

# **Green Occupants for Green Buildings**

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A thesis submitted in fulfilment of the requirement for the degree of  
DOCTOR OF PHILOSOPHY

**Department of Environment and Geography**

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**Macquarie University**

June 2012

To dearest Patti: for teaching me the gift of giving

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## List of Abbreviations and Symbols

AC	Air-Conditioned
ACS	Adaptive Comfort Standard
AMV	Actual Mean Vote
ANOVA	Analysis of Variance
APD	Actual Percentage Dissatisfied
ARC	Australian Research Council
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
AWS	Automatic Weather Station
BMS	Building Management System
BoM	Australian Bureau of Meteorology
BUS	Building Use Studies
CBE	Center for the Built Environment
CEN	Comité Européen de Normalisation (European Committee for Standardisation)
CO <sub>2</sub>	Carbon Dioxide
CO <sub>2</sub> -eq	Carbon Dioxide Equivalent
EIT	Economies in Transition
GBCA	Green Building Council of Australia
GHG	Greenhouse Gas
Gt	Giga-tonne = 1,000,000,000 tonnes
HVAC	Heating, Ventilation and Air-Conditioning
HYBVENT	Hybrid Ventilation in New and Retrofitted Office Buildings
IAQ	Indoor Air Quality
IEA	International Energy Agency
IEQ	Indoor Environmental Quality
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
MM	Mixed-Mode
MQ	Macquarie University
MRT	Mean Radiant Temperature
Mt	Mega-tonne = 1,000,000 tonnes
NEP	New Ecological Paradigm
NV	Naturally-Ventilated

OECD	Organisation for Economic Cooperation and Development
OFM	Macquarie University Office of Facilities Management
PMV	Predicted Mean Vote
POE	Post-Occupancy Evaluation
PPD	Predicted Percentage Dissatisfied
PROBE	Post-occupancy Review of Buildings and their Engineering
RIBA	Royal Institute of British Architects
RH	Relative Humidity
SBS	Sick Building Syndrome
SCATs	Smart Controls and Thermal Comfort

°C	Degrees Celsius
clo	Clothing insulation
$\epsilon$	Emissivity
m/s	Metres per second
met	Metabolic rate

## **Glossary of Terms**

### **Actual Mean Vote (AMV)**

A subjects' actual thermal sensation as expressed on the seven-point thermal sensation scale from 'cold' (-3) through 'neutral' (0) to 'hot' (+3). Throughout this thesis, AMV is also referred to as the 'observed thermal sensation'.

### **Actual Percentage Dissatisfied (APD)**

A person in comfort is taken to be one who is 'slightly cool' (-1), 'neutral' (0) or 'slightly warm' (+1) on the seven-point thermal sensation scale (ASHRAE, 2010). APD is calculated as the proportion of AMV thermal sensation votes that fall outside this range of 'comfortable' votes divided by the total number of votes for that sample.

### **Adaptive Model**

The adaptive model relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters (de Dear and Brager, 1998; ASHRAE, 2010). This model recognises the role of human adaptation in establishing thermal comfort, taking into account people's thermal perception, behaviour and expectations, allowing for a wider range of acceptable temperatures in NV buildings.

### **Comfort Temperature**

This is the operative temperature at which either the average person will be thermally neutral, or at which the largest proportion of a group of people, will be comfortable (ASHRAE, 2010).

### **Commercial Building**

This term refers to a non-residential building that contains office spaces and primarily used for commercial use.

### **Green Building**

A building that aims to reduce its impact on the environment and increase the quality of life for people who live and work in them (GBCA, 2008). Also referred to as 'green-intent' buildings, such buildings are designed to use less energy and water and consider the life cycle

of the materials used by incorporating environmentally sustainable design, construction and operational practices.

### **Green Occupant**

An occupant is a person who occupies a building; also known as a ‘building user’. A ‘green’ occupant is one who is in-tune with their building’s performance and understands their building’s environmental features and energy-efficient control systems. ‘Green’ occupants can also have high levels of pro-environmental attitudes, and as a result, actively partake in sustainable behaviour that reduces their own energy, water and waste consumption.

### **Low-Energy Building**

Low-energy buildings are designed to maximise the passive use of the building’s form and fabric to collect, store and distribute energy considering gross and operational energy. These can also be referred to as ‘high performance’ buildings.

### **Predicted Mean Vote and Predicted Percentage Dissatisfied (PMV-PPD) Model**

Also referred to as the ‘static’ model of comfort, the PMV-PPD model is based on the principles of the human heat-balance equation (Fanger, 1970). The model calculates thermal comfort as the relationship between four environmental variables: air temperature, radiant temperature, air velocity and relative humidity; and two physiological variables: clothing insulation (clo) and metabolic activity.

### **Predicted Mean Vote (PMV)**

Predicted Mean Vote (PMV) is the average thermal sensation vote for a large group of subjects on the seven-point thermal sensation scale when exposed to a particular environment (Fanger, 1970; ASHRAE, 2010).

### **Predicted Percentage Dissatisfied (PPD)**

Predicted Percentage Dissatisfied (PPD) is derived from PMV and is defined as an index describing the percentage of occupants that are dissatisfied with the given thermal conditions (Fanger, 1970; ASHRAE, 2010).

## **Abstract**

Given contemporaneous concerns of climate change and increasing fossil fuel prices, architects and building designers are exploring mixed-mode (MM) ventilation as a way of combining the best features of air-conditioned (AC) and naturally-ventilated (NV) buildings. MM or ‘hybrid’ buildings utilise a ‘free-running’ NV mode whenever outdoor weather conditions are considered favourable, but revert to mechanical systems for heating, ventilation and air-conditioning when external conditions are deemed less favourable for occupants. This thesis explores how occupant expectations and environmental attitudes may influence thermal comfort and occupant satisfaction within the context of the indoor thermal environment. In doing so, it evaluates the potential for climate change mitigation in NV and MM buildings through occupant behavioural adaptations.

Two academic office buildings with different ventilation strategies (i.e. MM and NV) from a university in Sydney, Australia were used as case studies for this research. Post-occupancy evaluations (POEs) supplemented with the 15-item New Ecological Paradigm (NEP) questionnaire, measuring strength of endorsement (from low to high) of an ecological worldview, were conducted in both buildings to examine how environmental attitudes can influence occupants’ tolerance of the indoor environmental performance of green buildings. Parallel thermal comfort studies, along with continuous indoor and outdoor climate measurements, were also conducted to investigate the differences in occupant satisfaction and comfort perceptions between each building and between the POE and comfort questionnaires.

The POE ‘forgiveness factor’ attempts to quantify the users’ tolerance of a building’s environmental conditions by taking into account the user’s scores for thermal, acoustic and visual comfort. This study found a possible association between environmental beliefs and

occupants' forgiveness factor, which suggests that despite having less-than-ideal thermal conditions, occupants with higher NEP scores were more tolerant of their building's shortcomings compared to occupants with lower NEP scores. Analyses of subjects' thermal sensation within the MM building indicated that observed comfort votes (Actual Mean Vote – AMV) measured in AC mode were congruent to those predicted using the Predicted Mean Vote (PMV) equation. During NV mode, however, observed AMV values did not conform to the PMV values, suggesting that occupants were more adaptive to indoor operative temperatures during NV mode as opposed to when the building was in AC mode. In comparison, whilst occupants experienced significantly warmer operative temperatures in the NV building, observed thermal sensations were also found to differ from the predicted values, suggesting adaptive behaviours of the occupants. Thermal satisfaction and acceptability, along with participant comments and anecdotal evidence from each building, were analysed to investigate the effectiveness of POE methods in evaluating building performance. Results from this study suggest occupants can and do use POE as a vehicle for complaint about general workplace issues, unrelated to their building.

This thesis underscores the importance of occupant expectations and attitudes within the indoor thermal environment. Each study highlights significant differences between occupants' thermal responses under different indoor environmental conditions, suggesting people's environmental attitudes and expectations affect their perception of comfort and satisfaction within MM and NV buildings. Furthermore, the complexity of thermal perception and the inadequacy of static models to describe occupant comfort in MM buildings are discussed in the context of whether such design approaches fall within the scope of international adaptive comfort standards. This research provides evidence to support extending the psychological dimensions of thermal comfort and building performance studies

to account for the contextual influences at play in green buildings, such as environmental attitudes, expectations and personal control.

## **Declaration**

I certify that the work in this thesis entitled “Green Occupants for Green Buildings” has not been submitted for a higher degree to any other university or institution.

I also certify that this thesis is an original piece of research and has been written by me. Any help and assistance that I have received in my research work and the preparation of this thesis itself have been appropriately acknowledged. In addition, I certify that all information sources and literature used are indicated in this thesis.

The research presented in this thesis was approved by Macquarie University Ethics Review Committee, reference numbers: HE22AUG2008-D06019 on 29 August 2008 and HE26SEP2008-D06064 on 16 October 2008.

Max Paul Deuble



## Statement of Contribution

This thesis follows the structure of *thesis by publication*, containing peer-reviewed journal papers that constitute the ‘Results and Discussion’ chapter. The candidate’s individual contribution with respect to the other co-authors of each paper is stated in the introduction of the Results and Discussion chapter.

### **Research Thesis by Publication (s): a preferred Macquarie University model**

“...Theses may include relevant papers (including conference presentations) published or accepted for publication during the period of candidature, together with a comprehensive and critical introduction and an integrative conclusion. A candidate may only include published work which is part of the distinct contribution to knowledge of the thesis if the research and publication of the work occurred during the candidature for the degree. These papers should form a coherent and integrated body of work, which should be focussed on a single project or set of related questions of propositions; however, it is not necessary to reformat published works in the thesis. These papers may be single authored or co-authored – in the case of co-authored papers the candidate must specify his/her specific contribution...The contribution of others to the preparation of thesis or to individual parts of the thesis should be specified in the thesis Acknowledgements and/or in relevant footnotes/endnotes. It is not necessary to reformat published works in a thesis”.<sup>1</sup>

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<sup>1</sup> Macquarie University (2011) ‘Thesis by Publication Guidelines’, Retrieved 21<sup>st</sup> December, 2011, from [http://www.mq.edu.au/policy/docs/hdr\\_thesis/guideline\\_by\\_publication.html](http://www.mq.edu.au/policy/docs/hdr_thesis/guideline_by_publication.html)

## **Publications List**

This thesis is presented in accordance to Macquarie University's guidelines for a thesis by publication. Results from this thesis are published in, or submitted for publication, in the following papers:

### **Peer-Reviewed Journal Papers**

1. Drake, S., de Dear, R., Alessi, A. and Deuble, M. (2010) 'Occupant comfort in naturally ventilated and mixed-mode spaces within air-conditioned offices', *Architectural Science Review*, 53(3): 297-306  
DOI: <http://dx.doi.org/10.3763/asre.2010.0021>
2. Deuble, M.P. and de Dear, R.J. (2012) 'Mixed-mode buildings: A double standard in occupants' comfort expectations', *Building and Environment*, 54(8): 53-60  
DOI: <http://dx.doi.org/10.1016/j.buildenv.2012.01.021>
3. Deuble, M.P. and de Dear, R.J. (2012) 'Green occupants for green buildings: The missing link?', *Building and Environment*, 56(10): 21-27  
DOI: <http://dx.doi.org/10.1016/j.buildenv.2012.02.029>
4. Deuble, M.P. and de Dear, R.J. (2012) 'Is it hot in here or is it just me? Validating the post-occupancy evaluation' (submitted to *Intelligent Buildings International*, May 2012).

### **Peer-Reviewed Conference Papers**

1. Deuble, M. and de Dear, R. (2009) 'Do green buildings need green occupants', *Proceedings of the Healthy Buildings 2009 Conference*, Syracuse, NY, USA, 13-17 September 2009

2. Drake, S., de Dear, R., Alessi, A. and Deuble, M. (2009) 'Occupant comfort in naturally ventilated and mixed-mode spaces within air-conditioned offices', *Proceedings of the 43<sup>rd</sup> Annual ANZAScA Conference 2009: Performative Ecologies in the Built Environment - Sustainability Research Across Disciplines*, Launceston, Tasmania, Australia, 25-27 November 2009
3. Deuble, M. and de Dear, R. (2010) 'Green occupants for green buildings: The missing link?', *Proceedings of the 2010 Windsor Conference: Adapting to Change: New Thinking on Comfort* Windsor, London, UK, Network for Comfort and Energy Use in Buildings, <http://nceub.org.uk>, 9-11 April 2010
4. Deuble, M. and de Dear, R. (2011) 'Mixed-mode buildings: A double standard in comfort', *Proceedings of Indoor Air 2011 Conference*, Austin, TX, USA, 5-10 June 2011

## Acknowledgements

First and foremost I offer my sincerest gratitude to Professor Richard de Dear, without whom this thesis would not have been possible. Your generous supervision and patient guidance over the years has been an endless source of inspiration and support. You have become one of my life's great mentors, constantly driving me to "get more questionnaire data..." until my legs give out and I am truly honoured to have been one of your PhD students.

I would like to thank Associate Professor Paul Beggs for his much appreciated assistance during this research. Upon taking the reins of the administrative duties associated with this thesis, you have given me great advice and skills to deal with some unfortunate worst-case budget scenarios. I cannot thank you enough for your dedicated attention and expertise, and most of all, allowing me to travel to the Indoor Air 2011 conference which has truly been the highlight of my candidature.

I am thankful to Associate Professor Scott Drake and Angela Alessi for our many stimulating discussions regarding our respective projects. Thank you for your supportive and encouraging contributions to this thesis.

I would like to thank Macquarie University's Climate Science Laboratory staff for providing the equipment and instruments necessary to conduct the indoor climate measurements. Many thanks should be given to Macquarie University's Office of Facilities Management, especially Messrs Kerry Russell and Dennis Harrold, for their assistance in gathering the data needed for this research. Special thanks go to the Office of Sustainability's Leanne Denby for

her support as well as Chris Arkins for his help in providing data and information related to the mixed-mode building.

I am enormously grateful to Adrian Leaman for permission to use the Building Use Studies Post-Occupancy Evaluation questionnaire under licence and his assistance in data analysis. I would also like to express my appreciation to all the participants who gave up their time to respond to all, and I mean ALL, of my questionnaires.

Thanks also to the staff and students of the Department of Environment and Geography, Macquarie University. Their enthusiasm and interest in my research was greatly appreciated. Special thanks go to Christhina Candido and Richard de Dear's University of Sydney IEQ crew: Thomas Parkinson, Hisham Allam, Craig Roussac, Junsoo Kim and Libby Gallagher. Thank you for your enthusiastic comments during our discussions, especially during those Comfort Zone Seminars.

I would like to also thank Xiaofeng Li, Mohammad Kotbi and Michelle Lakeridou for our friendly email discussions, allowing me to value and understand my own work as well as see things from a different perspective. Thanks also to Riley Dunlap and Michael Humphreys for their generous feedback and encouraging comments received during this research. Many thanks are owed to everyone I had the chance to meet and talk with at all the conferences I attended at different stages of this research. Thank you for viewing my presentations and your many thought-provoking questions.

This research was financially supported in part by an Australian Research Council (ARC) Discovery Project Grant (DP0880968) from 2008 to 2011. Macquarie University also

provided annual funding for project-related costs and conference attendance between 2008 and 2011.

Lastly, but certainly not least, I would like to thank my beloved family and partner Antania who always support me in everything I do, with everything they have. I'd personally like to thank you for your tremendous patience and for giving me the strength to endure the journey that was this PhD.

# Chapter 1. Introduction

*“Life begins at the end of your comfort zone.” Bear Grylls*

In providing an introduction to the thesis, this chapter presents a background to the thesis topic and states the significance and motivation of this research. This is followed by the aims and objectives of the thesis as well as an outline of the thesis structure.

## 1.1. Background

Fossil fuel combustion, population growth and land use change (i.e. urbanisation) since 1750 are the primary causes for the global increases in atmospheric concentrations of carbon dioxide, resulting in a gradual warming of the Earth’s climate. It is well documented that the construction process and activities within buildings demand significant use of greenhouse gas (GHG) emitting energy sources. In its Fourth Assessment Report, the Intergovernmental Panel on Climate Change (IPCC, 2007) estimated that annual emissions from the buildings sector through electricity use were 8.6 Giga-tonnes of carbon dioxide (GtCO<sub>2</sub>), equivalent to a quarter of the global total in 2004 (Price et al., 2006; Levine et al., 2007). The commonly used IPCC Special Report on Emissions Scenarios (IPCC, 2000) projects these estimates to grow to 15.6 GtCO<sub>2</sub> (A1 scenario<sup>2</sup>) and 11.4 GtCO<sub>2</sub> (B2 scenario<sup>3</sup>) by 2030 (Levine et al., 2007; Urge-Vorsatz et al., 2007), representing approximately 30% of total CO<sub>2</sub> emissions in both scenarios. The buildings sector has also been identified as possessing the greatest potential for climate change mitigation (Urge-Vorsatz et al., 2007; Levermore, 2008a). Based on GHG emission mitigation potentials for three separate valuations per tonne of carbon dioxide equivalent (CO<sub>2</sub>-eq – the combined global warming

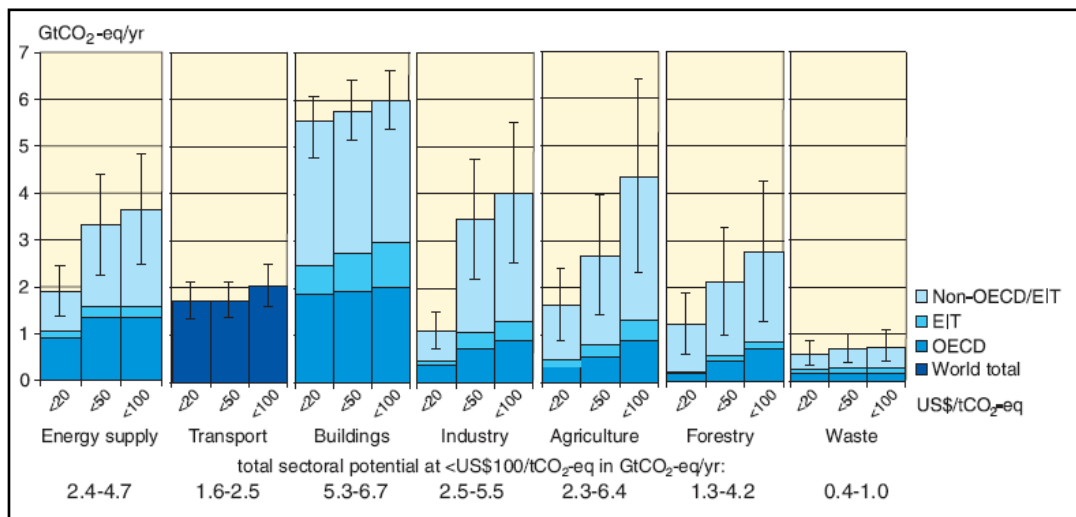
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<sup>2</sup>The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, with the rapid introduction of new and more efficient technologies.

<sup>3</sup>The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population, intermediate levels of economic development, and less rapid and more diverse technological change than the A1 storyline.

potential for all greenhouse gases expressed in terms of carbon dioxide), Figure 1.1 estimates the global potential to reduce projected baseline emissions in the built environment through cost-effective engineering measures as 29% by 2030. As illustrated in Figure 1.1, from technical options alone, the buildings sector far out-ranks the other sectors in terms of its economic mitigation potential, i.e. taking into account social costs and benefits assuming market efficiency is improved by policies and measures and barriers are removed (Levermore, 2008b). According to IPCC reports, a significant portion of these reductions in CO<sub>2</sub> emissions can be attributed to ways that reduce a building's life-cycle costs.

Occupant behaviour, culture and use of technologies are major determinants of energy use in buildings and hence play a pivotal role in determining CO<sub>2</sub> emissions. However, the potential of lifestyle and behaviour change policies and programmes are rarely assessed and have been omitted from Figure 1.1. It is often suggested that the greenhouse mitigation potential for the buildings sector would be significantly higher had these non-technical options been incorporated (Urge-Vorsatz et al., 2007).



**Figure 1.1:** Estimated economic mitigation potential by sector in 2030 from bottom-up studies, compared to the respective baselines assumed in the sector assessments. The potentials do not include non-technical options such as lifestyle changes. OECD represents developed countries part of the Organisation for Economic Cooperation and Development; EIT represents Economies in Transition, i.e. developing countries; and non-OECD/EIT represents countries not part of the OECD and not EIT (IPCC, 2007).

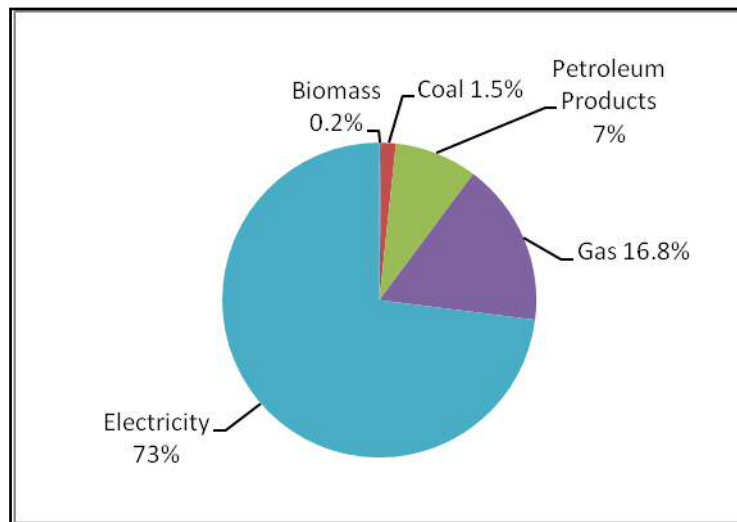


### *1.1.1. Energy and Buildings*

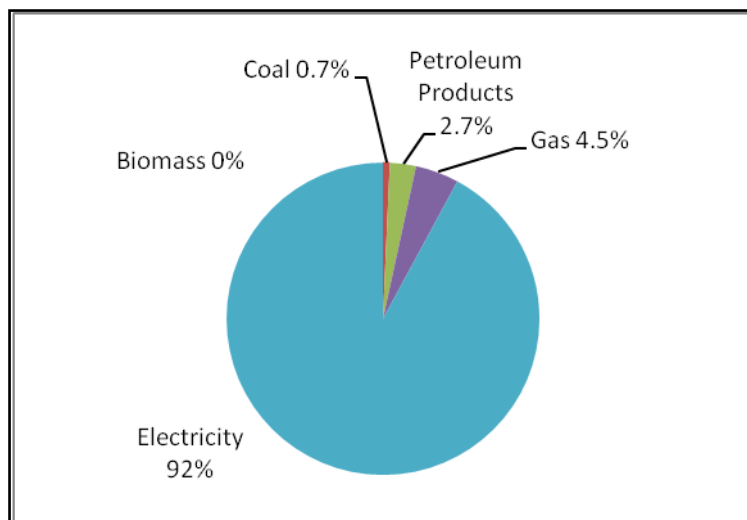
Within OECD countries, buildings account for up to 40% of energy end-use. According to the US Department of Energy's Buildings Energy Data Book, the buildings sector accounted for 73% of total electricity consumption in 2008 (DOE, 2008) and nearly half (47%) of US CO<sub>2</sub> emissions (Architecture 2030, 2011). Of this energy, almost 40% is used by buildings for space heating, ventilation and air-conditioning (HVAC) (Butera, 2010). Similarly, in the UK, approximately 55% of the energy consumed in offices is for HVAC building services (Perez-Lombard et al., 2009). Whilst energy conservation strategies in developed nations present enormous scope for improvement, even more mitigation potential is present in the developing world. Countries such as China and India are emerging as the world's largest carbon emitters (Zhang, 2010). China's buildings sector accounts for 46.7% of the country's total energy consumption, with heating and air-conditioning end-use alone contributing to 65% of the sector's total energy consumption (Wang et al., 2010). In India, the rapid expansion of Grade A, air-conditioned (AC) office buildings is a key contributor to the country's soaring demand for electricity (Lall et al., 2010; Thomas et al., 2010).

Within Australia, CO<sub>2</sub> emissions from fossil fuel energy used directly or as electricity to power equipment and condition the air (including heating and cooling) is by far the largest source of GHG emissions in the Australian buildings sector (CIE, 2007; DCC, 2008). As Figure 1.2 demonstrates, electricity accounts for 65% of energy usage, representing 89% of GHG emissions (shown in Figure 1.3) (DCC, 2008). In 1990, the Australian buildings sector was responsible for 21% of Australia's total greenhouse emissions and 28% of the energy-related emissions; the non-residential and residential sectors contributing 40% and 60% respectively (AGO, 1999a; AGO, 1999b). Since 1990, reports estimate that Australian buildings accounted for nearly 20% of Australia's final energy end-use and were responsible for 23% of Australia's GHG emissions in 2005 (ABARE, 2003; ABARE, 2006b; CIE, 2007).

Driven mainly by its end use, and/or demand for electricity, buildings sector emissions are projected to grow from 130 Mega-tonnes (Mt) per annum in 2005 to 210 Mt by 2030 (ABARE, 2006a). According to CIE (2007), these are projected to grow to 280 Mt by 2050 with commercial sector emissions expected to grow at a faster pace than the residential sector.



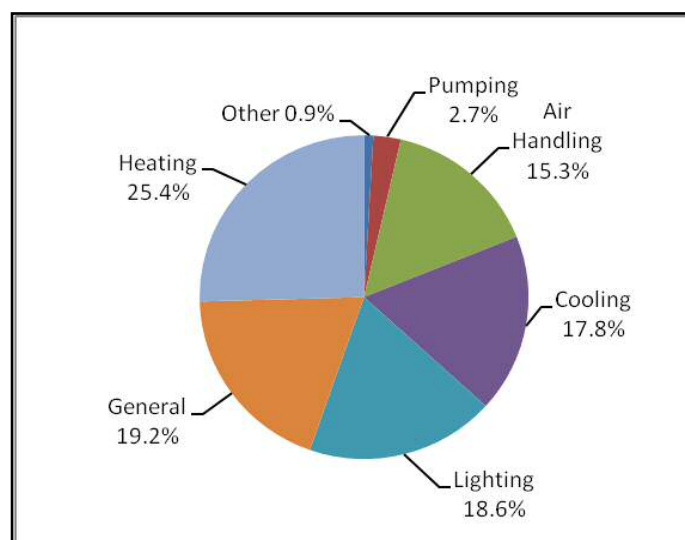
**Figure 1.2:** Commercial buildings energy share by energy source (DCC, 2008).



**Figure 1.3:** Commercial building greenhouse gas emissions by energy source (DCC, 2008).

Globally, space heating and cooling are the dominant energy end-uses in the buildings sector (IPCC, 2007). Within Australia's commercial sector, climate control (HVAC) is a major contributor to the sector's energy needs, accounting for 61.2% in 2005, as illustrated in

Figure 1.4 (CIE, 2007; DCC, 2008). The basic purpose of an HVAC system is to provide comfortable interior thermal conditions to all occupants, i.e. thermal comfort (ASHRAE, 2010). As the core concept of ‘thermal comfort’ is more of a state of mind (reflecting different cultural, class and geographical conditions) than a technical certainty (ASHRAE, 2001), assessing the right level of thermal comfort is critical to setting building performance standards (Cena and Clark, 1981; Kwok and Rajkovich, 2010). This requires an understanding of the extent to which people are ready to make behavioural changes to achieve comfort in their environment. This, in turn, affects the way building occupants interact with their environment – from choosing to pull down external blinds to limit sun penetration at certain times of day (rather than switching on the air-conditioning) to putting on a sweater when the temperature drops (rather than turning up the thermostat). Typically, green buildings require a more proactive engagement between the occupant and the built environment, which reflects the greater reliance on the “passive” versus “active” environmental control strategies available (Barlow and Fiala, 2007).



**Figure 1.4:** Commercial building energy share by end-use (DCC, 2008).

## 1.2. Significance

Many non-residential buildings in the second half of the 20<sup>th</sup> century and later were designed to be sealed envelopes heated or cooled with centralised HVAC systems. These

buildings were engineered to maintain fairly constant conditions throughout the interior for all occupants, consuming excessive amounts of energy in the process. In contrast, emergent 'green' buildings, often with increased capability for natural ventilation and minimised dependence on heating or cooling systems, present more sustainable, less energy-intensive solutions. These buildings are more loosely controlled, providing greater internal environmental variation (e.g. de Dear and Brager, 1998; Humphreys and Nicol, 1998; de Dear and Brager, 2002; Nicol and Humphreys, 2002; Brager et al., 2004) via operable windows, user-adjustable shade devices, etc., or by adaptive comfort algorithms that more closely match indoor thermal conditions to temperatures prevailing outdoors. This shift towards more variable indoor environmental conditions represents a recurring theme in contemporary sustainable building design, providing thermal comfort while reducing energy use and associated GHG emissions (de Dear and Brager, 2002). However, while occupants appreciate a high degree of adaptive opportunities (Baker and Standeven, 1996), as found in naturally-ventilated (NV) buildings, they do not necessarily appreciate the thermally uncomfortable conditions in NV buildings during unusually hot weather (Bordass et al., 2001b; Leaman and Bordass, 2003). In response, architects and engineers are exploring 'mixed-mode' (MM) ventilation as a way of combining the benefits of air-conditioning and natural ventilation (Brager, 2006; Rijal et al., 2008; Brager and Baker, 2009).

The basic concept of MM or 'hybrid' ventilation is to maintain satisfactory indoor thermal environments by alternating between and combining natural and mechanical systems, thereby minimising the significant energy use and operating costs associated with air-conditioning. Predominantly designed as NV structures with operable windows, MM buildings also have the capability of switching into an AC building whenever the outdoor weather conditions make the NV option untenable for the occupants. This design strategy allows the building to 'change-over' between NV and AC modes on a seasonal or even daily basis (CBE, 2005).

There are many variations on this theme, such as concurrent strategies that utilise air-conditioning and operable windows in the same space and at the same time; and zoned strategies whereby different zones within the same building have different cooling modes (CBE, 2005; Brager et al., 2007).

Following the adoption of the adaptive comfort standard (ACS) in ASHRAE Standard 55 (ASHRAE, 2004) as an alternative to the PMV-based method for NV buildings, many studies (e.g. Brager and de Dear, 1998; de Dear and Brager, 2002; Nicol and Humphreys, 2002; Turner, 2008) believe the standard should have included MM buildings. But at the time of ASHRAE 55-2004 going to press, insufficient comfort studies undertaken in MM buildings meant they were excluded from the scope of the ACS (de Dear and Brager, 2002). Despite the most recent revisions to the standard (ASHRAE, 2010), the ACS is still constrained in scope to naturally conditioned, occupant-controlled spaces in which thermal comfort conditions are primarily regulated by operable windows. Furthermore, ASHRAE explicitly states that when mechanical cooling systems are provided for the space, as is the case for MM buildings, the ACS is not applicable (Nicol and Humphreys, 2002; Turner, 2008; de Dear, 2011). Thus, the GHG mitigation potential afforded by the standard does not extend to the NV mode of MM buildings. Because of the presence of HVAC capabilities, MM buildings fall under the scope of the more restrictive PMV-PPD method (de Dear and Brager, 2002; Nicol and Humphreys, 2002; Turner, 2008). The European counterpart standard, EN15251 (CEN, 2007), however, allows the more flexible adaptive comfort standard to be applied to NV buildings which can include MM buildings during times when they are not employing mechanical cooling, i.e. whilst in NV or ‘free-running’ mode (Nicol and Humphreys, 2010).

### *1.2.1. Motivation*

Launched in 2002, the Green Building Council of Australia's (GBCA) Green Star is a comprehensive environmental rating system used to evaluate the environmental design and construction of buildings in Australia (GBCA, 2008). However, Reed et al., (2009), summarises some of the potential shortfalls and dangers associated with such building sustainability indices. These tools are primarily based on building materials, energy systems and cooling technologies, giving very little attention to the behaviour and culture of the building occupants, and even less to their environmental attitudes. Despite being a positive driving force in Australia's green construction industry, Green Star building ratings are potentially misleading if occupants do not behave in a way that complements the building's design intent. Thus in order to fully maximise the carbon mitigation potential of green buildings, occupants need to be sympathetic to the building's green design-intent. The aphorism 'green buildings need green occupants' (Browne and Frame, 1999) summarises this point.

