The indices reduced most by 40% and 25% during December and February, respectively. The highest reductions on the ground floor were 40% and 33% for WEH and amplitude indices in February.

The simulated hourly temperatures on the top floor before and after retrofitting showed that the maximum temperature in a typical day dropped by 4 °C and the minimum temperature increased by less than 1 °C (Figure 6.6). The effect of retrofitting on the hottest day was not as significant as typical days, as the maximum temperature decreased by less than 2 °C and the minimum temperature increased by 1.5 °C (Figure 6.7).

Table 6.5 Indices for before and after retrofitting resulted from house F simulations (Re: reduction, Bef: before, Aft: after)

	Top Floor						Ground Floor					
	WEH			Amplitude			WEH			Amplitude		
	Bef	Aft	Re (%)	Bef	Aft	Re (%)	Bef	Aft	Re (%)	Bef	Aft	Re (%)
Dec	988	560	40	13	12	7	358	319	10	6	6	0
Jan	676	536	20	10	9	10	61	37	40	2	2	0
Feb	717	516	39	16	12	25	47	29	40	3	2	33

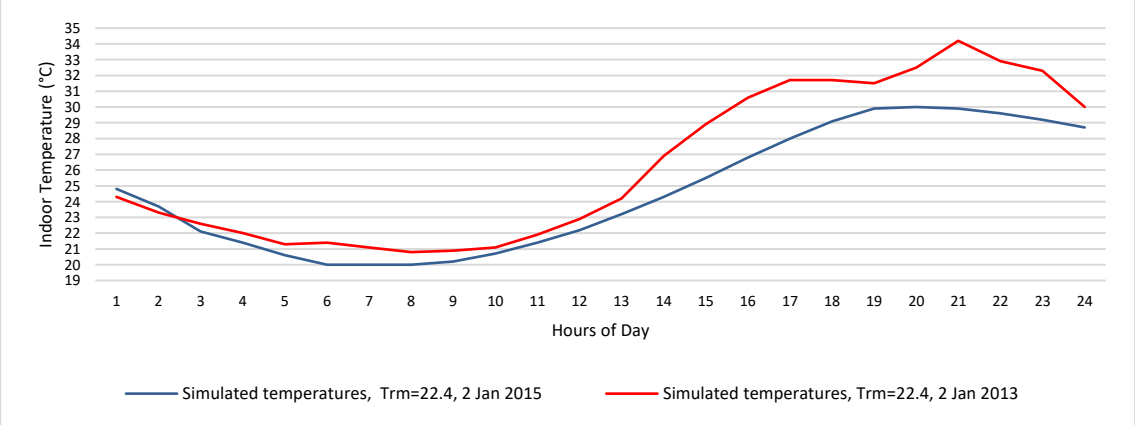


Figure 6.6 Hourly temperatures in a typical summer day by simulation before and after retrofitting

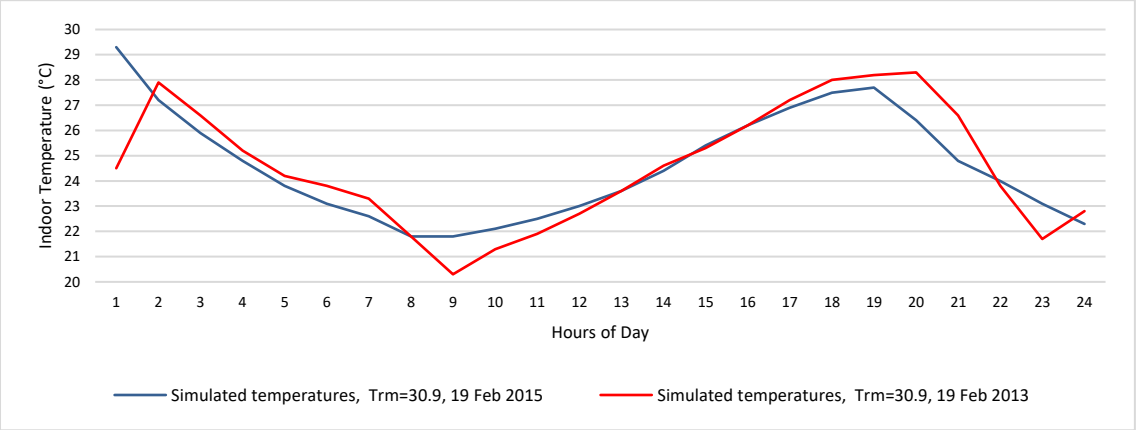


Figure 6.7Hourly temperatures in the hottest summer day by simulation before and after retrofitting

The comparison of monitored temperature with simulated temperatures showed that monitored temperatures were greater than the simulated temperature for 87% of hours in four investigated days (Figures 6.8–6.11). The monitored temperatures were higher than the simulated ones for a typical day, with a maximum of 5.4 °C at 6:00 am (Figure 6.8). This difference reduced to 4.4 °C at 11:00 after retrofitting (Figure 6.9). The minimum difference between monitored and simulation for the typical day was between 14:00–21:00 (Figures 6.8 and 6.9). Monitored temperatures were higher than simulated ones for the hottest day, with a maximum of 10.8 °C at 8:00 (Figure 6.10). This difference stayed the same with 10.7 °C at 9:00 after retrofitting (Figure 6.11). The minimum difference between monitoring and simulation for the hottest day was between 16:00–20:00 (Figures 6.10 and 6.11).

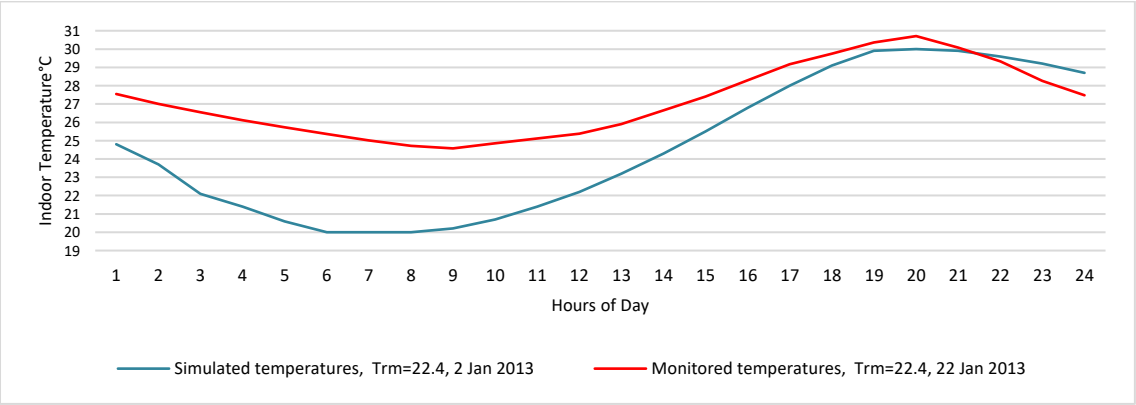


Figure 6.8 Hourly temperatures on the top floor in a typical summer day of 2012-13 by simulation and monitoring before retrofitting

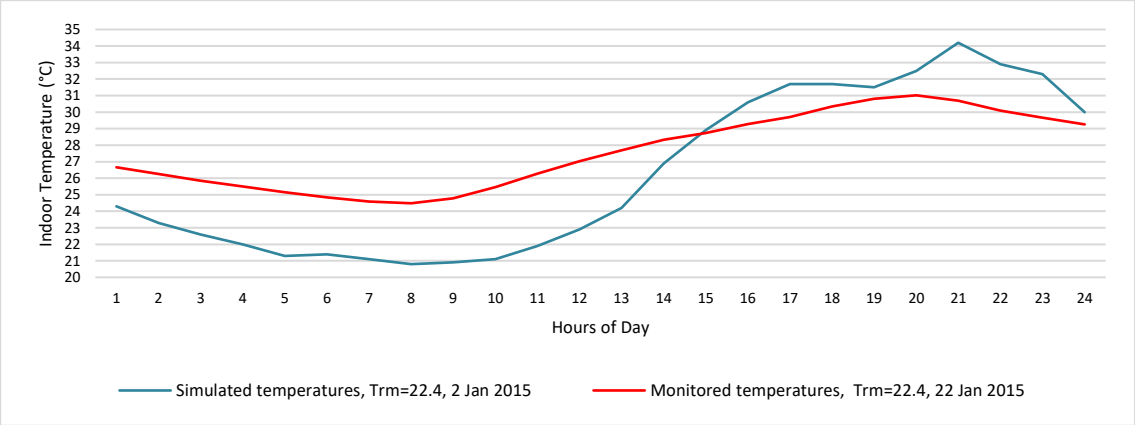


Figure 6.9 Hourly temperatures on the top floor in a typical summer day of 2014-15 by simulation and monitoring after retrofitting

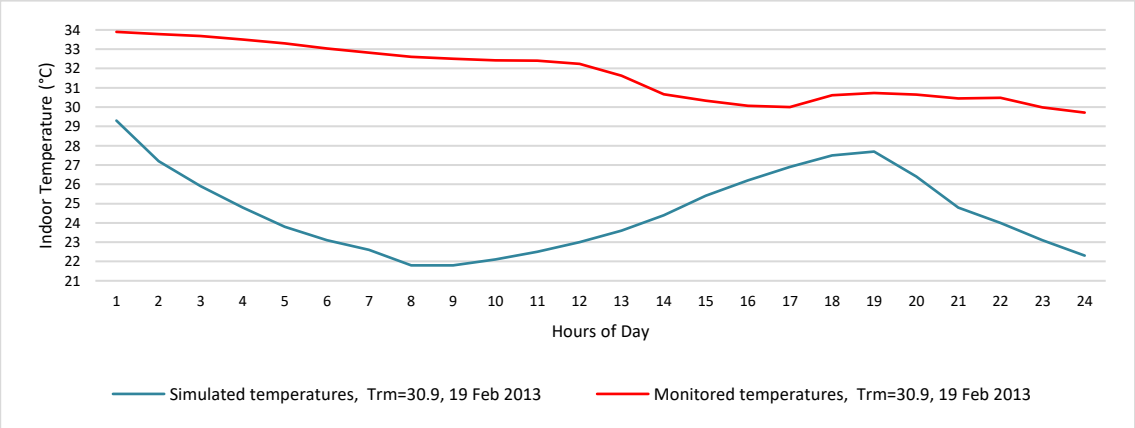


Figure 6.10 Hourly temperatures on the top floor in the hottest summer day of 2012-13 by simulation and monitoring before retrofitting

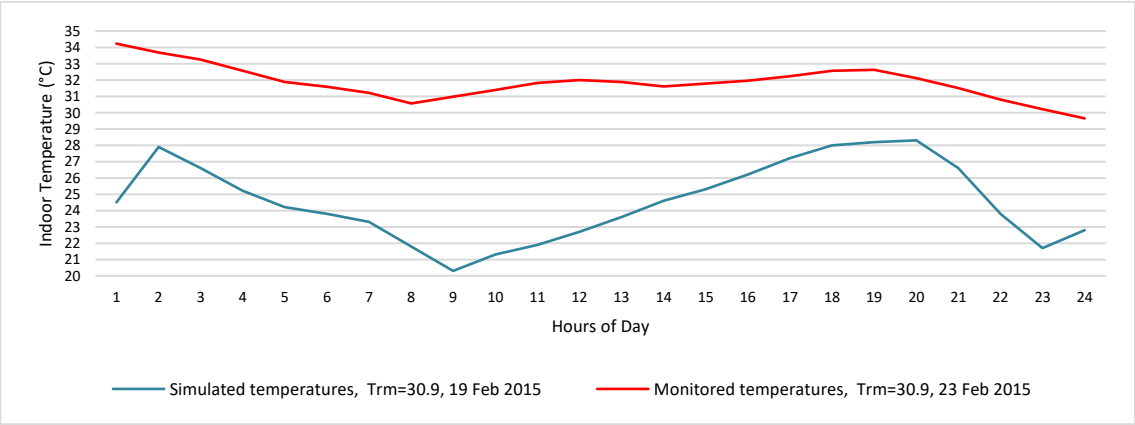


Figure 6.11 Hourly temperatures on the top floor in the hottest summer day of 2012-13 by simulation and monitoring before retrofitting

6.2.2.4 Discussion

The measures employed for retrofitting house F were part of the most extensively used measures for retrofitting in 100 climate zones (Carratt, Kokogiannakis & Daly 2020) which are wall insulation following by improved glazing and roof insulation.

Comparing the most similar months showed that retrofitting decreased the indoor temperature for all typical hours. The hourly temperature in a typical day after retrofitting dropped in the afternoon by about 1 °C. A study that compared monitoring and simulation in Lochiel Park, showed a similar result in another way. This study found that better-insulated houses use less energy for both cooling and heating (O'Leary et al. 2016), which indicates decreased temperature for summer. Adding less than 2 cm of Polyurethane to the external walls reduced the cooling load of the building by 28% in Qatar as shown by simulation (Kharseh & Al-Khawaja 2016). The average indoor temperature became cooler by about 1 °C after retrofitting. Similarly, monitoring and simulation for a passive house in Cyprus showed reduced average indoor temperature compared to outdoor temperature (Fokaides et al. 2016).

In total, 67% of calculated overheating indices reduced due to retrofitting. All overheating indices decreased in December and January, while the intensity index stayed unchanged in February and two indices (WEH and frequency) increased. The principal value of the frequency index in a typical day was shifted to 16.00–24.00 by retrofitting. A monitoring study from 14 various archetype dwellings in the tropical part of Brazil found that the overheating period is 17.00–24.00 (Gamero-Salinas, Monge-Barrio & Sanchez-Ostiz 2020). Therefore, the retrofitting of house F could shorten the overheating period. However, there are two studies with different results about the frequency period and value. Monitoring of an energy-efficient case in the north of the UK found that overheating occurred substantially during 23.00–7.00 (Fletcher et al. 2017) which is not in common with this study or other studies. Simulating typical Italian dwellings resulted in an increased frequency of exceeded temperature above 26 °C (Pyrgou et al. 2017). The retrofitting dropped amplitude about 1 °C, mainly at 5.00 am. A contrasting finding is that in Melbourne, higher energy rated homes increased the maximum indoor temperature based on monitoring (Willand, Ridley & Pears 2016). However, it is not clear which floors of dwellings were compared as there is a big difference between the ground floor and top floors in all archetypes considered (Monge-Barrio & Sánchez-Ostiz Gutiérrez 2018; Sharifi, Saman & Alemu 2019).

On similar days, the average time lag for the maximum indoor temperature increased by 30 minutes. The average time lag for the minimum indoor temperature decreased by 2 hours. This time lag shows that after retrofitting, the indoor temperature retches to its maximum later and its minimum earlier compared to before retrofitting. This result indicates less overheating. Although the maximum and minimum temperatures show an increase, there is a decrease in overheating as a whole. This decrease is due to the reduction of overheating frequency by about 2.5 hours.

House simulations before and after retrofitting showed that the highest reduction happened on the top floor, particularly for the WEH index. The reduced amplitudes were not as significant as that of WEHs. Using these measures just on the top floor could reduce overheating on the ground floor too. Retrofitting house F increased the minimum difference between simulated and monitored temperatures on a typical day whilst reduced the maximum difference between simulated and monitored temperatures. Retrofitting house F increased the minimum difference between simulated and monitored temperatures on the hottest day and reduced slightly the maximum difference between simulation and monitored.

The limits of this investigation are the lack of information about the ventilation rate (air changes per hour) and residents' home use pattern and their behaviour. Thus, the pattern of room occupancy, opening of windows and probably nocturnal ventilation may have an impact on the results. The differences observed between the simulation and monitoring results point out that the behaviour patterns assumed in the simulation package are not close to representing actual behaviour patterns of households.

6.3 Simulation of overheating measures

This section presents the implication of applying available passive design measures on overheating as evaluated by using the proposed criteria for overheating. House F is used in this study as an example. The impacts of various measures are evaluated through simulation. In addition to investigating the effectiveness of individual overheating measures on house F, applying a combination of measures to find the optimum combination was carried out. In many cases, extreme values of these measures are used to evaluate their maximum potential impacts. It may be noted here that these extreme values, in most cases, may not be the most practical and economic values to use in practical applications.

6.3.1 Method

The software AccuRateSustainability was employed for the simulation as this software (Australian Government Department of the Environment and Energy 2019; Department of Planning Transport and Infrastructure 2020; NatHERS 2021): a) is based on NatHERS as the benchmark software for house energy rating in Australia, b) covers all 69 different climate zones of Australia. The simulations are run in NV mode and the temperature output were analysed for evaluating the overheating indices.

House F was employed for simulation using typical weather data for Adelaide and the measures are selected from Table 2.11. Table 6.6 lists the measures used in this investigation based on the categorization of Table 2.11.