Post-occupancy evaluation (POE) studies provide a general overview of occupant satisfaction for any given building. Surveys done in the UK and US (e.g. Abbaszadeh et al., 2006; Leaman and Bordass, 2007; Brager and Baker, 2009) indicate that occupants are more favourably disposed to green buildings. As noted by Leaman and Bordass (2007) and Brager and Baker (2009), occupant satisfaction scores for green-intent buildings tend to be better than those in conventional AC buildings. Green buildings show greater levels of occupant satisfaction and better ratings for perceived health and productivity compared to non-green buildings. However, based on objective indoor environmental quality (IEQ) performance criteria, such buildings don't necessarily outperform conventional AC alternatives. They are often hotter in summer, colder in winter and contain more solar glare from the sun and sky. Recent surveys of post-occupancy literature (Leaman and Bordass, 2007; Baird, 2010)

however, suggest that green building users are prepared to forgive such conditions if they possess a modicum of environmental control. The term ‘forgiveness factor’ was coined by Leaman and Bordass (2007) to describe this phenomenon. Could this ‘forgiveness’ be due to the occupants having more relaxed expectations for green buildings as opposed to conventional AC settings? Or perhaps occupants’ environmental attitudes and beliefs can influence their tolerance of green buildings? Perhaps occupants who are fully cognisant of the role played by HVAC energy in global climate change will be more tolerant of green buildings than those occupants who are in denial of anthropogenic climate change?

In recent decades there has been a growing awareness of the problematic relationship between modern industrialised societies and the physical environments upon which they depend (Oskamp, 2000; Stern, 2000; Dunlap, 2008). As such, there is an increasing focus on the quantification of public sentiment to these issues, as well as the determinants of pro-environmental or sustainable behaviour change. Environmental attitudes are defined as ‘the collection of beliefs, affect and behavioural intentions a person holds regarding environmentally-related activities or issues’ (Himmelfarb, 1993; Schultz et al., 2004; Milfont and Duckitt, 2010). Furthermore, it has been established that environmental attitudes are powerful predictors of pro-environmental behaviour (Kaiser et al., 1999; Milfont and Duckitt, 2004).

Whereas several environmental attitudinal scales and measures have been developed since the 1960s (e.g. Maloney and Ward, 1973; Weigel and Weigel, 1978), very few have been successfully validated or been adapted to measure building occupants’ level of ‘greenness’. Dunlap and van Liere’s New Environmental Paradigm (Dunlap and van Liere, 1978), later revised as the New Ecological Paradigm (NEP) scale (Dunlap et al., 2000), has become the most widely used index of pro-environmental attitudes. This 15-item questionnaire consists

of 8 pro-NEP and 7 anti-NEP items to determine whether a person's attitudes and behaviours are pro- or anti-environmental. As such, it represents a quick and easy metric of building occupants' level of 'greenness' based on their endorsement of an ecological worldview (Dunlap, 2008; Hawcroft and Milfont, 2010). After extensive application across a diverse range of studies (e.g. Stern et al., 1995; Blake, 2001; Ewert and Baker, 2001; Poortinga et al., 2004) a broad consensus has emerged in the environmental psychology literature that the NEP represents a valid and reliable scale for measuring levels of ecological beliefs and attitudes (Dunlap and Jones, 2002; Cordano et al., 2003). However, prior to this research, the NEP scale has never been used in conjunction with building occupant studies and could potentially identify the link between successful occupancy of green buildings and environmental attitudes.

### **1.3. Research Aim and Objectives**

This thesis aims to evaluate how occupant expectations and environmental attitudes influence thermal comfort and occupant satisfaction within the context of low-energy indoor thermal environments, as found in MM and NV buildings. This aim is split into three main studies, i.e. environmental attitudes and occupant satisfaction in green buildings; thermal comfort in MM buildings; and the validity of contemporary POE methods. The research objectives specific to each study, which will be addressed throughout this thesis, are as follows:

#### *1.3.1. Environmental Attitudes and Occupant Satisfaction in Green Buildings*

1. By conducting POEs within two 'green' buildings, i.e. a MM and a NV building, this study aims to evaluate the occupants' 'forgiveness factor' in relation to their thermal environment.



2. Through the use of the NEP questionnaire, this study investigates occupants' levels of environmental attitudes within the MM and NV buildings. It is hypothesised that broadly pro-environmental attitudes are associated with the stronger 'forgiveness factors' towards indoor thermal environmental performance often reported in green building POE studies in the research literature.

#### *1.3.2. Thermal Comfort in Mixed-Mode Buildings*

1. This study aims to understand how MM ventilation affects occupant comfort by comparing both observed and predicted thermal sensation votes recorded in AC and NV modes. In doing so, this study will test whether the adaptive comfort model can be applied to MM buildings, especially during times of natural ventilation.
2. By evaluating the current definition and scope of the adaptive comfort standards in ASHRAE 55-2010 and EN15251-2007, the implications of this research are discussed in the context of whether adaptive comfort standards for NV buildings should be applied to MM buildings.

#### *1.3.3. The Validity of Contemporary Post-Occupancy Evaluation Methods*

1. By comparing the results from the POE and thermal comfort field studies in the MM and NV buildings, this study aims to test the validity of assessing building performance using the POE method.
2. Occupant satisfaction and thermal acceptability levels, along with participants' comments and anecdotal evidence, were analysed between each method to examine how POEs may generate over-exaggerated responses of poor building performance.
3. Finally, this study makes recommendations as to how these tools can be improved, encouraging a more holistic approach to building performance evaluation.

## **1.4. Thesis Structure**

This chapter introduced the broad context, significance and motivation for this research, stating the key aims and objectives pursued during the development of this thesis. Chapter 2 presents a review of the current literature related to the research questions of this thesis. The first section of this chapter focuses on the emergence of MM ventilation in the built environment, highlighting numerous thermal comfort studies from both the ‘static’ and ‘adaptive’ approaches. Current debates surrounding the applicability of MM buildings within the ACS, as well as issues of overheating and occupant control are also discussed. The second section critiques the current use of POEs in evaluating building performance in the field of IEQ research. A brief summary of the literature review chapter is presented.

Chapter 3 explains the methods applied throughout this thesis. In describing the design and development of each questionnaire used, the two separate projects conducted within Sydney from March 2009 to April 2010 are presented, along with their respective data collection and survey techniques. The instruments and resources utilised to record both the indoor and outdoor climatic data are provided along with detailed descriptions of the site’s climatic context, each case study building and their occupants. Documents relating to the ethical and methodological design of this research, e.g. ethics approvals and questionnaires are presented in Appendices A to I.

Chapter 4 presents the main results and discussions of this thesis, which includes research papers that have been submitted to, or published in peer-reviewed journals during the course of this research. Based on the corresponding peer-reviewed journal papers, three key topics of analysis relating to the thesis’ research aims are presented: environmental attitudes and occupant satisfaction in green buildings (Paper 4.1); thermal comfort in MM buildings (Paper 4.2); and the validity of contemporary POE methods (Paper 4.3). Complementary research

results, such as those published in peer-reviewed journals and/or conference proceedings are presented in Appendices J to P. A summary of the main results and discussions, as well as the limitations of this research, is also presented.

Finally, Chapter 5 presents the concluding remarks derived from the results and suggests recommendations in which further research may be necessary.

### **1.5. Chapter Summary**

This chapter provided an introduction to the thesis, the significance and motivation of this research as well as the key objectives. The next chapter presents a review of the current literature related to this thesis.

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## **Chapter 2. Literature Review**

This chapter presents a review of the current literature related to this thesis. The first section introduces the concept of MM ventilation, highlighting thermal comfort studies from both the ‘static’ and ‘adaptive’ approaches. Topical debates surrounding the future inclusion of MM buildings into international comfort standards are also discussed, along with the issues of overheating and occupant control. The next section critiques the use of contemporary POE methods in building performance evaluations, as well as the emerging topic of occupant forgiveness and satisfaction in green buildings. Finally, a chapter summary is provided.

### **2.1. Air-Conditioning vs. Natural Ventilation and the Rise of Mixed-Mode**

The main purpose of any building is to provide a safe and comfortable environment that neither impairs the health of its occupants nor hinders their performance. Prior to the 21<sup>st</sup> century, office buildings were generally designed with a building-centred, energy-intensive approach focussed on providing standardised indoor climates for all occupants through HVAC technology (Cooper, 1998; Ackermann, 2002). Following the energy crises of the 1970s, many countries started to rethink the design of, and services, within buildings. Since then, many governmental and professional bodies have sought to improve the energy efficiency of buildings by reducing energy consumption without compromising occupant comfort, health and productivity levels (e.g. Roaf, 2006; Perez-Lombard et al., 2009). However, a central issue in the efficiency, and effectiveness, of buildings are the occupants (Janda, 2011).

Architects are now diversifying opportunities available in buildings to provide comfort for occupants (Roaf, 2006). This shift to more heterogeneous indoor environments, often using

natural ventilation as opposed to compressor-based air-conditioning, suggests occupants are no longer passive recipients of an active environment (Forwood, 1995; de Dear, 2007). Increasingly they expect more control over their environment and want a rapid response to any discomfort they experience, which is difficult to achieve in AC buildings (Bordass et al., 1993). In order to provide such behavioural, or 'adaptive' opportunities (Baker and Standeven, 1996), buildings must be designed to re-engage 'active' occupants in the achievement of comfort. NV buildings require a more proactive engagement between the occupier and the environment. In offering more 'adaptive opportunities' (Baker and Standeven, 1996) for the occupants, a higher degree of interaction among the occupants is required to achieve thermally comfortable environments; active occupants for passive buildings (Barlow and Fiala, 2007; de Dear, 2007; Cole et al., 2008).

According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE, 2001), mechanical HVAC systems were purposely built to maintain constant thermal environmental conditions throughout the interior, aiming for an optimum 'steady-state' temperature setting based on Fanger's Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) model (Fanger, 1970). Many argue that since the advent of air-conditioning in the early 20<sup>th</sup> century, occupant expectations of the indoor environment have changed (Prins, 1992; Cooper, 1998; Ackermann, 2002). Countless studies in recent decades have made the case for greater environmental variation inside buildings, either through user operable windows and shade devices, or by other adaptive opportunities such as control algorithms that more closely match indoor thermal conditions to prevailing outdoor temperatures (e.g. Busch, 1992; de Dear and Brager, 1998; Humphreys and Nicol, 1998; de Dear and Brager, 2002; Brager et al., 2004; Rowe, 2004; Humphreys et al., 2007; Rijal et al., 2007). Spatially, thermally differentiated zones can accommodate a variety of individual thermal requirements (Kwok, 2000; Kwok and Rajkovich, 2010). Temporally,

indoor temperatures can gradually drift towards outdoor conditions and encourage occupant adaptations such as clothing changes and use of operable windows (Brager and de Dear, 1998; Brager and de Dear, 2000).

While occupants generally prefer indoor environments with ‘adaptive opportunities’ (Baker and Standeven, 1996), they may not appreciate the thermally uncomfortable conditions likely to occur in NV buildings during unusually hot weather. However, they are often prepared to forgive such conditions if they possess a modicum of environmental control (Cohen, 1997; de Dear and Brager, 1998; de Dear and Brager, 2002; Brager et al., 2004). MM or ‘hybrid’ buildings represent a compromise that combines the best features of NV and AC buildings (Brager, 2006; Brager and Baker, 2009; Rijal et al., 2009). It should be noted that the terms ‘hybrid’ and ‘mixed-mode’ are used interchangeably to describe any building that combines the use of both natural and mechanical systems for cooling and ventilation.

#### *2.1.1. Classifications of Mixed-Mode Buildings*

The energy consumption of buildings depends significantly on the criteria used for the indoor environment, which also affects health, productivity and comfort of the occupants (Olesen, 2007). Considering HVAC systems are the single largest energy end-use in the built environment, it is inevitable that we should look critically at our dependence on mechanically cooled indoor climates. In a numerical analysis of strategies to adapt existing building stock for changes in the UK climate, CIBSE (2005) discerned four basic design principles:

1. Minimise heat gains (solar shade) and ensure internal equipment is switched off when not required (‘switch off’);
2. The impact of gains can be reduced by attenuating peaks by means of thermal mass (‘spread out’);

3. Ventilation systems should be properly controlled to ensure gains are removed and not added to, e.g. by not introducing outside air when that air is at a temperature higher than that in the building (other than that required to maintain air quality) ('blow away'). To this end a mechanical system may be preferable to natural ventilation systems; and finally,
4. If all else fails 'peak lopping' cooling will be required ('cool'). This, commonly known as a MM building, is likely to become the sustainable building of the future (Holmes and Hacker, 2007).

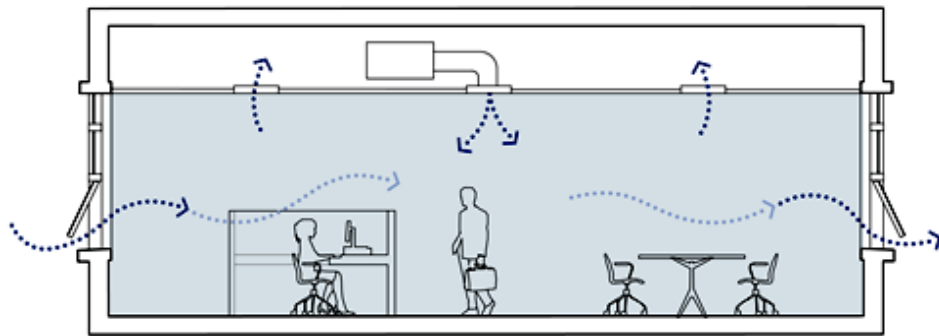
MM ventilation refers to a hybrid approach to space conditioning that uses a combination of natural ventilation from operable windows (either manually or automatically controlled), and mechanical systems that provide air distribution and some form of cooling (Arnold, 1997; Brager, 2006). Such buildings provide good air quality and thermal comfort using a NV or 'free-running' mode whenever the outdoor weather conditions are favourable, but revert to mechanical systems for HVAC whenever external conditions make the NV option untenable for occupants (Brager, 2006; Heiselberg, 2006; Holmes and Hacker, 2007; Lomas et al., 2007). Whilst all MM buildings combine both elements of natural and mechanical systems for cooling and ventilation, many variants exist (Bordass and Jaunzens, 1998; Brager et al., 2000; Brager, 2006). In their database of over 150 MM building case studies, the Centre for the Built Environment (CBE) at University of California, Berkeley, has identified three distinct design strategies (CBE, 2005; IEA, 2006):

#### 2.1.1.1. Concurrent

The most prevalent design strategy in practice today, concurrent MM operation utilises air-conditioning and operable windows in the same space and at the same time (illustrated in Figure 2.1) (Brager et al., 2007). In this case, fresh air is provided throughout



the year by operable vents in the building façade. In addition, larger quantities of fresh air can flow through operable windows during the cooling season to reduce the cooling load on the mechanical system (Brager, 2006). The HVAC system may serve as supplemental ventilation and cooling while occupants are free to open windows based on individual preferences (Rowe, 2004). In warmer climates, concurrent MM systems usually require higher set-points such that the building is primarily in passive mode most of the time, and mechanical cooling is only needed to control the peaks. This can be an effective and energy efficient solution if implemented within a building designed for high thermal stability, having efficient fans, heat recovery and night cooling (Brager et al., 2000; CBE, 2005).

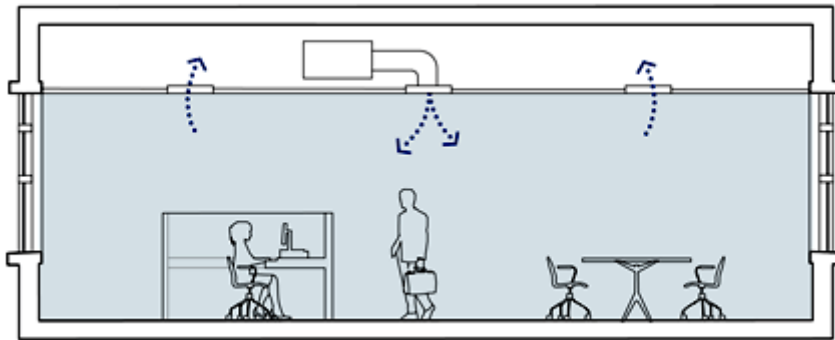


**Figure 2.1:** Concurrent mixed-mode operation (CBE, 2005).

#### 2.1.1.2. Change-over

Change-over designs (shown in Figure 2.2) are becoming increasingly common, where the building ‘switches’ between NV and AC modes on a seasonal, synoptic or even daily basis (Brager et al., 2000; Brager, 2006). Brager et al. (2007) further define the operating parameters that dictate which timescale(s) of control are appropriate, such as climate (from seasonal changes to current conditions), building characteristics (e.g. massing and orientation), and microclimatic conditions. The building automation system may determine the mode of operation based on outdoor temperature, an occupancy sensor, a window (open or closed) sensor, or operator commands (Bordass and Jaunzens, 1998; IEA, 2006). Typical examples include individual offices with operable windows, and when a certain temperature is exceeded during the day the building switches to mechanical cooling.

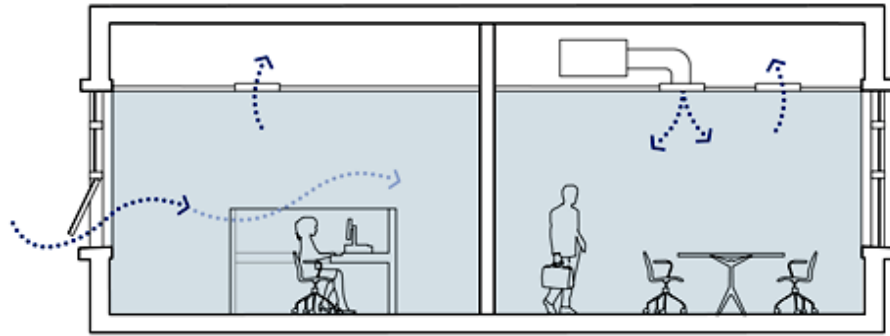
Such a building requires a control system that can switch automatically between natural and mechanical modes in such a way that minimises energy consumption (Brager et al., 2007; Henze et al., 2007) without compromising indoor air quality or occupant thermal comfort (McCartney and Nicol, 2002).



**Figure 2.2:** Change-over mixed-mode operation (CBE, 2005).

#### 2.1.1.3. Zoned

This category generally refers to when passive and mechanical strategies occur at the same time but in different zones within the building. This is usually the case when parts of the building differ in their requirements for ventilation and heating/cooling, either due to their occupancy and usage, different internal loads, or to their planning and location, as Figure 2.3 illustrates (Bordass and Jaunzens, 1998; CBE, 2005). This design is quite climate-restrictive because it assumes that natural ventilation will be able to fully handle portions of the building throughout the year. This MM option is best suited where buildings have deep floor plates creating large interior zones, or there are ventilation requirements in parts of the space that cannot be met by natural ventilation, e.g. labs or kitchen areas (Drake, 2005; Brager et al., 2007). Such a configuration may also be appropriate where there are other programmatic differences dictating the use of different strategies, e.g. NV office buildings with operable windows and a ducted heating/ventilation system providing heating/cooling only to conference rooms (Brager et al., 2000; CBE, 2005).



**Figure 2.3:** Zoned mixed-mode operation (CBE, 2005).

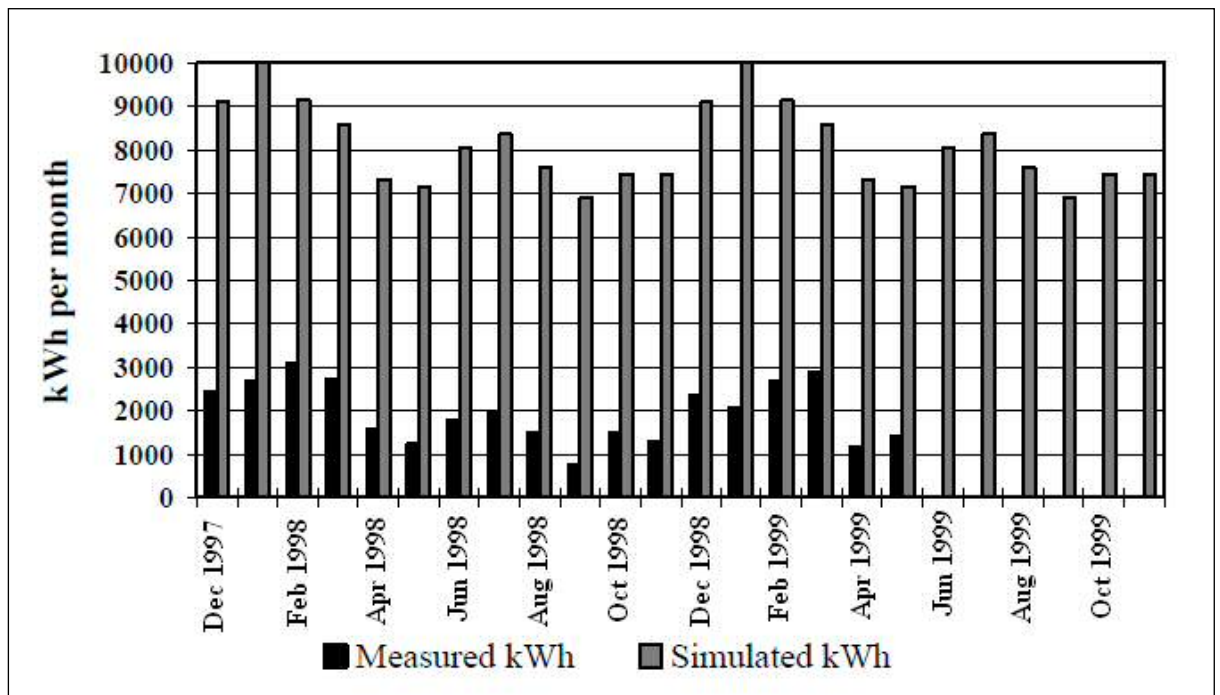
### *2.1.2. Making the Business Case for Mixed-Mode*

The expansion of large-scale mechanical ventilation and cooling in the 1950s, along with other technologies such as curtain walls and fluorescent lighting, led to the more common office building forms of today; typically all-glass, flush-skin buildings with large floor plates and no operable windows (Brager et al., 2000; Brager, 2006). These enclosed glass towers were designed to maintain constant, static conditions throughout the interior (Brager and de Dear, 1998), and in doing so, shifted the locus of indoor environmental control away from the occupants and towards a facilities manager (Cooper, 1982; Brager et al., 2004). Many researchers have stated that these buildings miss out on the large number of documented benefits of operable windows, such as reduced energy consumption (Rowe, 2003; Emmerich and Crum, 2005; Henze et al., 2007), fewer dissatisfied occupants (Leaman and Bordass, 2007; Brager and Baker, 2009), and fewer sick building syndrome (SBS or building-related) illness symptoms compared to conventional AC buildings (Mendell, 1993; Seppanen and Fisk, 2002). In reviewing the current literature, the following sub-sections elaborate some of the benefits of MM ventilation:

#### 2.1.2.1. Energy

Albeit assessed through numerical simulations rather than physical monitoring, the potential energy savings from MM buildings have been frequently documented (Daly, 2002;

Rowe, 2003; Emmerich and Crum, 2005; Emmerich, 2006). Through the use of building simulations, Emmerich and Crum (2005) demonstrated that the use of MM ventilation in the US can contribute to HVAC energy savings ranging from 13% (medium-sized office building with a variable air volume system in Miami), to 29% (small office building with a constant air volume system in Atlanta), to 79% (small office building with a constant air volume system in Los Angeles) (Emmerich, 2006). Similarly in the UK, building simulations estimated that MM buildings could reduce energy costs by over 35% when compared to all-mechanically cooled alternatives (Ogden et al., 2004). A real building study undertaken by Rowe (2003), later acknowledged in Forwood and Rowe (2006), also examined the potential for reduced energy consumption in MM offices. Compared with estimated energy consumption if the same spaces were enclosed and mechanically ventilated with full time air-conditioning, Figure 2.4 illustrates that since the hybrid system was activated, annual measured energy consumption was less than 25% of the simulated annual consumption. These findings are congruent with a similar study conducted in Indonesia (Karyono, 2000). Over a 12 month period, energy consumption data was monitored for an AC, NV and hybrid building (wherein occupants had personal control over individual AC units). The hybrid building was found to use 80% less energy than the AC building, while at the same time allowing a slightly greater proportion of workers to be thermally comfortable (Karyono, 2000).

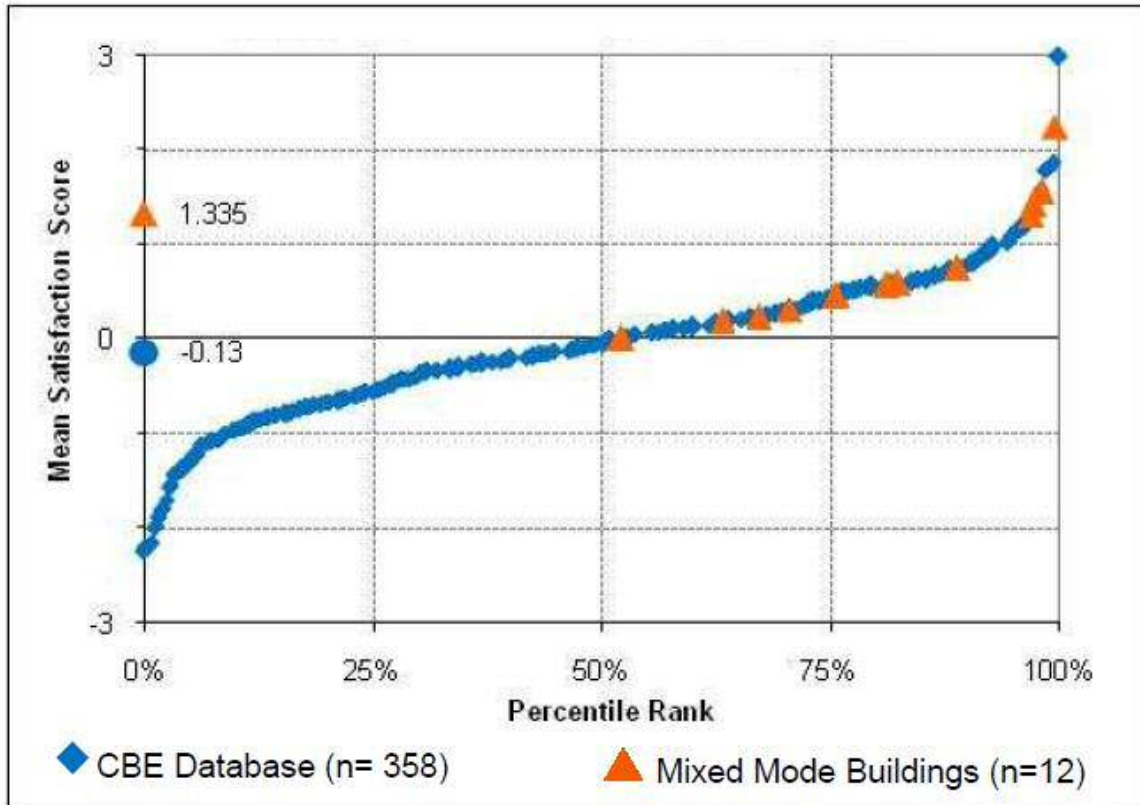


**Figure 2.4:** Actual monthly metered energy consumption used by the supplementary cooling and heating system in University of Sydney’s Wilkinson building between December 1997 and May 1999 compared with estimates from a simulation model of a conventional AC system (Rowe, 2003).

#### 2.1.2.2. Occupant Satisfaction

In addition to the energy benefits of using natural ventilation in place of mechanical cooling, MM buildings have the potential to offer occupants higher degrees of control over their local thermal and ventilation conditions, and as a result, increase occupant satisfaction (Rowe, 2003; Hellwig et al., 2006; Brager et al., 2007). In an analysis of CBE web-based post-occupancy survey responses, Brager and Baker (2009) established that 8 out of 12 MM buildings (from a CBE database of 358 buildings) ranked in the top quartile in terms of thermal satisfaction, with two more in the upper third (as shown in Figure 2.5). Rowe (2003) also observed that occupants in MM spaces rated better levels of thermal comfort and occupant satisfaction. In their analysis of 177 POE studies within the UK, Leaman and Bordass (2007) also noted that MM buildings had more satisfied occupants than conventional AC buildings. Whilst many NV and MM buildings were perceived as hotter in summer and cooler in winter (Baird et al., 2012), occupants of these buildings were found to be more

forgiving of these conditions provided they could exercise control over their own thermal environment (Leaman and Bordass, 2007). These results were also consistent with the findings of a study in Australian MM buildings (Leaman et al., 2007).



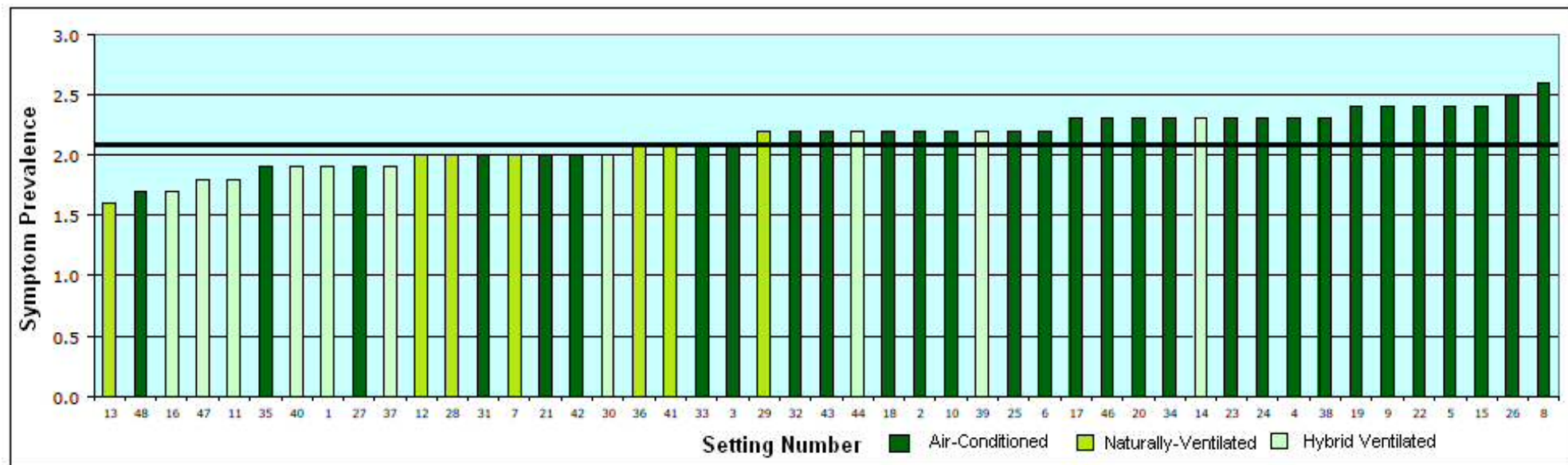
**Figure 2.5:** Cumulative frequency distribution for thermal satisfaction in mixed-mode buildings (n=12) compared to CBE database (n=358). Coloured symbols on the y-axis represent the median satisfaction score for each building set (Brager and Baker, 2009).