Table 6.6 Measures for reducing overheating that were used separately in simulation compared with the measures for asbuilt dwelling

	Building element	Values for measures in simulation		Values in the existing dwelling	
Envelope	**Shading/ Blind**	Horizontal shading for north and west-facing windows	Vertical shading for north and west-facing windows	No shading	No shading
	Roof	Solar absorptance = 30% Roof window		Solar absorptance = 50% No roof window	
		R = 6, 8, 12	Hip roof with no ceiling	R = 4	Single slope
	Wall	Wall solar absorptance = 30%	R = 6, 8	Wall solar absorptance = 50%	R = 3.5
		R = 6, 8	Brickwork inside or Brickwork outside or Double brick	R = 3	Fiber-cement sheet
	Window	Emissivity = 0.1 SHGC = 0.28 U = 2.5 W/m^{2}K Double-glazed Argon-filled Thermal- break profile Open the fixed glazing 100% outdoor shading Indoor shading by roller blind	Solar absorptance = 30% Reduce north and west-facing windows area by 30% compared to existing dwelling	Emissivity = 0.5 SHGC = 0.48 U = 3.00 Timber frame Double-glazed Air-filled Fixed glazing for void windows No outdoor shading Indoor shading by roller blind	Solar absorptance = 50%
Inside	**Internal walls, Ventilation**	Ventilation chimney Nocturnal ventilation	R = 2.5 Eliminate void	No ventilation chimney No record on nocturnal ventilation	R = 1.5 With void

More details about these measures are as below:

- Reduce direct solar radiation to windows: shading to all unshaded north and west-facing windows with no shading. The length of each shading is equal to its related window and the width is 900 mm for all of them. The shadings devices are installed on the lintels' height.

- Increase thermal mass and reduce the conduction through external walls: a) Insulation with R4 and 8 are applied to external walls, b) For the original walls with R4, a layer of extruded brick with a thickness of 110 mm is used in three separate ways. First, the

brick substitutes for plasterboard inside; second, the brick substitutes for the fibre-cement sheet outside and third, the brick substitutes for both the plasterboard and fibre-cement (double brick).

- Add nocturnal ventilation: windows are kept open between 24:00–7:00.
- Minimise the convection between two levels: the top floor is separated from the ground floor zone and the staircase is considered as a controlled opening.
- Increase the ventilation by natural convection through:

  a) adding a 1 m^2 openable skylight to the roof on the void zone, which includes double glazing with an air gap, outdoor shading of 100%, indoor shading by roller blind and 90% openable area (Figure 6.12).

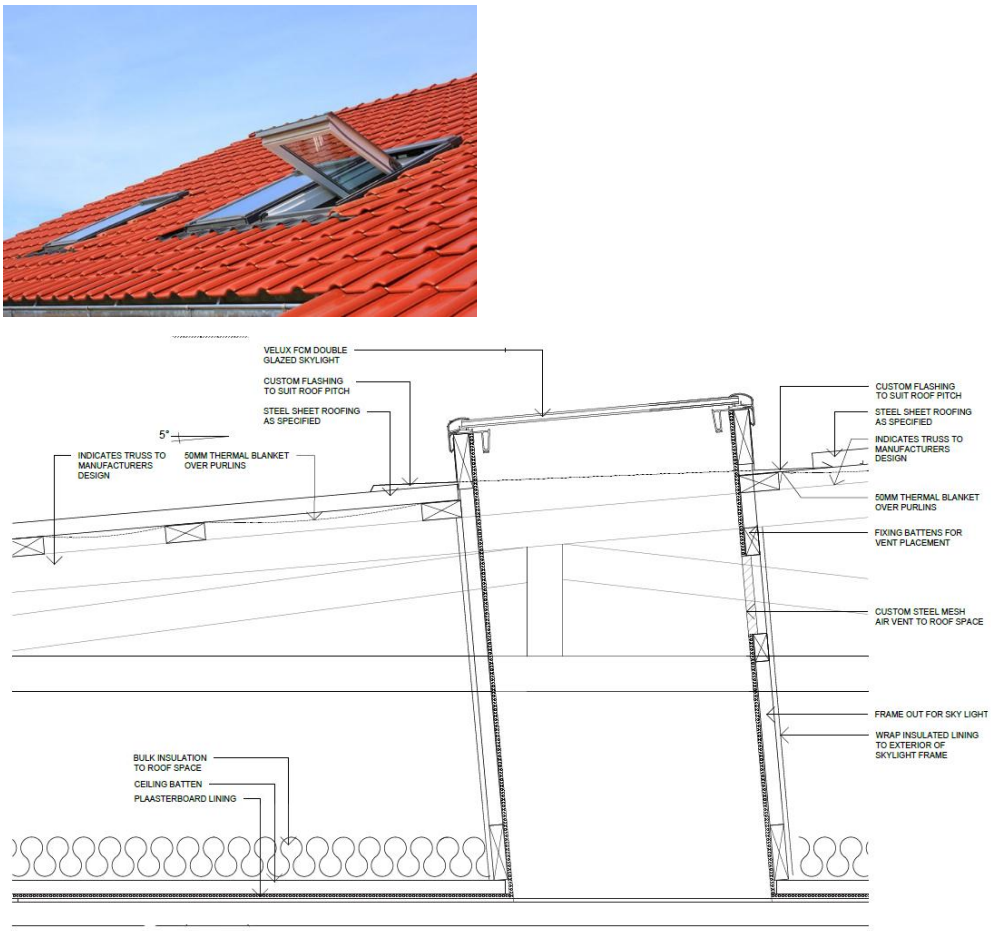


Figure 6.12 Details of the skylight (skylights 2020; Wright 2018)

b) add a 1 m^2 base ventilation chimney to the roof on the void zone, which includes two layers of polycarbonate with an air gap, 100% outdoor shading, R4 insulation for shaft with a length of 1000 mm (Figure 6.13).

c) change the fixed glazing in the external wall to openable windows with the same properties as the other original windows.

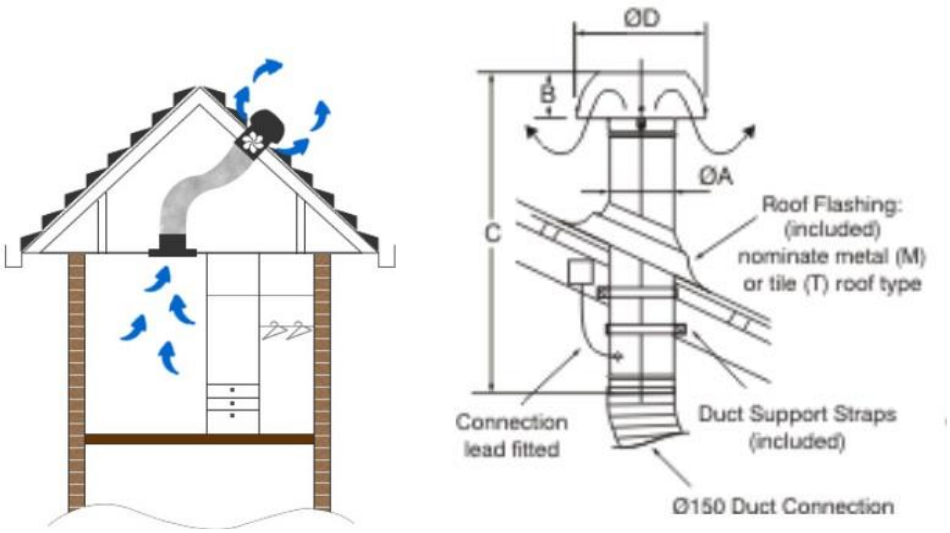


Figure 6.13 Picture and drawing of a ventilation chimney
(Feantech Intelligent Ventilation 2021; xchange air 2019)

The fixed default for air infiltration in simulation is 0.7 air change per hour (ACH) for no mechanically supplied outdoor air as per the NCC requirement.

The effect of employing each measure was investigated separately and then the most effective measures were combined to reduce overheating to be under the limits of the proposed criteria.

The results of simulating each measure were analyzed in three steps:

1. The measures were selected based on the literature review and Table 2.11. Table 2.11 lists the measures that studies have recommended to reduce overheating. Therefore, the following measures will be employed in the simulations:

   - Building envelope– shading for windows, low-e glazing, high R-Value frames, double glazing, low SHGC, high R-Value insulation for roof and walls, increase

thermal mass for walls, light colour for roof and walls, change the fixed glazing to openable windows, reduce window area and add a ventilation chimney

- Inside of building– daytime ventilation, nocturnal ventilation, separate the top floor from ground floor zone and control staircase ventilation

2. Find the percentage of reduction for the WEH and amplitude indices for each measure. List measures based on the reduction of these indices separately.

3. Employ a combination of measures to reduce overheating in house F with emphasis on overheating reduction measures on the top floor to investigate the effectiveness of these combinations.

6.3.2 Results and discussion

The results of step 1, simulating the selected 18 measures to reduce overheating, showed that the effect of each measure has a different impact on each of the two indices for both floors (Figure 6.12). The comparison shows that most of the measures impact the WEH index, while only two of the measures significantly affect the amplitude index. Some measures that decrease one index might slightly increase other indices on the same floor or another floor, with some of the results being difficult to explain. This phenomenon is not unexpected, as adding some measures would have an impact on the overall thermal performance pattern. The approach for this section is analysing each floor shadowed by another floor and finding measures that decrease the overheating and achieve equal temperature on both floors with an emphasis on the top floor.

6.3.2.1 Step1

Envelope- The results demonstrate the key role in reducing overheating played by increasing thermal mass, particularly close to the internal space and reducing the window area. Adding the horizontal window shading reduces overheating on both floors with more effect for the ground floor.

Investigating the R-Value shows that if the R-Value increases beyond a specific limit, it might not result in a further reduction in the overheating and can even exacerbate the overheating. R6 for insulation in the roof increases the overheating indices for the ground and top floors, while R8 decreases all indices significantly for both floors (Figure 6.12). There was little advantage in adding further roof insulation. For the external walls, the

disadvantages of R8 were more than their advantages and R6 showed more decreased indices than increased ones.

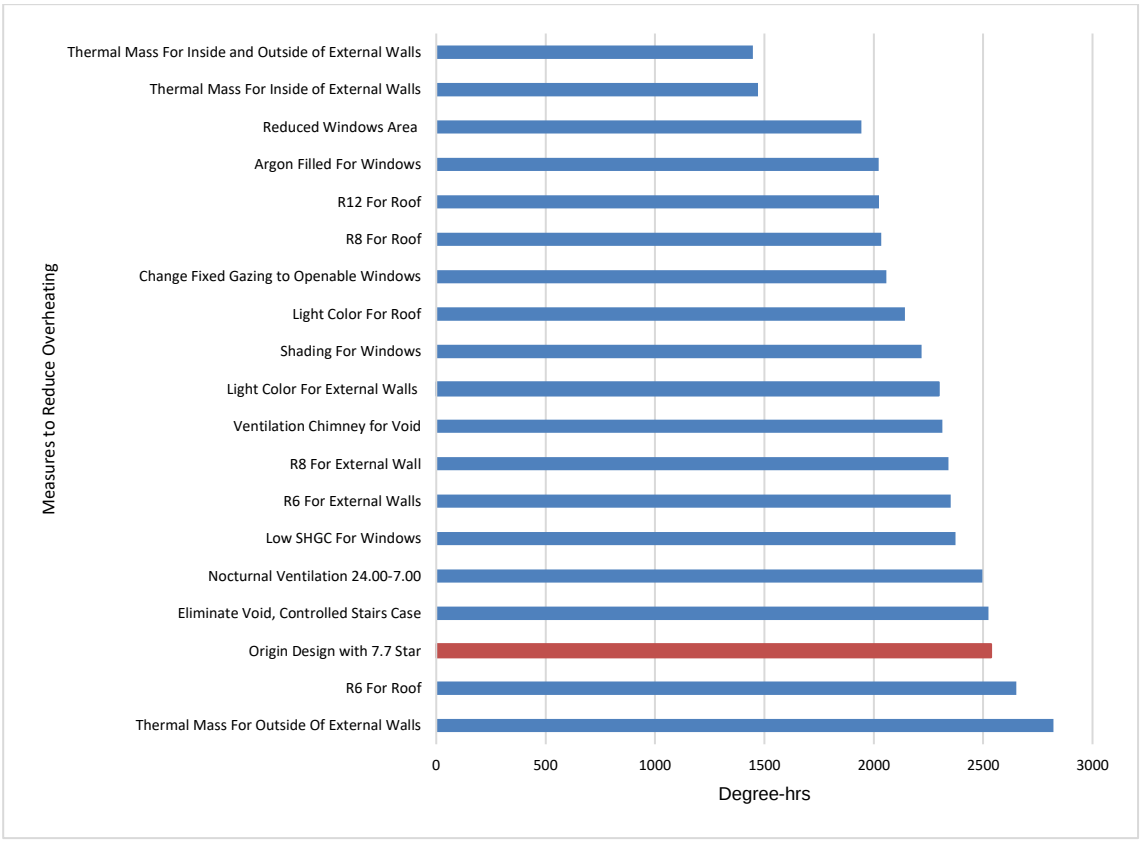
Light colour for the roof or external walls decreases all indices on both floors (Figure 6.12).

Changing the fixed glazing to openable windows reduces all indices, except the intensity index on the top floor. Thus, this measure needs coupling with a measure that reduces intensity. The ventilation chimney decreases the overheating on both floors if its shaft is insulated. The skylight exacerbates the overheating even when it has 100% shading outside with a blind inside and 100% open ability. This is not surprising as the skylight allows more heat into the house. It is usually added to improve daylighting.

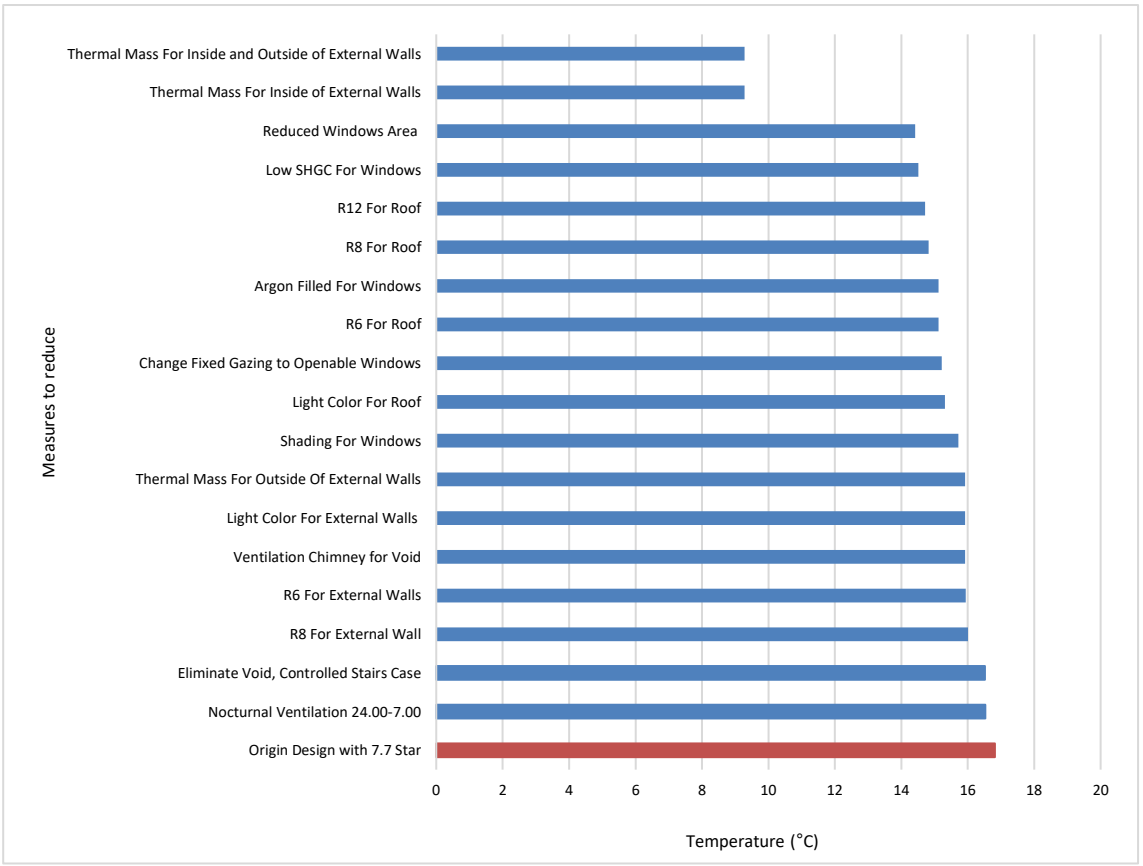
Using a hip roof increases the overheating significantly for both floors, particularly on the ground floor. Studies have shown that ventilated hip roofs reduce energy use in hot and temperate climate compared with non-ventilated hip roofs (Yeang & Woo 2010).

The argon-filled thermal break windows are remarkably effective in reducing overheating on both floors.

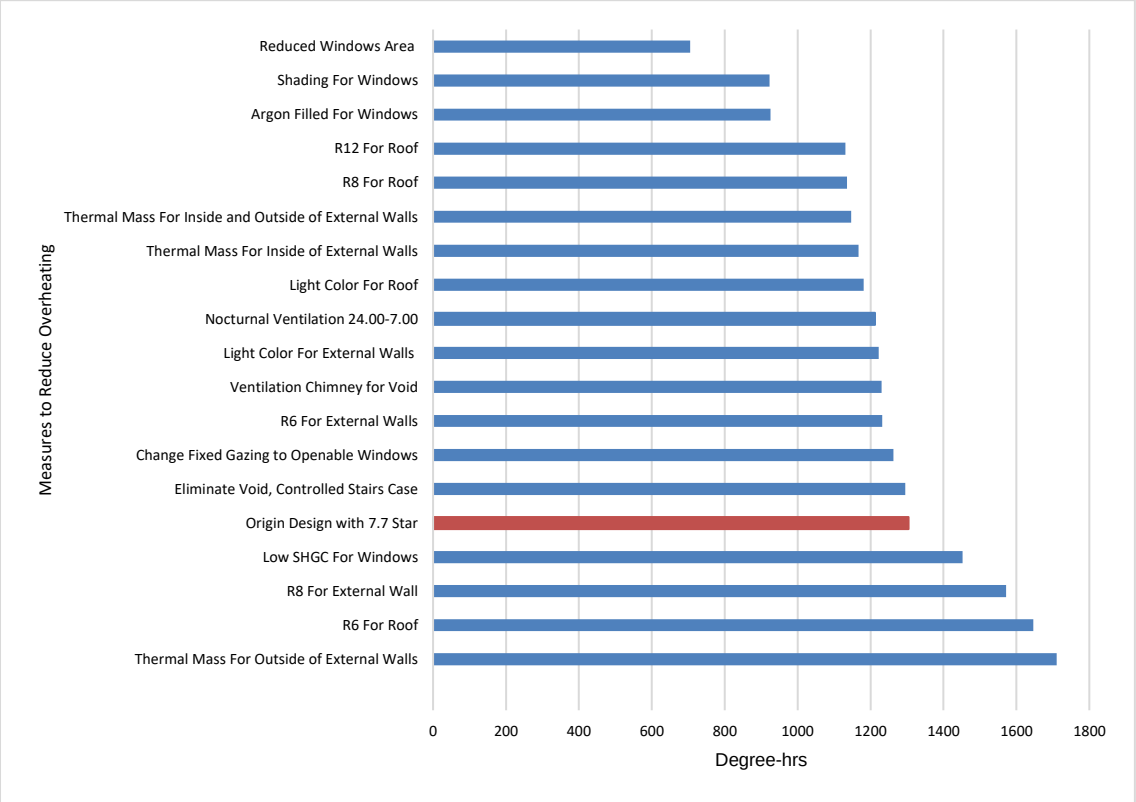
Inside- Nocturnal ventilation is beneficial for cooling both floors with more effect on the ground floor.



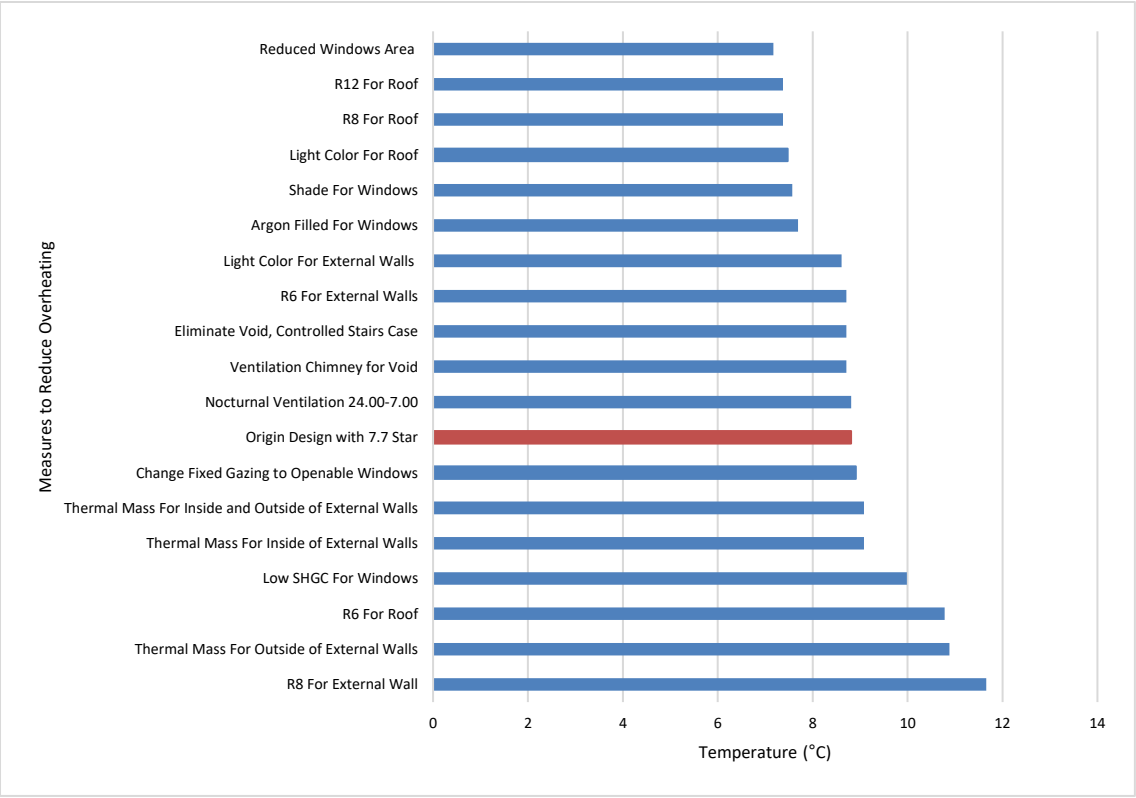
a) WEH index on the top floor



b) Amplitude index on the top floor



c) WEH index on the ground floor



d) Amplitude index on ground floor

Figure 6.14 Impact of potential measures for reducing overheating on WEH and amplitude indices for both the ground and top floors of house F

6.3.2.2 Step 2

The impact of each measure was effective up to a specific level with little effect when increases further. For example, R8 decreased the WEH index on the top floor by 20% more than R6 (Table 6.7), while R12 produced no change compared with R8. Also, reducing the solar absorptance up to 30% was effective, while reducing it more had a little effect (Table 6.7). Therefore, R12 in the roof will not be used for the simulation. Some research has found that insulating buildings higher than the necessary R-Value results in increasing indoor temperature. Simulation of five building standard typical UK dwellings found a higher level of insulation increased the temperature of indoor finishing overnight (Mark & Spyridon 2016). Overheating risk in highly insulated dwellings is significantly higher than in the Netherlands' older poorly insulated dwellings (Hamdy et al. 2017). The simulation for retrofitting an apartment block in Bilbao, Spain, showed cladding the exterior walls with insulation increase cooling demand in summer (Karmele Urbikain 2020).

Table 6.7 The percentage of reducing the values for indices

	Percentage reduction			
	Top Floor		Ground Floor	
Measure	**WEH**	**Amplitude**	**WEH**	**Amplitude**
Reduced mainly west and north-face window area	23	14	46	19
Argon filled for windows	20	10	29	13
R8 for roof	20	12	13	16
R12 for roof	20	12	13	16
Light Color for roof	16	9	9	15
Shading for windows	13	7	29	14
Low SHGC for windows	6	14	----	----
Ventilation chimney for void	9	5	6	1
R6 for external walls	7	5	6	1
Eliminate void, controlled stairs case	1	2	1	1
Thermal mass for inner side and outer side of the external walls	43	45	12	----
Thermal mass for inner side of external walls	42	45	11	----
Change fixed glazing to openable windows	19	10	3	----
Light color for external walls	9	5	6	2
Nocturnal ventilation 24.00-7.00	2	----	7	0
R8 For external wall	8	5	----	----
R6 for roof	----	10	----	----
Thermal mass for outside of external walls	----	5	----	----

Due to the aim of this research in reducing overheating on the top floor, the measures were arranged based on their effect on reducing the WEH index on the top floor (Table 6.8). The selection of this index to prioritise the measures is based on the index integrating both the magnitude and frequency values of overheating. This arrangement removes R6 for roof and thermal mass for outside of external walls.

The top 13 measures are attributed to the envelope, showing the importance of the envelope in controlling overheating. Two measures of the last four priorities are related to the inside of building (Table 6.8) which show these measures contribute less to reducing overheating. Table 6.9 shows that the measures that were on the last four priorities did not reduce amplitude on the top floor while other measures have reduced both WEH and amplitude indices. This indicates that selecting WEH reduction percentage to prioritise the measures resulted in a reasonable order.

Table 6.8 Order of measures based on the percentage of reducing the values for WEH on the top floor

Measure	WEH	Priority
Thermal mass for inner side and outer side of the external walls	43	A
Thermal mass for inner side of external walls	42	B
Reduced mainly west and north-face window area	23	C
Argon-filled for windows	20	D
R8 for roof	20	E
Change fixed glazing to openable windows	19	F
Light Color for roof	16	G
Shading for windows	13	H
Low SHGC for windows	6	I
Ventilation chimney for void	9	J
Light colour for external walls	9	K
R8 For external wall	8	L
R6 for external walls	7	M
Nocturnal ventilation 24:00-7:00	2	N
Eliminate void, controlled stairscase	1	O
R6 for roof	0	P
Thermal mass for outside of external walls	0	Q

Table 6.9 Indices with reduced values by employing the measures

	Top Floor		
Measure	WEH	Amplitude	Priorities
Thermal mass for inner side and outer side of the external walls	✓	✓	A
Thermal mass for inner side of external walls	✓	✓	B
Reduced mainly west and north-face window area	✓	✓	C
Argon-filled for windows	✓	✓	D
R8 for roof	✓	✓	E
Change fixed glazing to openable windows	✓	✓	F
Light Color for roof	✓	✓	G
Shading for windows	✓	✓	H
Low SHGC for windows	✓	✓	I
Ventilation chimney for void	✓	✓	J
Light colour for external walls	✓	✓	K
R8 For external walls	✓	✓	L
R6 for external walls	✓	✓	M
Nocturnal ventilation 24.00-7.00	✓		N
Eliminate void, controlled stairs case	✓	✓	O
R6 for roof		✓	P
Thermal mass for outside of external walls		✓	Q

6.3.2.3 Step 3

For reducing overheating, different combinations of priorities A to Q were simulated. The top priorities were combined first. Then some of the lower priorities were added and

higher ones were deleted to test various combinations. The following combinations are considered as shown in Figure 6.15. Figure 6.16 shows the percentage reductions of the indices as a result of the measure combinations used:

Simulation 2- A, C, D, E, G, H, I, O. Compared to the original design, the indices decreased by 54-94% on the top floor and 83-99% on the ground floor (Figure 6.16).

Simulation 3- B, C, D, E, G, H, I. Compared to the original design, the indices decreased by 66-97% on the top floor and 83-100% on the ground floor to values well below the overheating thresholds set previously. The results show that an opening between floors was more beneficial for the top floor. Simulation 3 showed that, in total, the effect of closing the void and uncontrolled open staircase on reducing the overheating was not significant (Figure 6.15).

Simulation 4- B, C, D, H, J, K, N, P. Compensating for the produced temperature, nocturnal ventilation (N) was added for the period 1:00-5:00. Various periods from 24:00–7:00 were investigated for this simulation and it was found that the best period for nocturnal ventilation was 1:00-5:00. When simulating each measure separately, the most effective period was 24:00-7:00. All indices were less than Simulation 3 for the top and ground floors (Figure 6.15). Studies found that nocturnal ventilation is very effective for super-insulated walls and overheated rooms and reduces the inside wall surface temperature by 1.5 °C (Stazia et al. 2015). This measure is the first technique suggested by CIBSE TM 59 to prevent overheating (CIBSE 2017) and affects buildings' thermal performance (Pellegrino, Simonetti & Chiesa 2016).

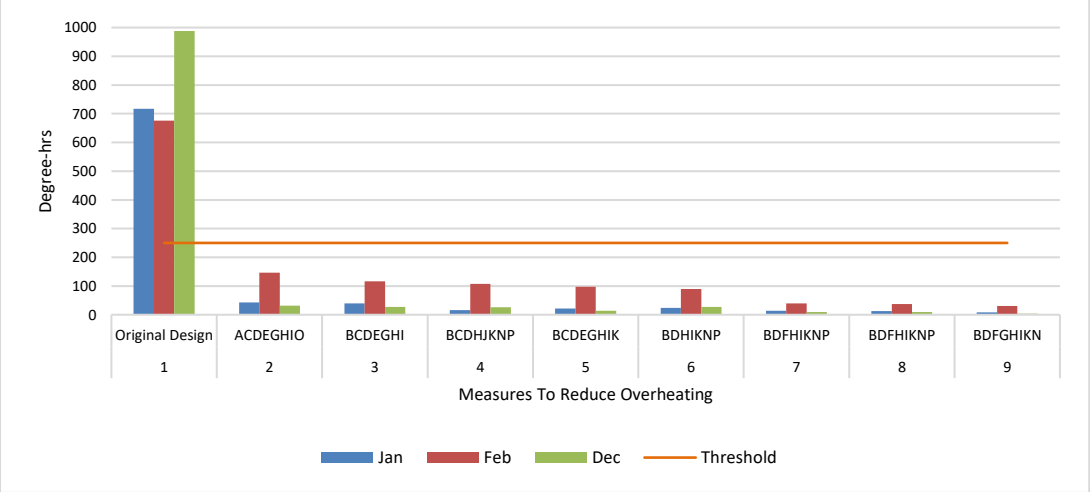
Simulation 5- B, C, D, E, G, H, I, K. Compared to the original design, all indices reduced more than 87% and 57% on the top floor and ground floor, respectively (Figure 6.16).

Simulation 6- B, D, H, I, K, N, P. All indices decreased compared to the original design with a minimum of 73% and 42% for the top floor and ground floor, respectively (Figure 6.16).

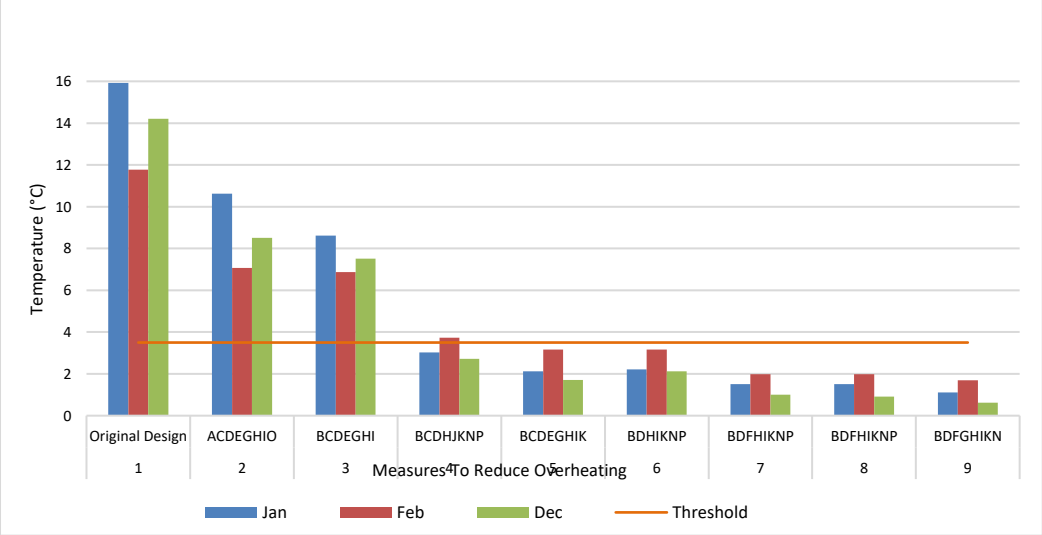
Simulation 7- B, D, F, H, I, K, N, P. All indices are significantly below the proposed thresholds on both floors (Figure 6.13).

Simulation 8- B, D, F, H, I, K, N, P. All indices are below the thresholds and overheating is almost to eliminated (Figure 6.13). Compared to the original design, the indices decreased by 94-98% on the top floor and 68-99% on the ground floor (Figure 6.15).