#### 2.1.2.3. Health, Productivity and Indoor Air Quality

Very few accurate studies have been conducted on the effects of hybrid ventilation on occupant health and productivity. However, many researchers believe that these spaces could increase worker performance, improve occupant health and potentially reduce problems associated with indoor air quality (IAQ) (Smith, 2008). Rowe (2003), in combining the ratings for SBS symptoms (Figure 2.6), showed that the mean prevalence scores for hybrid and NV settings are all at or below the whole population average. Similarly, Brager and Baker (2009) noticed that all but two MM buildings in their study fell in the upper quartile of air quality satisfaction. These results mirror what is already known about thermal comfort and

health within NV office buildings. In an extensive cross-sectional analysis, Seppanen and Fisk (2002) highlight that relative to NV buildings, AC buildings (with or without humidification) showed 30-200% higher incidences of SBS symptoms. Mendell's review (1993) of several large SBS field studies, reiterated these findings with SBS symptoms being significantly less prevalent in NV buildings.

Rowe (2003) also estimated an 18% improvement in self-assessed productivity in offices with MM conditioning, as compared to offices with mechanical air-conditioning. While it seems increased worker productivity in high air temperatures would be counter-intuitive, many argue that improvements to productivity in NV and MM buildings would be attributed to higher degrees of occupant control in such temperatures (Leaman, 1995; Leaman and Bordass, 1999; Boerstra, 2010; Frontczak et al., 2012). Carnegie Mellon University's Guidelines for High Performance Buildings (NSF/IUCRC, 2004) assessed the productivity benefits of NV and MM buildings from eight case studies. These guidelines state that replacement of supplemental mechanical ventilation with NV or MM conditioning systems achieved an average reduction in health costs of 1.1% annually (\$60 per employee) and that individual productivity was improved by an average of 8.5% annually (\$3900 per employee) for an average return on investment of at least 120% (NSF/IUCRC, 2004; Brager et al., 2007).



**Figure 2.6:** Comparison of prevalence scores for sick building syndrome symptoms from 40 office surveys. Population average symbolised by solid black line (modified from Rowe, 2003; Forwood and Rowe, 2006).



## **2.2. Thermal Comfort in Mixed-Mode Buildings**

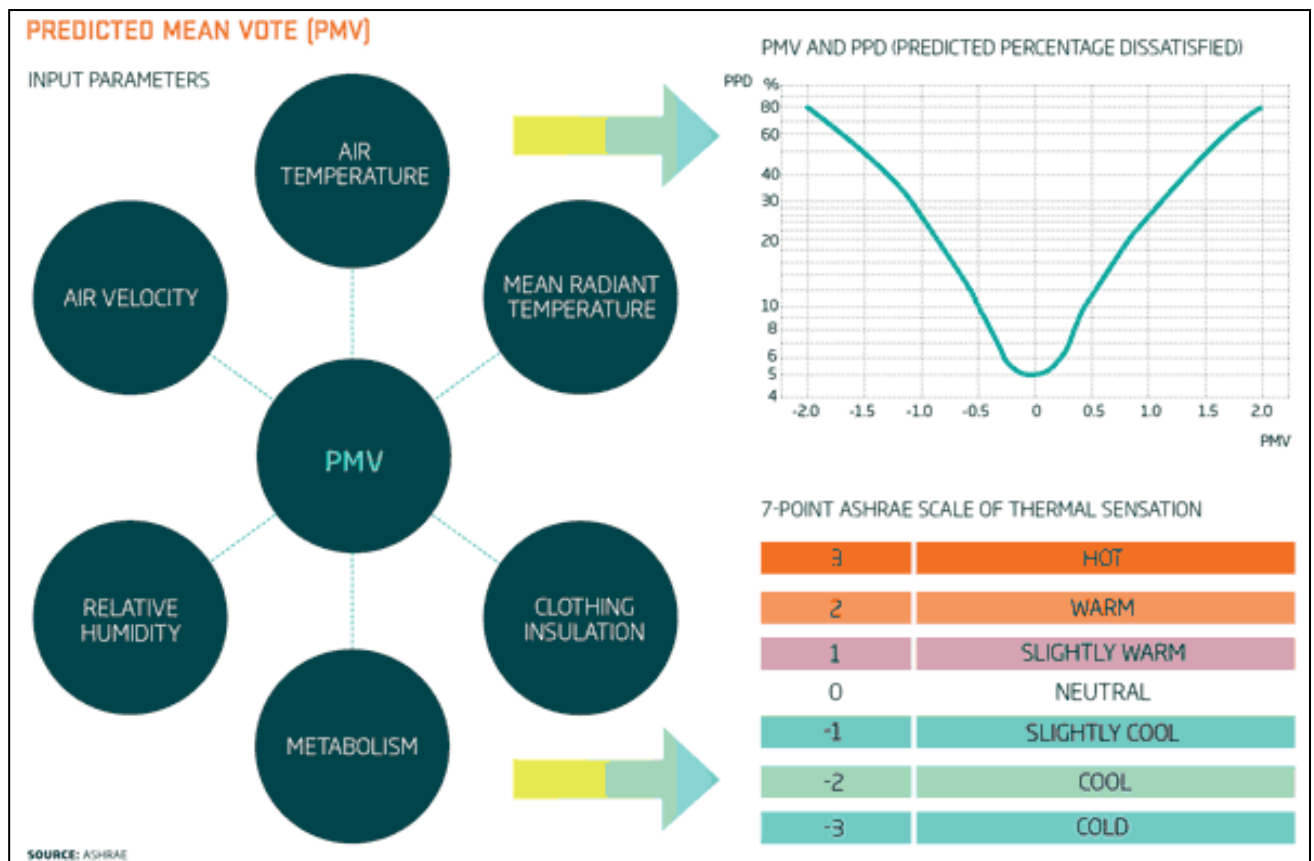
The ‘adaptive’ thermal comfort model (de Dear and Brager, 1998; Humphreys and Nicol, 1998; Nicol and Humphreys, 2002) advocates the shift towards variable indoor thermal environmental conditions in support of sustainable building design. However, despite an increasing interest in MM buildings, few thermal comfort field studies have been conducted. Topical debates on whether the adaptive comfort standard should be applied within buildings with MM spaces (Brager and de Dear, 2000; de Dear, 2004; Lomas et al., 2007; Turner, 2008), the problems of overheating given future changes in climate (Holmes and Hacker, 2007; Holmes and Hacker, 2008; Borgeson and Brager, 2011), and the use of occupant vs. automated control algorithms (Brager et al., 2007; Borgeson and Brager, 2008; Rijal et al., 2009) present key barriers in the uptake of MM ventilation and areas requiring further research.

### *2.2.1. Static vs. Adaptive Thermal Comfort*

It has often been assumed that another perceived benefit of MM buildings is enhanced thermal comfort of its occupants. Despite countless studies documenting the improved comfort conditions in NV buildings, as opposed to AC buildings, how occupants’ achieve thermal comfort, or how their comfort is affected, in a building that switches from AC to NV environments remains a key research question. Therefore, in order to understand how thermal comfort may be affected by MM ventilation, the concepts of both thermal comfort models/theories need to be discussed. Thermal comfort is defined as ‘a condition of the mind which expresses satisfaction with the thermal environment’ (ASHRAE, 2010). Povl Ole Fanger’s famous climate chamber studies of the 1960s and 1970s pioneered the conventional theory of thermal comfort, which has shaped international standards for HVAC systems ever since. In establishing the ideal environmental temperature at which people could maintain their internal body temperatures based on the human heat balance equation (thermal

neutrality), Fanger (1970) produced a 'comfort' equation indentifying six factors affecting thermal comfort: air temperature, radiant temperature, humidity, air speed, clothing insulation and metabolic rate (Olesen, 1982). Parsons (1993) agrees that the resultant model should be universally applicable, regardless of building type, climate zone or population, although the weight of empirical evidence disagrees (Busch, 1992; de Dear and Brager, 1998; Humphreys and Nicol, 1998).

The comfort equation led Fanger to develop the PMV and PPD indices (Fanger, 1970) (illustrated in Figure 2.7). The thermal sensation index (PMV) is a standard 7-point psychophysical rating scale for a large group of persons exposed to a given combination of thermal environmental factors, ranging from -3 (cold) to +3 (hot) with 0 as 'neutral' representing the most comfortable condition (Figure 2.7). The PPD index predicts what portion of a large group of persons will be uncomfortable with a particular set of environmental conditions. The relationship between these two indices is shown in Figure 2.7. Even in an ideal thermal situation, there will be a PPD of 5%, because it is impossible to satisfy an entire group of people in a single thermal environment (Fanger, 1973). This notion that one can determine (and maintain) an ideal, or 'static', temperature for most people within a controlled environment forms the basis of modern thermal comfort standards.



**Figure 2.7:** Fanger’s (1970) Predicted Mean Vote and Predicted Percentage Dissatisfied indices (sourced from Solomon, 2011).

This laboratory-based research, and the standards it subsequently spawned, established acceptable indoor temperature ranges much narrower than those that have been tolerated by human populations for millennia (Brager and de Dear, 1998). Furthermore, Nicol and Humphreys (2002) argue this ‘one-size-fits-all’ approach was unnecessary and unsustainable. As concern for IEQ and energy conservation grew towards the end of the 20th century, so did the interest among researchers and practitioners to re-examine the thermal comfort assumptions embedded in the current standards.

In contrast to the PMV-PPD model, adaptive thermal comfort theory assumes building occupants play an active role in creating their own thermal preferences (de Dear and Brager, 1998). In other words: “if a change occurs producing discomfort, people, if given the opportunity, will react in ways which tend to restore their comfort” (Humphreys and Nicol,

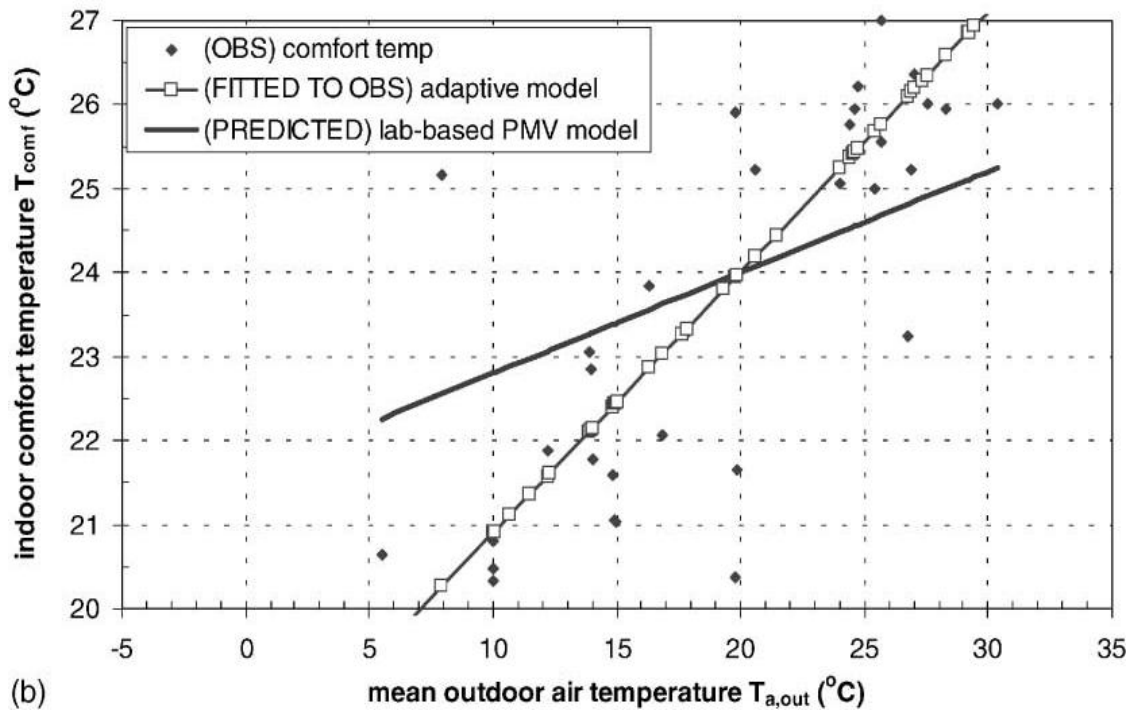
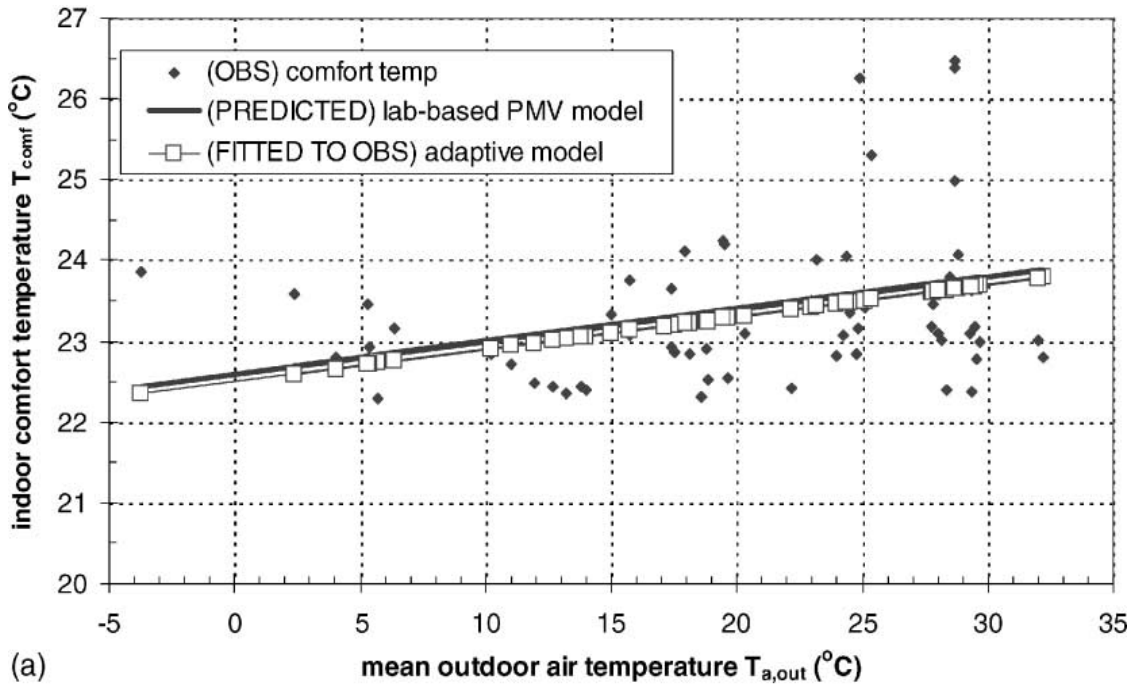
1998). According to Brager and de Dear (1998), this theory introduced three categories of adaptation: behavioural (e.g. adjustment of clothing, body movement, opening windows, adjusting thermostats, using fans, redirecting air, changing blinds), physiological (e.g. body's acclimatisation to long term exposure to thermally stressful environments) and psychological (e.g. complex combinations of contextual factors, past thermal experiences and expectations). Both de Dear (1994) and Humphreys (1995) argue that this adaptive, people-centred way of regarding thermal comfort suggests it would be advantageous to reformulate temperature standards for buildings to reflect the empirical relation between climate and thermal comfort, and make due allowance for human adaptability.

Building on the work of such predecessors as Humphreys (1978) and Auliciems (1981), de Dear and Brager (1998) studied standardised comfort survey data from over 160 office buildings in countries spanning four continents across a variety of climate zones, including Australia, Greece, Indonesia, North America, Pakistan, Thailand, and the UK. Buildings were categorised into those with centrally controlled HVAC systems, in which occupants have little to no control over their immediate thermal environment; and those that were NV with occupant-controlled operable windows and no mechanical air-conditioning.

de Dear and Brager (1998) explain two dominant patterns emerging from their data analysis (Figures 2.8a and 2.8b show the separate analyses for HVAC and NV buildings respectively). The observed responses (Y variable) represent each building's resultant 'comfort temperature'; calculated as the average indoor temperature within the building at which most occupants felt comfortable, i.e. thermal sensation was zero or 'neutral'. Firstly, the steeper gradient, i.e. greater climate sensitivity of observed responses ('comfort temperatures') in NV buildings (Figure 2.8b) compared to HVAC buildings (Figure 2.8a) suggests occupants of the latter (HVAC buildings) become more finely attuned to the narrow, constant conditions

typically provided by mechanical conditioning. In contrast, occupants of NV buildings prefer a wider range of conditions that more closely reflect outdoor climate patterns. Secondly, a comparison of the observed (labelled as OBS) and predicted (labelled as PMV) lines within each graph, clarifies the role of adaptation in these two building types (de Dear and Brager, 2002). In HVAC buildings, PMV was remarkably successful at predicting comfort temperatures, demonstrating that behavioural adjustments of clothing insulation and room air speed (both inputs to the PMV model) fully explained that relationship between indoor comfort temperature and outdoor climatic variations. In contrast, within NV buildings (Figure 2.8b), the difference between these PMV-based predictions and the adaptive model shows that such behavioural adjustment accounted for only half of the climatic dependence of comfort temperature. Upon further analysis, de Dear and Brager (1998) posit that indoor comfort temperatures within NV buildings are strongly influenced by shifting thermal expectations resulting from a combination of higher levels of perceived control, and a greater diversity of thermal experiences and expectation in such buildings, which are not among the six input parameters to Fanger's PMV-PPD model.

The work of de Dear and Brager (1998) firmly established that building occupants' adaptations to the broader outdoor climatic setting have a profound effect on their expectations of indoor climates (Fountain et al., 1996). It appears that thermal comfort is not only a function of standard variables recognised by the conventional theory (PMV-PPD), but is also affected by psychological variables ranging from people's expectations (due to outside conditions or cultural norms) to how much control they have over their immediate workspaces (by being able to open windows, adjust blinds, or even move to a different location). These adaptations, when acknowledged and understood by designers and engineers, can bring about major energy reductions in buildings (de Dear and Brager, 2002).



**Figure 2.8:** Observed (OBS) and predicted (PMV) indoor comfort temperatures from RP-884 database for **(a)** HVAC buildings and **(b)** NV buildings (de Dear and Brager, 2002).

### 2.2.2. International Comfort Standards

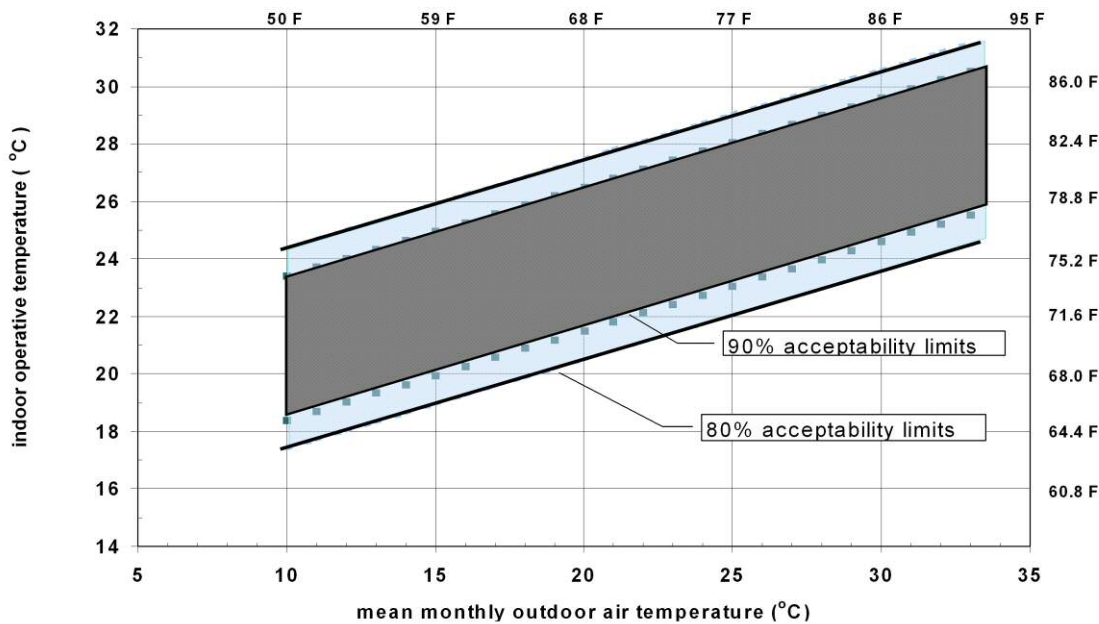
Existing international comfort standards, such as ASHRAE's Standard 55 '*Thermal environmental conditions for human occupancy*' (ASHRAE, 2010), the Comite Europeen de

Normalisation (CEN) Standard EN15251 '*Indoor environmental input parameters for design and assessment of energy performance of buildings: addressing indoor air quality, thermal environment, lighting and acoustics*' (CEN, 2007) and the International Organization for Standardization (ISO) Standard 7730 '*Moderate thermal environments – calculation of the PMV and PPD thermal comfort indices*' (ISO, 2005) specify combinations of temperature and humidity, indoor environments and personal factors that will be deemed acceptable to 80% or more of the occupants. Following the international standardisation of Fanger's (1970) PMV-PPD model of thermal comfort, subsequent comfort research has been polarised into the two fundamentally different approaches between the heat-balance and adaptive models. As Brager and de Dear (1998) explain, the former accounts for thermal comfort in terms of the microclimate immediately affecting the energy exchanges, i.e. heat balance of the subject, whereas adaptive models predict comfort from broad-scale, contextual factors. One context where these latter factors play a particularly important role is NV buildings (de Dear and Brager, 2002).

Dating back to the 1960s, earlier versions of these standards mainly cover thermal comfort under steady-state conditions based on laboratory experiments, such as the PMV-PPD model (Fanger, 1970), which is still featured prominently in the most current version of ASHRAE Standard 55 (ASHRAE, 2010). However, more recent revisions have utilised global field study databases, e.g. ASHRAE RP-884 (de Dear, 1998) and Smart Controls and Thermal Comfort (SCATs) (Nicol and Humphreys, 2010). This plethora of field data highlighted the inadequacy of 'static' models, like PMV-PPD, for describing thermal comfort in 'free-running' buildings (Busch, 1992; de Dear and Brager, 1998; Nicol and Humphreys, 2010).

These findings led to the inclusion of an adaptive comfort standard (ACS) (shown in Figure 2.9) in the 2004 edition of ASHRAE's Standard 55 (ASHRAE, 2004) to serve as an

alternative to the PMV-based method for NV or ‘free-running’ buildings, i.e. buildings with no mechanical heating or cooling (de Dear and Brager, 2002; Lomas et al., 2008; Turner, 2008; Nicol and Humphreys, 2010). However, at the time of ASHRAE 55-2004 going to press, insufficient comfort studies undertaken in MM buildings meant they were excluded from the scope of the ACS (de Dear and Brager, 2002).



**Figure 2.9:** The ASHRAE Standard 55-2010 adaptive comfort standard for NV buildings (ASHRAE, 2010).

Despite the most recent revisions to the standard (ASHRAE, 2010), the ACS is still constrained in scope to naturally conditioned, occupant-controlled spaces in which thermal comfort conditions are primarily regulated by operable windows. Furthermore, ASHRAE clarifies that when mechanical cooling systems are provided for the space, as is the case for MM buildings, the ACS is not applicable (Nicol and Humphreys, 2002; de Dear, 2004; Turner, 2008; Nicol and Humphreys, 2010). Thus, the potential flexibility offered by the standard is not available to hybrid buildings, which may operate in a passive, natural ventilation mode preferentially, equipped with only supplemental cooling/heating for peak periods; or to spaces where operable elements are not connected to the outdoors. As a result, such spaces or buildings fall within the scope of the more restrictive PMV-PPD method



(Baker and Standeven, 1996; de Dear and Brager, 2002; Nicol and Humphreys, 2002; Turner, 2008). This begs the question as to why MM buildings are precluded from applying the ACS in their NV mode of operation.

The inclusion of the ACS in ASHRAE 55-2004 was significant in mainstreaming NV buildings (van der Linden et al., 2006). In the years following the publication of ASHRAE's adaptive comfort model, a European counterpart named SCATs (McCartney and Nicol, 2002; Nicol and Humphreys, 2002; Nicol and Humphreys, 2010) replicated the exercise in a longitudinal design in which 26 offices located in European countries, e.g. France, Greece, Portugal, Sweden and the UK, were surveyed over approximately one year. Originally intended to develop a European adaptive comfort algorithm, the SCATs project was later used in the development of the adaptive comfort annex in the European standard EN15251 (McCartney and Nicol, 2002; CEN, 2007; Nicol and Humphreys, 2010). Unlike its American counterpart, EN15251 allows the more flexible ACS to be applied to NV buildings which can include MM buildings during times when they are not employing mechanical cooling, i.e. whilst in NV or 'free-running' mode. Currently, the International Standard ISO 7730 (ISO, 2005) has resisted the 'adaptive trend' altogether and makes no allowance for differences in NV and mechanically cooled or 'AC' buildings.

### *2.2.3. Thermal Comfort in Mixed-Mode Buildings: What Do We Know So Far?*

At the beginning of the 21<sup>st</sup> century, some preliminary research interest had been focussed upon the use of natural and hybrid ventilation solutions for low-energy comfort cooling. Under the auspices of the International Energy Agency's (IEAs) Implementing Agreement on Energy Conservation in Buildings and Community Systems, sixteen IEA countries participated from 1998 to 2002 in Annex 35: a research collaborative on *Hybrid Ventilation in New and Retrofitted Office Buildings* (HYBVENT) (IEA, 2006). The objective

of this project was to not only understand the purpose and use of hybrid ventilation systems, but to develop suitable control strategies and analysis methods for hybrid buildings. Pilot studies from countries such as Australia, Germany, Japan, Norway, the UK and the USA, helped HYBVENT designate a working definition of hybrid ventilation: systems that provide a comfortable internal environment using both natural ventilation and mechanical systems, but using different features of these systems at different times of the day or season of the year (i.e. mixed-mode) (Heiselberg, 2002). Underlying this definition were two chief concepts: firstly, the recognition that under suitable conditions, natural ventilation may be satisfactory, even preferable, for thermal comfort and IAQ, implying a potential decrease in the environmental impact of building operations; and secondly, the acknowledgement that supplementary mechanical systems, for fresh air distribution as well as climate control, may well be required during the harshest of conditions (Heiselberg, 2006).

The analysis of the ASHRAE RP-884 database in de Dear and Brager (1998) indicates that indoor temperatures falling outside ASHRAE's Standard 55-1992 comfort zones may, in fact, be quite acceptable, if not preferable, in NV or MM buildings (de Dear, 2004; Hellwig et al., 2006). While very few field studies have been conducted in MM buildings, those that have been done seem to agree with this statement. Findings from Karyono (2000) demonstrate that thermal comfort in a hybrid building can be as good as, if not better than, that of an AC or NV building. Over a 12 month monitoring period, the hybrid building allowed a greater proportion of occupants, i.e. 90%, to be thermally comfortable, which was higher than that measured in the AC and NV buildings (Karyono, 2000). From their analysis of neutral temperatures for buildings during free-running (or NV) mode, Humphreys et al. (2010) suggested no discomfort if the temperatures in a MM building were allowed to drift seasonally in NV mode according to the prevailing outdoor temperature, with cooling supplied over 28°C and heating below 18°C. However, they reiterate that these limits are

likely to vary depending on culture and climate (Nicol and Wilson, 2011). In principle, it is possible to design and operate buildings that provide comfort in the free-running mode at least within a range of prevailing mean outdoor temperatures from 10-30°C (Humphreys et al., 2010).

Similarly, Frank et al. (2007) found that the measurement of thermal comfort parameters within a MM building in Switzerland met the criteria for EN15251's category I band ( $PMV \pm 0.2$ ) for 86% of occupied hours. Despite the onset of a heatwave during the study period for 17 consecutive days, operative temperatures were still in the category I comfort range, reaching the upper limit of 26°C towards the end of the heat wave period. During the daytime, relative humidity was between 40-60% and between 60-80% during night-time due to temperature drops caused by the night cross-ventilation. From the few studies mentioned above, it is apparent that thermal comfort conditions can be provided by a low-energy building, including MM ventilation, provided the building has been correctly designed for the climate (Cron et al., 2002; Rowe, 2003; Fato et al., 2004). Furthermore, for buildings designed in accordance with acceptable temperature bands for NV mode, e.g. between 18-28°C, such thresholds would need to be adaptive and shift with future increases in outdoor temperatures, along with occupant adaptation to the indoor thermal environment.

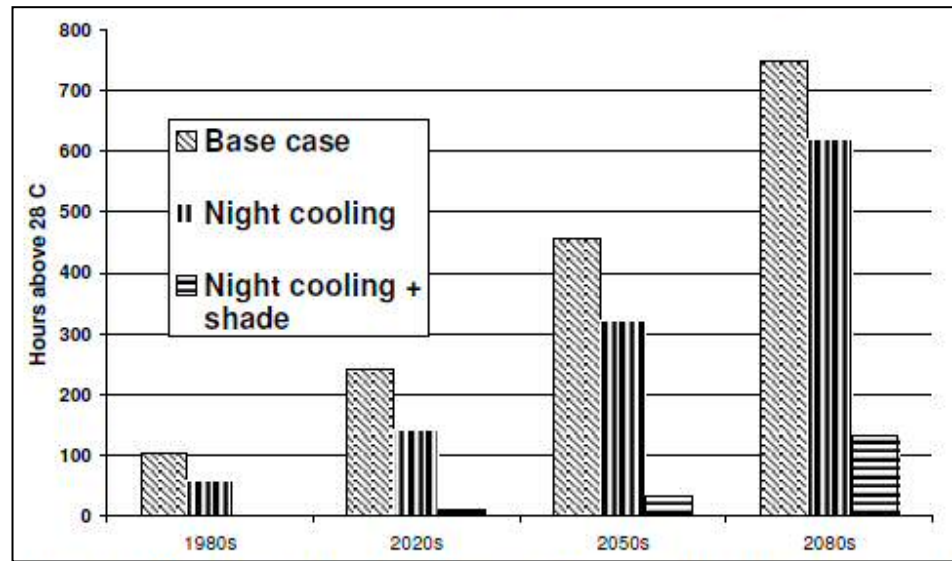
#### *2.2.4. Overheating*

While not directly relevant to this thesis, the issue of overheating in MM buildings presents major concerns given the likely increase in outdoor temperatures in the near future, and as such, should be discussed. Low-energy designs, in particular natural ventilation, by definition, tend to be more sensitive to changes in external climate conditions. Thus building engineers and designers express concern as to how such buildings will perform throughout their lifetime under extreme climatic conditions, and in turn, how this will impact occupant

comfort, e.g. the risks of overheating (CIBSE, 2005). When designing or assessing the performance of these buildings, it is important to have criteria by which overheating may be judged to have occurred. In order to address these issues, generated climatic data must be representative of the future, which, for all the intents and purposes of sustainable design, should also take into account climatic change (Holmes and Hacker, 2007). By using computer models of the global climate system based on different GHG emission scenarios, CIBSE (2005) presents several energy performance simulations in the UK for various different low-energy building designs, such as natural ventilation and MM cooling.

The underlying concept of low-energy design requires that internal heat gains in summer are minimised (Holmes and Hacker, 2007). Studies modelling different building types, comparing different control strategies to estimate the performance of MM ventilation systems for different climates (e.g. Cron et al., 2003; CIBSE, 2005; Holmes and Hacker, 2007; Coley and Kershaw, 2010; de Wilde and Tian, 2010; Roetzel et al., 2010) have highlighted an emerging focal point of many debates surrounding MM buildings, i.e. what is likely to happen to internal temperatures when outside temperatures continue to rise? Performance predictions for a MM office building (Figure 2.10) were based upon the number of ‘summer’ hours above the acceptable temperature predicted by the CIBSE adaptive method (CIBSE, 2005; Holmes and Hacker, 2007). The simulations were carried out with peak lopping cooling added to ensure peak temperatures do not exceed 28°C for more than 1% (or 20 occupied hours) in any one year. Clearly visible in Figure 2.10 is the increased number of days during which internal temperatures rise above the acceptable upper limit of NV mode (28°C). Under all scenarios, the frequency of overheating, i.e. hours above 28°C, are set to increase by 20% in each time slice. While additional low-energy cooling options can reduce these occurrences by 20-85% (Figure 2.10), Holmes and Hacker (2007) conclude, as

reiterated by de Wilde and Tian (2009), that the risk of overheating still presents a concern by the middle of the century.