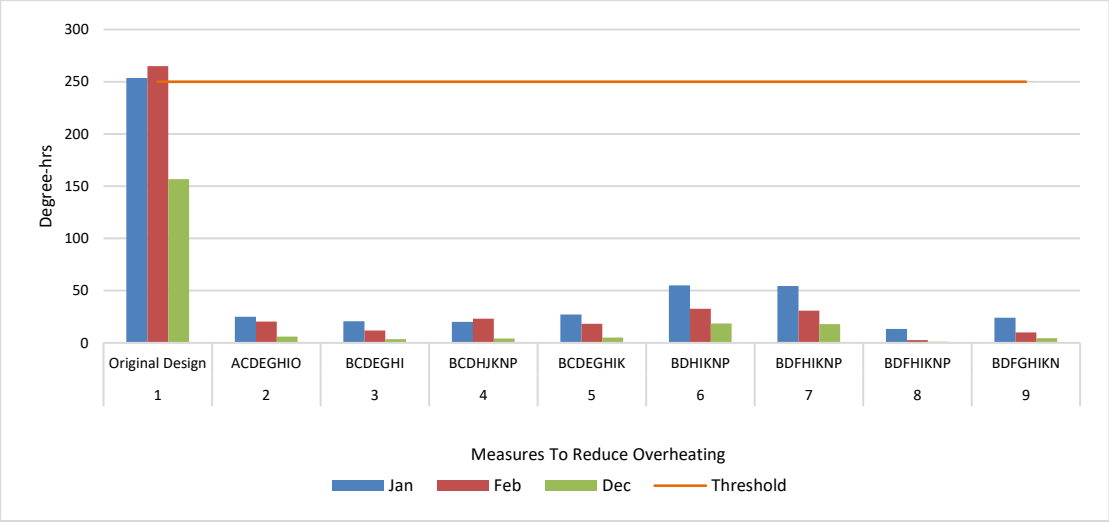
Simulation 9- B, D, F, G, H, I, K, N. R6 for the roof was substituted by R4 and light coloured roof (Figure 6.15). Compared to the original design, the indices decreased by 95-100% on the top floor and 57-97% on the ground floor (Figure 6.15). This simulation had the minimum values for indices on the top floor. Simulation 9 revealed that using a light coloured roof is more effective than an insulation R-Value of 2 m^2K/W.



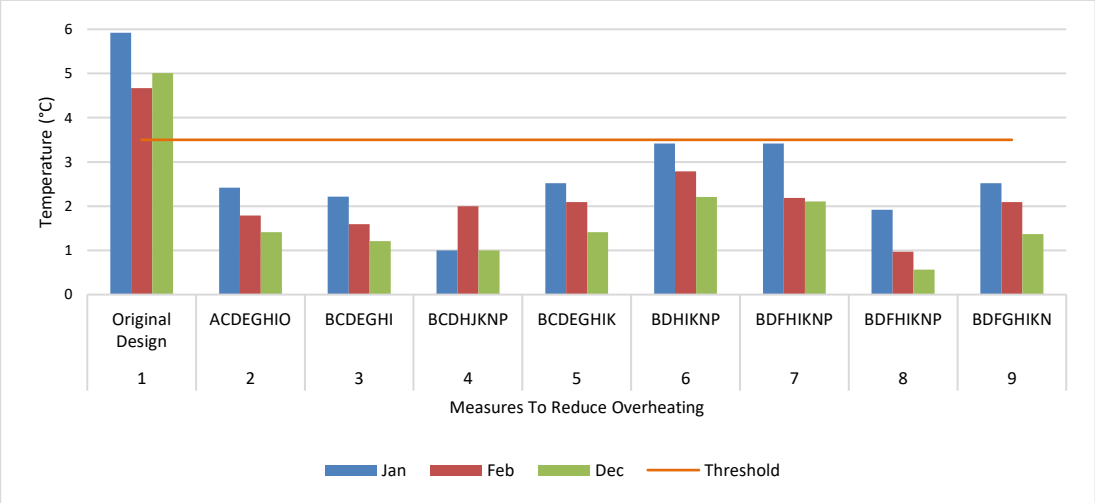
a) WEH indices on the top floor



b) Amplitude indices on the top floor

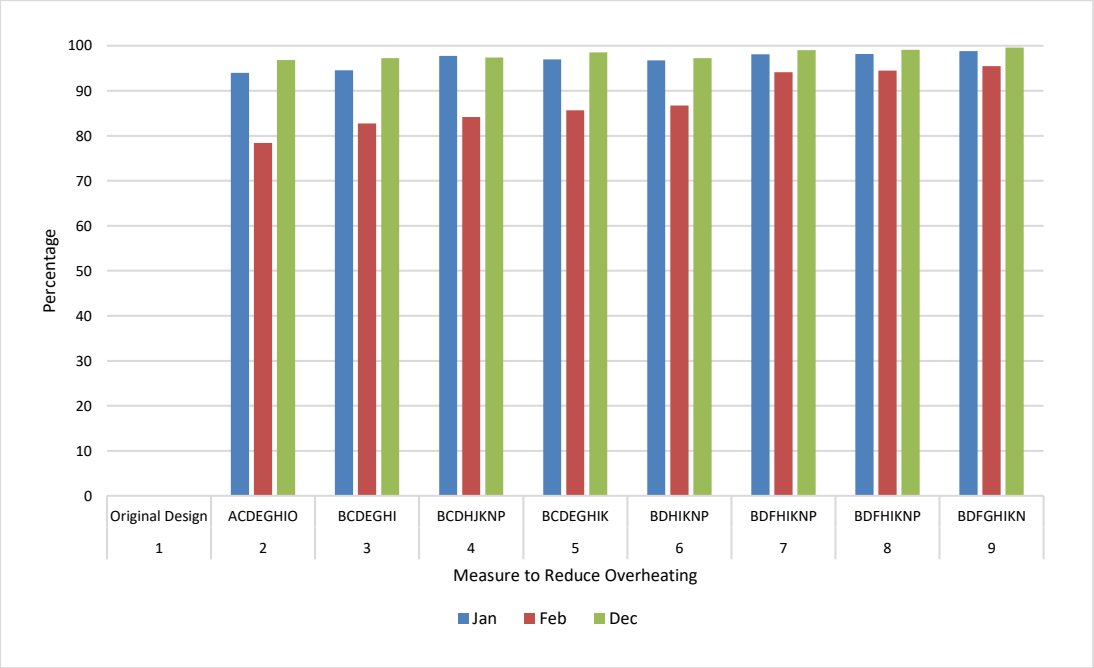


c) WEH indices on the ground floor

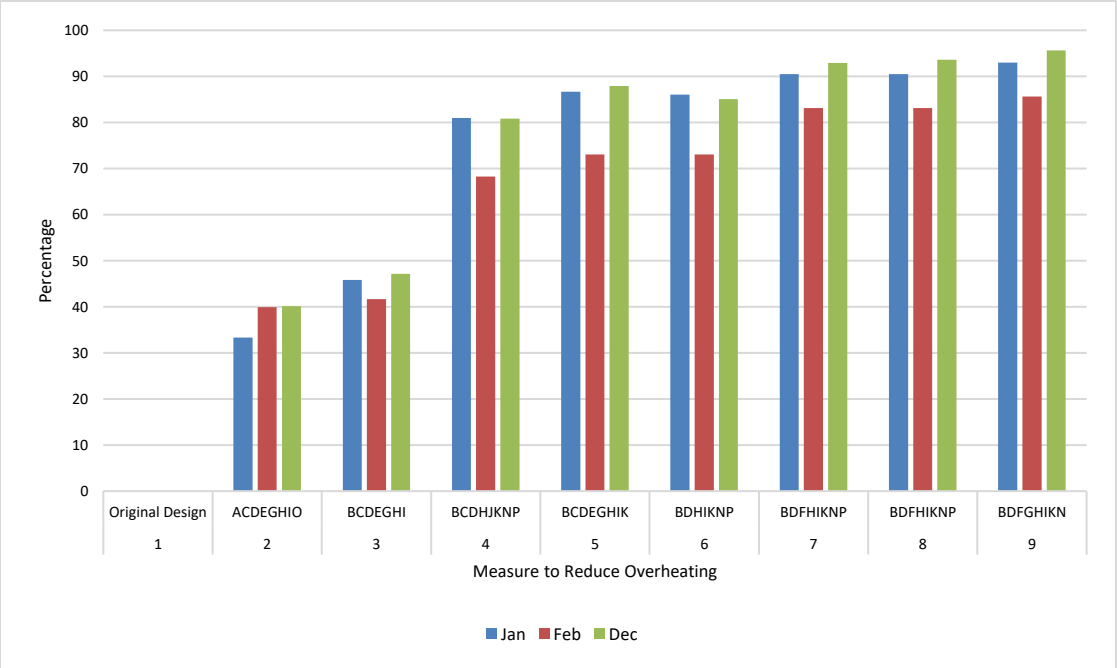


d) Amplitude indices on the ground floor

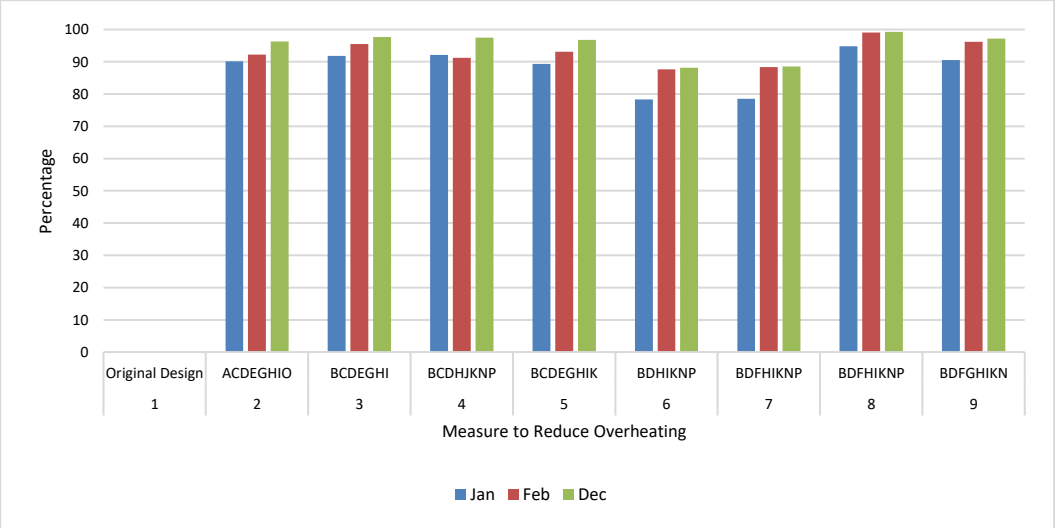
Figure 6.15 WEH and amplitude indices when the measures of reducing overheating were employed for both ground and top floors of house F



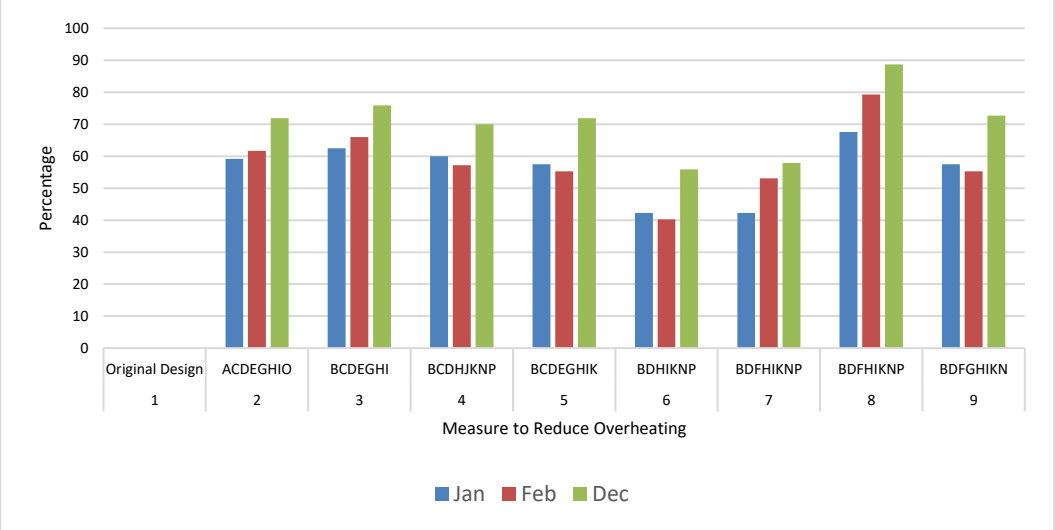
a) WEH indices on the top floor



b) Amplitude indices on the top floor



c) WEH indices on the ground floor



d) Amplitude indices on the ground floor

Figure 6.16 Percentage of indices reduction on the top and ground floors compared to the original design

6.4 Conclusion and further requirements

Section 6.2 demonstrates that the retrofitting carried out for house F was partially successful in reducing overheating and has resulted in reduced overheating indices for two months, but, they were still above the set overheating threshold. Insulation of the external envelope alongside upgrading windows is known to improve the building performance for both heating and cooling climates. After retrofitting:

- The hourly temperature, on average, decreased with a maximum reduction in the afternoon by 1 °C.

- The average indoor temperature compared to outdoor temperature is reduced by 1 °C.
- The frequency of overheating shifted more to 16:00–24:00.
- The maximum temperature typically dropped by more than 1 °C at 5:00 pm.
- The maximum indoor temperature occurred 30 minutes later and the minimum indoor temperature occurred 2 hours earlier.

While the results demonstrate a clear improvement in thermal comfort, the need to investigate the impact of other options is necessary in order to find the best combination of overheating reduction measures.

Simulating house F before and after retrofitting showed that implementing the measures on the top floor could result in reduced overheating on both floors. The comparison showed that the retrofitting measures on house F increased the difference between simulated and monitored temperatures on the typical and hottest day.

Section 6.3 showed that overheating could be substantially reduced and even eliminated in the NV mode with suitable measures. The modifications for eliminating overheating are: Increased thermal mass, reduction of window area, argon filled double glazed low SHGC windows, shading for windows, R6 for the roof, light colour for the roof, thermal mass for the inner side of external walls on the top floor, light colour for external walls, making the highest glazing on the top floor 100% openable, nocturnal ventilation.

A number of combinations of these measures were effective for reducing the overheating threshold in house F below the designated threshold. However, the exact outcome cannot be generalized for all dwellings under Adelaide and other climatic conditions. Cost and practical considerations need to be taken into account for selecting appropriate measures as some overheating is acceptable, particularly in rooms that are not normally used during summer days/nights, such as spare rooms, bathroom and toilets. It is most important to eliminate overheating during anticipated use hours. Some of the measures have a high cost of implementation, such as R8 on walls, but others make little difference to the cost. For instance, reducing the window area saves money. In making decisions on the selection of measures, it is important to note that many of these measures will improve thermal comfort for heating as well as cooling, while others may be unsuitable for the winter

season performance. While the focus of this research is to reduce overheating, all year performance needs consideration when the design elements and measures are selected.

The major findings from the analysis are:

- The most challenging index to reduce was the amplitude, as it was not affected by measures in the same way as the WEH index.
- The most significant measure to reduce overheating on top floors for all months is thermal mass, particularly on the external walls' inner side.
- When measures were combined, their effects on the overheating indices do not add linearly together. Rather, the combination of two highly effective measures could change indices slightly. This means that the measures work in parallel with each other.
- The roof insulation of R12 did not reduce overheating more than that of R8.
- Removing the void and open staircase have no significant effect on reducing overheating.
- Nocturnal ventilation could affect the same as insulation with R-Value of 2 m^2K/W in the roof.

Selecting the measures to reduce indices is a multi-objective optimization, as more than one object should be optimised simultaneously and enriching one measure can decrease the effectiveness of some other measures (Hillier & Miettinen 1998). Multi-objective optimization is applied to many fields, including engineering, when there is a need for an optimal decision between a few objectives that may be in conflict (Chang 2015). These kinds of problems are usually solved by Pareto optimality/efficiency and a set of Pareto optimaly is known as Pareto frontier (Chang 2015). The Pareto optimality have been usefully employed in engineering such as building performance optimisation (Bre, Roman & Fachinotti 2020), building retrofitting (Cappelletti et al. 2016) (Costa-Carrapiço, Raslan & González 2020) and building design factors (Xu, J et al. 2015). Studies have shown that Pareto frontier in building engineering has been adapted for: heating and cooling load, optimal cost, life cycle cost, global retrofits costs, total cost, payback period, life cycle and conservation compatibility. Therefore, the Pareto frontier can be useful to find the optimum combination for multi-measures. More study and simulations can drive this suggestion to produce a usable algorithm in AccuRate.

6.5 Summary

This chapter presents the results of a) thermal analyses of house F before and after retrofitting; b) simulations of house F for before and after retrofitting and c) simulations of house F with the aim of reducing or eliminating overheating.

The first analysis found that retrofitting the top floor by adding insulation to the external envelope and improving windows decreased the overheating indices for December and January. The retrofitting reduced the hourly and maximum temperature by 1 °C, shifted the frequency of overheating to 16:00–24:00 and increased the time lag for daily maximum temperature by 30 minutes. However, the indices were still above the defined criteria and the top floor needed an air conditioner. This outcome highlights that there is a significant need to find optimum combinations of measures that effectively reduce overheating. The method of finding optimal combinations would be usable for both retrofitting and designing new buildings.

The second analysis revealed that applying overheating measures just for the top floor has a reducing effect on the ground floor overheating indices. Monitored temperatures on a typical day and the hottest day were 87% higher than simulated temperatures. This finding demonstrates the need to reconsider the assumptions made in the software regarding house use and occupancy patterns.

The third analysis found that reducing the intensity index (i.e. the maximum temperature rise above the overheating limits) is the most difficult part of reducing or eliminating overheating. Some measures that reduce overheating for single floor dwellings increase the overheating for multilevel dwellings. Thermal mass inside the external walls substantially reduces all indices on both floors. A method to find an optimized combination for each individual design is an urgent priority.

The results of this chapter show the need for developing a Pareto frontier simulation to find a multi-measure optimization for houses to eliminate overheating. Finding the algorithm for the Pareto frontier would be very helpful to designers and owners who want to reduce overheating risk in dwellings and enable them to select the most effective combinations of measures. This method can also be used to optimize other key parameters in the house design, including energy efficiency, cost, winter comfort as well as avoiding overheating.

7 Conclusions

This research has been prompted by evidence of overheating reported by occupants of the top floors of multilevel houses in Adelaide. To address this issue, this research explored the occurrence of overheating through household surveys and the use of extensive temperature monitoring data. It also reviewed available methods and proposed new ways of characterizing overheating in energy-efficient multilevel houses. This was done by defining some indices for overheating and proposing limits for them. The research also examines the viability of employing a number of measures separately and in combination to avoid overheating in an example of a low energy house.

This chapter consists of four sections. Section 7.1 explains how the project objectives are met through the thesis findings. Section 7.2 summarises the outcomes and recommendation arising from this research. Section 7.3 presents opportunities for future research. Finally, section 7.4 concludes the thesis with closing remarks.

7.1 Findings

This research has responded to the aims and met the objectives set out in section 1.4. The literature review demonstrated worldwide evidence of the existence of overheating in energy-efficient houses. Data were collected through surveying dwellings in Adelaide to address objective 1. Analysis of minute-by-minute monitored data from the in-depth case studies was used in response to objectives 2 and 3. A combination of survey and monitoring results provided the background evidence for proposing an alternative numerical scale to assess thermal comfort perception, which met objective 4. Simulation using the developed overheating criteria addressed objective 5. A number of valuable contributions to knowledge in the thermal comfort area have been made through this research. They are summarized below:

7.1.1 Objective 1

To address overheating as an extreme issue on the top floor of energy-efficient dwellings

The literature review of global research publications revealed that many energy-efficient buildings have an overheating issue. Furthermore, it showed that overheating has no worldwide definition or limits. Instead, the limit of overheating varies for each study. The

literature review indicated that the two approaches of Steady-state and Field-state have resulted in different limits for overheating from steady temperatures to a range of temperatures, which are related to the running mean outdoor temperature. It was found that the limits of the Field-state approach were more acceptable as this approach covered contextual factors, physiological and psychological aspects of individuals. The literature review showed that to define overheating, three indices are used, which are the frequency of times when the temperature exceeded the upper thermal comfort threshold, the maximum temperature reached above the limit and WEH, which evaluated the total degree hours of exceedance of the limit. Recent studies also highlighted a difference between overheating during sleeping and waking hours. Studies have rarely focused on finding the primary location of overheating in the dwellings. Reviewing the Energy Efficiency Provisions of BCA showed that this provision is not comfort-based and it is assumed that an energy regulated dwelling can provide thermal comfort for occupants. However, in summer and extreme weather conditions, this assumption is incorrect as presented by the survey and monitoring results in this research. Furthermore, the literature indicated that there is no specific design strategy or guidelines for avoiding overheating on the top floor of multilevel dwellings. The most commonly suggested measures in the literature to reduce overheating are nocturnal ventilation, shading and ceiling insulation.

The extensive survey of Adelaide households received 168 responses. The analysis of this survey showed that more than 50% of 6 and 7.5-star dwellings experienced overheating in their top floors for 43.5% of occupied hours during summer. The overheating was common on the top floor rooms facing north and west. This study has found that the top floors of apartments experienced the most severe overheating.

Through general screening of eight years of monitoring data from nine highly energy-efficient dwellings, this research has determined that energy-efficient dwellings generally suffers from extreme overheating. Also, it was found that overheating occurs, particularly on the top floors, based on the maximum acceptable steady temperature (32 °C) in the standards.

7.1.2 Objective 2

To identify the adaptive thermal comfort neutral and upper threshold for Adelaide

The survey of nine houses in Lochiel Park which had minute-by-minute monitored temperatures on all floors for eight years, provided extensive sufficient evidence and metadata for screening in each floor during the NV mode. The findings of the analysis in this study relating to objective 2 were the top floor and ground floor temperature differences as well as the temperature range on the ground floors of high-performance houses. This research has found that the largest difference between the top floors and ground floors happened when both levels have their maximum daily temperature. Another result was developing a modified adaptive thermal comfort and upper threshold equation for Adelaide.

7.1.3 Objective 3

To define criteria for analysing overheating risk in naturally ventilated rooms of dwellings during summer

The upper threshold of adaptive thermal comfort formed the basis for setting the overheating indices in Adelaide. The detailed screening of high-performance houses found the overheating limits for three indices that were specified as most important. The monthly limits of these indices were 250 °C-hrs for WEH, 10 hrs for frequency and 3.5 °C for intensity.

Comparing these limits with others recently proposed by CSIRO found that the criteria developed in this research were the closest to the actual condition. It was also demonstrated that particular emphasis must be placed on even temperature distribution in various levels of the dwelling.

7.1.4 Objective 4

To propose a numerical thermal comfort perception scale

In the absence of temperature monitoring, occupants' perception of their comfort level is the only way to gauge their overall comfort level. In the survey conducted in this research, a numerical 10-point scale was proposed and investigated as a potential means for gauging residents' long-term thermal comfort perception alongside the verbal TSV scale. Both scales were converted to degree hours for houses that had monitored temperatures on the ground floor and top floor. The relation between scores of both scales with overheating indices were extracted. The findings identified that the 10-point numerical scale provided a better definition of thermal comfort in comparison with the TSV scale

based on the interpretation of specific words. It was found that the TSV scores, particularly ‘Slightly Warm’ and ‘Neutral’ did not have the same meaning for different individuals and ‘Neutral’ did not reflect an ideal thermal satisfaction condition. The numerical scale presented a more representative relationship between measured parameters and scale scores compared to the TSV.

7.1.5 Objective 5

To investigate the combination of passive systems to maintain thermal comfort on the top floors of a multilevel dwelling.

One of the monitored houses was retrofitted during the monitoring period. Overheating was investigated on both floors before and after retrofitting. Using the indices developed in this research, the evaluation revealed that retrofitting by some of the commonly used measures did not reduce overheating to the required level. However, the adopted retrofitting measures could decrease the maximum indoor temperature and average indoor temperature by 1 °C. Besides, the measures increased the time lag of maximum temperature by 30 minutes. The research highlighted that there is a significant need for a method for finding the best combination of measures to reduce overheating.

Taking the same house as a case study, twenty seven measures that can potentially reduce overheating were simulated separately by AccuRate. The measures were prioritised based on their effect on reducing one index of overheating on the top floor. Additional insights were gained by combining some of the more effective measures. It was found that the intensity was the most challenging index to reduce. Finding the optimum combination of measures to provide thermal comfort or reduce overheating to the desired level was challenging and context-specific. This research has proposed the option of incorporating the evaluation of overheating levels into an available mathematical simulation procedure to select the most effective and appropriate measures for each dwelling for reducing overheating.

7.1.6 Summary of findings

Using a combination of occupants’ surveys, analysis of extensive temperature monitoring data and thermal simulation, the thesis has added the following contributions to knowledge in the area of thermal comfort of dwellings:

- Overheating is more prevalent on the top floors of dwellings

- Based on monitored or simulated hourly temperature values, indices are proposed to characterize the level of overheating in a particular space, namely, to evaluate the amplitude and frequency of overheating above the adaptive thermal comfort limits. These can be integrated into the WEH index. Limits for the values of the indices, based on adaptive thermal comfort evaluation, are set for the Adelaide region.

- A 10-point numerical scale is proposed for evaluating occupants' long-term perception of overheating. Survey evidence suggests that the scale is more representative and easier to use than available scales.

- The simulation software AccuRate Sustainability can be adapted to integrate the proposed sustainability indices in order to determine overheating in various zones and to incorporate suitable design measures to avoid overheating at the design stage.

While the results can only strictly apply to the Adelaide region, the methodologies developed can be equally applied to other climate zones both within Australia and throughout the world in areas where overheating is experienced.

7.2 Recommendations

Besides the findings summarized above, it is recommended that the basis of the outcomes of the research are applied in the energy rating software to ensure that dwellings are not only energy-efficient but also provide an appropriate level of thermal comfort in the living/sleeping zones. This can also be incorporated into the Building Code of Australia. The recommendation can help to control and reduce overheating and reinforce the need to meet minimum thermal comfort requirements. Providing thermal comfort in the NV mode reduces the use of air conditioners and the energy use peaks during summer heatwaves. This will lead to reduced energy bills. A global approach is required to assess overheating in various dwellings based on local adaptive thermal comfort thresholds. With the increasing frequency and severity of overheating worldwide due to climate change, the resilience of dwellings to overheating is necessary to cope with heat events.

7.2.1 Energy rating software

Using the approach developed in this thesis, the home energy rating software, including AccuRate in Australia, needs to assess the quality of thermal comfort inside the dwellings in natural ventilation mode in order to ensure both low energy use and thermal comfort

throughout the dwelling. To evaluate the overheating risk, the assessment method used in this research is recommended. Incorporating the proposed overheating criteria in AccuRate Sustainability for assessing overheating in Australia is recommended to provide a clear pass/fail thermal comfort assessment in the architectural design stage. Assessing the values of the overheating indices are required to evaluate the thermal heterogeneity in all levels and zones of a dwelling during NV mode.

Reflecting on the results of this study, the 10-point long-term thermal comfort perception scale is recommended in comfort research surveys.

7.2.2 Incorporation of comfort provision in the Building Code of Australia

There is a need for a regulatory requirement to minimise the risk to occupants from rising indoor temperatures. Thermal comfort should be addressed in the building regulations as an independent matter alongside energy efficiency. In addition, design guidelines need to include the measures necessary to assess and avoid overheating both in mixed and NV modes in different zones, particularly on upper floors, to improve the performance of dwellings.

7.3 Suggestions for future research

While the current study has highlighted the need to assess and avoid overheating in dwellings, its findings are based on limited data gathered in Adelaide. Building on this research, providing criteria for assessing and avoiding overheating in all climate zones of Australia would create a fundamental platform for ensuring comfortable indoor building performance around the country. It is apparent that more research and a broader survey is needed to test the 10-point thermal comfort perception scale. Further work is required to incorporate overheating assessment in house energy building tools to facilitate the selection of the most economical design features to ensure thermal comfort on the top floors as well as overall energy efficiency. While the research has focused on a Mediterranean climate zone, other climatic regions, including colder regions and those having hot/humid climates, need additional research to ensure thermal comfort. The research needs to cover fully air-conditioned, mixed and natural ventilation modes with the aim of achieving thermal comfort.

7.4 Closing remarks

This research's motivation has been to enable the use of all spaces in a dwelling during summer and improving the quality of building performance. This study's approach was combining health and engineering in experimental and modelling to assess and achieve adaptive thermal comfort. This thesis showed that incorporating a mathematical approach to architecture can provide thermal comfort within the spaces in which we celebrate life.

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Appendix A. Participants information sheet

University of South Australia

School of Engineering

Division of Information Technology, Engineering and the

Participant information sheet

Research Project: *Evaluating and Improving Indoor Thermal Comfort in Top Floors of Multilevel Energy-Regulated Dwellings*

Researcher: *Sormeh Sharifi, PhD candidate,* sormeh.sharifi@mymail.unisa.au,
Text message: +61 4120 3 4321

Invitation and purpose of study

Hello,
I would like to invite you to participate in my study. The study is about evaluating and improving thermal comfort in top-floors of energy regulated dwellings during summer and heatwaves. The overheating of top floors during summer can make a part of home unbearable for hours or days. This study will be a part of the next-generation energy rating that directly considers thermal comfort.
For this study, I need to document all adult residents' experiences of overheating in the top floor of this dwelling. You have been selected as participants for this study due to your house star-rating and design characters. All information collected will remain confidential and no information which might lead to the identification of any individual will be asked in the questionnaires- unless required by law.
While we would be pleased to have you participate, we respect your right to decline. Participation in this study is voluntary and participants are free to withdraw from the research project at any time, now or in the future.
By completing and submitting the survey, you are indicating that you have read and understood the Participant Information Sheet and give your consent to be involved in the research.

Description of survey

- The questions in this study have been developed based on a literature review and relevant international standards.
- The questions are intended to measure thermal discomfort in the top-floor of multi-level dwellings or the upper-floor of apartments in South Australia.
- The results once gathered will be used as a reference for optimising the integration of thermal comfort and energy use in Australia.
- Data collected from this project may be used to establish a database which may be used for future research projects

Benefits for participants

By participating in this survey, you will have your voice in a survey that identifies overheating and thermal discomfort of top-floors. Your participation in the research is one of the fundamentals in establishing a method to evaluate indoor thermal comfort of dwellings.

Confidentiality and disclosure information

Please contact the researcher at any time if you wish to withdraw from the study. The information collected will not include any personal information. All

information collected will remain confidential and no information which might lead to the identification of any individual will be asked in the questionnaires. There will be no following contact from the research team.
The information collected through the study will be kept in a computer file and stored at the School of Engineering, Mawson Lakes Campus, University of South Australia, for a period of 5 years. Access to the data will be restricted.
The project has been approved by the University of South Australia's Human Research Ethics Committee. If you have any ethical concerns about the project, instruments position and about your rights as a participant please contact Executive Officer of this committee, Tel: +61 8 8302 3118; Email: Vicki.Allen@unisa.edu.au

This research is funded by Australian Postgraduate Award and CRC for Low Carbon Living.

For further information

If you would like to receive a summary of the research findings or you have any questions about the survey, or would like to withdraw from the survey please contact me on:

Tel: 04120 3 4321
Email: sormeh.sharifi@mymail.unisa.edu.au

Your participation is greatly valuable to us and appreciated.

Yours Sincerely,

SORMEH SHARIFI
PhD Candidate, A2-05, Mawson Lakes Campus, University of South Australia, Mawson Lake Blv, SA

Appendix B. Questionnaire

UniSA

Questionnaire for Identifying Overheating and Overheating Zones in Energy-Efficient Dwellings

The questionnaires should be completed separately **by each resident** older than 18.

Please tick as appropriate.

Date: ..... Street..... Suburb: .....

1. Do you have any physical issue on temperature perception? Yes No

2. Age	20-29	30-39	40-49	50-59	60-69	70 and above
3. Sex	Male Female					

4. Type of your dwelling	Multi-storys house	Apartment

If you have ticked 'Apartment' please write the:

Total number of storys ..... The story you live in.....

5. On average, on which hours of a 24-hour cycle were you usually at home during weekdays and weekends in the last summer (multiple choices)?

8am- 12pm	12pm- 16pm	16pm- 20pm	20pm- 24am	24am- 4am	4am- 8am

6. Please state the space you spent most of your time within your home in the last summer during:

	Lounge	Dining	Kitchen	bedroom	Open plan	Others (please specify)
Daytime						
Nighttime						

7. How many minutes daily in average were you using your cooking appliances, located in the kitchen, during the last summer?