**Figure 2.10:** Performance projections for a mixed-mode office under the effects of future climate change (Holmes and Hacker, 2007).

Experts relate the risks of overheating to people’s adaptive capabilities, assuming office occupants will need to adapt to changes in the climate over the next 40-50 years. Adaptive comfort theory (de Dear and Brager, 1998; Nicol and Humphreys, 2002) predicts that building occupants should gradually adapt to the temperatures that happen to occur in NV buildings in future climates. Many studies found that for buildings without mechanical cooling or heating, people can maintain thermal neutrality over a large interval of indoor temperatures (e.g. de Dear and Brager, 1998; de Dear and Brager, 2002; Nicol and Humphreys, 2002). This relationship explains that as the environmental conditions change, the occupants will, if possible, adapt to such changes. Occupants in MM buildings are likely to experience some degree of psychological adaptation, such as habituation and altering one’s perceptions of, or responses to, the thermal environment through thermal experiences and expectations. Physical adaptations can occur through changes to posture, clothing and activity level, and possibly by adjustment of, if applicable, shading devices, operable windows, etc. Physiological adaptation, such as acclimatisation, may also occur as people become more

attuned to the greater range of internal temperatures experienced throughout the building's lifetime (Brager and de Dear, 1998). As mentioned previously, the overheating threshold in MM buildings should also be responsive to changes in the prevailing outdoor conditions, i.e. adapt to changes in future climates (Nicol and Wilson, 2011).

In terms of overheating, and the subsequent risks of occupant heat stress, very few written sources offer guidance for MM buildings (CIBSE, 2000; Heiselberg, 2002; CIBSE, 2005). Despite the need, the current ASHRAE Standard 55-2010 offers little advice on comfort in MM buildings. The European standard EN15251-2007, on the other hand, has recently provided some exceedance calculations and recommendations on acceptance in its Annexes F and G (CEN, 2007). While these may not be definitive methods (Nicol and Wilson, 2011), Annex F on the '*Long term evaluation of the general thermal comfort conditions*' describes the following three exceedance metrics:

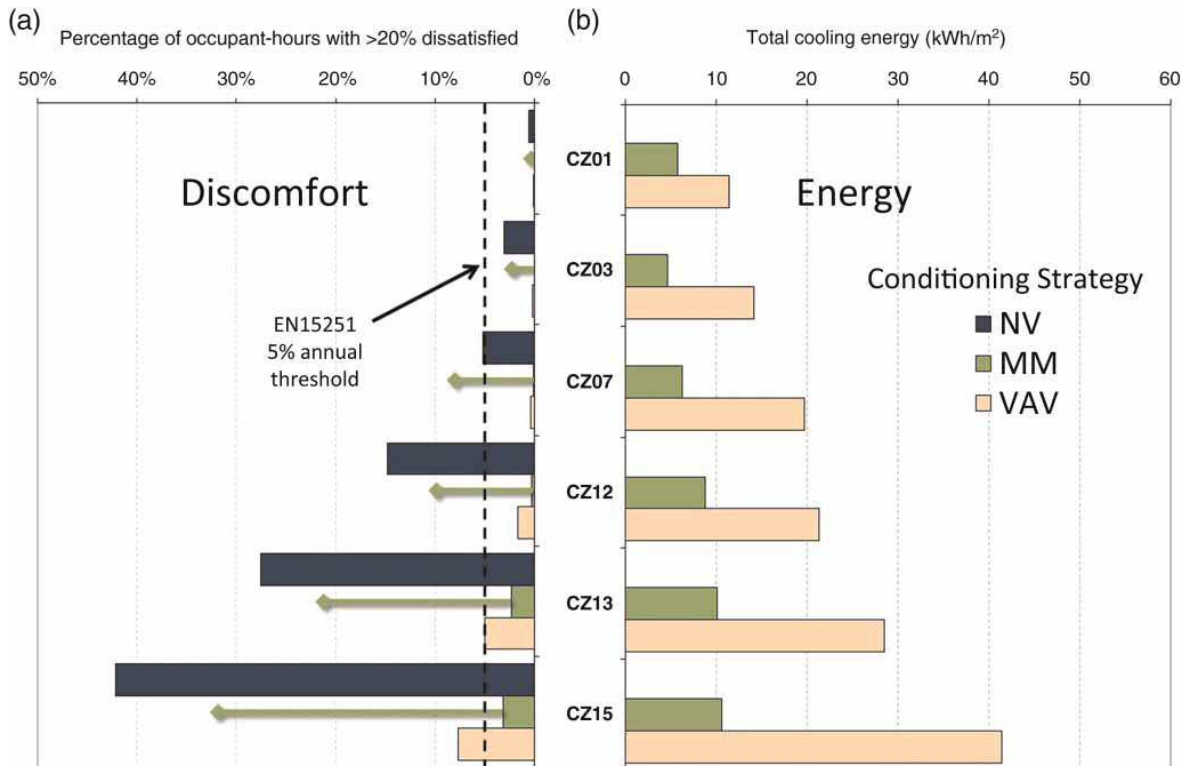
- **Percentage outside the range:** The percentage of occupied hours when the PMV of the operative temperature is outside a specified range.
- **Degree-hours criteria:** The time during which the actual operative temperature exceeds the specified comfort range during occupied hours, weighted by a factor based on the number of degrees beyond the range.
- **PPD weighted criteria:** The accumulated time outside the range, weighted by PPD.

Olesen (2007) explains that since the criteria are based on instantaneous values, values outside the recommended range should be acceptable for short periods during a day. EN15251 therefore recommends an arbitrary rule of thumb for acceptable 'length of deviation' exceedance values in buildings; 3-5% of occupied time (occupied working hours) (Olesen, 2007). Although the standard has broken new ground with the inclusion of exceedance criteria, it is unclear whether or how the 3-5% of occupied working hours rule

should be applied to the weighted calculations (Borgeson and Brager, 2011). Based on this knowledge and a selection of previous work modelling MM and radiant systems, Borgeson and Brager (2011) developed their own exceedance criteria, i.e. the percentage of occupied hours where conditions exceed the 20% dissatisfied threshold, weighted by the time varying occupancy and expressed in percentage of occupied working hours. EnergyPlus models were used to simulate a range of parametric studies to investigate the potential tradeoffs between comfort and energy use in the context of varying climate conditions combined with a range of passive performance attributes and internal gains.

Figure 2.11 depicts the percentage exceedance and cooling energy intensity metrics for NV, MM and mechanical ventilation (labelled as VAV) cooling strategies across six climate zones in California (from coastal Mediterranean climates in the north, to moderately sub-tropical climates along the southern coast, and more continental and semi-arid climates inland). Apart from demonstrating the reduced energy consumption of MM ventilation compared to mechanical ventilation, Figure 2.11 illustrates the sensitivity of the comfort results to both the conditioning strategy and comfort model being applied in the MM scenario. The NV option alone was sufficient for maintaining comfort exceedance near or below 5% in the milder climates (3 of the 6 representative climate zones) suggesting some form of supplemental cooling would be required for the other climates. Assuming the ASHRAE Standard 55 ACS applies, the analysis shows that the MM strategy would imply acceptable comfort conditions (less than 5% exceedance) in all six climate zones (Borgeson and Brager, 2011). However, using the PPD metric, MM buildings could only bring exceedance below 5% in two of the six climate zones. Borgeson and Brager (2011) highlight that the choice of comfort metric used in a MM building significantly changes the level of exceedance in this scenario. Furthermore, these findings reveal that even under the most extreme climate zone, the sealed building with

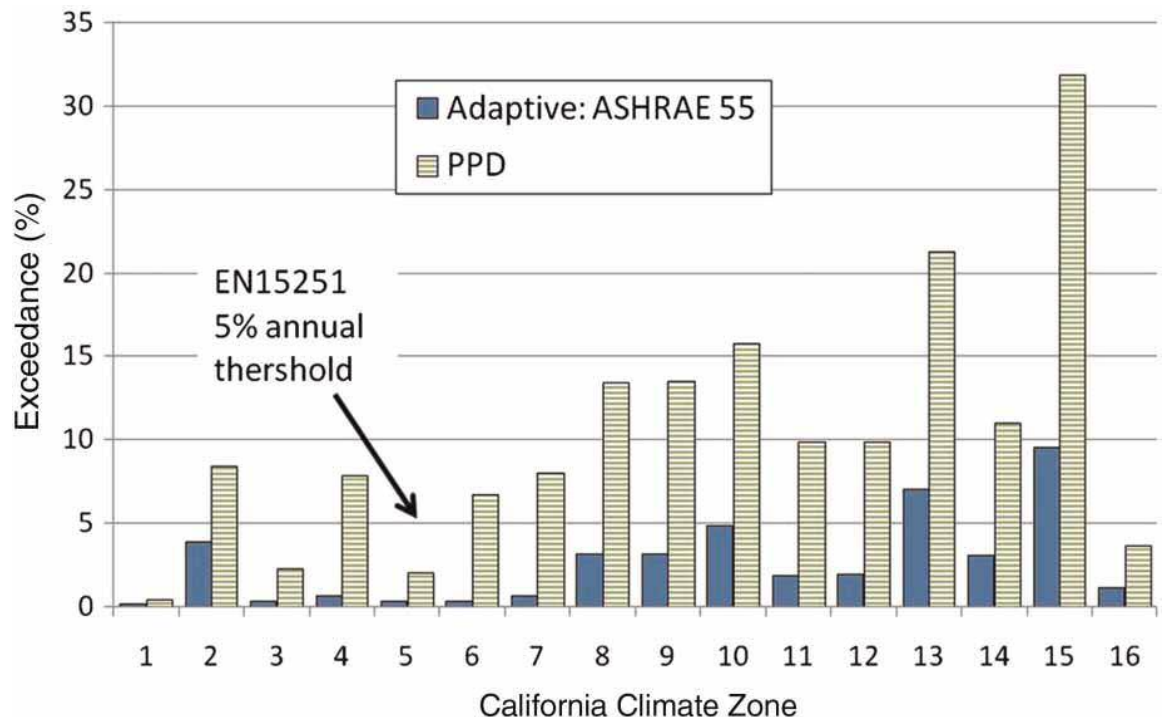
a mechanical ventilation system had difficulty maintaining comfort levels within acceptable exceedance limits, which would require significant amounts of energy.



**Figure 2.11:** Simulation results displaying the trade-offs between **(a)** comfort and **(b)** energy consumption for naturally-ventilated (NV), mixed-mode (MM) and mechanical ventilation (labelled as VAV) cooling strategies. For the mixed-mode case, comfort exceedance predictions are bracketed using both the ASHRAE 55 adaptive model (base bar) and the PPD model (line extension) (Borgeson and Brager, 2011).

Figure 2.12 summarises the effect of climate on this sensitivity, comparing predicted exceedance from applying the ASHRAE 55 adaptive comfort model vs. PPD for the MM case with baseline gains in every climate zone in California. The magnitude of the gap between the two metrics is significant in most climates. In using adaptive comfort standards, exceedance is less than 5% (as recommended in Annex G of EN15251) in 14 climate zones. PPD, however, predicts exceedance below this 5% threshold in only four. This analysis underscores the need to better understand how comfort models apply to MM buildings. All too often the choice of the model will make the difference between whether one predicts thermal success or failure.





**Figure 2.12:** Exceedance predictions in the mixed-mode scenario with baseline gains using the ASHRAE 55 adaptive comfort model and the PPD model across all 16 climate zones in California (Borgeson and Brager, 2011).

Borgeson and Brager (2011) conclude that their study correlated well with received wisdom and observed success of NV and MM buildings in California, especially in terms of climate sensitivity. Temperate coastal climates allowed MM configurations to deliver low exceedance values, and warmer climates were predicted to have higher exceedance values. The study confirms that predicting comfort using exceedance metrics is highly sensitive to variations in shell quality, internal gains, insulation, but also which comfort model is used to set the exceedance threshold. Furthermore, it is clear from the diversity of definitions in circulation that there is no consensus on how to best define or apply exceedance metrics, especially on whether such thresholds should be ‘static’ or ‘adaptive’.

#### 2.2.5. Personal vs. Automated Control

The success of any NV or MM building design is also greatly dependent on the extent to which it accommodates occupant behaviour (Nicol and Humphreys, 2004). To date, no standard protocols exist for control strategies in MM buildings, nor is there consensus about

the optimum ratio between degrees of personal vs. automated controls. As Brager (2006) clarifies, the ultimate objective is to optimise both comfort and energy efficiency. Whilst numerous control algorithms for hybrid ventilation buildings have been proposed in recent years (CIBSE, 2000; IEA, 2006; Brager et al., 2007), they typically consist of a discomfort threshold temperature at which the transition from natural to mechanical mode is ‘triggered’ (Arnold, 1997; McCartney and Nicol, 2002; CIBSE, 2005).

What is often overlooked in this ‘trigger temperature’ approach of MM switch-over is the fundamental concept of the adaptive thermal comfort model; that the discomfort threshold is not a constant, but rather a function of recent outdoor weather and seasonal temperature trends (Zhang and Barrett, 2012). In other words, people are tolerant of warmer indoor temperatures after a spell of hot weather and cooler indoor temperatures are more acceptable in cold weather (Brager and de Dear, 1998; de Dear and Brager, 2002). However, there are issues regarding whether windows and vents are automated, or the establishment of thermostat set-points that determine when mechanical heating/cooling will turn on, or whether there are override controls for the HVAC system (Borgeson and Brager, 2008; Rijal et al., 2009; Ackerly et al., 2011).

#### 2.2.5.1. Personal Control

Adaptive comfort theory posits that greater personal control allows occupants to fine-tune their thermal environment to match their own personal preferences; creating a wider acceptable range of temperatures in the building (de Dear and Brager, 1998; Humphreys and Nicol, 1998; Brager et al., 2004). A typical approach to adaptive comfort is to use simpler, manual controls that depend on educating occupants to operate the building efficiently and in response to their own comfort needs (Karjalainen and Koistinen, 2007). Eschewing automation is unlikely to optimise energy performance, however, it is more than likely to

create much higher levels of occupant satisfaction within the building (Bordass et al., 1993; Leaman and Bordass, 2007; Brager and Baker, 2009). Additionally, Leaman and Bordass (1999) have observed that occupants are more forgiving of discomfort if they have access to effective remediation strategies. Extending from his research on adaptive comfort, de Dear (2004) notes that people who know they do not have control over their air-conditioning temperature at work have the expectation that their thermal comfort will be automatically achieved at a constant level. On the other hand, occupants of NV buildings know that the indoor climate will be more variable and that they need to be more actively engaged in making their indoor environment pleasant (Leaman and Bordass, 1999; de Dear, 2004).

Occupants of a NV office building who had more control over the environmental conditions of their workspace had a higher neutral temperature (warmer by a statistically significant 1.5°C over summer) than those with little or no control (Brager et al., 2004). Given the two groups were broadly exposed to the same average thermal conditions, with similar clothing insulation and metabolic rates, the group with more control shifted their neutrality closer to their average thermal exposure. This finding confirms the hypothesis that subjects with greater access to control are more tolerant of, and in fact may prefer conditions that deviate from the centre of the comfort zone. The corollary of this is that people who have limited or no control over their office environment, as witnessed in countless thermal comfort studies in AC offices, tend to be less tolerant of sub-optimal thermal environmental conditions (Brager et al., 2004; Leaman and Bordass, 2007).

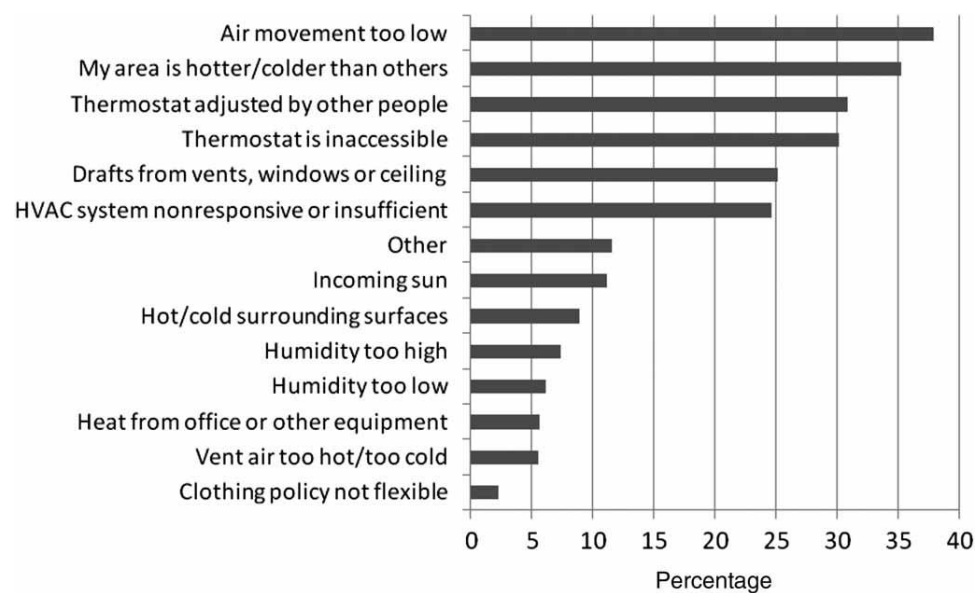
Building users place great emphasis upon the ability to manually control their indoor environment (Rowe, 2003; Rijal et al., 2009), especially during uncomfortable situations (Leaman and Bordass, 2001). The control of windows is often regarded as the most preferred adaptive opportunity (Baker and Standeven, 1996; Barlow and Fiala, 2007; Zhang and

Barrett, 2012). Studies in the UK reveal occupants tend to use their controls, such as windows, more often if they perceive to have greater degrees of control are available to them (Rijal et al., 2007; Yun et al., 2008; Rijal et al., 2012). A study in Finland showed that most occupants changed their clothing (dress less/more) in response to thermal discomfort, but using their window was quite popular (Karjalainen and Koistinen, 2007).

Rijal et al. (2009) found that in summer people opened their windows to decrease the indoor air temperature and to increase the air movement. The time taken for the cool external air to mix with the warm indoor air and cool it enough for comfort to occur was also found to influence how long occupants left their windows open. Occupants tended to leave windows open until they felt cold, corresponding with a drop of approximately 4°C in indoor air temperature (Rijal et al., 2007). However, studies argue the interaction of occupants with adaptive controls is more related to the external rather than the internal environment (e.g. Raja et al., 2001; Haldi and Robinson, 2008; Herkel et al., 2008; Rijal et al., 2012). Based on a study in the UK, Raja et al. (2001) showed that very few windows were opened during the cooler Autumn and Winter months when external temperatures were below 15°C. In contrast, when the outdoor temperature was above 25°C (from Spring to Summer), almost all windows were open.

Research into the effects of personal control over environmental conditions suggests that productivity and health improve when people have more control (e.g. Bordass et al., 1993; Leaman and Bordass, 2001; Leaman and Bordass, 2007; Brager and Baker, 2009; Brown et al., 2010; Steemers and Manchanda, 2010). Nevertheless, results from a study in Finland suggests even when controls are made available in offices, occupants often do not know how to operate the them, or the controls are not readily accessible, or the occupants feel the heating/cooling system does not respond quickly enough (Karjalainen and Koistinen, 2007).

Based on a field study in MM buildings in the US, Figure 2.13 reiterates the main causes for dissatisfaction with the indoor environment are related to lack of control (Brager and Baker, 2009). Guidance on MM controls (CIBSE, 2000; Bordass et al., 2007) specify that occupants must be aware of the building control concepts as a pre-requisite to their effective operation. CIBSE (2000) goes on to state that making control systems legible might mean adopting a ‘standard’ control solution unless there are over-riding benefits in adopting an innovative approach. More recently, Brown and Cole (2009) commented that contemporary green buildings seldom communicate how building systems function, and that occupants become passive when they lack knowledge and positive feedback on the use of environmental controls (Brown and Cole, 2009; Brown et al., 2009).



**Figure 2.13:** Reasons for thermal dissatisfaction in mixed-mode buildings in the US (Brager and Baker, 2009).

The manual natural ventilation control referred to in CIBSE (2005) assumes that occupants would begin to open windows when space temperatures reached a threshold (22°C) and then continually open windows further, becoming fully open by a temperature limit (28°C). This solution, however, can be problematic if the occupants have not been pre-exposed to the thermally demanding conditions occurring within NV buildings. Within the context of MM buildings in Sydney, Rowe (2003) deduced that a majority of occupants surveyed (n = 1550)

applied passive control methods preferentially; the supplementary mechanical system was left in the off mode until passive means of control were exhausted. However, it is still uncertain whether occupants generally prefer narrow temperature ranges, e.g. 22-25°C, and systematically opt for mechanical cooling, while others readily welcome the wider temperature swings of NV environments (Rowe, 2003; Bourgeois, 2005).

#### 2.2.5.2. Automated Control

Drawing on the fundamentals of ergonomic design, Fanger (1970) contends that the machine (building) should be adapted to the human, and not vice versa - that buildings can be adjusted to serve people: buildings are merely the servant and occupants the master. Fanger's ergonomic principle does not facilitate energy conservation. The adaptive model, on the other hand, relies on the principle that occupants can adapt to the building (de Dear and Brager, 1998; Nicol and Humphreys, 2002). The sophisticated integration of HVAC and building fenestration systems, window sensors, actuators, and control algorithms that respond to indoor and outdoor climatic conditions, can be employed to optimise both energy and comfort (Brager, 2006; Brager et al., 2007). These highly engineered solutions make building behaviour more predictable and are well suited to energy optimisation (Heiselberg, 1999). However, as one moves towards a fully automated central control system, there is the concomitant loss of adaptive opportunities (Brager et al., 2000; Ackerly et al., 2011).

Typical automatic control strategies assume that ventilation openings have mechanical dampers to control ventilation areas (window openings) using a central building management system (CIBSE, 2005; IEA, 2006). However, it is difficult to find an acceptable window automation strategy that satisfies all occupants. CIBSE (2005) describes a typical algorithm for automatic natural ventilation controls:

- *IF space is occupied AND air temperature is between 18-22.5°C, THEN modulate the ventilation area to obtain a specified minimum ventilation rate*
- *IF space air temperature is greater than 22.5°C AND lower than outside temperature, THEN maintain the ventilation controls above*
- *IF space air temperature is greater than 22.5°C AND higher than outside air temperature, THEN fully open the dampers to maximise ventilation*
- *IF a space is unoccupied and air temperature is less than 18°C, THEN start to close vents. This prevents overcooling of the space during night cooling.*

The research literature identifies window automation as best suited in multi-occupant open-plan offices or meeting rooms, and outside occupied hours during night-purge cycles (Brager, 2006; IEA, 2006; Brager et al., 2007). In contrast, if windows are operated automatically during occupied hours, and external temperatures are lower than internal temperatures, there is a heightened risk of user dissatisfaction due to the sensation of draught (Heiselberg, 2006). Therefore, it is important that occupants have the opportunity to override the control for openings in the vicinity of their workstation (Borgeson and Brager, 2008). Automatic solar shading control may also prove beneficial as it ensures action as soon as indoor temperatures begin to increase (Johansson, 2009). But still, there are no current standards in relation to how much or how little automated control is appropriate for MM buildings (El Mankibi and Michel, 2009).

Buildings today are still mostly constructed with centralised mechanical and electrical control, typically designed for the range and not the mean (Bordass, 1990). Air-conditioning set points are usually viewed as universal settings rather than adjusted to the building or its users (Fountain et al., 1996; Brager and de Dear, 1998). Research into the adaptive comfort model would encourage management with central control to have a greater connection with

the users so they had more local control. This, in turn, would enhance occupant satisfaction and productivity (Leaman and Bordass, 1993). Leaman and Bordass (1999) suggest the absence of effective control adjustments to the indoor climate of a building, especially in generic space planned offices, makes the difference between acceptable comfort and dissatisfaction. In addition, Bordass (1990) advises the need for more appropriate, not necessarily more advanced, technology. Buildings with complex energy management systems don't run themselves: they need considerable effort at the design stage to make them user-friendly, care during installation and at handover, careful training, and constant vigilance during operation (Ackerly et al., 2011). After all, they are a management tool and not a fit-and-forget item (Bordass et al., 1993).

Appropriate measurement and control of significant indoor environment factors are crucial if technical installations in buildings are to meet the requirements for a healthy, comfortable and productive indoor environment (Clements-Croome, 2008; Toftum, 2010). Inexpensive sensors can be widely distributed in IEQ intelligence networks, allowing HVAC control systems to monitor and respond to very detailed input. This development may also promote new strategies and algorithms for HVAC component control (Toftum, 2010). To better accommodate occupants' needs and give greater satisfaction, such algorithms should provide a rapid response to the indoor environment (Bordass et al., 1993; Bordass et al., 2007). As sensor and control technology advances and becomes more complex, the user's control opportunities may decrease accordingly. Leaman and Bordass (2001) conclude that it is a mistake to allow automation to remove occupants completely from the control loop.

Even if we accept the adaptive principle that occupants should have the maximum possibility of controlling their own environment, automatic control is still required to support the users in achieving a comfortable indoor climate and to take over during non-occupied hours. In



rooms for several people (e.g. open-plan offices) and in rooms occupied by different people (e.g. meeting rooms), a higher degree of automation is appropriate (Brager et al., 2000). It is also very important to carefully consider how user interaction is integrated within the control system, both with regard to the type of functions that can be overruled and how and when the automatic control regains control after being overruled by the occupant (Brager et al., 2007). For systems with presence detection, the automatic control system usually takes over when the occupants leave the room (Mahdavi and Kumar, 1996). For other systems, it can take over after the normal occupant period has ended or after a certain time period, which can be adjusted as a part of the commissioning of the hybrid ventilation system (CIBSE, 2000; Aggerholm, 2002). The Post-occupancy Review of Buildings and their Engineering (PROBE) studies in the UK (Leaman and Bordass, 2001) highlight both the success and failure of combining automatic and manual control solutions within MM buildings. Findings suggest that buildings with more automated and complex natural ventilation control solutions require tighter management to ensure performance. However, they cite the following common shortcomings of automated window controls (Cohen et al., 1998):

- Draughts from windows opened to remove heat on sunny but cool days
- The inability to close windows which were letting in fumes, noise or insects
- The denial to occupants of the opportunity to trade off different types of discomfort (noise versus overheating).

### **2.3. Post-Occupancy Evaluation**

Buildings are primarily designed and built for their intended occupants, but in many cases this is done without much consideration of the building's end-users' needs or preferences (Vischer, 2001; Way and Bordass, 2005). As a result, many occupants do not understand how to operate their building which can often lead to high levels of discontent (Leaman and Bordass, 2007). As building managers and designers continually strive to

improve occupant satisfaction and productivity by ensuring comfortable and healthy working conditions, POE represents a systematic quality assurance process towards these ends.

POE is a global and rather general term for a variety of types of field studies in built environments based on assessing the responses, behaviour and perceptions of a building's occupants. In the past, POEs have been viewed as a means to measure the performance of a building from the occupant's perspective in a systematic and rigorous manner after they were built and occupied for some time (Preiser et al., 1988; Preiser, 2001a; BCO, 2007). Used extensively worldwide, POE studies aim to investigate whether buildings are performing as intended/designed. In effect, they provide 'feedback' to the architects and building managers on potential areas for improvement (Vischer, 2004; Bordass and Leaman, 2005b). They are often targeted towards the users' perception of the building rather than actual building performance metrics, such as energy consumption, temperature and humidity, lighting, noise, etc (Zimring and Reizenstein, 1980; Hartkopf et al., 1986; Preiser, 1995; Derbyshire, 2001; Nicol and Roaf, 2005).

### *2.3.1. Post-Occupancy Evaluation: An Evolutionary Background*

Before we can effectively critique POE methods it is instructive to review the context in which they were originally developed. Up until the 1950s, systematic information on building performance from the occupants' perspective was not easily accessible. Following the rapid expansion of architectural projects in the UK in the 1960s, the Royal Institute of British Architects (RIBA, 1962) identified the need to gather and disseminate information and experience on the requirements of building users. The RIBA called for the study of buildings in use, from both the technical and cost points of view, as well as in terms of design (RIBA, 1962; Cooper, 2001; Derbyshire, 2001). The RIBA's Handbook of Architectural Practice and Management (RIBA, 1965) was instrumental in defining the sequence of stages

related to building construction, including briefing/programming, design, specification, tendering, completion and use (Cooper, 2001; Preiser and Vischer, 2005; Preiser and Nasar, 2008). This report also incorporated a final stage to the building life-cycle called 'feedback'. Within this stage, architects were advised to inspect their completed buildings after they had been built as a means of improving service for future clients (Preiser, 2001b; Bordass and Leaman, 2005a). Thus, the concept of 'POE' was born from this need to provide feedback to building managers on the performance of their building after completion (Derbyshire, 2001; BCO, 2007). Despite RIBA's best efforts, POE was largely ignored by the design and construction industry in the UK because of its potential to deliver evidence to clients about under-performance or just plain building design (Cooper, 2001; Hadjri and Crozier, 2009). Following the large number of housing studies in the 1970s and 1980s in the USA, POE has steadily gained credibility as a mechanism of scientific inquiry for user satisfaction within buildings (Preiser, 1995; Vischer, 2001; Bordass and Leaman, 2005a). However, it wasn't until the 1990s that the UK construction industry realised the true potential and value of POE as a significant development in architectural research (Cooper, 2001).

Over the past 30 years, numerous adaptations and improvements have been made to POE methods (Preiser and Vischer, 2005). The term POE was originally intended to reflect that assessment taking place after the client had taken occupancy of a building (Preiser, 2001a; Zimring and Rosenheck, 2001). Early descriptions focused on POE as a stand-alone practice aimed at understanding a building from the users' perspective (Preiser, 2001a; Bordass and Leaman, 2005a; Preiser and Vischer, 2005), and often included aspects of architectural design, technical performance, indoor climate, occupant satisfaction and environmental impact (Zimring and Reizenstein, 1980; Hartkopf et al., 1985; Vischer and Fischer, 2005; Loftness et al., 2006; Gonchar, 2008). POEs are generally classified into three main types, as identified in Preiser et al., (1988): (1) Indicative POEs involve walk-through observations as

well as selected interviews which typically raise awareness of the major strengths and weaknesses of a particular building's performance; (2) Investigative POEs carry out more in-depth evaluations and often comply with particular building performance standards or guidelines on a given building type. One of the most commonly found type of POEs, these provide a thorough understanding of the causes and effects of issues in building performance; and (3) Diagnostic POEs provide very detailed information about the buildings performance. These evaluations gather physical environmental data which are then correlated with subjective occupant responses (Preiser et al., 1988; Preiser, 2001a). However, more recent applications of POEs, especially in office buildings, fail to recognize the limitations of POE studies. Despite more recent POE discussions having emphasized the need for a more holistic and process-oriented approach to evaluating building performance (Preiser, 2001a; Vischer, 2001; Preiser and Vischer, 2005; Vischer, 2008a; Meir et al., 2009), such notions are yet to be transformed into practice.

### *2.3.2. Uses and Misuses of Post-Occupancy Evaluation in Buildings*

Over the past four decades, POE has become a widely used tool in evaluating building performance (Preiser et al., 1988; Preiser, 1995; Riley et al., 2009). Since the early studies on the housing needs of disadvantaged groups in the 1970s (Bechtel and Srivastava, 1978; Vischer, 1985), POEs have broadened their scope to applications in various other building types, such as, healthcare facilities (McLaughlin, 1975; Cooper et al., 1991; Carthey, 2006; Leung et al., 2012), residential buildings (e.g. CABE, 2007; Gupta and Chandiwalla, 2010; Stevenson and Leaman, 2010), educational buildings (e.g. Baird, 2005; Watson, 2005; Loftness et al., 2006; Turpin-Brooks and Viccars, 2006; Riley et al., 2010; Zhang and Barrett, 2010), and commercial/office buildings (e.g. Leaman and Bordass, 1999; Leaman and Bordass, 2001; Zagreus et al., 2004; Bordass and Leaman, 2005c; Vischer, 2005; Abbaszadeh et al., 2006; Leaman and Bordass, 2007; Leaman et al., 2007). Apart from providing

designers with feedback, numerous researchers (e.g. Preiser, 2001b; Vischer, 2001; Whyte and Gann, 2001; Bordass and Leaman, 2005a; Loftness et al., 2006; Turpin-Brooks and Viccars, 2006; Preiser and Nasar, 2008; Hadjri and Crozier, 2009; Loftness et al., 2009; Riley et al., 2010) suggest a number of other plausible benefits of POE, including: (1) improving commissioning process; (2) definition of user requirements; (3) improving management procedures; (4) providing knowledge for design guides and regulatory processes; and (5) targeting of refurbishment.

Notwithstanding these benefits, many barriers to conducting POEs have also been identified (Cooper, 2001; Vischer, 2001; Zimmerman and Martin, 2001; Zimring and Rosenheck, 2001). The extensive discussion of these problems suggests a growing frustration with the lack of progress towards POE becoming a mainstream activity in the process of building procurement (Hadjri and Crozier, 2009; Meir et al., 2009). The more commonly identified barriers to the widespread adoption of POE include cost, fragmented incentives and benefits within the procurement and operation processes, potential liability for designers, engineers, builders, and owners, lack of agreed and reliable indicators, time and skills (Bordass et al., 2001a; Cooper, 2001; Vischer, 2001; Zimmerman and Martin, 2001). Moreover, Zimmerman and Martin (2001) suggest that standard practice in the facility delivery process does not recognise the concept of continual improvement or any ongoing involvement on the part of the designers. Despite one of the primary goals for conducting POEs is to enable designers to revisit their designs, improve their skills and produce more efficient buildings, the idea of continual improvement via feedback has lacked emphasis in both the North American and UK contexts (Derbyshire, 2001; Preiser, 2001b; Preiser and Vischer, 2005). Whilst many agree with these barriers, there are still some challenges in the use of contemporary POE methods (Preiser and Vischer, 2005), especially in commercial office buildings. From the literature, three key issues in the POE method have been identified: ‘lack of context’; ‘lack of

feedback’ and the ‘lack of instrumental data’ (Hartkopf et al., 1986; Vischer, 2001; Jarvis, 2009; Loftness et al., 2009). It should be noted that the following issues are predominantly focused on POE studies conducted in office buildings.

#### 2.3.2.1. Lack of Context:

Traditionally, POE has been viewed as a final, one-off process as the term ‘post’ reflects only that time after a building was completed (Bordass and Leaman, 2005a; Preiser and Vischer, 2005). Yet, POE is not the end phase of a building project; rather it is an integral part of the building delivery process (Federal Facilities Council, 2001; Preiser, 2001b; Vischer, 2001). The technique should be used more regularly to ensure buildings continue to deliver at their intended design specifications and, in return, appropriate levels of satisfaction among the end-users (Preiser, 2001b; Preiser and Nasar, 2008; Vischer, 2008a; Riley et al., 2010). Much literature suggests POE should be cyclical in nature rather than simply providing a final feedback component in the occupancy phase (e.g. Preiser, 1995; Bordass et al., 2001a; Cohen et al., 2001; Vischer, 2001).

POE practice has mainly focused on assessing specific cases (Federal Facilities Council, 2001; Turpin-Brooks and Viccars, 2006). Even when evaluators have been able to create databases of findings, they have often been used to benchmark single cases rather than to develop more general conclusions (Zimring and Rosenheck, 2001; Baird, 2011a). POE studies involving office buildings often lack the contextual information in which the building was built and occupied. Prior to moving into their new building or space, occupants could already harbour distrust of management (Vischer, 2001; Vischer and Fischer, 2005; Vischer, 2008b). Workers may also have high expectations that are not met when balanced against the possible constraints of an existing building that limits the creation of effective workspace (Schwede et al., 2008). Ultimately, the uncertainty generated by moving to a new building or

space affects employee's perception of their environment (Vischer, 2005; Vischer and Fischer, 2005). If left unresolved, these attitudes and predispositions are likely to carry forward into the new workspace. As such, the actual impact a building has on its users remains unaccounted for in the analysis and interpretation of the results. Many discussions have risen for the evaluation of a building prior to occupation (Federal Facilities Council, 2001; Preiser and Vischer, 2005). Leaman et al., (2010) suggest that building performance studies should seek and reveal the context behind the building, i.e. occupants' personal history and attitudes towards the building. These psychosocial factors play an important role in determining people's concerns with their environment (Vischer, 1986; Chigot, 2005; Vischer and Fischer, 2005; Turpin-Brooks and Viccars, 2006) and may well affect their perception of the building. Furthermore, the consideration of occupants' demands and experience in the design process helps to achieve more positive design outcomes (Vischer, 1985; Fischer et al., 2004; Vischer, 2005; Schwede et al., 2008).

#### 2.3.2.2. Lack of Feedback (Or Has the Loop Become A Noose?):

Improvement of building performance requires the identification of positives and negatives through rapid feedback (Cohen et al., 2001; Bordass and Leaman, 2005b). The UK's Building Use Studies (BUS) in the 1990s launched the Post-occupancy Review of Buildings and their Engineering (PROBE) project (Cohen et al., 2001; Cooper, 2001; Derbyshire, 2001; Fisk, 2001). In conducting POE studies for a wide range of non-domestic buildings, the PROBE project helped develop a standardised POE method; accumulating a wide range of studies around the world into a homogenized database against which future POE studies could be benchmarked (Bordass et al., 2001a; Leaman and Bordass, 2001). Following these landmark PROBE studies, POE advocates stressed the need to close the loop between building managers and the building's end-users (NCEUB, 2004; Building Research and Information, 2005). In agreement, Leaman and Bordass (2001) suggest the provision of a

knowledge base of lessons learned from users in completed projects should be utilised to either improve spaces in existing buildings or form a programming platform for future buildings (Leaman and Bordass, 2001; Zimmerman and Martin, 2001; Preiser and Schramm, 2002). Ten years on, however, there is evidence to suggest that a lack of communication and feedback still exists amongst these parties (Preiser and Vischer, 2005; Thomas, 2010).

POE has lost its initial aim to close the loop between building designers/managers and the occupants (Jaunzens et al., 2003; Jarvis, 2009; Leaman et al., 2010); suggesting the loop has now become the noose. To date, occupants still remain a largely untapped source of information to building managers and, as such, are rarely involved in the stages of building construction and commission (Zagreus et al., 2004). Due to this lack of involvement, many occupants do not understand how to operate nor occupy their building, which often leads to high levels of discontent. Consequently, as Cohen et al., (2001) suggests, occupants will blame ‘negative’ workplace feelings on the physical environment as a way of voicing their dissatisfaction. Furthermore, occupants will often resort to using the POE as a means to report problems in the workplace, e.g. uncomfortable conditions, poor lighting or ventilation, lack of control, and even bullying which is not measured in POEs (Loftness et al., 1989; Preiser, 2001b; Vischer, 2004; Vischer and Fischer, 2005; Turpin-Brooks and Vickers, 2006).

#### 2.3.2.3. Lack of Instrumental Data:

POEs were originally intended to provide information regarding the in-use performance of a building using instrumental data (Hartkopf et al., 1986; Vischer, 1986; Ventre, 1988; Loftness et al., 1989; Vischer and Fischer, 2005). The landmark PROBE studies in the UK set the benchmark as to how such studies should be conducted (Loftness et al., 2009; Meir et al., 2009). These studies relied on three evaluation components: Energy Assessment and Reporting Methodology (EARM); BUS occupant questionnaire; and an air



pressure test (Cohen et al., 2001). Subsequent use of these tools, however, has focused more on occupant satisfaction with the building, thereby relying on more subjective criteria (Federal Facilities Council, 2001; Fisk, 2001; Turpin-Brooks and Vickers, 2006; Jarvis, 2009; Leaman et al., 2010). While many agree such metrics are more easily assessed than alternatives, such as productivity or health (Leaman and Bordass, 1999), it is often argued that occupant satisfaction is not a meaningful measure for judging building performance (Hartkopf et al., 1985; Hartkopf et al., 1986; Heerwagen and Diamond, 1992; Leaman et al., 2010). Despite providing a first-hand account of how the building is affecting the occupants, such assessments are susceptible to bias. Since POEs don't account for any psychosocial or contextual (non-physical) factors that may affect occupants in the workplace, participants' responses may be either positively or negatively biased. Sometimes known as the 'Hawthorne effect', the behaviour or responses of an individual or group will often change to meet the expectations of the observer/researcher (Roethlisberger and Dickson, 1939).

The use of such measures therefore presents a specific challenge: respondents' subjective assessments of their environment might be affected by non-building-related factors (Ventre, 1988; Zagreus et al., 2004; Jarvis, 2009; Loftness et al., 2009). Many aspects of building performance are readily quantifiable, such as lighting, acoustics, temperature and humidity, durability of materials, amount and distribution of space, etc. (Hartkopf et al., 1985; Hartkopf et al., 1986; Preiser, 2001a). Despite this, POEs typically do not obtain instrumental measurements of indoor building environmental conditions, potentially leading to unsubstantiated complaints against a building's indoor environment. In order to get a complete picture of a building's actual performance from a technical and occupants' perspective, the subjective data from occupant feedback surveys needs to be correlated against the quantitative data measured from physical monitoring (Vischer, 1986; Ventre, 1988; Turpin-Brooks and Vickers, 2006; Choi et al., 2010; Gupta and Chandiwala, 2010).

Several researchers, however, argue there are inherent difficulties in matching user's subjective responses with objective environmental data (Vischer, 1986; Vischer and Fischer, 2005; Jarvis, 2009; Loftness et al., 2009). POEs often record occupant perceptions of thermal comfort on past seasonal events occurring 3 to 12 months before the survey was administered. In order to achieve a successful correlation between the occupants' thermal comfort ratings and the internal thermal environment of the building, the surveys need to be conducted on a 'right-here-right-now' basis for the results to be reliable. However, Vischer (1993) also suggests that humans draw on experience outside the immediate time-frame of the present to make their summary judgements of comfort conditions. Instruments, on the other hand, are temporally limited to sampling actual building conditions as a snapshot or over a prolonged period of time. By adopting a more diagnostic approach to POEs the temporal and calibration limitations on instrument-based data collection can be avoided. Furthermore, measurements of building systems performance can be carried out as a follow-up procedure to help understand the meaning behind the feedback yielded by users on their perceptions of building conditions (Vischer, 1986; Vischer, 2001; Vischer and Fischer, 2005).

### *2.3.3. The Forgiveness Factor and Occupant Satisfaction in Green Buildings*

Green buildings aim to minimise their impact on the environment by reducing fossil fuel use through energy efficiency as well as on-site use of renewable energy. Such buildings often incorporate natural ventilation capabilities to reduce the energy consumption and emissions associated with air-conditioning and to enhance the health and comfort of their users. Many researchers agree that green buildings often tend to be hotter in summer, colder in winter and contain more glare from the sun and sky than their conventional AC alternatives (Abbaszadeh et al., 2006; Brager and Baker, 2009; Baird et al., 2012). However, recent POE studies from the UK (Leaman and Bordass, 2007) and USA (Abbaszadeh et al.,

2006; Brager and Baker, 2009) suggest that occupants are favourably disposed to green buildings. Notwithstanding occasional discomforts, occupants of green buildings tend to forgive minor discomforts provided they can exercise a modicum of personal indoor environmental control. Coined by BUS, the ‘forgiveness factor’ (Equation 2.1) (Leaman and Bordass, 1999) is an index derived from specific items on the BUS post-occupancy questionnaire. In particular it is the ratio of the occupants **overall** evaluation of the building’s comfort over the average score on specific comfort ratings on thermal, lighting, air quality and noise. So if the overall comfort rating is larger than the specific comfort scores, the forgiveness factor comes in greater than unity. This would suggest the willingness to overlook the specific discomforts of their building when they were casting their overall comfort vote. Therefore, this ‘forgiveness factor’ represents an attempt at quantifying how occupants extend their comfort zone by overlooking inadequacies of their thermal environment (Leaman et al., 2007; Kwok and Rajkovich, 2010):

$$\text{Forgiveness Factor} = \frac{\text{Comfort Overall}}{\left( \frac{\text{AirW} + \text{AirS} + \text{TempW} + \text{TempS} + \text{Light} + \text{Noise}}{6} \right)} \quad \text{Equation 2.1}$$

where ventilation/air in winter (*AirW*) and summer (*AirS*), temperature in winter (*TempW*) and summer (*TempS*), lighting (*Light*) and noise (*Noise*).

Furthermore, Kwok and Rajkovich (2010) discuss this toleration of moderate discomfort and suggest that occupants may have an understanding of, and connection with the outdoor climate by virtue of the building’s design, suggesting that increased knowledge of the adaptive opportunities in buildings yields a greater likelihood of reduced discomfort (Leaman and Bordass, 2007; Baird, 2011b).

## 2.4. Chapter Summary

This chapter discussed the current knowledge and recent developments within the fields of thermal comfort and building performance evaluation. This section provides a brief summary of the topics covered:

- MM ventilation represents a key aspect of sustainable building design; providing comfortable work conditions whilst reducing energy consumption and associated carbon emissions. MM buildings, especially those with change-over control strategies, aim to provide good air quality and thermal comfort using a NV mode preferentially and only reverting to mechanical HVAC systems when the outdoor conditions are too harsh. Studies suggest that MM or ‘hybrid’ ventilation, as opposed to conventional air-conditioning, generates greater occupant satisfaction, improves health and productivity, and enhances thermal comfort.
- The debate between the conventional and adaptive comfort models can be seen in countless papers. Fanger’s PMV-based model for thermal comfort is derived from pre-calculated temperatures and humidity levels. On the contrary, the adaptive model recognises the role of human adaptation in establishing thermal comfort, taking into account people’s thermal perception, behaviour and expectations, allowing for a wider range of acceptable temperatures in NV buildings. The inclusion of the adaptive model in international comfort standards, such as ASHRAE Standard 55 and EN15251, has offered the application of adaptive comfort principles, i.e. operable windows and greater indoor environmental variations, in current and future building design.
- The conflicting applicability of MM buildings between the international comfort standards presents a key barrier to the future uptake of such buildings. Currently, MM buildings are precluded from the scope of the ACS within ASHRAE Standard 55, which is heavily constrained to naturally conditioned, occupant-controlled spaces in

which thermal comfort conditions are primarily influenced by operable windows. Whenever mechanical cooling systems are provided for the space, regardless of whether they are used or not, the adaptive model is not applicable. The European standard EN15251, however, allows its ACS to be applied to NV buildings and can include MM buildings during times they are not employing mechanical systems, i.e. whilst in NV or ‘free-running’ mode. Many argue that occupants in MM buildings likely experience some degree of psychological adaptation beyond the behavioural adjustments incorporated into the PMV model. However, future field studies in these types of buildings would provide a better understanding of how occupant comfort is affected by MM ventilation as well as warrant their inclusion into ASHRAE’s ACS.

- Given future increases in outdoor temperatures as a result of climate change and urbanisation, it is clear that more work can and should be done to improve quantitative models of comfort and to evaluate the risks of overheating in real world situations, particularly in MM buildings where there is no consensus on the relative applicability of the PMV-PPD vs. adaptive comfort standards. Currently, there is very little guidance as to how overheating potential (exceedance) should be measured, and even less to how much or little occupant control can be afforded to the building users. Since the possibility to open a window inside office buildings is now considered an important adaptive behavioural opportunity, the perception of control has shifted away from the facilities manager and towards the occupants. However, there still remains the question of whether use of the windows and adjustments to indoor temperatures should be controlled by the occupants or the building. Whereas automated control can provide optimum levels of energy efficiency, the inclusion of individual control, such as operable windows, is more likely to create much higher levels of occupant satisfaction within the building.

- POE was developed in the 1970s as a means to evaluate a building's performance after it had been built and occupied for some time. Subsequent use of this tool however has been more focussed on subjective criteria, such as occupant satisfaction, rather than the instrumental measurements of actual building performance, e.g. energy consumption, indoor temperatures, etc. Contemporary POE methods merely provide a face-value assessment of buildings by their occupants. Despite recommendations to close the feedback loop between occupants and building designers, building users are continually omitted from the building design and construction stage. As a result, many occupants use POE surveys as a vehicle to voice their dissatisfaction with the building which may or may not be attributed to poor building performance. Since such studies don't typically obtain parallel instrumental measurements of these variables, e.g. indoor climate, they lack an objective benchmark against which poor satisfaction ratings can be verified. The combination of objective building performance data and subjective satisfaction ratings may therefore offer a more valid and reliable evaluation of a building's success.
- Green buildings, by design, tend to be hotter in summer and colder in winter than their conventional AC counterparts. However, recent POE studies suggest occupants of green buildings are more forgiving of these less-than-ideal conditions provided they possess a modicum of environmental control. But could this 'forgiveness' be attributed to more relaxed expectations of the thermal environment? Or could occupants' environmental attitudes boost their forgiveness of green buildings?

The next chapter presents detailed information about the case study buildings, questionnaire design, data collection techniques and analysis methods applied throughout this thesis.

## **Chapter 3. Methods**

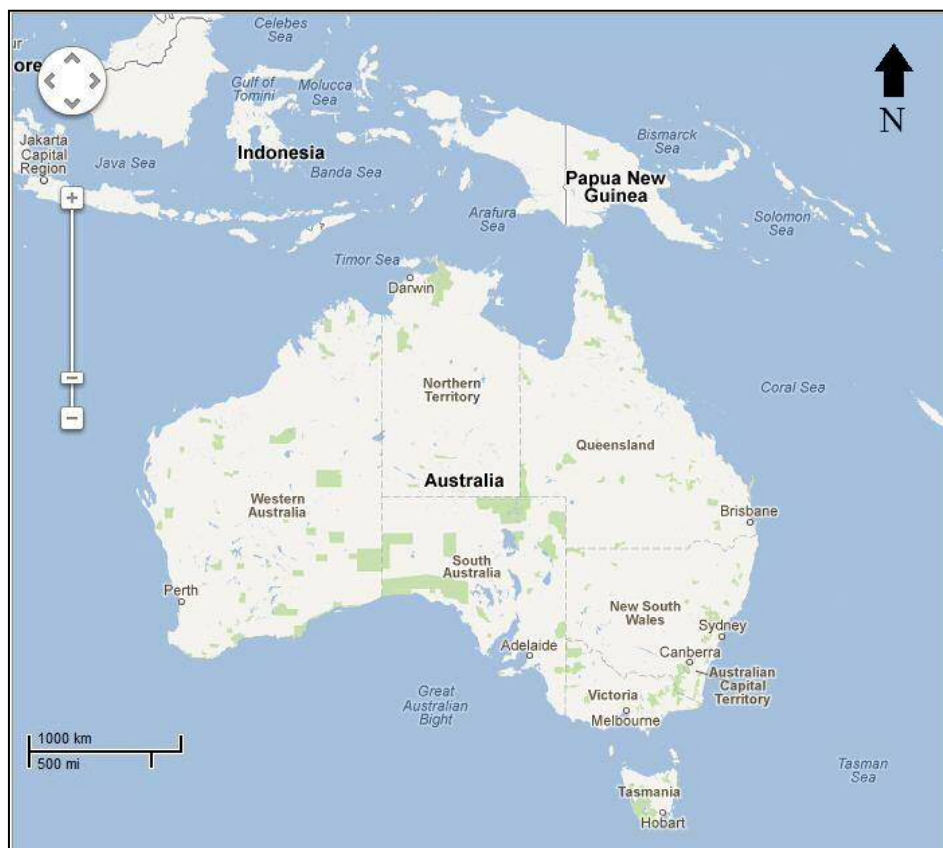
The field research design undertaken within this thesis combines several distinct studies conducted using two different methods in two case study buildings in the same location. Firstly, POEs, supplemented with an environmental attitudes questionnaire, were conducted within a MM and a NV building located in Macquarie University's North Ryde campus. Secondly, these buildings were also used in a longitudinal thermal comfort field study (starting in March 2009 and concluding in April 2010). This chapter presents detailed information about the research design and methods applied in each project, including the development of each questionnaire, the data collection techniques used and the statistical analytic approaches. Discussions regarding the indoor and outdoor climatic instrumentation and measurement protocols are presented along with detailed descriptions of each case study building.

### **3.1. Sydney's Climatic Context**

The Sydney metropolitan region, located on the eastern coast of Australia (shown in Figure 3.1) (34°S, 151°E), is characterised by a humid sub-tropical climate with warm-to-hot summers and cool-to-cold winters with an annual rainfall of 1200mm. This weather is influenced by the complex elevated topography to the north, west and south and by proximity to the Tasman Sea to the east. Due to its coastal location and latitude, Sydney avoids the high temperatures commonly associated with the more inland regions and the high humidity of tropical coastal areas respectively (BoM, 1991). The warmest month is January, with an average air temperature range of 18.6°C to 25.8°C. In contrast, its winters are mildly cool, with temperatures rarely dropping below 5°C in the coastal areas. The coldest month is July, with an average range of 8.0°C to 12.6°C (BoM, 1991; BoM, 2011). Given the city's yearly seasonal variations, its climate is well suited to MM buildings. For much of the year, people

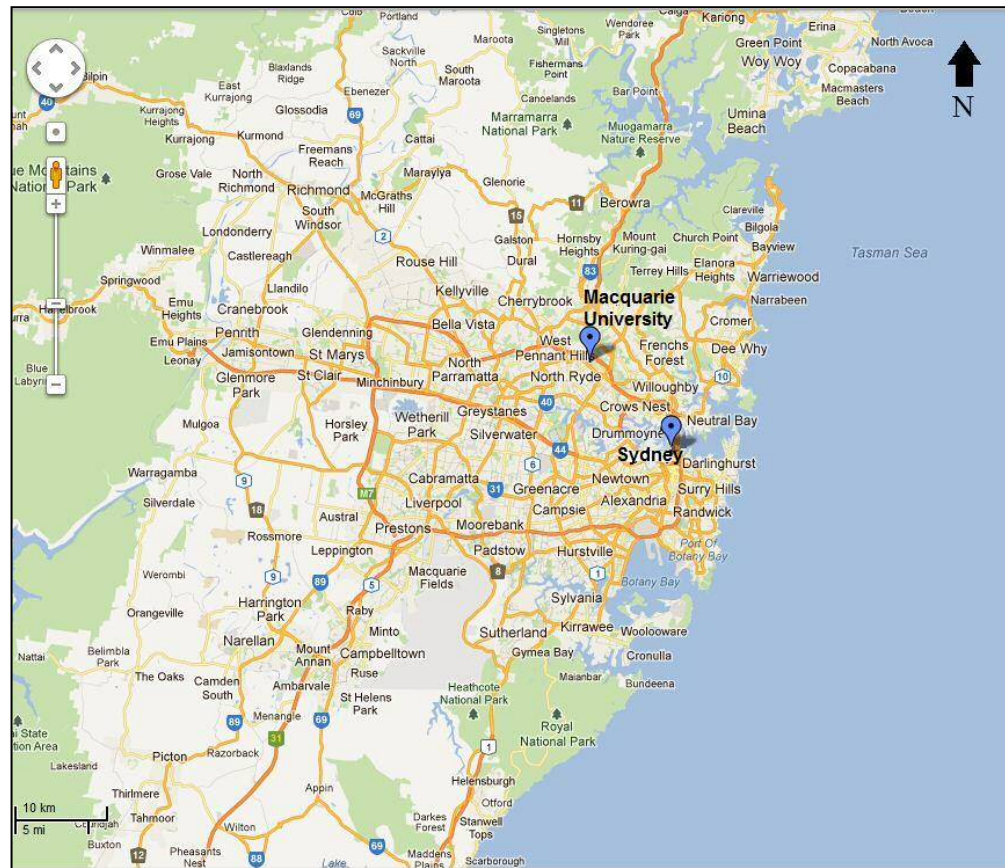
can achieve thermal comfort indoors through passive means by way of adaptive behaviours, such as opening/closing windows, adjusting their clothing or by change of position (Aggerholm, 2002; Rowe, 2003).

Macquarie University (MQ), is located on a 126 hectare-site in the Sydney's North Ryde approximately 18km north-west of Sydney's central business district ( $33^{\circ}46'$  S,  $151^{\circ}6'$  E) (Figure 3.2). As summarised in Figure 3.3, variations in the site's climate are fairly consistent with the city's seasonal variability (BoM, 2011). According to the latest Building Code of Australia climate zone maps shown in Figure 3.4, this area is classified as warm temperate (zone 5) (ABCB, 2009).

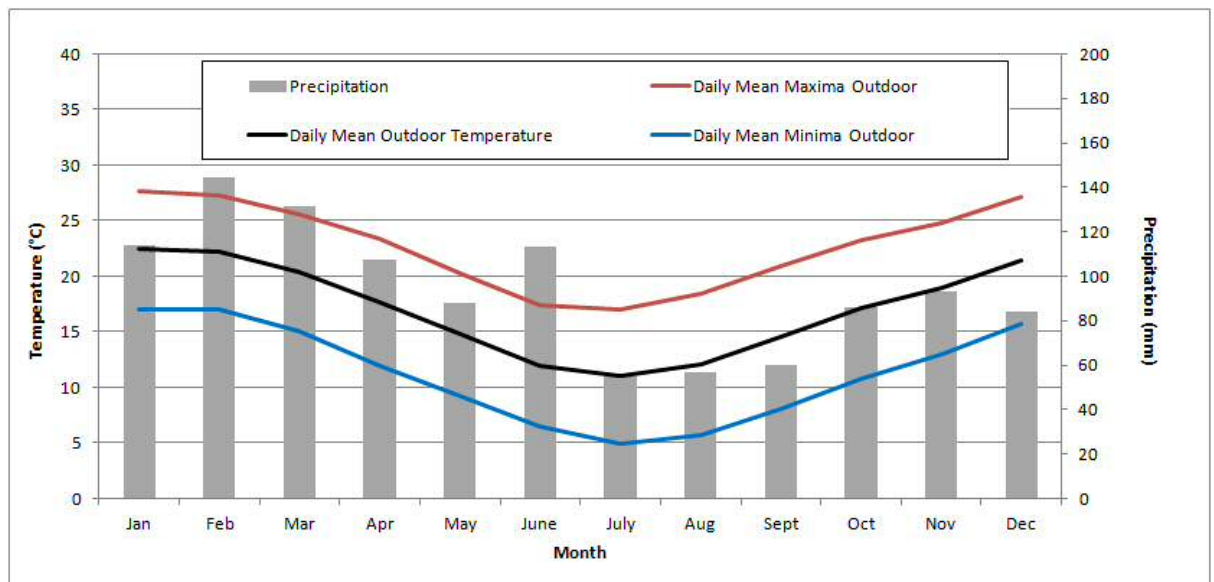


**Figure 3.1:** Location of Sydney, Australia (sourced from Google, 2012).





**Figure 3.2:** Location of Macquarie University in relation to the Sydney Central Business District (sourced from Google, 2012).



**Figure 3.3:** Climate of Macquarie University, North Ryde between 1985-2010. Data was sourced from the Willandra Village weather station in Marsfield (33°78' S, 151°11' E) located 1 km from the campus (BoM, 2011).

# NEW SOUTH WALES

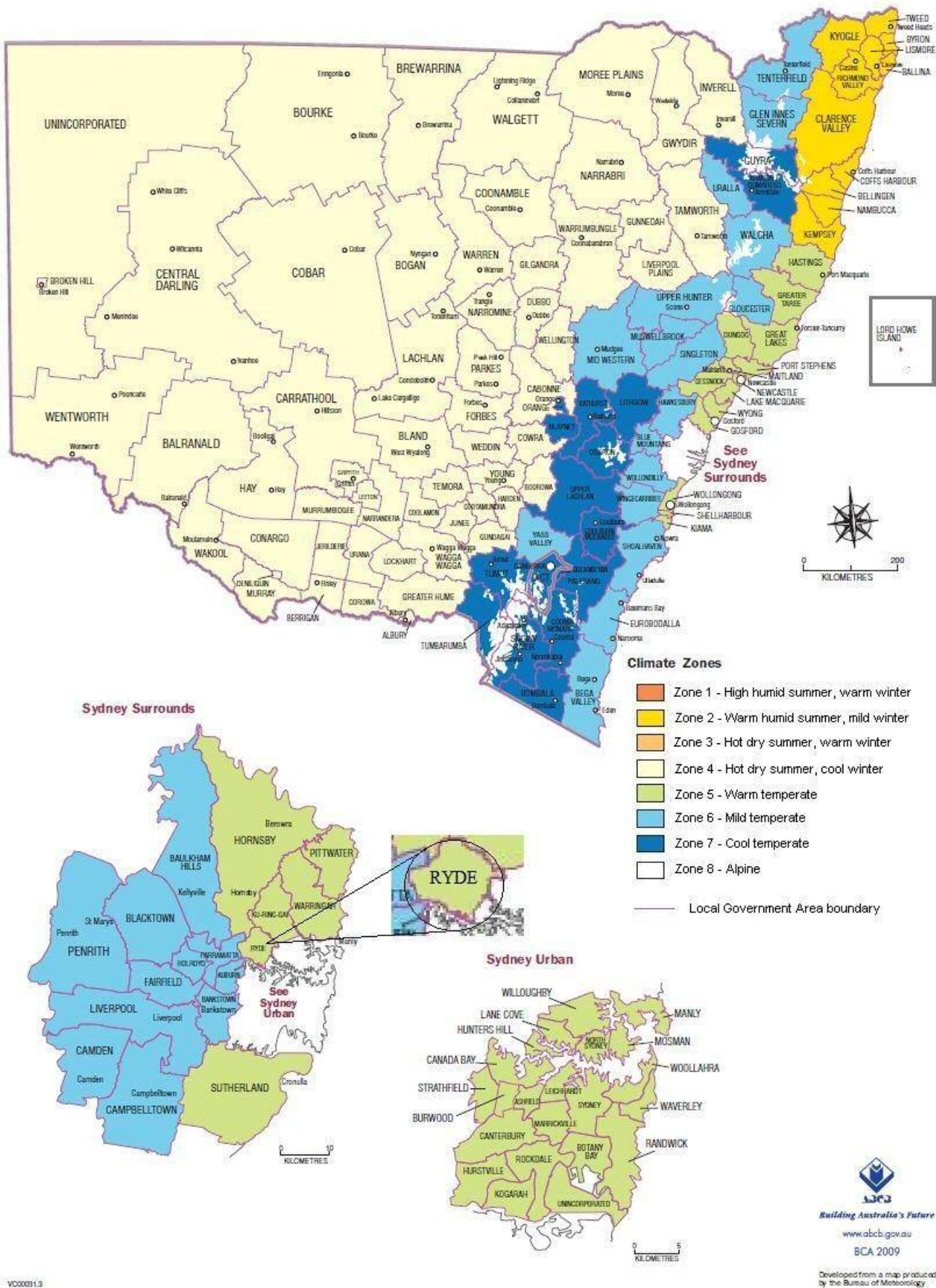


Figure 3.4: New South Wales Climate Zones (modified from ABCB, 2009).