Less than 30	30-60	60-90	90-120

8. Which items of clothing below did you generally wear at home during the last summer (multiple choices)?

Short sleeve shirt/blouse	Long sleeve shirt/blouse	Trousers/ Long skirt	Vest	Shorts/ Short skirt	Dress	Pullover	Jacket

9. What was your major activity in your home in the summer?

Long socks	Short socks	Tights	Tie	Slippers	Sandals	Shoes	Boots	Others (specify)
	Resting	Light manual work		Continues arm work		Intense work	arm	Very intense activity at fast to maximum pace
Daytime								
Nighttime								

10. What was the usual set-point of your cooling system during typical summer days?

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Top-floor															
Down floor															

11. What was the usual set-point of your cooling system during the heatwaves?

	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Top-floor															
Down floor															

12. Have you experienced any overheating in your dwelling during the last summer despite the running of air-conditioner/cooling system? Yes No

If yes:

In which story was that?
In which room was that?
How long did the overheating take approximately?
Did you shut the curtains/ blinds during overheating?
Have you used any addition mechanical device to cool that area?
If you have answered "yes" to the above question, what that device was?

13. The heatwaves are periods in which the outdoor maximum temperature is more than 33 for 3 days or more.

How do you rate the long-term thermal comfort of your dwelling in the summer and during heatwaves without AC from 1 (worse) to 10 (best) for?

	1	2	3	4	5	6	7	8	9	10
Top floor										
Ground floor										

14. How would you like to describe the long-term thermal condition of your dwelling in the last heat event without AC?

	Cold	Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot
Top floor							
Ground floor							

15. How many hours or minutes during a day can you tolerate the thermal discomfort in the summer in your dwelling?

16. Do you have any comments or additional information on your thermal comfort during the last summer?

Appendix C. Survey analysis

Table C1: Analysis of 91 surveyed multilevel dwellings with overheating in 13 suburbs of Adelaide

Descriptions		Proportion	Percentage
		to 91 dwelling	
Four participants in this group claimed that totally their home is “slightly cool” whilst they rated the down-floor and top-floor less than 5 and 3 respectively.			
Live at homes during	Just day time	2/91	2.2%
	Just night time	45/91	49.5%
	Partly day time and partly nighttime	9/91	9.9%
	All 24 hours	35/91	38.5%
Spaces live in	Open plan	82/91	8.8%
	BR	6/91	6.6%
	Study on top-floor	3/91	3.3%
Appliances on	less than 30 minutes	28/91	30.8%
	for 30-60 minutes	39/91	42.9%
	for 60-90 minutes	18/91	19.8%
	for 90-120 minutes	3/91	3.3%
Set-point in summer	= set-point in heatwaves	43/91	47.3%
	1 °C l more than set-point in heatwaves	6/91	6.6%
	2 °C more than set-point in heatwaves	16/91	17.6%
	3 °C more than set-point in heatwaves	4/91	4.4%
	4 °C more than set-point in heatwaves	6/91	6.6%
	5 °C more than set-point in heatwaves	2/91	2.2%
	6 °C more than set-point in heatwaves	1/91	1.1%
	turn on the AC just in heatwaves	3/91	3.3%
	18 °C	1/91	1.1%
	19 °C	1/91	1.1%
	20 °C	1/91	1.1%
	21 °C	6/91	6.6%
	22 °C	12/91	13.2%
	23 °C	26/91	28.6%
	24 °C	18/91	19.8%
	25 °C	9/91	9.9%
	26 °C	8/91	8.8%
	27 °C	1/91	1.1%
	28 °C	3/91	3.3%
Low floor thermal comfort rate based on 10-point scale (1-10)	1	1/91	1.1%
	2	4/91	4.4%
	3	8/91	8.8%
	4	5/91	5.5%
	5	10/91	11%
	6	11/91	12.1%
	7	17/91	18.7%
	8	21/91	23.1%
	9	13/91	14.3%
	10	1/91	1.1%
Top-floor thermal comfort rate based on 10-point scale (1-10)	No rate	7/91	7.7%
	1	16/91	17.6%
	2	24/91	26.4%
	3	15/91	16.5%
	4	8/91	8.9%
	5	7/91	7.7%
	7	9/91	9.9%
	8	3/91	3.3%
Low floor thermal comfort rate value more than top-floor based on 10-point scale (1-10)	0	5/91	5.5%
	1	14/91	15.4%
	2	9/91	9.9%
	3	10/91	11%
	4	14/91	15.4%
	5	14/91	15.4%
	6	12/91	13.2%
	7	3/91	3.3%

	8	2/91	2.2%
Total home thermal comfort rating based on 7-scale ASHRAE55 and ISO EN15251	Hot	18/91	19.8%
	Warm	18/91	19.8%
	Slightly warm	30/91	33%
	Neutral	17/91	18.7%
	Slightly cool	4/91	4.4%
	Cool	4/91	4.4%

Table C 2: Analysis of 58 surveyed multilevel dwellings without overheating in 13 suburbs of Adelaide

Descriptions		Proportion	Percentage
		to 58 dwellings	
20 participants in dwellings without overheating rated contrastingly in two systems of rating. In ASHRAE and ISO EN15251 rating method, they chose “warm” or “cool” whilst on 10-point scale, they rated more than 5. These responses indicate they are happy with the thermal condition expressed discomfort in ASHRAE55 and ISO EN15251, which could be due to the personal preferences of theses people.			
Live at homes during	Just day time	1/58	1.8%
	Just night time	45/58	77.6%
	Partly day time and partly nightime	12/58	20.7%
	All 24 hours	13/58	22.4%
Spaces live in	Open plan	52/58	89.7%
	BR	6/58	10.3%
Appliances on	less than 30 minutes	26/58	44.8%
	for 30-60 minutes	23/58	39.7%
	for 60-90 minutes	9/58	15.5%
Set-point in summer	= set-point in heat waves	32/58	55.2%
	1 °C more than set-point in heatwaves	4/58	6.9%
	2 °C more than set-point in heatwaves	7/58	12.1%
	3 °C more than set-point in heatwaves	4/58	6.9%
	4 °C more than set-point in heatwaves	1/58	1.8%
	5 °C more than set-point in heatwaves	2/58	3.4%
	turn on the AC just in heatwaves	4/58	6.9%
	19 °C	1/58	1.8%
	20 °C	1/58	1.8%
	21 °C	3/58	5.2%
	22 °C	9/58	15.5%
	23 °C	13/58	22.4%
	24 °C	9/58	15.5%
	25 °C	7/58	12.1%
	26 °C	1/58	1.8%
	27 °C	3/58	5.2%
	28 °C	4/58	6.9%
	29 °C	1/58	1.8%
Low floor thermal comfort rate based on 10-point scale (1-10)	5	1/58	1.8%
	6	2/58	3.4%
	7	10/58	17.2%
	8	24/58	43.4%
	9	12/58	20.7%
Top-floor thermal comfort rate based on 10-point scale (1-10)	2	2/58	3.4%
	4	3/58	5.2%
	5	10/58	17.2%
	6	8/58	13.8%
	7	12/58	20.7%
	8	12/58	20.7%
	9	7/58	12.1%
	10	2/58	3.4%
Low floor thermal comfort rate value more than top-floor based on 10-point scale (1-10)	0	14/58	24.1
	1	19/58	32.8
	2	11/58	19%
	3	9/58	15.5%
	4	2/58	3.4%
	6	1/58	1.8%
Total home thermal comfort rating based on 7-scale ASHRAE55 and ISO EN15251	Warm	6/58	10.3%
	Slightly warm	19/58	32.8%
	Neutral	16/58	27.6%
	Slightly cool	4/58	6.9%
	Cool	13/58	22.4%

Table C 3: Results and analysis of 40 surveyed 7.5-star multilevel overheated houses in Lochiel Park

	Descriptions	Proportion	Ratio
Live at homes during	Just night time	10/40	25%
	Partly day time and partly nightime	3/40	7.5%
	All 24 hours	26/40	65%
Spaces live in	Open plan	38/40	95%
	BR	1/40	2.5%
	Study on top-floor	1/40	2.5%
Appliances on	less than 30 minutes	14/40	35%
	for 30-60 minutes	16/40	40%
	for 60-90 minutes	7/40	17.5%
	for 90-120 minutes	1/40	2.5%
Set-point in summer	= set-point in heat waves	25/40	62.5%
	1 °C more than set-point in heatwaves	4/40	10%
	2 °C more than set-point in heatwaves	4/40	10%
	3 °C more than set-point in heatwaves	2/40	5%
	turn on the AC just in heatwaves	3/40	7.5%
	20 °C	1/40	2.5%
	21 °C	4/40	10%
	22 °C	3/40	7.5%
	23 °C	12/40	30%
	24 °C	6/40	15%
	25 °C	2/40	5%
	26 °C	7/40	17.5%
	27 °C	1/40	2.5%
Low floor thermal comfort rate based on 10-point scale (1-10)	4	2/40	5%
	5	3/40	7.5%
	6	4/40	10%
	7	9/40	22.5%
	8	13/40	32.5%
	9	8/40	20%
	10	1/40	2.5%
Top-floor thermal comfort rate based on 10-point scale (1-10)	1	6/40	15%
	2	10/40	25%
	3	12/40	30%
	4	4/40	10%
	5	5/40	12.5%
	7	2/40	5%
	8	1/40	2.5%
Low floor thermal comfort rate value more than top-floor based on 10-point scale (1-10)	1	4/40	5%
	2	3/40	2.5%
	3	6/40	12.5%
	4	9/40	20%
	5	7/40	17.5%
	6	6/40	12.5%
	7	3/40	7.5%
	8	2/40	5%
Total home thermal comfort rating based on 7-scale ASHRAE55 and ISO EN15251	Hot	4/40	10%
	Warm	10/40	25%
	Slightly warm	17/40	42.5%
	Neutral	5/40	12.5%
	Slightly cool	1/40	2.5%
	Cool	2/40	5%

Table C 4: Results and analysis 13 surveyed 7.5-star multilevel dwellings without overheating in Lochiel Park

	Descriptions	Proportion	Ratio
Live at homes during	Just nightime	4/13	30.8%
	Just day time	1/13	7.7%
	Partly day time and partly nightime	1/13	7.7%
	All 24 hours	7/13	53.8%
Spaces live in	Open plan	13/13	100%
Appliances on	less than 30 minutes	7/13	53.8%
	for 30-60 minutes	3/13	23.1%
	for 60-90 minutes	2/13	15.4%
	for 90-120 minutes	1/13	7.7%
Set-point in summer	= set-point in heat waves	6/13	46.2%
	2 °C more than set-point in heatwaves	1/13	7.7%
	4 °C more than set-point in heatwaves	1/13	7.7%
	5 °C more than set-point in heatwaves	1/13	7.7%
	turn on the AC just in heatwaves	1/13	7.7%
	21 °C	1/13	7.7%
	22 °C	2/13	15.4%
	23 °C	4/13	30.8%
	24 °C	3/13	23.1%
Low floor thermal comfort rate based on 10-point scale (1-10)	8	9/13	69.2%
	9	1/13	7.7%
	10	2/13	15.4%
Top-floor thermal comfort rate based on 10-point scale (1-10)	4	1/13	7.7%
	5	3/13	23.1%
	6	2/13	15.4%
	7	4/13	30.8%
	8	2/13	15.4%
Low floor thermal comfort rate value more than top-floor based on 10-point scale (1-10)	0	1/13	7.7%
	1	3/13	23.1%
	2	2/13	15.4%
	3	3/13	23.1%
	4	1/13	7.7%
Total home thermal comfort rating based on 7-scale ASHRAE55 and ISO EN15251	Warm	1/13	7.7%
	Slightly warm	8/13	61.5%
	Neutral	2/13	15.4%
	Slightly cool	1/13	7.7%
	Cool	1/13	7.7%

Table C 5: Results and analysis of 51 surveyed 6-star multilevel overheated houses in 12 suburbs of Adelaide except Lochiel Park

	Descriptions	Proportion	Ratio
Live at homes during	Just night time	36/51	70.6%
	Just daytime	2/51	3.9%
	Partly day time and partly nightime	4/51	7.8%
	All 24 hours	9/51	17.6%
Spaces live in	Open plan	44/51	86.3%
	BR	7/51	13.7%
Appliances on	less than 30 minutes	14/51	27.5%
	for 30-60 minutes	23/51	45.1%
	for 60-90 minutes	11/51	21.6%
	for 90-120 minutes	2/51	3.9%
Set-point in summer	= set-point in heat waves	20/51	39.2%
	1 °C more than set-point in heatwaves	5/51	9.8%
	2 °C more than set-point in heatwaves	14/51	27.5%
	3 °C more than set-point in heatwaves	2/51	3.9%
	4 °C	6/51	11.7%
	5 °C	2/51	3.9%
	6 °C	1/51	2%
	18 °C	1/51	2%
	19 °C	1/51	2%
	21 °C	2/51	3.9%
	22 °C	9/51	17.6%
	23 °C	15/51	29.4%
	24 °C	11/51	21.6%
	25 °C	7/51	13.7%
	26 °C	2/51	3.9%
	28 °C	3/51	5.9%
Low floor thermal comfort rate based on 10-point scale (1-10)	1	1/51	2%
	2	4/51	7.8%
	3	8/51	15.7%
	4	4/51	7.8%
	5	6/51	11.8%
	6	7/51	13.7%
	7	8/51	15.7%
	8	8/51	15.7%
	9	5/51	9.8%
Top-floor thermal comfort rate based on 10-point scale (1-10)	1	10/43	19.7%
	2	15/43	29.4%
	3	3/43	5.9%
	4	4/43	7.8%
	5	2/43	3.9%
	7	7/43	13.7%
	8	2/43	3.9%
Low floor thermal comfort rate value more than top-floor based on 10-point scale (1-10)	1	9/43	17.6%
	2	11/43	21.6%
	3	4/43	7.8%
	4	5/43	9.8%
	5	6/43	11.7%
	6	2/43	3.9%
Total home thermal comfort rating based on 7-scale ASHRAE55 and ISO EN15251	Hot	13/51	25.5%
	Warm	8/51	15.7%
	Slightly warm	14/51	27.5%
	Neutral	10/51	19.7%
	Slightly cool	3/51	5.9%
	Cool	3/51	5.9%

Table C 6: Results and analysis of 45 surveyed 6-star multilevel houses without overheating in 12 suburbs of Adelaide except Lochiel Park

	Descriptions	Proportion	Ratio
Live at homes during	Just night time	29/45	64.4%
	Partly day time and partly nightime	11/45	24.4%
	All 24 hours	5/45	11.1%
Spaces live in	Open plan	39/45	86.7%
	BR	6/45	13.3%
Appliances on	less than 30 minutes	18/45	40%
	for 30-60 minutes	6/45	13.3%
	for 60-90 minutes	20/45	44.4%
Set-point in summer	= set-point in heat waves	2645	57.8%
	1 °C more than set-point in heatwaves	4/45	8.9%
	2 °C more than set-point in heatwaves	7/45	15.6%
	3 °C more than set-point in heatwaves	4/45	8.9%
	5 °C more than set-point in heatwaves	1/45	2.2%
	turn on the AC just in heatwaves	2/45	4.4%
	19 °C	1/45	2.2%
	20 °C	1/45	2.2%
	21 °C	2/45	4.4%
	22 °C	8/45	17.8%
	23 °C	9/45	20%
	24 °C	7/45	15.6%
	25 °C	7/45	15.6%
	26 °C	1/45	2.2%
	27 °C	3/45	6.7%
	28 °C	4/45	8.9%
Low floor thermal comfort rate based on 10-point scale (1-10)	5	1/45	2.2%
	6	2/45	4.4%
	7	10/45	22.2%
	8	15/45	33.3%
	9	11/45	24.4%
	10	5/45	11.1%
Top-floor thermal comfort rate based on 10-point scale (1-10)	2	2/45	4.4%
	4	2/45	4.4%
	5	7/45	15.6%
	7	8/45	17.8%
	8	10/45	22.2%
	9	7/45	15.6%
	10	2/45	4.4%
Low floor thermal comfort rate value more than top-floor based on 10-point scale (1-10)	1	16/45	35.6%
	2	8/45	17.8%
	3	4/45	8.9%
	4	1/45	2.2%
	5	1/45	2.2%
	6	1/45	2.2%
Total home thermal comfort rating based on 7-scale ASHRAE55 and ISO EN15251	Warm	5/45	11.1%
	Slightly warm	11/45	24.4%
	Neutral	14/45	31.1%
	Slightly cool	3/45	6.7%
	Cool	12/45	26.7%

Table C 7: Results and analysis of 10 surveyed top floor units of 6-star overheated apartments in three suburbs of Adelaide