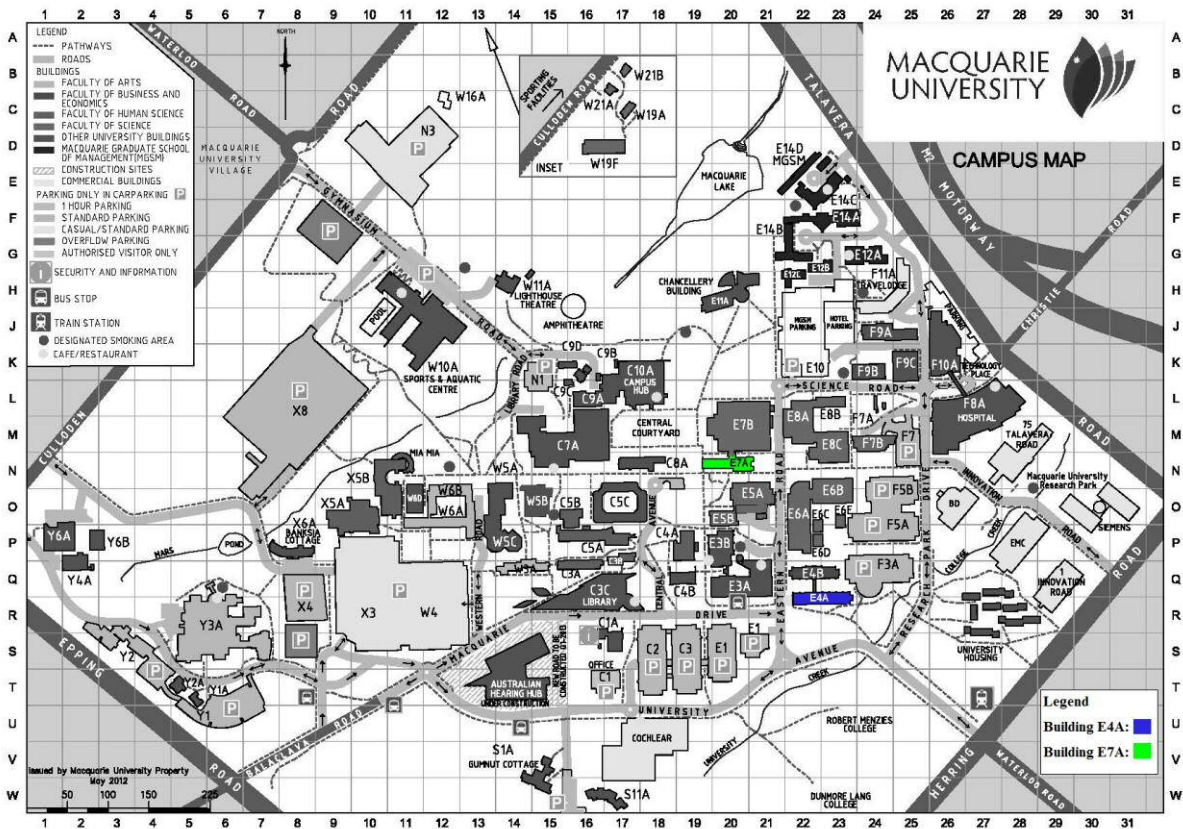
### **3.2. Case Study Buildings and Their Occupants**

Two academic office buildings from MQ were selected as case studies for this thesis. These consist of a MM or ‘hybrid’ ventilation building (Building E4A) and a NV building (Building E7A). The selection of these buildings as case studies will be explained in detail in the following sections.

#### *3.2.1. Building E4A*

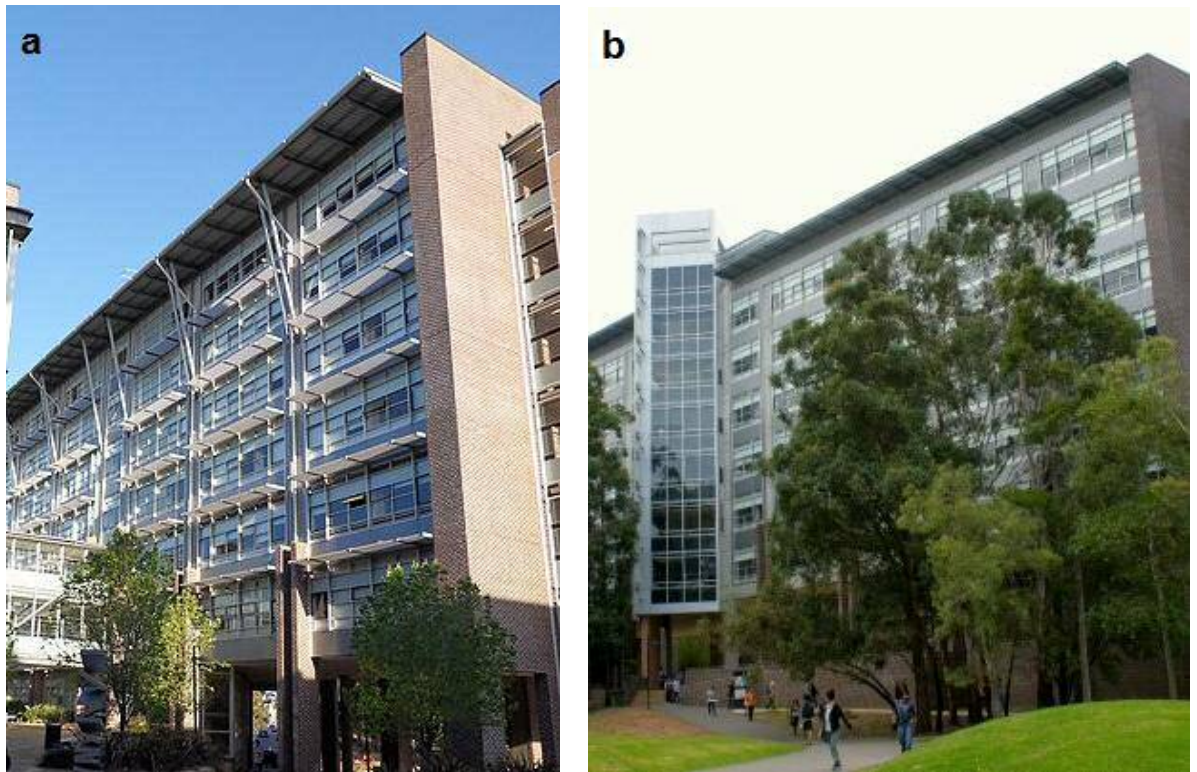
As depicted in Figure 3.5, the MM building (E4A) is located in the south-eastern quadrant of the campus. Commissioned in 2006, this 7-storey office building is occupied by academic and administrative staff from the departments of the Faculty of Business and Economics. A detailed floor plan and occupant profile of this building is provided in Figure 3.6f and Table 3.1. Designed to consume approximately 40% less energy than a conventionally AC alternative, the building operates as a change-over MM or ‘hybrid’ ventilation system that switches between natural ventilation and air-conditioning whenever outdoor and indoor conditions are amenable (Arkins, 2007). The building’s central core features constantly AC open-plan office space: heating is supplied when indoor temperatures fall below 19°C, and cooling when temperatures rise above 25°C. As shown in Figures 3.6a and b, the north and south perimeter zones consist of MM cellular offices with operable windows. The entire façade is built on a semi-automated louvre system featuring solar shading over the northern windows (Figure 3.6a). Automated high and low external louvres provide natural ventilation to each floor, with adjustable internal grilles to control airflow, supplemented by user-operable windows (Figure 3.6c).



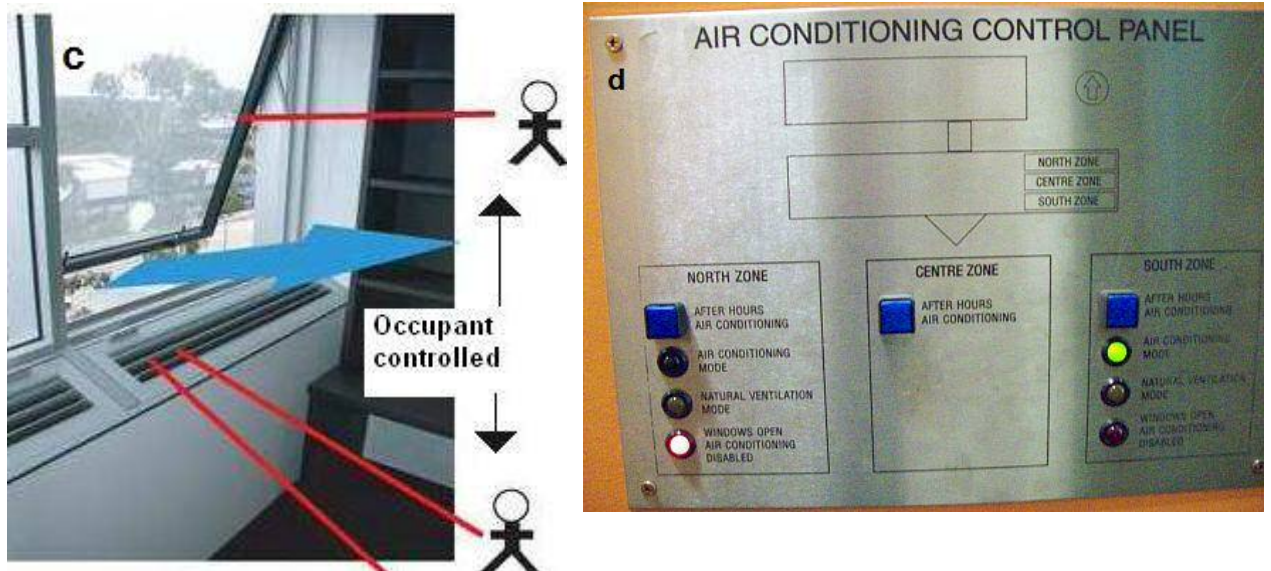


**Figure 3.5:** Macquarie University North Ryde campus (sourced from MQ, 2012).

Indoor temperature and outdoor weather sensors prompt the building’s management system (BMS) to switch between AC and NV mode dependent on the prevailing outdoor and indoor conditions. Each floor of the building is split into three individual zones, i.e. North, Central and South. Panels located at the entrance of each corridor indicate the zone’s current mode of operation (Figure 3.6d). As outlined in Figure 3.6e, the building switches into AC mode whenever internal temperatures in any given zone peak above 25°C. During this mode, internal temperatures are maintained at a set-point of 24°C (±1°C). BMS switch-over to NV mode is conditional when the external meteorological conditions and indoor thermal environment are suitable for the occupants. During such an event, the automated external louvres will open allowing natural airflow to the space, and occupants can then open their windows for additional ventilation. The building can also revert to NV mode if more than 30% of windows are opened in any given zone, which automatically shuts off AC mode for that zone.

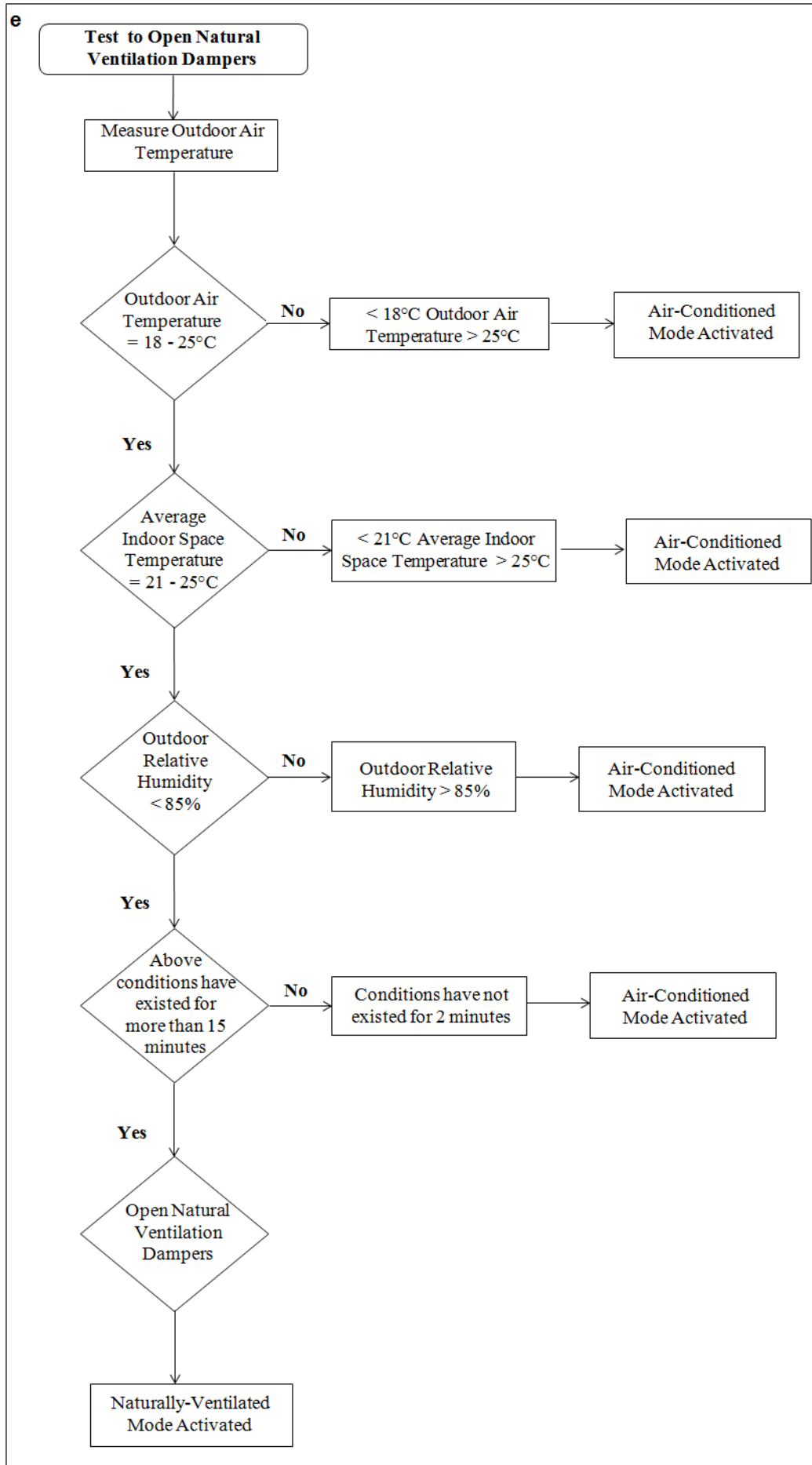


**Figure 3.6:** Macquarie University's Building E4A as viewed from the a) north facade and b) south facade.



**Figure 3.6c:** Operable windows and internal grilles in NV mode.

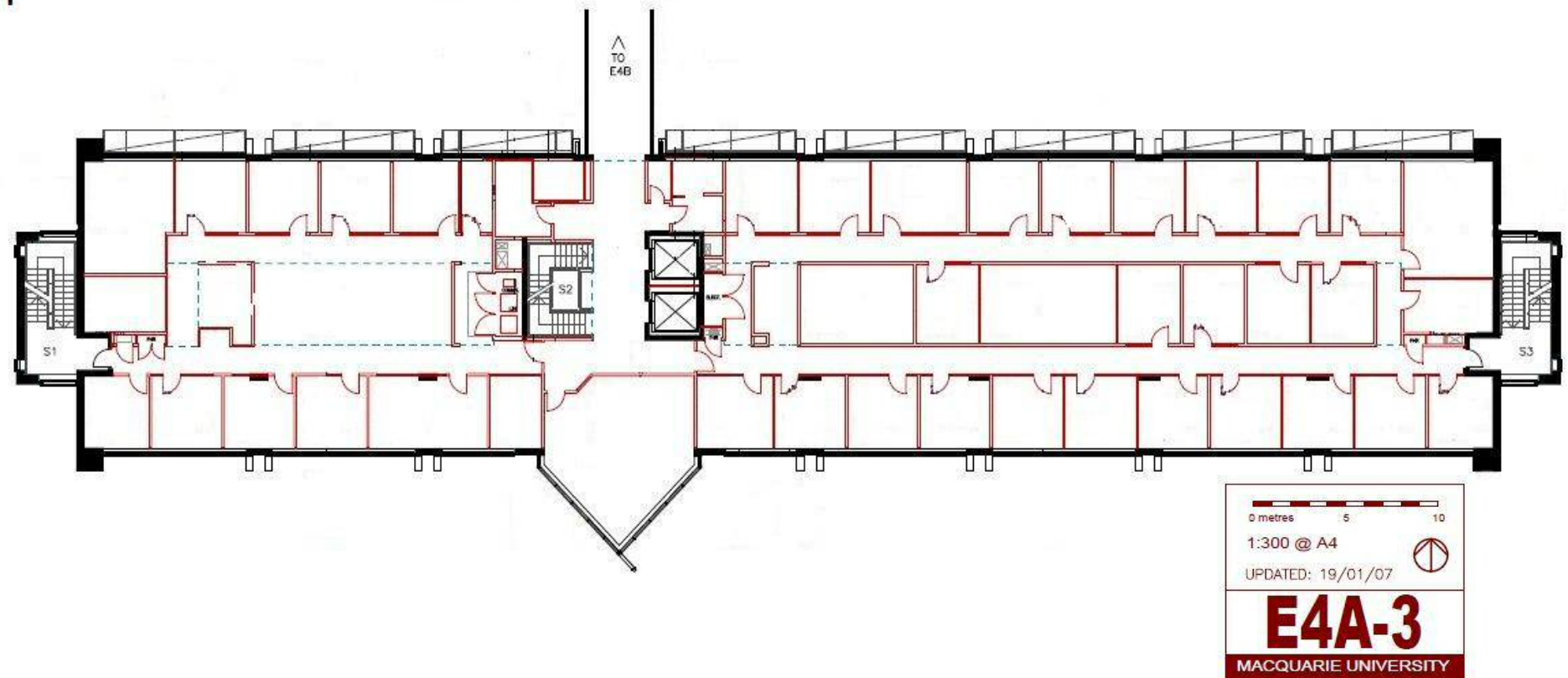
**Figure 3.6d:** Air-conditioning status display located on each floor. The green light indicates AC mode; yellow light indicates NV mode and a red light indicates when windows have been opened and AC mode has been disabled.



**Figure 3.6e:** Building E4A BMS Algorithm.



f



**Figure 3.6f:** Floor plan of Building E4A – Level 3.

### 3.2.1.1. Building Selection Rationale

Building E4A represents the University's only MM building. Normalised according to the total usable floor area, the building consumes 145 kWh/m<sup>2</sup> per annum which is far less than conventional fully AC buildings. As such, the selection of this building allows for an interesting comparison with the other academic office buildings on campus. The design of this building is also unique in that each floor consists of MM offices along the north and south facades, separated by a fully AC central zone. Moreover, since it was built, the occupants of this building have expressed much discontent about its performance, thereby making it a perfect candidate to undergo a POE study.

**Table 3.1:** Building Descriptions and Occupant Profiles.

	<b>Building E4A (MM)</b>	<b>Building E7A (NV)</b>
Type of Building:	Faculty of Business and Economics; academic office building	Faculty of Science; academic office building
Departments:	Accounting and Finance, Economics, Statistics <sup>4</sup> , Business, Actuarial Studies, and Applied Finance Centre	Physics, Chiropractic, Mathematics, Earth and Planetary Sciences, Environment and Geography and Risk Frontiers Centre
Usable Floor Area:	6541 m <sup>2</sup> (7 storeys – isolated office cells with some open partitioned cubicles)	5808 m <sup>2</sup> (8 storeys – isolated office cells)
Number of Occupants:	~228 (± 10 or 4%) (as of 2011)	~206 (± 10 or 5%) (as of 2011)
Males:	117 (51%)	107 (52%)
Females:	111 (49%)	99 (48%)
Occupant Density:	28.7 m <sup>2</sup> / occupant	28.2 m <sup>2</sup> / occupant

### *3.2.2. Building E7A*

Located in the north-eastern quadrant of MQ campus (see Figure 3.5, page 70), the Faculty of Science building was one of the first buildings ever built for MQ when it first opened in 1966. Typical of a large proportion of the original office buildings within MQ, this 8-storey office building was designed to be NV (see Figure 3.7e for a detailed floorplan of

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<sup>4</sup> Prior to 2010, the Statistics department was part of the Faculty of Business and Economics and hence its occupants are located in Building E4A. This department is now affiliated with the Faculty of Science but remains physically accommodated within the Faculty of Business and Economics building.



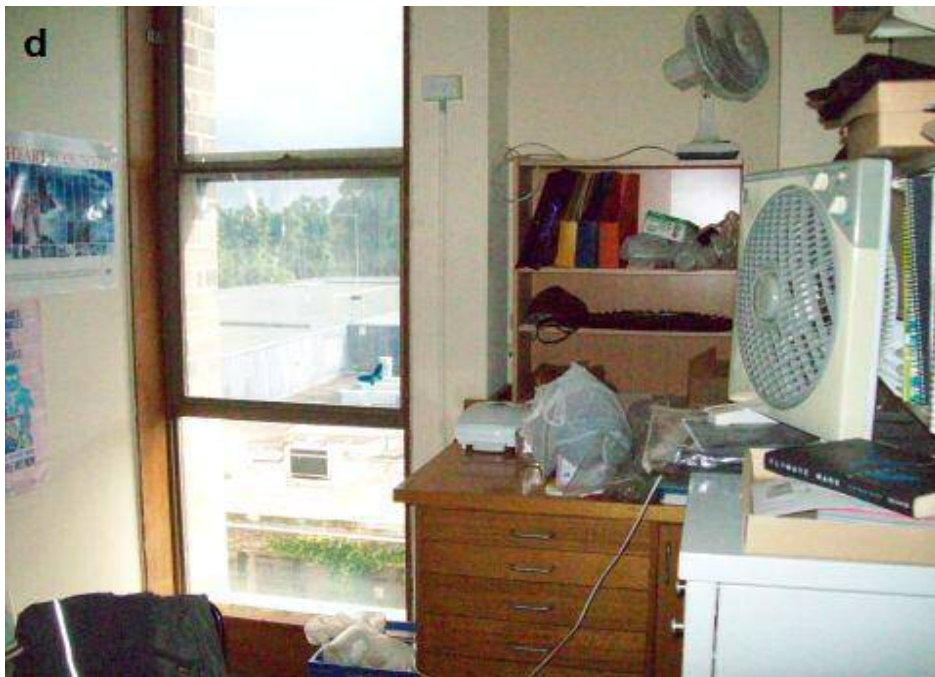
this building and Table 3.1 for its occupant profile). The building features a narrow floor-plate traversed by a central corridor with single- and dual-occupant offices on either side (Figures 3.7a and 3.7b). Each office contains at least two occupant-operated sash windows that can be opened to create effective cross-ventilation throughout the building interior. The building does not have any external shading along the north facade (facing towards the sun in the Southern hemisphere) which results in increased solar heat gains in the north-facing offices. While Building E7A has no centralised heating/cooling systems, occupant-controlled room air-conditioners were retrospectively added to some offices (as illustrated in Figures 3.7c). Figure 3.7d reveals that many occupants use pedestal or ceiling fans to supplement cross-ventilation and air movement during warm weather. Postgraduate students and academic and administrative staff from various science-related departments, such as Environment and Geography, Earth and Planetary Science, Physics, and Mathematics occupy this building.



**Figure 3.7:** Macquarie University's Building E7A as viewed from the **a)** north-west corner and **b)** south-west corner.

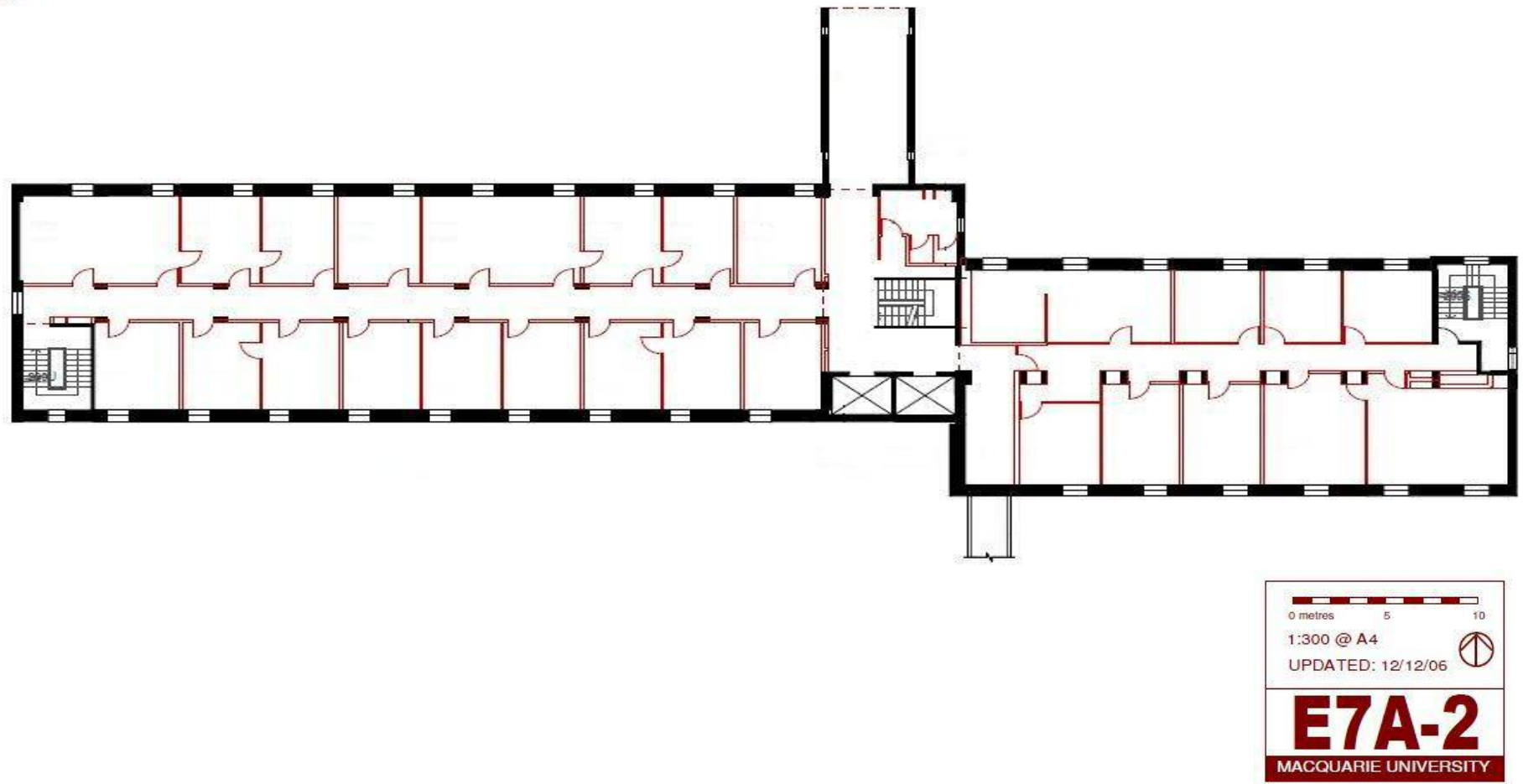


**Figure 3.7c:** Part of the North façade of Building E7A showing some offices with room air-conditioning units installed. The photo also shows ventilation fans in the windows of the toilets in the east-facing wall of the “dog-leg” of the north façade.



**Figure 3.7d:** Office on the north side of E7A showing some pedestal/portable fans that occupants often use for additional air movement.

e



**Figure 3.7e:** Floor plan of Building E7A – Level 2.



### 3.2.2.1. Building Selection Rationale

It was important to select a NV building that would contrast well with the MM building. While the University contains several NV academic office buildings, many of these are located in the western corner of the campus. Given potential differences between the microclimates of these locations, Building E7A was selected due to its physical proximity to Building E4A. Furthermore, these make for an ideal comparative case study as both buildings are occupied by the same organisation in the same location. As Building E7A consumes less energy per unit of usable floor area, i.e. 84 kWh/m<sup>2</sup> per annum, it can be considered as ‘greener’ than the MM building in terms of energy performance. Nonetheless, its thermal environment is also widely acknowledged to be uncomfortable during summer and winter. The occupant profile of this building is also unique in that it houses many academics and postgraduate students from environmental science departments, such as physical and human geography, as well as non-environmental science departments, e.g. physics, astronomy and mathematics, which enables a useful comparison to the business and economics academics within Building E4A.

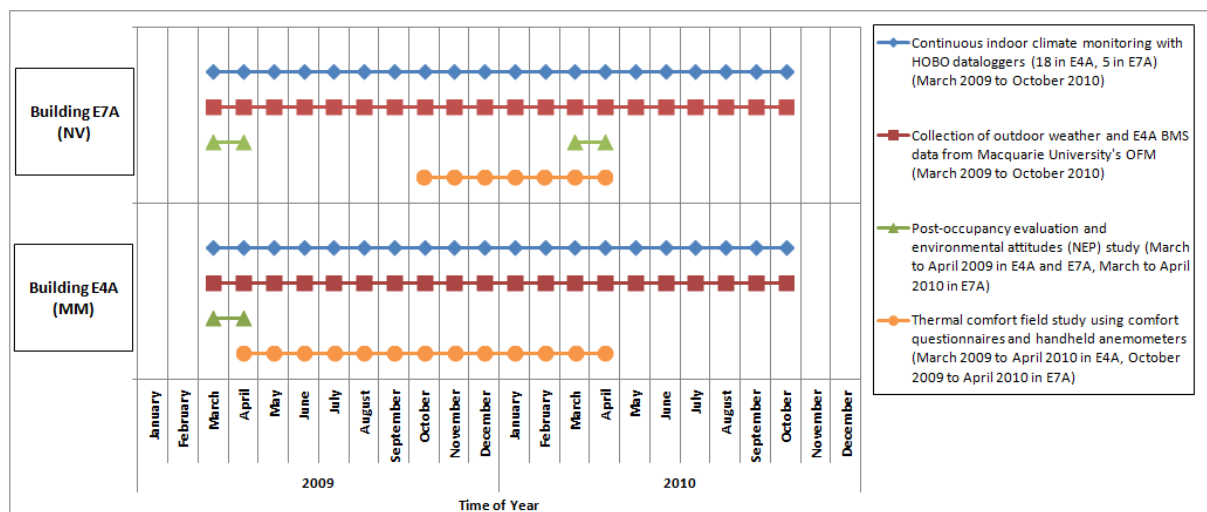
### **3.3. Questionnaires and Survey Techniques**

The questionnaires used in this thesis use a combination of qualitative (open-ended questions) and quantitative (structured, multiple-choice questions) methods in order to obtain data. Each of the four different questionnaires used, i.e. the POE, environmental attitudes, thermal comfort background and ‘right-here-right-now’ comfort questionnaires, were carefully designed to maximise the robustness of the data collected. As all questionnaires focussed on subject-based responses, various 7-point (Likert) scales and rank questions were used, in which their reliability can be assessed by statistical tests. While such instruments are considered relatively crude when it comes to accurate measurement, their chief function is to divide people into a number of broad groups or categories (Haynes and Price, 2004). As a

result, the sensitivity of word choice was a major factor in the questionnaire design. Prior to use in the major projects, all questionnaires were administered to a small pilot sample of 10 people. General feedback and suggestions from these pilot studies were considered to enhance or alter the statements, ensuring minimal confusion with participants. The time taken to complete these questionnaires was also recorded to allow minimal interruption with the subject's schedule.

### 3.3.1. Post-Occupancy Evaluation and Environmental Attitudes Questionnaires

Figure 3.8 presents a timeline depicting the various data collection stages throughout this thesis. This project was initially conducted within Building E4A and levels 6 to 8 in Building E7A between March and April 2009. A separate follow-up survey was conducted in March 2010 using the rest of the occupants located in Building E7A (located on floors 2 to 5). Whilst undertaken one year apart, these surveys were conducted under comparable climatic conditions, both representative of Sydney's autumnal weather. Each questionnaire, its design and survey techniques are outlined in the following sub-sections.



**Figure 3.8:** Timeline outlining each stage of both projects.

#### 3.3.1.1. Justification and Design

Within the field of POE research there are many questionnaires and analysis methods available worldwide (Leaman and Bordass, 2003). Whilst all approaches essentially contain two components: measurement and benchmarking, no universally-standardised method exists for conducting these studies (Peretti and Schiavon, 2011). Some urge the use of online computer-based questionnaires while others still rely on the more traditional paper-based, face-to-face method with its lower rejection rate. With a strong consideration towards Australian and international benchmarking, the BUS POE questionnaire was selected and used under licence (refer to Appendix B). Developed by Adrian Leaman and William Bordass as part of the PROBE studies carried out from 1995-2000 (Cohen et al., 2001), the BUS survey is one of the world's most widely used POE instruments. As of 2011, its database comprised over 350 building performance studies including a separate database for international green buildings, and is used extensively to benchmark current and new studies. With over 25 years of experience in conducting building performance studies, Leaman and Bordass have refined their survey techniques, and therefore the techniques utilised for this part of the research did not stray away from the guidelines recommended in BUS (2009).