	Descriptions	Proportion	Ratio
Live at homes during	Just night time	7/10	70%
	Partly day time and partly nightime	1/10	10%
	All 24 hours	2/10	20%
Spaces live in	Open plan	7/10	70%
	BR	3/10	30%
Appliances on	less than 30 minutes	3/10	30%
	for 30-60 minutes	6/10	60%
	for 60-90 minutes	1/10	10%
Set-point in summer	= set-point in heat waves	5/10	50%
	2 °C more than set-point in heatwaves	3/10	30%
	3 °C more than set-point in heatwaves	2/10	20%
	turn on the AC just in heatwaves	1/10	10%
	16 °C	2/10	20%
	22 °C	2/10	20%
	23 °C	2/10	20%
	24 °C	2/10	20%
	25 °C	2/10	20%
Unit thermal comfort rate based on 10-point scale (1-10)	1	1/10	10%
	2	2/10	20%
	3	3/10	30%
	4	3/10	30%
	5	1/10	10%
Total home thermal comfort rating based on 7-scale ASHRAE55 and ISO EN15251	Hot	5/10	50%
	Warm	5/10	50%

Table C 8: Results and analysis from 9 surveyed top floor units of 6-star apartments without overheating in three suburbs of Adelaide

Descriptions		Proportion	Ratio
Live at homes during	Just night time	5/9	55.6%
	Partly day time and partly nightime	2/9	22.2%
	All 24 hours	2/9	22.2%
Spaces live in	Open plan	8/9	88.9%
	BR	1/9	11.1%
Appliances on	less than 30 minutes	5/9	55.6%
	for 30-60 minutes	4/9	44.4%
Set-point in summer	= set-point in heat waves	4/9	44.4%
	2 °C more than set-point in heatwaves	4/9	44.4%
	turn on the AC just in heatwaves	1/9	11.1%
	17 °C	2/9	22.2%
	20 °C	1/9	11.1%
	21 °C	2/9	22.2%
	22 °C	1/9	11.1%
	24 °C	2/9	22.2%
Unit thermal comfort rate based on 10-point scale (1-10)	3	1/9	11.1%
	5	3/9	33.3%
	8	4/9	44.4%
	9	1/9	11.1%
Total home thermal comfort rating based on 7-scale ASHRAE55 and ISO EN15251	Warm	5/9	55.6%
	Slightly warm	2/9	22.2%
	Neutral	2/9	22.2%

Appendix D. Specifications of the Lochiel Park houses

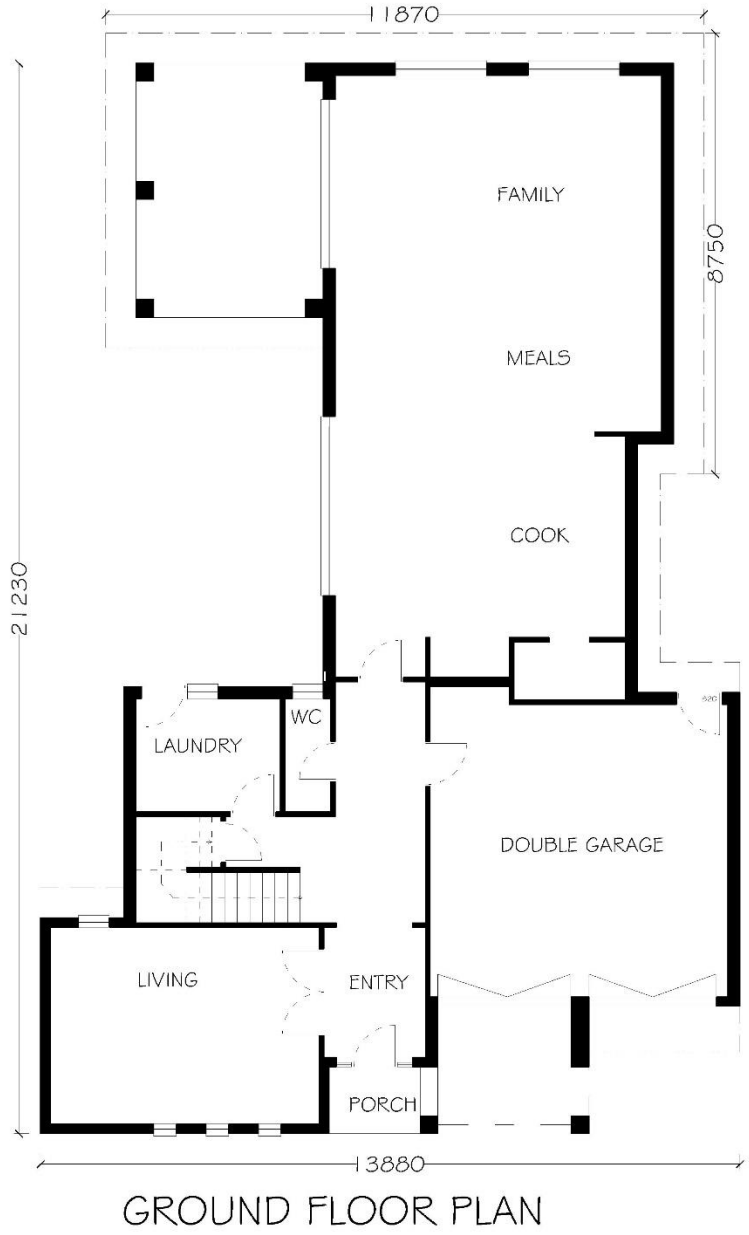
Table D1 Specifications of typical construction elements of houses located in Lochiel Park

Construction Element	Material	Thickness (mm)	R-Value (m^2K/W)
External wall	Rock wool batt	99	3
		83	2.5
	Plaster/Plasterboard	5	0
		10	0.06
		13	0.08
		26	0.15
	Brickwork	110	0.18
	Fiber-cement sheet	6	0.02
	Air gap	40	0.16
		90	0.16
	Aerated autoclaved concrete block	75	0.58
Window	Glass	4	0.32
	Air gap	12	
	Aluminium thermally broken	5	
Entrance door	Timber	50	0.47
	LNDR	100	0.63
Ceiling/ Floor	Rock wool batt	50	1.52
		66	2
		90	3
		132	4
	Glass fibre batt	88	2
	Plasterboard	10	0.06
		13	0.08
		22	0.18
	Air gap	90	0.15
	Timber	6	0.04
		19	0.12
	Conceret slab	100	0.07
	Ceramic tile	8	0.01
	Carpet	20	0.43
Internal wall	Rock wool batt	50	1.52
		99	3
	Plasterboard	10	0.06
		13	0.08
	Air gap	20	0.16
	Brickwork	110	0.18
Pitched/Hip Roof	Cellulose fibre batt	40	1
		176	4
	Rock wool batt	132	4
	Plasterboard	13	0.08
	Air gap	40	0.18
	Steel	2	0

Table D2 House A Base specification

External Wall	The internal lining for all walls is 10mm plasterboard. Generic extruded clay brick (typical density), R3 rockwool batt, color: brick (red clay).
	Weatherboard fixed directly to timber stud, R4 rockwool batt, color: medium. Plaster (cement:sand, 1:4), aerated autoclaved concrete block, R4 rockwoolbatt, color: medium. Concerete block 190 densweights, color: medium.
Roof	Steel deck, reflective sarking, color: medium.
Roof pitch	22.5
Eave sheets	Fiber-cement sheet
Floor	Concerete on ground 100mm thick.
Floor coverings	Carpet with 10mm felt underlay. Ceramic tiles 8mm thick fixed directly to the floor.
Ceilings	13mm plasterboard, R4 rockwool. 13mm plasterboard, R3 rockwool, horizobtal airgap 90mm, particleboard 22mm thick, ceramic tiles 8mm thick. 13mm plasterboard, R3 rockwool, horizobtal airgap 90mm, particleboard 22mm thick, carpet with 10mm felt underlay.
Internal walls	90mm timber studs, R1.5 rockwool batt, 10mm plasterboard to each side. 90mm timber studs, R3 rockwool batt, 10mm plasterboard to each side.
Awing windows	Alluminium thermally brocken double glazed argon fill low solar gain low E, external canvas awing, weather stripped, insect screen, internal holand blinds.
	Alluminium thermally brocken double glazed argon fill low solar gain low E, weather stripped, insect screen, internal holand blinds.
Sliding doors	Alluminium thermally brocken double glazed argon fill low solar gain low E, weather stripped, insect screen, internal holand blinds.
Louvre windows	
External doors	Front door: timber (solid), 50mm thickness, medium gap size, no weather strip or seals, no insect screen. Bed1 and Laundry door: timber (solid), 50mm thickness, medium gap size, no weather strip or seals.
Exhaust fans (sealed)	1 to ensuite.
Exhaust fans (unsealed)	1 each to kitchen/family, living, bed2 WIR, bed1 retreat.
Wall heights	External walls: 2700 mm

Appendix E. House plans of the Lochiel Park houses



GROUND FLOOR PLAN

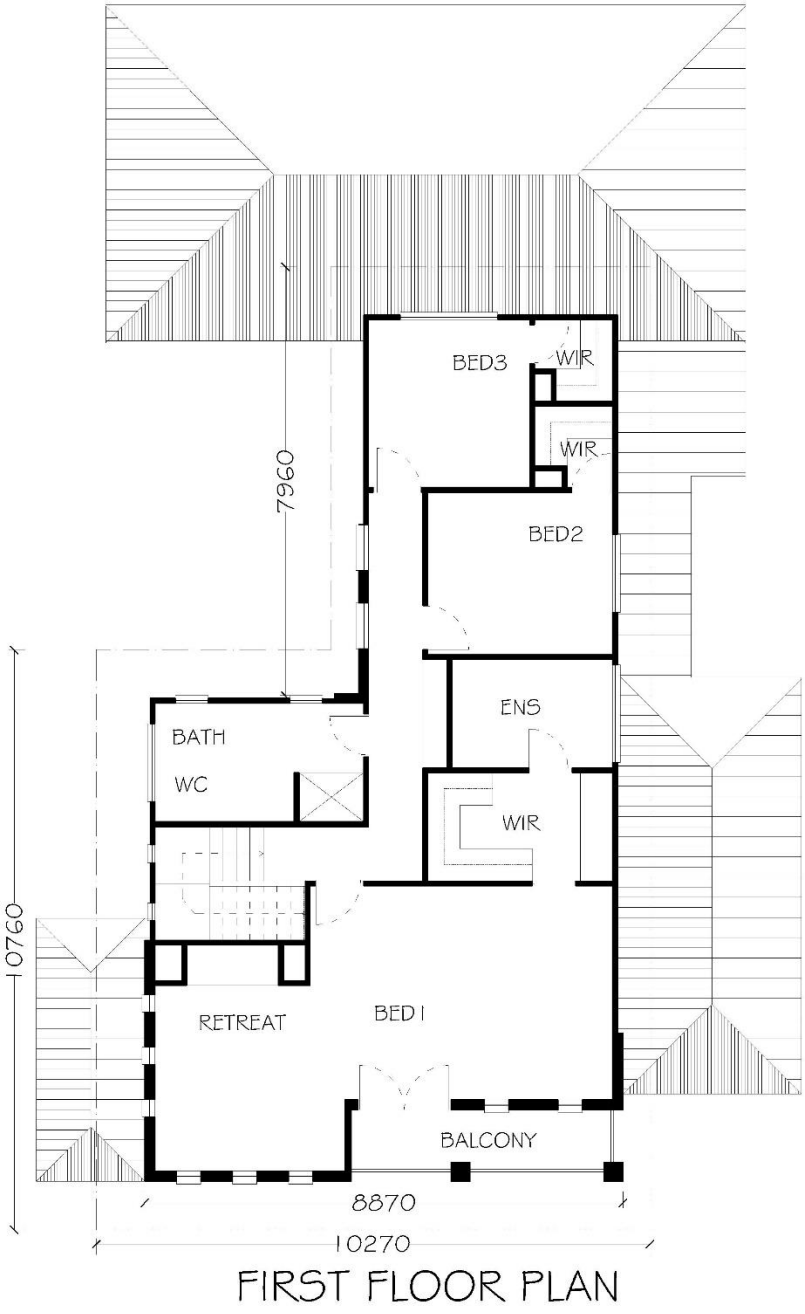
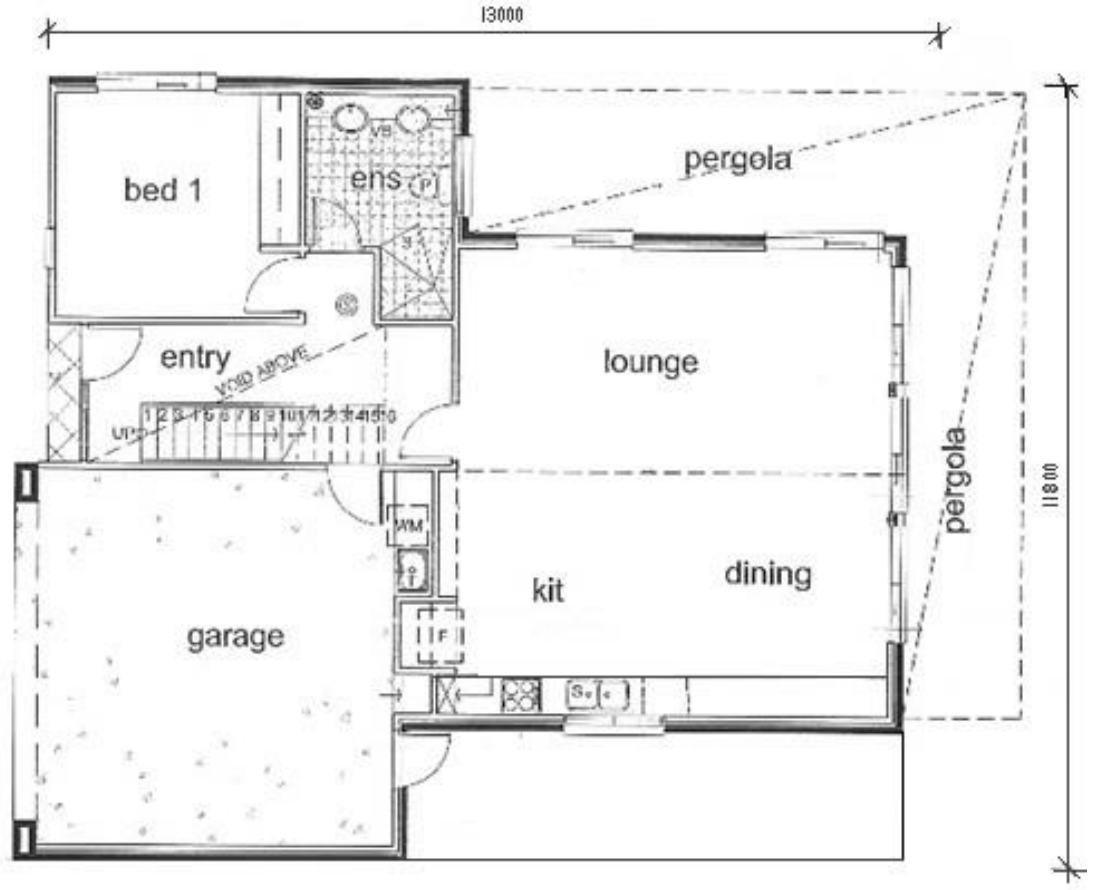
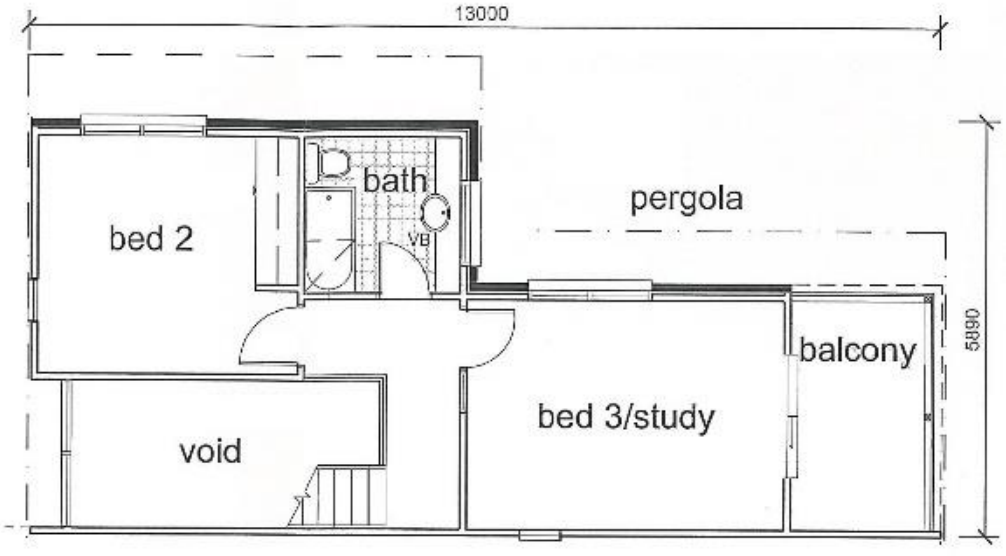