The 3-page BUS POE questionnaire (BUS, 2009) features numerous 7-point Likert scales with space for commentary covering all variables relating to occupant satisfaction, e.g. thermal, visual and acoustic comfort, indoor air quality, perceived health and productivity, as well as general acceptance of the workplace. Combinations of these scores enable the calculation of various comfort and satisfaction indices unique to the BUS survey. One of the distinguishing features of this survey is its 'forgiveness factor' index. This is simply calculated as the ratio of the Overall Comfort score to the average of the scores for the six environmental factors: Lighting Overall, Noise Overall, Temperature Overall in both winter and summer, and Air Overall in both winter and summer. It represents an attempt to quantify

the users' tolerance of the environmental conditions within the building, with values greater than 1 taken to indicate that occupants may be more tolerant, or 'forgiving', of a building's indoor environmental conditions (Leaman and Bordass, 2007).

Accompanying the BUS occupant survey was an environmental attitudes questionnaire. Based on the 15-item version of the NEP scale (Dunlap et al., 2000), this questionnaire was developed to measure strength of endorsement (from low to high) of an ecological worldview (Dunlap and van Liere, 1978; Dunlap, 2008). The NEP questionnaire uses 5-point response scales ranging from *Strongly Disagree* to *Strongly Agree*, with higher scores on the scale from 1 (*low*) to 5 (*high*) indicating greater levels of environmental concern. A copy of the Environmental Attitudes/NEP questionnaire is provided in Appendix D. All scales were converted to a NEP score by summing each item response and dividing by the total number of items in the scale.

#### 3.3.1.2. Survey Techniques and Protocol

After obtaining approval from the University's Human Ethics Committee (see Appendix A), emails were sent to all occupants within the building, informing them of the project, when it was being conducted and what it involved should they consent to participate (refer to Appendix C for this email consent form). Consent was recognised if a recipient replied to the email.

Each survey was conducted over the course of one week in March to allow for comparable outdoor climatic conditions for both buildings (Figure 3.8, page 79). Both the POE and NEP questionnaires, along with an instruction sheet, were placed inside an envelope and handed out to every occupant within each building on a Tuesday morning<sup>5</sup>. If at the time of delivery

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<sup>5</sup> BUS (2009) suggests studies conducted on either Tuesday or Wednesdays generate the best response rates

the occupant wasn't in their office, it was placed under their door. The sheet of instructions (see Appendix E) reiterated the aims and objectives of the project and also asked the participants to place their completed questionnaires inside the envelope provided, which would be collected in person at the end of the day. Should the participant not be in their office at this time, then they were asked to leave the envelope in a prominent place for collection. Naturally, not all questionnaires delivered were collected at the end of the day, in which case the participants were given until Monday of the following week to complete the questionnaires for collection. Due to time constraints, any questionnaires collected after these dates were excluded from the final data analysis.

### *3.3.2. 'Right Here, Right Now' Thermal Comfort Questionnaires*

As illustrated in Figure 3.8 (page 79), this project was conducted simultaneously in Building E4A from March 2009 to April 2010 and Building E7A between October 2009 and April 2010 to provide a summertime comparison. The questionnaires, their design and the surveying techniques used are explained in detail below.

#### 3.3.2.1. Justification and Design

A multitude of thermal comfort field studies have been conducted around the world, each of which has used very similar questionnaire designs. The questionnaires developed by de Dear and Fountain (1994) and Cena and de Dear (1998) have become some of the most commonly used in thermal comfort research. While there is no universally-accepted comfort questionnaire, several international comfort standards offer their own guidelines and recommendations as to how they should be designed (ASHRAE, 2004; ISO, 2005; CEN, 2007). Often using very similar layouts and employing the same metrics with only minor differences in word choice, these questionnaires represent the most widely used formats in



thermal comfort research. It was decided that the questionnaires used for this project would be adapted from these examples.

Two separate questionnaires were used in this project: a background questionnaire and a 'right here, right now' subjective comfort questionnaire, both adapted and based on those used for ASHRAE's RP-702 and RP-921 projects in Australia (de Dear and Fountain, 1994; Cena and de Dear, 1998). During the initial phases of the project, the background questionnaire (as shown in Appendix H) was used to gather generic information about each subject, e.g. age, demographic and contextual factors, etc. While this questionnaire consists of slightly overlapping age categories, these did not cause any skewed results since age was not factored into the analysis of thermal comfort data. Subjects were asked to specify their gender, age group, how long they had occupied the building as well as the type and location of the building they previously occupied. Participants were also required to estimate how many hours per week they spend inside the building and how many hours they spend each day at their workspace. A section on the use of air-conditioning away from the office was also included. The final questions referred to a range of adaptive behaviours the subjects could employ in their office, and how often they used them on a seasonal basis, i.e. during summer and winter.

The other part of this project was the 'right here, right now' comfort questionnaire. These were used to record occupant perceptions of the thermal environment and their workplace at the time the questionnaire was administered. Appendix I is an amalgamated version of the summer and winter questionnaires. Questions were formatted into columns and tables with a variety of tick boxes to ensure occupants could complete the questionnaire quickly and easily. Thermal sensation was rated along the ASHRAE 7-point scale, ranging from -3 (cold) to +3 (hot), with 0 as neutral. Thermal acceptability was addressed with a binary 'acceptable' or

‘unacceptable’ question, while thermal preference was assessed on the 3-point McIntyre scale (McIntyre, 1980), wherein occupants listed if they preferred to be ‘warmer’, ‘cooler’ or ‘no change’. Air movement questions focused on the subjects’ acceptability as it related to the air speed. Subjects registered if the air velocity was ‘acceptable’ or ‘unacceptable’ and their reason, whether it was ‘too low’, ‘too high’ or ‘enough’ air movement. Subjects were also asked if they preferred ‘more’ or ‘less air movement’ or ‘no change’. Standardised clothing and metabolic activity checklists were assessed using the current values in ASHRAE (2001) and ISO (2003). Subjects were asked to circle the items corresponding to the clothes they were wearing at the time the questionnaire was administered. Any items worn by the participant but not listed were specified by the subject. Typical undergarments were assumed to be worn by all subjects and were hence omitted from this list (Morgan and de Dear, 2003). In regards to metabolic activity, subjects were asked to record their general activity at 10, 20, and 30 minutes before the questionnaire was delivered, from which an overall metabolic rate could be established. The question referring to perceived productivity was derived from the BUS POE survey used in the previous project. The wording was modified, enabling subjects to assess their own daily productivity based on their interpretation of an average day’s work. Adaptive behaviours were also addressed by enquiring if subjects had used any personal thermal environment/comfort strategies on the day the survey was conducted, such as opening/closing windows, adjusting their clothing, or using a portable heater or fan.

#### 3.3.2.2. Survey Techniques and Protocol

After obtaining approval from the University’s Human Ethics Committee (see Appendix F) and attaining approval from the Dean of each building’s Faculty to survey their staff members, a building-wide email was sent informing the occupants of the project and what was going to be asked of them should they consent to participate (refer to Appendix G for a copy of this occupant email consent form). Again, consent was formalised if a recipient

replied to the email. To ensure statistically appropriate sample sizes, 60 occupants were recruited in each building. The field study was conducted using a longitudinal design, i.e. the samples of subjects were surveyed across a long period of time across a wide variety of different indoor and outdoor climatic conditions.

On each day of the project, subjects were selected based on their availability. If a subject was in their office at the time of the survey, they were first asked if they could afford to spend 60 seconds to complete the questionnaire. During the time when subjects were filling in the questionnaires, instrumental measurements were being made of the subjects' thermal environment, which will be explained in further detail in the next section.

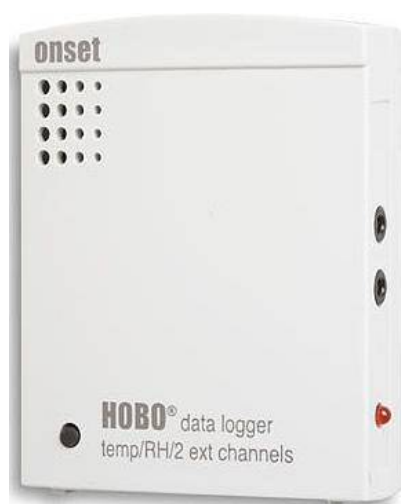
### **3.4. Indoor and Outdoor Climatic Instrumentation and Measurement Protocols**

Both projects used a variety of instruments to measure the indoor and outdoor climatic conditions. These included some continuous monitoring dataloggers and weather stations as well as some spot-readings recorded at the time questionnaires were being completed, such as air velocity and clothing insulation. All dataloggers were calibrated against accurate, industrial-grade mercury thermometers while the anemometers were calibrated inside a wind tunnel. Data generated from Building E4A's BMS was also gathered to identify times of opening and closing of windows, indoor and outdoor temperatures as well as the building's modes of operation.

#### ***3.4.1. Indoor Climate Measurements***

Eighteen offices in Building E4A (7 in the north; 4 in the central; and 7 in the south zones) and five offices in Building E7A (3 in the north and 2 in the south zones) were equipped with HOBO dataloggers to continuously record air temperature (°C) and relative humidity (RH) (%) throughout each project. Several of these were equipped with a 40mm

ping pong ball painted matte black attached to an external temperature sensor to record radiant globe temperature ( $^{\circ}\text{C}$ ). Each logger was placed at a height of 0.6 m within 1 metre of the occupant's workstation to characterise the immediate thermal environment experienced by the occupant under normal working conditions. The data recorded by the HOBOS were regularly uploaded every month. During each questionnaire session, air speed/velocity (m/s) was also measured at the same height and distance from the subject. Figures 3.9-3.13 and Table 3.2 detail each instrument used and their specifications.



**Figure 3.9:** “HOBO” U12-013 Temperature and Relative Humidity Datalogger.



**Figure 3.10:** “HOBO” U12-013 Temperature and Relative Humidity Datalogger with 40mm sphere painted matte black attached to TMC1-HD Water/Soil Temperature Sensor.



**Figure 3.11:** “TSI VelociCalc” Anemometer.



**Figure 3.12:** “Vaisala HM34C” Humidity and Temperature Meter.



**Figure 3.13:** “Vaisala” HM34C Humidity and Temperature Meter with 40mm sphere painted matte black.

**Table 3.2:** Indoor Climate Instrument Specifications.

Figure Reference	Figure 3.9	Figure 3.10	Figure 3.11	Figure 3.12	Figure 3.13
<b>Instrument</b>	“HOBO” U12-013 Temperature and Relative Humidity Datalogger	“HOBO” U12-013 Temperature and Relative Humidity Datalogger	“TSI VelociCalc” Anemometer (Model 8345)	“Vaisala HM34C” Humidity and Temperature Meter	“Vaisala” HM34C Humidity and Temperature Meter
<b>Attachments</b>		40mm sphere painted matte black ( $\epsilon = 0.99$ ) attached to TMC1-HD Water/Soil Temperature Sensor			40mm sphere painted matte black ( $\epsilon = 0.99$ )
<b>Variables (units)</b>	Air Temperature (°C); Relative Humidity (%)	Radiant Globe Temperature (°C)	Air Speed/Velocity (m/s)	Air Temperature (°C); Relative Humidity (%)	Radiant Globe Temperature (°C)
<b>Specifications</b>					
	<b>Range</b>	Air Temperature: -20 to +70°C; Relative Humidity: 5 to 95%	-40 to +50°C	0 to 30 m/s	Air Temperature: -20 to +60°C Relative Humidity: 0 to 100%
	<b>Accuracy</b>	Air Temperature: $\pm 0.35^\circ\text{C}$ ; Relative Humidity: $\pm 2.5\%$	$\pm 0.25^\circ\text{C}$ (at 20°C)	$\pm 0.015$ m/s (or 3% of reading)	Air temperature: $\pm 0.3^\circ\text{C}$ (at 20°C) Relative Humidity: $\pm 1\%$ (at 20°C)
	<b>Resolution</b>	Air Temperature: 0.03°C; Relative Humidity: 0.03%	0.03°C (at 20°C)		Air Temperature: 0.1°C Relative Humidity: 0.1%
<b>Sampling Technique</b>	1 sample measured every 5 minutes	1 sample measured every 5 minutes	Time constant: 10 seconds; 3-5 samples averaged over a 1 minute period	3-5 samples averaged over a 1 minute period	3-5 samples averaged over a 10 minute period

### 3.4.2. Clothing Insulation Estimates

Throughout the thermal comfort project, standardised clothing garment checklists were used to track the subjects' clothing behaviour as it related to the concurrent indoor and outdoor climatic variations. Based on garment checklists defined in ASHRAE's Handbook of Fundamentals (ASHRAE, 2001), Standard 55 (ASHRAE, 2004) and ISO 7730 (ISO, 2003), clothing insulation (clo) values were differentiated according to those typically worn in summer (lightweight) and those typically worn in winter (heavyweight) (as seen in Table 3.3). As defined in Equation 3.1, intrinsic clo values ( $I_{cl}$ ) were calculated for each subject by adding the value of each article of clothing circled on the subject's questionnaire:

$$I_{cl} = \sum_i I_{clu, i} \quad \text{Equation 3.1}$$

where  $I_{clu, i}$  is the effective insulation value of the  $i^{th}$  garment (ASHRAE, 2001).

Although clothing ensemble insulation values were calculated based on the subjects' own self-assessment, some limitations may exist in the accuracy of this data. ASHRAE (2004) suggests that measuring ensemble insulation values from checklists of published garment values (the method used in this project) is likely to deviate  $\pm 25\%$  (0.1-0.2 clo) from the benchmark thermal manikin measurements due to differences in fabric material, construction and fit, as well as variations in people's different definitions of certain garments and clothing layers. The subjective self-assessed method represents the most practical solution to the need for high-speed observations in a real-world setting. Nonetheless, in some cases, observations had to be made to verify the subject's clothing matched their response on the questionnaires. Whatever errors exist in the raw data, they are unsystematic and uniformly distributed throughout the sample.



**Table 3.3:** Individual clothing garments and their effective insulation values ( $I_{clu, i}$  (clo)). Ensemble intrinsic insulation values were derived by summing individual garment effective insulation values (ASHRAE, 2001; ISO, 2003; ASHRAE, 2004).

<b>Garment Description</b>	<b><math>I_{clu, i}</math> (clo) 'Thin'</b>	<b><math>I_{clu, i}</math> (clo) 'Thick'</b>	<b>Garment Description</b>	<b><math>I_{clu, i}</math> (clo) 'Thin'</b>	<b><math>I_{clu, i}</math> (clo) 'Thick'</b>
Bra	0.01	0.01	Short-sleeve dress shirt	0.17	0.19
Panties	0.03	0.03	Short-sleeve knit sport shirt	0.19	0.22
Men's briefs	0.04	0.04	Long-sleeve dress shirt	0.22	0.25
Singlet	0.04	0.04	Long-sleeve flannelette shirt	0.25	0.34
Half-slip	0.14	0.14	Short shorts	0.06	0.08
Long underwear bottoms	0.15	0.15	Walking shorts	0.08	0.12
Full-slip	0.16	0.16	Straight trousers	0.15	0.24
Long underwear top	0.20	0.20	Sweatpants	0.28	0.28
Neck-tie	0.05	0.05	Overalls	0.30	0.30
Ankle-length athletic socks	0.02	0.03	Knee-length skirt	0.14	0.23
Pantyhose/stockings	0.02	0.02	Sleeveless dress	0.23	0.27
Sandals/thongs	0.02	0.02	Short-sleeve dress	0.29	0.29
Calf-length socks	0.03	0.03	Long-sleeve dress	0.33	0.47
Shoes	0.02	0.02	Suit vest	0.10	0.17
Knee-socks	0.06	0.06	Single breasted jacket	0.36	0.42
Boots	0.10	0.10	Double breasted jacket	0.44	0.48
Short-sleeve T-shirt	0.08	0.10	Sleeveless vest	0.13	0.22
Long-sleeve T-shirt	0.12	0.16	Long-sleeve sweater	0.25	0.36
Sleeveless/scoop-neck blouse	0.13	0.17	Standard office chair	0.09	0.15
Scarf	0.05	0.05			

#### 3.4.2.1. Effects of Chair Insulation on Clothing Insulation

It is now generally accepted that an occupant's chair has the ability to inhibit heat loss from the body in the area of body-chair contact. This is likely to have some effect on the subject's thermal balance, and hence, augment the feeling of warmth (McCullough et al., 1994). Given that all participants answered the questionnaires while sitting in a standard office chair, these were included in the final calculation of each subject's clo value and subsequent comfort indices. Figures 3.14a and b show the most frequently encountered chair

type in these studies, which according to ASHRAE (2001) were estimated to add between 0.09 and 0.15 clo to the occupants' total clothing insulation.



**Figure 3.14:** Typical example of office chairs used in **a)** Building E4A and **b)** Building E7A.

#### *3.4.3. Building Management System Data*

Various sensors located within the interior and exterior of the MM building continuously relay information to the BMS to determine if the building's zones should be in either NV or AC mode. Obtained from MQ's Office of Facilities Management (OFM), this BMS data was useful in gathering information about how the building performs beyond what the dataloggers and subjective questionnaires could provide. Weather stations situated atop Building E4A recorded outdoor air temperature, precipitation, wind direction and wind speed every minute. Located in over 100 offices within the building, sensors recorded the internal air temperature and current mode of operation every 5 minutes. Recorded in 15 minute intervals, on an open or closed basis, the status of each window was also collected from the BMS.

#### *3.4.4. Outdoor Climate Measurements*

Local and concurrent outdoor meteorological data was obtained from many different sources for this thesis. Initially, it was decided that MQ's automatic weather station (AWS), located within the University's sports grounds (33°46' S, 151°7' E) about 1 km from the sample buildings, would be used extensively throughout both projects. However, due to technical difficulties encountered during the data collection stages, this source of data became unreliable and hence alternative sources were utilised. Outdoor climate data from the weather station atop Building E4A was obtained from the BMS data collected from OFM. The data included air temperature (°C), wind speed (m/s) and wind direction (°) at 1 minute intervals over the duration of the project. However, since other important outdoor weather variables were needed, additional sources of data were consulted. Two nearby weather stations serviced and operated by Australia's Bureau of Meteorology (BoM) were also used to gather outdoor weather data. It should be noted that while the BoM weather station at Willandra Village in Marsfield (33°78' S, 151°11' E) is located within 1 km from the University's campus, it is only used to record rainfall. As illustrated in Figure 3.15, the stations at Sydney Olympic Park in Homebush (33°84' S, 151°7' E) and Terrey Hills (33°68' S, 151°22' E) were located within a 10-13km radius of the campus. Recorded at 1 minute intervals over and beyond the period of each project, this data offered a multitude of outdoor climatic variables, including dry- and wet-bulb temperature (°C), relative humidity (%), wind speed (m/s), wind direction (°) and global surface radiation measurements ( $\text{W/m}^2$ ).



**Figure 3.15:** Location of nearby BoM weather stations in relation to Macquarie University (at red square). The Terry Hills and Sydney Olympic Park weather stations are located at the blue squares (sourced from BoM, 2011).

### 3.5. Data Analyses and Complementary Calculations

A wide range of quantitative and qualitative data was collected for this thesis. As such, statistical analyses were determined based on the type of data collected. For example, Oppenheim (2000) suggests that the statistical techniques applicable to quantitative data are means and standard deviations, two sample t-tests, F-tests, analysis of variances (ANOVA), regression models and correlation coefficients. Since qualitative data are not always measured along a continuum, alternative statistical methods had to be used, such as percentages, chi-squared tests and other non-parametric devices (Oppenheim, 2000).

### *3.5.1. Statistical Analyses*

To enable easy data storage, data were collated and entered into Microsoft Excel 2007 and analyses were performed using MiniTab (MiniTab versions 15.0 and 16.0 for Windows) statistical software. Data collected from the POE questionnaires were sent to Adrian Leaman to benchmark the scores against the BUS Australian green building database. As many of the climatic variables are continuous in nature, they could be analysed using linear regression models, providing the data met the appropriate assumptions for parametric tests (which they did). The relationship between clo values and the prevailing indoor and outdoor conditions was investigated using many techniques and methods derived from previous studies (Morgan and de Dear, 2003; de Dear, 2006; De Carli et al., 2007). More robust techniques were required for more complex analyses, such as probit regressions (Ballantyne et al., 1977). Scatter plots were useful in visualising these statistical analyses. Analyses that required comparisons among categorical variables, such as gender, mode or office location, were analysed using two sample t-tests and graphed using comparative box plots and column graphs.

### *3.5.2. Thermal Comfort Indices*

Many thermal comfort indices were used throughout both projects. ASHRAE's WinComf program (Fountain and Huizenga, 1997) was used to calculate the PMV and PPD values for each subject. Using these calculations and the adaptive thermal comfort model (de Dear and Brager, 2001) enabled the comparison of PMV and PPD values with the occupants' observed thermal sensation and acceptability, as expressed as Actual Mean Vote (AMV) and Actual Percentage Dissatisfied (APD).

### **3.6. Chapter Summary**

This chapter has outlined the methods used in this research. It introduced the study location; provided detailed information on each case study building, the questionnaires and survey techniques used within each project, as well as the collection of objective indoor and outdoor climate data. Since the majority of data collected for these projects were during Sydney's summer months, their results (presented in Chapter 4) will primarily focus on the use of air-conditioning for cooling purposes. The methods for data analysis and subsequent calculations have also been described. The following chapter provides the results and discussion of this thesis, with these largely being presented in three peer-reviewed journal articles.

## Chapter 4. Results and Discussion

In accordance with Macquarie University's guidelines for a thesis by publication, this chapter comprises peer-reviewed papers that have been published in, or submitted to journals during the course of this candidature. Complementary publications that have been published in peer-reviewed journals and/or conference proceedings are included in Appendices J to O.

The concept and design of each article were discussed with Professor Richard de Dear prior to the writing of each manuscript. Data collection, statistical analyses, interpretation of the results, and write-up of the manuscripts were all undertaken by the candidate with guidance from Richard de Dear in his role as Adjunct Supervisor.

The main results from this thesis are organised into three topics, each corresponding to a journal paper. Due to the varying stages of the publication of each paper, differences in their formatting will be found throughout this chapter. A section summarising the main topics within each paper and how they relate to the overall themes of the thesis, along with the limitations of this research, is presented at the end of this chapter. The three topics and corresponding publications are summarised below:

### **Topic 1: Environmental Attitudes and Occupant Satisfaction in Green Buildings**

Deuble, M.P. and de Dear, R.J. (2012) 'Green occupants for green buildings: The missing link?', *Building and Environment*, 56(10): 21-27

DOI: <http://dx.doi.org/10.1016/j.buildenv.2012.02.029>

## **Topic 2: Thermal Comfort in Mixed-Mode Buildings**

Deuble, M.P. and de Dear, R.J. (2012) 'Mixed-mode buildings: A double standard in occupants' comfort expectations', *Building and Environment*, 54(8): 53-60

DOI: <http://dx.doi.org/10.1016/j.buildenv.2012.01.021>

## **Topic 3: The Validity of Contemporary Post-Occupancy Evaluation Methods**

Deuble, M.P. and de Dear, R.J. (2012) 'Is it hot in here or is it just me? Validating the post-occupancy evaluation' (Submitted to *Intelligent Buildings International*, May 2012)



## **Paper 4.1. Environmental Attitudes and Occupant Satisfaction in Green Buildings**

**Status:** Published; Deuble, M.P. and de Dear, R.J. (2012) ‘Green occupants for green buildings: The missing link?’, *Building and Environment*, 56(10): 21-27

DOI: <http://dx.doi.org/10.1016/j.buildenv.2012.02.029>

**Journal Impact Factor (Thomson Reuters, 2012):** 2.131 (Ranked 3 of 53 Construction & Building Technology journals)

### *4.1.1. Paper Overview*

This paper investigates how environmental attitudes and beliefs may influence occupants’ tolerance of green buildings. POEs were conducted within the MM and NV buildings to record the occupants’ level of forgiveness and satisfaction with the building’s performance. These surveys were supplemented with the NEP environmental attitudes questionnaire to measure strength of endorsement (from low to high) of an ecological worldview. Occupants of the NV building, despite experiencing significantly warmer indoor temperatures, were more forgiving of these conditions than their MM counterparts. Likewise, the NV building, on average, recorded greater NEP scores than the MM building. Furthermore, a strong positive correlation between environmental attitudes and forgiveness factors was demonstrated within these two case study buildings. Despite their criticisms of the building’s IEQ, the ‘green’ occupants were prepared to overlook and forgive less-than-ideal conditions more so than their ‘brown’ (non-green) counterparts. These results provide evidence to support the hypothesis that pro-environmental attitudes are closely associated with the stronger ‘forgiveness factor’ often observed in green buildings.



## Green occupants for green buildings: The missing link?

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### ARTICLE INFO

#### Article history:

Received 2 December 2011

Received in revised form

12 February 2012

Accepted 26 February 2012

#### Keywords:

Green buildings

Post-occupancy evaluation (POE)

Forgiveness factor

New Ecological Paradigm (NEP)

### ABSTRACT

Green buildings, often defined as those featuring natural ventilation capabilities, i.e. low-energy or free-running buildings, are now at the forefront of building research and climate change mitigation scenarios. This paper follows the results of recent post-occupancy evaluation (POE) surveys within two academic office buildings located in sub-tropical Sydney, Australia. Supplemented with an environmental attitudes questionnaire, based upon the New Ecological Paradigm [1], it was found that occupant satisfaction levels on the POE were positively associated with environmental beliefs. Occupants with higher levels of environmental concern were more forgiving of their building, particularly those featuring aspects of green design, such as natural ventilation through operable windows. Despite their criticisms of the building's indoor environmental quality, the 'green' occupants were prepared to overlook and forgive less-than-ideal conditions more so than their 'brown' (non-green) counterparts. These results support the hypothesis that pro-environmental attitudes are closely associated with the stronger 'forgiveness factor' often observed in green buildings, but the question of causality remains moot.

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### 1. Introduction

The built environment contributes greatly to global energy use and greenhouse gas emissions [2]. Fossil fuel energy used directly, or, as electricity to power equipment and condition the air (including heating and cooling) within commercial buildings is by far one of the largest source of emissions in the built environment. Australian commercial buildings account for an estimated 27% of the total greenhouse gas (GHG) emissions within the buildings sector [3,4]. In energy terms, space heating, ventilation and air-conditioning combined represent the largest end-use in commercial buildings, accounting for almost two-thirds (61.2%) of total energy use; the other major end user is lighting (18.6%) and general uses (19.2%) [4].

Contemporaneous concerns over global warming and escalating fossil fuel prices have rapidly emerged into public consciousness. Over the last few years the world has witnessed a momentous change as governments, economies and businesses prepare for a carbon constrained future. Today, architects strive towards ambitious designs which often stretch the ability of building service engineers to provide robust, low-energy solutions [5–9]. With

present attempts at mitigating global warming, the buildings sector offers the greatest potential for cost-effective reductions in GHG emissions through the application of both technical and non-technical measures to existing building stock and new construction [2,10].

#### 1.1. Adaptive thermal comfort

Current practices in office buildings typically provide static thermal environments for all occupants using centralised heating, ventilation and air-conditioning (HVAC) technology. However, many adaptive comfort studies (e.g. [11,12]) have called for greater indoor environmental variability, either through user adjustments to operable windows, shade devices, etc., or automated controls shifting HVAC set-points in sync with weather and seasonal variations outdoors. A shift towards greater indoor climatic variability is integral to many sustainable building design solutions. Green buildings (also referred to as green-intent buildings) by definition, aim to reduce their environmental impact by using less energy in both their construction and operation. Thus, buildings featuring natural ventilation capabilities are typically defined nowadays as green buildings. Building users will often employ a wide range of passive cooling strategies and adaptive opportunities [13] available to them to adjust their own comfort conditions to suit their needs.

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It is widely believed that occupants prefer a high degree of adaptive opportunities [13], as can be provided within naturally ventilated (NV) buildings as opposed to centrally controlled air-conditioned (AC) designs. Many studies have found occupants are more favorably disposed to green buildings than their conventional energy-intensive predecessors [14–16]. Within their extensive database of post-occupancy evaluation (POE) studies, Leaman and Bordass [16] observed that occupant satisfaction scores for green buildings tend to be higher than those in conventional AC buildings. But despite occupants preferring greater adaptive opportunities, they do not necessarily *expect* the thermal excursions that sometimes occur in NV buildings, especially during heatwaves. Occupants are often prepared to “forgive” such conditions if they possess a modicum of personal environmental control [17–20].

## 1.2. Post-occupancy evaluation (POE) and the forgiveness factor

The POE has become an important tool for the improvement of building design and operations [21–23]. However, with clients often broadening their interests to include indoor environments, occupant health and productivity, gaps were often found between client and design expectations for a specific performance level [24]. Faced with the challenge of reducing building and energy costs to accommodate the expansion of its building industry, the UK's Building Use Studies (BUS) launched the PROBE project, which consisted of a series of POE studies for a wide range of non-domestic buildings [24]. This project helped develop a standardised POE method; accumulating a wide range of studies around the world into a BUS database against which future building POE studies could be benchmarked [25].

Recent POE studies from the UK [16] and USA [14,15] suggest that occupants of green buildings tend to forgive minor discomforts provided they can exercise a modicum of personal indoor environmental control. Coined by BUS, the ‘forgiveness factor’ [16] is an attempt at quantifying how occupants extend their comfort zone by overlooking inadequacies of their thermal environment [26,27]. Illustrated in Eq. (1) below, this index is derived by dividing ‘comfort overall’ scores on the BUS questionnaire by the average of the indoor environmental quality (IEQ) variables; overall temperature in summer (TempS) and winter (TempW), overall ventilation/air in summer (AirS) and winter (AirW), overall noise (Noise) and overall lighting (Light). All variables are rated along 7-point Likert scales ranging from 1 (unsatisfactory) to 7 (satisfactory). Many researchers agree that although green buildings often tend to be hotter in summer, colder in winter and have more glare from the sun and sky than their conventional AC alternatives [14,15], the occupants tend to be more forgiving. Furthermore, Kwok and Rajkovich [27] discuss this toleration of moderate discomfort and suggest that occupants may have an understanding of, and connection with the outdoor climate by virtue of the building's design, suggesting that increased knowledge of the adaptive opportunities in buildings, such as operable windows, individual shade control, aesthetics and glazing area, etc. yields a greater likelihood of reduced discomfort [16].

## 1.3. Environmental attitudes, behaviours and the New Ecological Paradigm (NEP)

In recent decades there has been a growing awareness of the problematic relationship between modern industrialised societies and the physical environments upon which they depend [28,29]. With the emergence of pervasive environmental problems such as climate change, many researchers have started exploring how to quantify public sentiment on these issues. Environmental attitudes represent a psychological tendency expressed by evaluating the natural environment with some degree of favour or disfavour [30,31]. Attitudes are related to other psychological and cultural dimensions, e.g. beliefs, intentions and behaviours. Since attitudes are a latent construct, they cannot be measured directly, and thus need to be inferred from overt responses [32]. A proliferation of environmental attitudinal measures has been proposed since the 1960s, the problem arises of using a reliable and valid set of measures or scales in order to quantify the unquantifiable [30,33].