Figure E1 House A

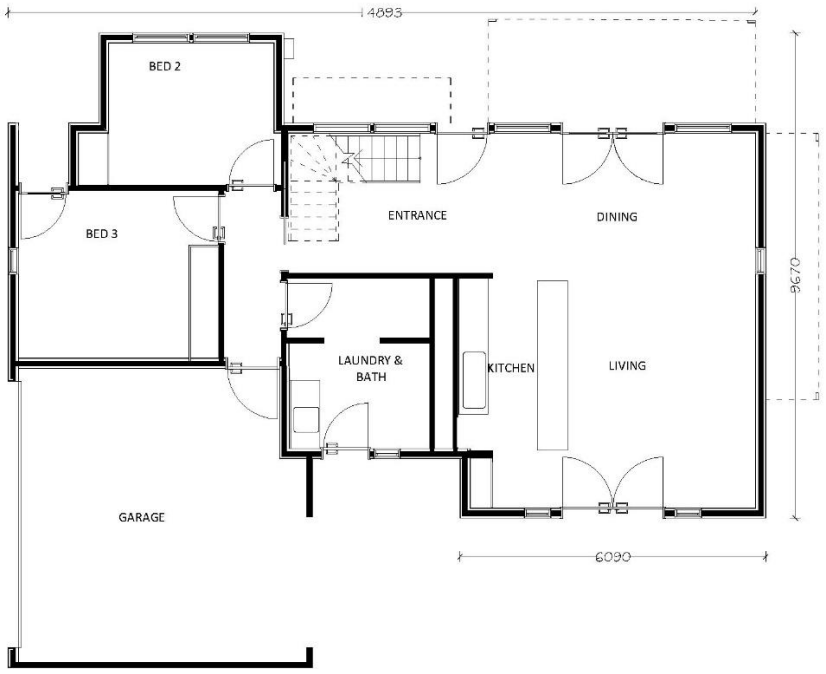


GROUND FLOOR PLAN

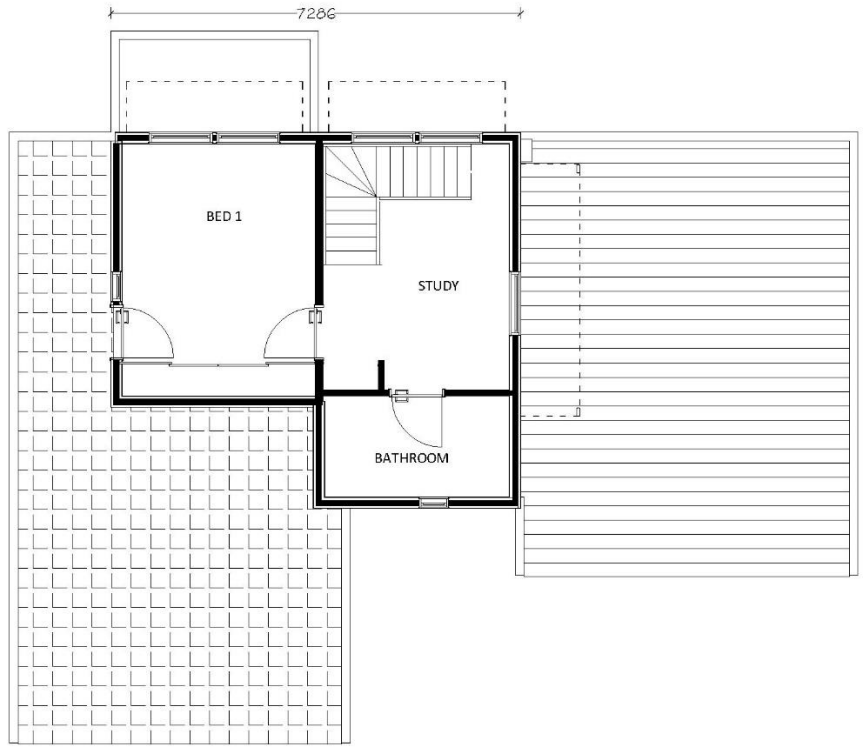


UPPER FLOOR PLAN

Figure E2. House G



GROUND FLOOR PLAN



UPPER FLOOR PLAN

Figure E3. House H

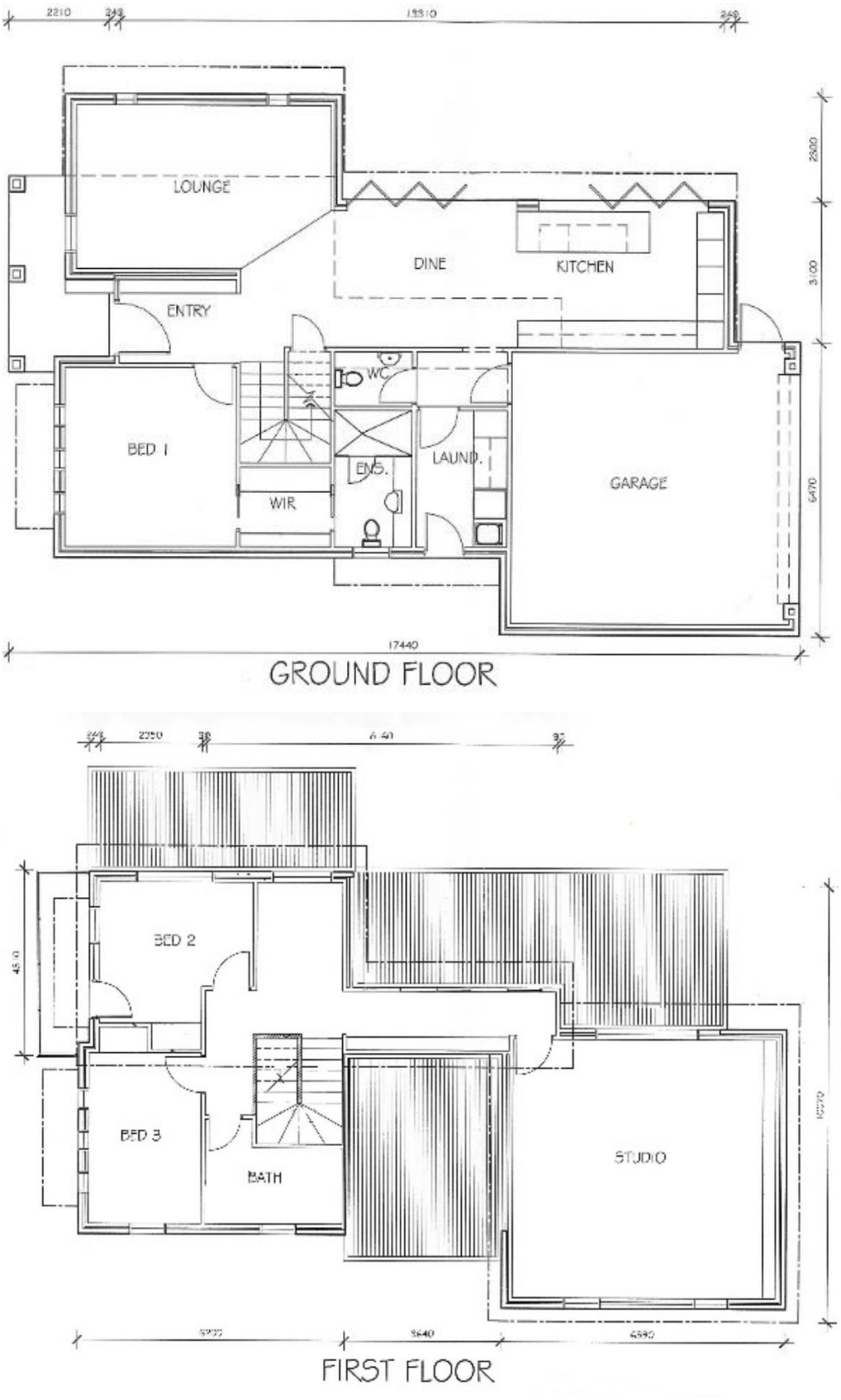


Figure E4. House I

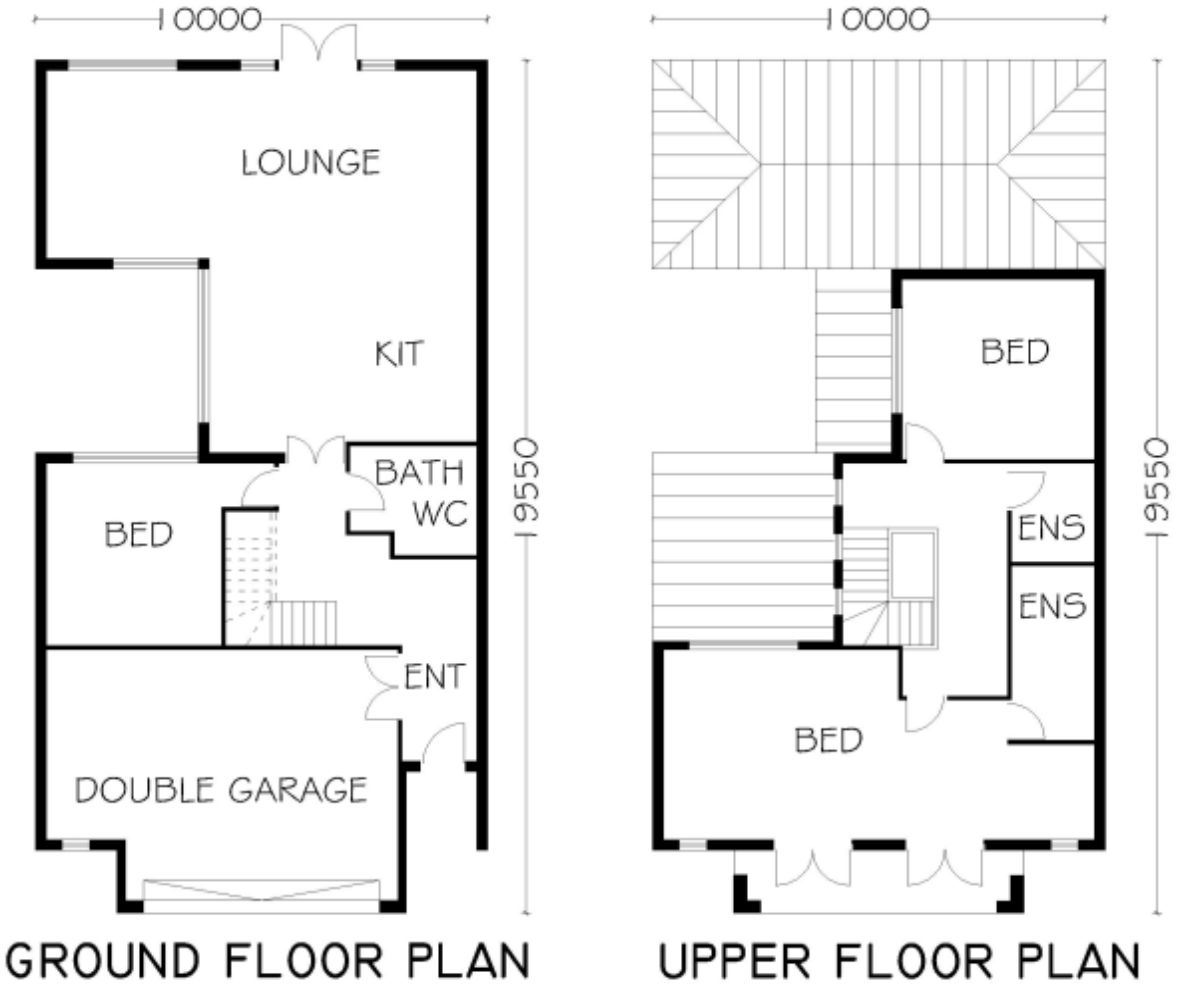
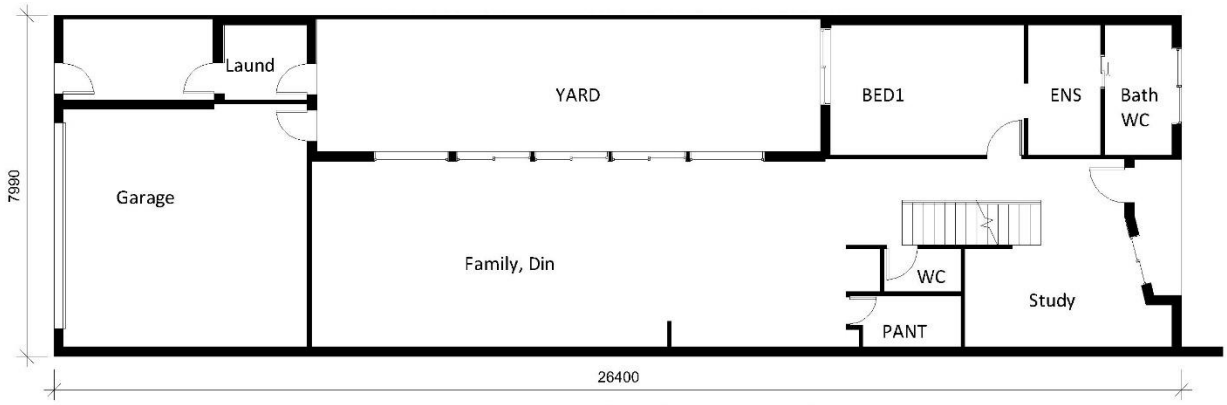


Figure E5 House J



Ground Floor Plan



First Floor Plan

Figure E6. House F

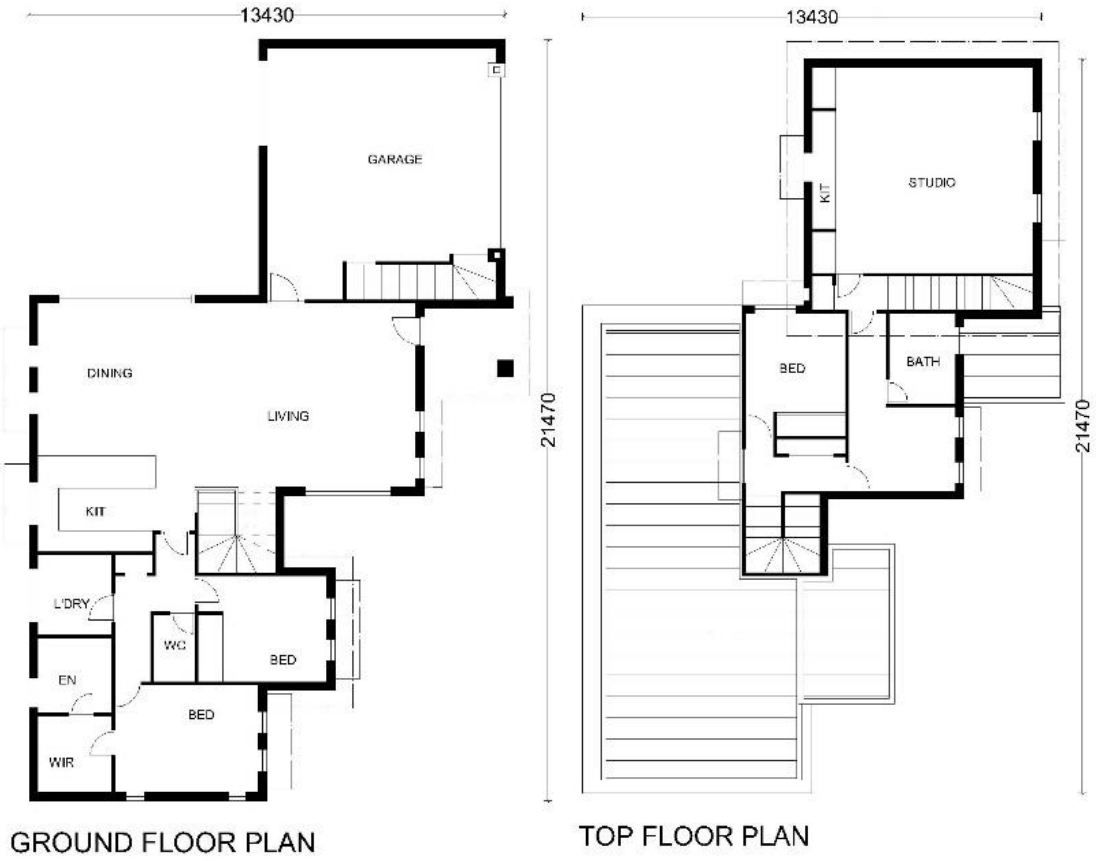


Figure E7. Typical drawing for the rest of the houses