The New Ecological Paradigm (NEP) Scale [1] is a revision of the NEP developed by Dunlap and van Liere [34]. This 15-item questionnaire consists of 8 pro-NEP and 7 anti-NEP items developed to measure strength of endorsement (from low to high) of an ecological worldview [29,35]. After extensive application across a diverse range of studies, a broad consensus is emerging in the environmental psychology literature that the NEP represents a valid and reliable scale for measuring levels of ecological beliefs and behaviours [36]. Despite its extensive use, the NEP scale has not been used in conjunction with building occupant studies and could potentially identify the link between successful occupancy of green buildings and environmental attitudes. Thus this paper investigates the hypothesis that broad environmental attitudes are closely associated with the stronger ‘forgiveness factor’ often observed in green buildings.

## 2. Methods

### 2.1. Sydney's climate

The Sydney metropolitan region is located on the eastern coast of Australia (34°S, 151°E) and is characterised by a moderately temperate, sometimes called humid sub-tropical climate. Influenced by complex elevated topography surrounding the region to the north, west and south and due to close proximity to the Tasman Sea to the east, Sydney avoids the high temperatures commonly associated with more inland regions, as well as the high humidity of tropical coastal areas [37]. The summer months of December to February can be described as warm-to-hot with moderate-to-high humidity peaking in February to March. Between June and August, Sydney experiences cool-to-cold winters. The tertiary institution is located in Sydney's suburbs, 16 km out of the Central Business District of Sydney. Seasonal variations are fairly consistent with the greater metropolitan region with a mean summer daily maximum temperature of 26–28 °C, a mean winter daily maximum of 17 °C and an annual mean daily maximum of 22–23 °C. Mean minimum daily temperatures range from 5–8 °C in winter, to 17–18 °C over the summer months, with an annual daily minimum temperature of 11–13 °C [38]. Given these yearly seasonal variations, Sydney's

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$$\text{Forgiveness factor} = \text{Comfort overall} / \left( \frac{\text{AirW} + \text{AirS} + \text{TempW} + \text{TempS} + \text{Light} + \text{Noise}}{6} \right) \quad (1)$$

mild climate is well suited to natural ventilation design strategies for much of the year.

## 2.2. Case study buildings

Two academic office buildings were selected for this study; a mixed-mode (MM) building commissioned in 2006 and an NV building dating back to the 1960s. Both buildings have a comparable occupancy density of 0.03 occupants/m<sup>2</sup>. Both buildings also have North–South orientations, with North facades being directly irradiated from the Sun, creating warmer internal temperatures than the South-facing perimeter zones:

1. *Mixed-mode building*: the MM building (see Fig. 1) features operable windows on all perimeter cellular offices arranged along North and South facades which have separating them an AC central open-plan office zone. Indoor temperature and outdoor weather sensors drive the Building Management System (BMS) to switch to AC mode when zonally averaged indoor temperatures increase above 25 °C. Around 200 academic and administrative staff from economics and finance disciplines occupy this building. Normalised according to the total usable floor area (the total area of all interior spaces in a building which are leasable to tenants, i.e. not including base-building areas like stairways, corridors, lift-wells, etc.), the building consumes 145 kWh/m<sup>2</sup> per annum, which is far less than conventional full-time AC buildings.
2. *Naturally ventilated building*: as illustrated in Fig. 2 below, the NV building used in this study features occupant-operated



Fig. 1. MM building (Sunny/north facade) featuring operable windows with external solar shading devices on north-facing windows.



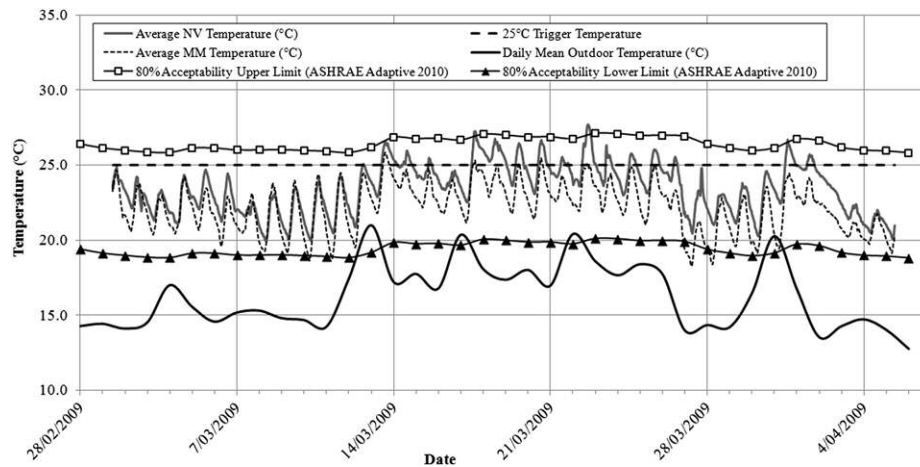
Fig. 2. NV building (North facade) featuring occupant-operated windows with some individual air-conditioner units.

windows and a narrow floor-plate traversed by a central corridor with single- and dual-occupant cellular offices on either side. There is no centralised heating or cooling systems inside this building. However, some exceptions have been given to occupants with individual window air-conditioner units, representing approximately 10% of the total building population. The building's total population of 200 occupants is composed of academic and administrative staff as well as post-graduate students from a variety of science-related disciplines. As the NV building consumes less energy per unit of usable floor area, i.e. 84 kWh/m<sup>2</sup> per annum, it is considered to be 'greener' than the MM building.

## 2.3. Measurements

Throughout the study, dataloggers have been randomly located throughout each building to record air temperatures and globe temperatures at 5-min intervals. Mean radiant temperature was calculated from the air and globe temperatures from the equation in ASHRAE [39]. Indoor operative temperature was thus calculated as the arithmetic average of air and mean radiant temperatures. Dataloggers were installed within 1-m of the subjects' workstation, so as to characterise the immediate thermal environment experienced by the occupant whilst working. In addition to indoor climate measurements, outdoor air temperature was also recorded during the survey period at a nearby automatic weather station on the same campus. Concurrent BMS data from the MM building during the survey period was collected from the University's Office of Facilities Management.





**Fig. 3.** Indoor and outdoor thermal environments comparing the NV and MM buildings for March 2009. Indoor data plots represent daily average of indoor operative temperature during occupied office hours (0800–1800 hrs).

#### 2.4. Questionnaires

Between March and April in 2009 (the Austral autumn), two questionnaires (the BUS POE and NEP) were distributed by hand to all staff in both buildings. For ease of collection and data matching purposes, questionnaires were administered together as a set. To preserve occupant anonymity, participants placed their completed questionnaires inside a blank, sealed envelope which was collected at the end of each day of the survey period. The two questionnaires used were:

1. *Post-occupancy evaluation*: the three-page BUS [40,41] POE is based on 7-point Likert scales with space for commentary, covering variables relating to occupant indoor environmental quality (IEQ) satisfaction, e.g. thermal, visual and acoustic comfort, indoor air quality, perceived health and productivity, and general acceptability of the workplace. The BUS methodology is further detailed in BUS [41]. Combinations of these Likert scores enable the calculation of BUS comfort and satisfaction indices, as well as the forgiveness factor (as defined in (1)). These questionnaires, in accordance to the original BUS methodology, were delivered in person to each occupant within the building.
2. *New ecological paradigm*: the environmental attitudes questionnaire is a 15-item version of the NEP Scale [1], using 5-point response scales ranging from *Strongly Disagree* to *Strongly Agree*, with higher scores on the scale from 1 (low) to 5 (high) indicating greater levels of environmental concern. All scales were converted to a NEP score by summing each item response and dividing by the total number of items in the scale. Results were analysed using MiniTab statistical software.

### 3. Results

In order to show the differences between each building based on objective measurements, i.e. internal temperature, it is instructive to show how both buildings performed under identical weather conditions. In order to generate congruent results under similar climatic conditions, both studies were conducted between the Autumn months of March and April in 2009 and 2010.

#### 3.1. Thermal environment

From operative temperatures averaged across all dataloggers, it was established that the NV building experienced significantly

warmer temperatures (average = 23.5 °C,  $p = 0.000$ ) than the MM building over the same period (average = 22.2 °C). Fig. 3 highlights discrepancies between the internal operative temperatures within these buildings. Temperatures inside both buildings were far greater than the surrounding outdoor air temperature throughout the day (mean = 16.3 °C,  $p = 0.000$ ). As an NV building, internal temperatures closely tracked changes in outdoor weather conditions, whereas the MM building maintained its indoor temperatures within a narrower band. Fig. 3 indicates that indoor operative temperatures within the MM building rarely exceed 25 °C due to the BMS switching into AC mode whenever average air temperatures reached the 25 °C trigger temperature. Less than 10% of occupied office hours (i.e. 8 am–6 pm weekdays) within this building experienced indoor operative temperatures greater than 25 °C. In contrast, temperatures inside the NV building varied between 20–28 °C. Internal temperatures in the NV building exceeded the 25 °C threshold almost 50% of all occupied office hours.

Using a 7-day running average of daily mean outdoor temperatures,<sup>1</sup> Fig. 3 also presents the 80% thermal acceptability band limits derived from the ASHRAE Standard 55 adaptive comfort model [46]. These represent ASHRAE's suggested range of internal operative temperatures that should not be exceeded within the occupied zone [44,45]. As illustrated in Fig. 3 below, average temperatures inside the NV building exceeded the upper limit of acceptable adaptive comfort on four separate occasions in March. In contrast, the MM building never exceeds these limits; in fact indoor temperature only exceeded the 25 °C trigger temperature on three occasions.

#### 3.2. POE and NEP analysis

In following the BUS methodology [41], both questionnaires were delivered to all staff in each building and were collected at the end of the day. In total, 163 POE and NEP questionnaires were

<sup>1</sup> Nicol and Humphreys [42] expresses a simplified version of the 7-day running mean temperature ( $T_{rm}$ ) equation:  $T_{rm} = (1 - \alpha)T_{od-1} + \alpha T_{rm-1}$  Where  $\alpha$  is a constant (0.8), and  $T_{od-1}$  and  $T_{rm-1}$  are the daily mean outdoor temperature and running mean temperature for the previous day respectively. In a detailed analysis of 7-day running mean equations using various decay values, de Dear [43] observes that a running mean with  $\alpha = 0.8$ , as recommended in Nicol and Humphreys [42], shows small responses to the sudden weather transients as compared to the same equation with  $\alpha = 0.6$  [44,45] which more closely matches the outdoor air temperature.

**Table 1**

A summary of POE and NEP results for the MM and NV buildings.

Study variable	MM (n = 86)	NV (n = 69)	Significance
Forgiveness factor <sup>a</sup>	0.99	1.14	$p = 0.032$
Comfort index <sup>b</sup>	−0.39	0.28	Not sig.
Satisfaction index <sup>c</sup>	0.02	0.10	Not sig.
Perceived productivity <sup>d</sup>	−5.34	−8.24	$p = 0.000$
NEP <sup>e</sup>	3.69	3.99	$p = 0.002$

<sup>a</sup> Forgiveness factor typically ranges from 0.8 to 1.2, with scores greater than 1 taken to indicate greater tolerance to the building's indoor environment.

<sup>b</sup> The Comfort Index is calculated as an aggregate of scores for temperature in summer and winter, ventilation in summer and winter, noise, lighting and overall comfort variables. The index scores from −3 to +3 with 0 being regarded as the optimal result.

<sup>c</sup> The Satisfaction Index is derived from an aggregate of scores for design, needs, health and productivity. This index ranges from −3 to +3 with 0 being regarded as the optimal result.

<sup>d</sup> Perceived productivity scores are self-assessed by the subject along a 9-point scale, ranging from −40% decrease to +40% increase in overall productivity with scores above 0 regarded as positive.

<sup>e</sup> NEP scores range from 1 to 5 with scores greater than 3 taken to indicate pro-environmental levels of concern.

distributed in the MM building and 120 in the NV building.<sup>2</sup> With a 53% response rate, the MM building returned 86 completed questionnaires (39 males, 47 females), and 69 (30 males; 39 females) were completed from the NV building (57% response rate). Incomplete responses were omitted from the samples after basic quality assurance. POE responses for both buildings were benchmarked against the Australian BUS database (as summarised in Table 1). The NEP questionnaire items were tested for internal consistency and were found to have strong coefficient alphas ( $\alpha = 0.82$ ) suggesting good internal consistency.

As shown in Table 1, both buildings generally measure poorly in regards to the POE summary variables, such as comfort and satisfaction. As mentioned above, the NV building had internal temperatures much closer to the acceptable upper limit (as defined by ASHRAE 55-2010 adaptive standard) compared to the MM building. However, it was found that this building's average forgiveness factor (1.14) was significantly higher than that for the MM building (0.99,  $p = 0.032$ ), with scores greater than 1.0 indicating greater levels of tolerance [16]. The NV building had a significantly higher mean NEP score (3.99,  $p = 0.002$ ) than the MM building (3.69), plausible for the majority of environmentally focussed academics occupying the NV building. Contrary to the stereotype, the NEP score for the MM building is relatively high for occupants associated with economics, finance and business studies as scores greater than 3.0 generally indicate pro-environmental attitudes.

In order to analyse environmental attitudes and their relationship to forgiveness factors within each building, it was important to isolate a control group whose scores would not be biased towards any pro-environmentalism, i.e. those occupants that do not teach in any environmentally-related disciplines. Ewert and Baker [47] suggest that environmentally based academics will often have higher NEP scores compared to academics of non-environmental disciplines. The NV building is occupied by academics from a variety of science-based disciplines, including environmental science. In order to eliminate any potential bias in the NEP scores, these occupants were subsequently categorised according to those who teach in the environmental sciences (labelled as the 'Eco' group) and those who teach in non-environmental science

**Table 2**

Analysis of forgiveness factor and NEP results for the MM and NV building.

Study variable	MM (n = 64)	NV eco (n = 29)	Significance
Forgiveness factor	0.99	1.17	$p = 0.002$
NEP	3.69	4.04	$p = 0.005$

Study variable	MM (n = 64)	NV control (n = 40)	Significance
Forgiveness factor	0.99	1.04	$p = 0.04$
NEP	3.69	3.62	Not sig.

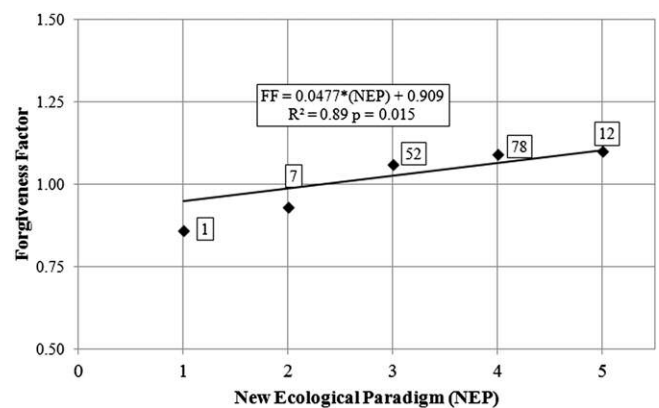
(e.g. Mathematicians, Physicists and Astronomers were collectively labelled as the 'Control' group). This group was therefore analysed separately from the environmentally inclined or 'Eco' group within the NV building (summarised in Table 2).

Table 2 indicates that the environmental (Eco) occupants of the NV building had significantly higher NEP scores (4.04) than those located inside the MM building (3.69,  $p = 0.005$ ). However, the 'control' occupants had very similar NEP scores (3.62) compared to the occupants of the MM building (0.99) was significantly lower than those measured in the MM building (0.99) was significantly lower than those measured in both staff groups of the NV building (Eco = 1.17,  $p = 0.002$ ; Control = 1.04,  $p = 0.04$ ).

Since the NEP questionnaire items are measured across a 5-point Likert scale, responses were binned according to their item response (from low to high, 1–5). Weighted according to the number of forgiveness factor samples within each NEP bin, a linear regression model was fitted to test any correlation between NEP and forgiveness factor scores for these two case study buildings. As illustrated in Fig. 4, there is a strong positive correlation between environmental attitudes and forgiveness factors ( $R^2 = 89\%$ ,  $p = 0.015$ ) suggesting higher levels of environmental beliefs yielded higher levels of tolerance.

#### 4. Discussion

With higher temperatures recorded in the NV building (Fig. 3), it is reasonable to expect that productivity (self-assessed) at temperatures up to 28 °C would be lower than in the MM building (shown in Table 1). Both case study buildings possess similar degrees of occupant-orientated environmental control, or adaptive opportunities [13] to control air movement/ventilation (operable windows) and lighting (shades, artificial lighting). The only difference being the MM building uses centralised HVAC whenever indoor temperatures exceed the 25 °C trigger temperature. Despite



**Fig. 4.** Relationship between NEP and forgiveness factor (FF) scores for both study buildings combined. Numbers next to data points represent sample size for weighted linear regression model.

<sup>2</sup> Questionnaires were administered to all occupants located on floors 6–8 in the NV building between March and April 2009. A separate follow-up study was conducted in March 2010 using the rest of the occupants (located on floors 2–5).

**Table 3**  
Forgiveness scores by ventilation type: Australian BUS database ( $n = 45$ ).

Study variable	Australian BUS database		This study	
	Green (NV, ANV, MM)	AC	MM	NV
Forgiveness factor	1.02	0.99	0.99	1.14
$n$	22	23		

Note: Higher values indicate occupants more tolerant or 'forgiving' of the conditions. Building types include natural ventilation (NV), advanced natural ventilation (ANV), mixed-mode (MM) and air-conditioning (AC).

this, occupants have often complained about indoor temperatures in summer months, particularly on the north-facing facades. This anecdotal feedback is consistent with a trend emerging from Australian green buildings that have undergone the BUS POE [26]. In comparing 22 green buildings against 23 conventional HVAC office buildings, Leaman et al. [26] reported that green buildings were perceived as hotter in summer and cooler in winter. Green buildings, such as the NV and MM buildings in this study, are expected to perform this way. In comparing the 'forgiveness' scores from Leaman et al. [26] (as summarized in Table 3 below) to those results in Table 1, it was found that the MM building in this study is poorly perceived by its users (forgiveness = 0.99, equal to that of conventional AC buildings in Australia). In contrast, the NV building occupants showed greater tolerance to perceived thermal variance (forgiveness = 1.14), consistent with other green buildings already in the BUS Australian database.

The correlation of NEP and forgiveness factors scores shown in Fig. 4 supports the hypothesis that green building users are more prepared to overlook and forgive less-than-ideal conditions than their 'brown' (non-green) counterparts suggesting there is a possible link between occupant satisfaction and environmental attitudes. Whilst the NEP Scale was originally designed to measure environmental concern of the general public, with both samples containing tertiary-educated participants there is a limit to what can be drawn from these results. Nonetheless, it amplifies how occupant attitudes and expectations play an important role in the way green buildings are designed, built and received.

## 5. Conclusions

It has been previously argued that in order for green buildings to perform effectively in the context of a low-carbon future, a shift is required from conceptualizing the occupant as a passive recipient of indoor conditions, to the inhabitant who may play a more active role in the maintenance and performance of their building [48,49]. Indoor environment research on thermal comfort [17,18] has shown that users are more tolerant of conditions where they have more control, irrespective of whether conditions are physically any different. One would expect the MM building to have a relatively higher forgiveness factor than AC buildings in the Australian BUS database. But these results reflect the nature of the occupants regardless of the degrees of control or adaptive opportunities offered by the building. Users appear to be happier if they understand how the building is supposed to work either because the design intent is made clear and/or because the controls are easy to understand and work well.

Green buildings have greater thermal variations compared to their AC counterparts, in which centralised HVAC provides static indoor temperatures to all occupants all-year round. This paper suggests green building users are more forgiving of their building, consistent with the hypothesis that 'green' buildings work best with 'green' occupants. Whilst the study only represents two 'green' office buildings from a tertiary institution in Sydney, Australia, it highlights the increasing awareness to the

psychological dimensions of occupant adaptation, such as attitudes, expectation and control. However, future studies across a broader sample of buildings are needed to understand how occupants' pro-environmental attitudes influence their tolerance of green buildings. In doing so, the causality between forgiveness factor and green buildings can be investigated further. Given the urgency to mitigate global warming, it has become apparent that people's attitudes, and the behaviours they entail, can be shifted. Whilst buildings take years to build or months to retrofit, the path to altering people's expectations of the built environment presents another, potentially more accessible strategy. According to this study, the forgiveness of green buildings can be cultivated. Given the multitude of sustainable and pro-environmental behaviour literature, there is great potential for occupants to be 're-educated' about the role buildings play in addressing global climate change. The emergent practical applications of adaptive building design calls for the clear communication of intent by designers to the users and building managers to ultimately assist in the transition to an energy efficient, low-carbon future.

## Acknowledgements

We are enormously grateful to Adrian Leaman for permission to use the BUS questionnaire under license and his assistance in data analysis. We would also like to thank Riley Dunlap for his valuable comments and encouragements, and the University's OFM, especially Kerry Russell, for their support. Finally, and most importantly, we express our appreciation to all the building occupants who responded to the questionnaires.

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## **Paper 4.2. Thermal Comfort in Mixed-Mode Buildings**

**Status:** Published; Deuble, M.P. and de Dear, R.J. (2012) ‘Mixed-mode buildings: A double standard in occupants’ comfort expectations’, *Building and Environment*, 54(8): 53-60

DOI: <http://dx.doi.org/10.1016/j.buildenv.2012.01.021>

**Journal Impact Factor (Thomson Reuters, 2012):** 2.131 (Ranked 3 of 53 Construction & Building Technology journals)

### *4.2.1. Paper Overview*

This paper investigates how MM ventilation affects occupant comfort. In doing so, this study aims to test whether the adaptive comfort model can be applied to MM buildings, especially during times of natural ventilation. Coincident indoor and outdoor climate measurements along with 1359 subjective comfort questionnaires were collected between March 2009 and April 2010 from the MM building. Both observed thermal sensations (Actual Mean Vote - AMV) and those predicted using Fanger’s PMV-PPD model (PMV) show very strong correlations with the indoor operative temperature during AC mode. However, AMV values during natural ventilation did not conform to the predicted PMV values suggesting occupants were able to adapt across a fairly broad range of indoor operative temperatures. Differences in thermal perception were also apparent between these two modes. Within AC mode, a PMV = +1 (*slightly warm*) environment elicited significantly ‘warmer-than-neutral’ thermal sensations than the same thermal environmental conditions within NV mode, suggesting thermal perceptions were affected by the building’s mode of operation over-and-above the objective indoor climatic conditions. These discrepancies between thermal comfort during AC and NV mode emphasise the complexity of thermal perception and the inadequacy of using PMV models to describe occupant comfort in MM

buildings. Results from this study shed light as to how MM buildings, especially those featuring change-over control strategies, should be categorised in future comfort standards.



# Mixed-mode buildings: A double standard in occupants' comfort expectations

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## ARTICLE INFO

### Article history:

Received 6 December 2011

Received in revised form

24 January 2012

Accepted 25 January 2012

### Keywords:

Thermal comfort

Mixed-mode ventilation

Adaptive comfort standards

Adaptive model

## ABSTRACT

This paper investigates how mixed-mode (MM) ventilation affects occupant comfort by presenting results from a longitudinal field study within an academic office building from a tertiary educational institution in sub-tropical Sydney, Australia. The building automatically switches into air-conditioned (AC) mode whenever indoor temperatures exceed 25 °C. Coincident indoor and outdoor climate measurements along with 1359 subjective comfort questionnaires were collected. Thermal sensations during natural ventilation did not conform to those predicted using Fanger's PMV-PPD [1]. Differences in thermal perception were also apparent between these two modes. Within AC mode, a PMV = +1 environment elicited much 'warmer-than-neutral' thermal sensations than the same PMV = +1 environment within naturally-ventilated (NV) mode, suggesting thermal subjective perceptions were affected by the building's mode of operation over and above the objective indoor climatic conditions. These discrepancies emphasize the complexity of thermal perception and the inadequacy of using PMV models to describe occupant comfort in MM buildings. ASHRAE's Standard 55 [2] currently classifies MM buildings as AC buildings, and as such, limits the operation of these buildings to the more restrictive PMV-PPD range of indoor thermal conditions. In contrast, EN15251 [3] permits the more flexible adaptive comfort standard to be applied to buildings operating under NV mode. Results from this study favour EN15251's application of the adaptive comfort model instead of PMV-PPD to MM buildings when they are operating in NV mode.

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## 1. Introduction

Prior to the 21st century, office buildings were generally designed with a building-centred, energy intensive approach focussed on providing standardised indoor climates for all occupants by relying on heating, ventilation and cooling (HVAC) technology. Intended to minimise legal liability and maximise comfort, the primary purpose of HVAC was to maintain constant thermal environmental conditions throughout the interior aiming for an optimum 'steady-state' temperature setting based on Fanger's Predicted Mean Vote and Predicted Percentage Dissatisfied (PMV-PPD) model [1]. In contrast, more recent studies [e.g. [4–8].] have made the case for greater environmental variation inside buildings, either via user adjustments to windows and shade devices or by other adaptive opportunities that more closely match indoor thermal conditions to prevailing outdoor temperatures. This person-centred approach deliberately provides variability across time and space [9–11]. Spatially, thermally differentiated zones can

accommodate a variety of individual thermal requirements. Temporally, indoor temperatures can gradually drift towards outdoor conditions and encourage occupant adaptations such as clothing changes and use of operable windows. This paper investigates how MM ventilation affects occupant comfort by presenting results from a longitudinal field study within an office building located in sub-tropical Sydney, Australia. Both observed and predicted thermal sensation votes recorded in AC and NV modes were compared to test whether the adaptive comfort model can be applied to MM buildings, especially during times of natural ventilation. By evaluating the current definition and scope of the adaptive comfort standards in ASHRAE 55-2010 and EN15251-2007, the implications of this research are discussed in the context of whether adaptive comfort standards for NV buildings should be applied to MM buildings.

### 1.1. Adaptive thermal comfort and mixed-mode ventilation

The 'adaptive' thermal comfort model [5,12,13] has advocated the shift towards variable indoor thermal environmental conditions in support of sustainable building design, i.e. providing thermal comfort while reducing energy use and associated

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greenhouse gas emissions. The move towards sustainability involves decreasing the reliance on active systems and pursuing more passive strategies of building thermal control. One alternative is naturally-ventilated (NV) buildings with occupant-controlled windows; however, while people may prefer greater “adaptive opportunities” [4,14], they may not appreciate the thermally uncomfortable conditions potentially occurring in such buildings during unusually hot or cold weather conditions. ‘Mixed-Mode’ (MM) ventilation represents a way of combining the best features of NV and AC buildings [15,16].

Over 150 MM buildings around the world have been documented in an online register [17], however despite this increasing interest in enabling comfort whilst reducing reliance on HVAC systems and its subsequent energy consumption, there remains a lack of thermal comfort research conducted in these buildings. The basic concept of MM or ‘hybrid’ ventilation is to maintain satisfactory indoor environments whilst minimising the significant energy use and operating costs associated with air conditioning by alternating between and combining natural and mechanical systems. MM buildings provide good air quality and thermal comfort using an NV or ‘free-running’ mode whenever the outdoor weather conditions are favourable, but revert to mechanical systems for HVAC whenever or wherever external conditions make the NV option untenable for occupants [15,18–20]. Such a building requires intelligent control systems that can switch automatically between natural and mechanical modes in such a way that minimises energy consumption [21–23], and without compromising indoor air quality or thermal comfort of its occupants [24].

## 1.2. International comfort standards: ASHRAE standard 55 vs. EN15251

Existing international comfort standards, such as the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Standard 55 ‘Thermal environmental conditions for human occupancy’ [2], the Comité Européen de Normalisation (CEN) Standard EN15251 ‘Indoor environmental input parameters for design and assessment of energy performance of buildings: addressing indoor air quality, thermal environment, lighting and acoustics’ [3] and the International Organization for Standardization (ISO) Standard 7730 ‘Moderate thermal environments – calculation of the PMV and PPD thermal comfort indices’ [25] specify combinations of temperature and humidity, indoor environments and personal factors that will be deemed acceptable to 80% or more of the occupants. However, following the international standardisation of Fanger’s [1] PMV-PPD model of thermal comfort, subsequent comfort research, along with the revision of these standards, has been met with much political and industrial backlash. Earlier versions mainly cover thermal comfort under steady-state conditions based on laboratory experiments; however, more recent revisions have utilised global field study databases, e.g. ASHRAE RP-884 [13] and Smart Controls and Thermal Comfort (SCATS) [26]. This multitude of field data highlighted the inadequacy of ‘static’ models, like PMV-PPD for describing thermal comfort in ‘free-running’ buildings [13,26,27] which led to the inclusion of an adaptive comfort standard in the 2004 edition of ASHRAE’s Standard 55 as an alternative to the PMV-based method for NV buildings [12,28]. In the years following the publication of ASHRAE’s adaptive comfort model, a European counterpart named SCATS [24] replicated the exercise in a longitudinal design in which 26 offices located in European countries, such as France, Greece, Portugal, Sweden and the UK, were surveyed over approximately one year. Originally intended to develop a European adaptive comfort algorithm, the SCATS project was later used in the development of the adaptive comfort annex in the European EN15251 standard [3,24].

But at the time of ASHRAE 55-2004 going to press, insufficient comfort studies undertaken in MM buildings meant they were excluded from the scope of the adaptive comfort standard [28]. Despite the most recent revisions to the standard [2] the adaptive comfort standard is still constrained in scope to naturally conditioned, occupant-controlled spaces in which thermal comfort conditions are primarily regulated by operable windows. Furthermore, ASHRAE clarifies that when mechanical cooling systems are provided for the space, as is the case in MM buildings, the adaptive comfort standard is not applicable [12,29]. Thus, the potential flexibility offered by the standard is not available to hybrid buildings, which may operate in a passive, natural ventilation mode preferentially, equipped with only supplemental cooling/heating for peak periods; or to spaces where operable elements are not connected to the outdoors. As a result, such spaces or buildings must therefore resort to the more restrictive PMV-PPD method [4,12,28,29]. This begs the question as to why MM buildings are precluded from applying the adaptive comfort standard in their NV mode of operation. The European counterpart, EN15251 [3], mainly describes non-adaptive temperature limits for various building uses, e.g. offices, schools, etc. If certain conditions are met, i.e. (1) having access to operable windows; and (2) no strict clothing protocol, then the standard allows the use of the more relaxed (upper) temperature limits stated in the adaptive model of the standard (Annex 2) [3]. Furthermore, EN15251 allows the more flexible adaptive comfort standard to be applied to NV buildings which can include MM buildings during times when they are not employing mechanical cooling, i.e. whilst in NV or ‘free-running’ mode. Currently, the International Standard ISO 7730 [25] makes no allowance for differences in NV and mechanically cooled or ‘AC’ buildings, so it will not be discussed any further in this paper.

## 2. Methods

### 2.1. Sydney’s climate

The Sydney metropolitan region is located on the eastern coast of Australia (34°S, 151°E) and is characterised by a moderate subtropical climate. Influenced from complex elevated topography surrounding the region to the north, west and south and due to close proximity to the Tasman Sea to the east, Sydney avoids the high temperatures commonly associated with more inland regions of the same latitude [30]. The summer months of December to February can be described as warm-to-hot with moderate-to-high humidity peaking in February to March. Between June and August, Sydney experiences cool-to-cold winters. The study building site is located in the suburbs, 16 km north-west of Sydney’s central business district (33° 46’ S, 151° 6’ E). Seasonal variations range from mean summer daily maximum temperatures of 26–28 °C, a mean winter daily maximum of 17 °C and an annual mean daily maximum of 22–23 °C (as shown in Fig. 1). Mean minimum daily temperatures range from 5 to 8 °C in winter, to 17–18 °C over the summer months, with an annual daily minimum temperature of 11–13 °C [31]. Given the city’s seasonal variations, Sydney’s climate is well suited to MM buildings. For much of the year, thermal comfort indoors can be easily achieved through simple passive design principles and various adaptive behaviours employed by the occupants, such as opening/closing windows, adjusting their clothing or by change of position [32,33].

### 2.2. Case study building

The building is located within the Sydney metropolitan region. Commissioned in 2006, the building (presented in Figs. 2, 3a, b, 4a, b and 5 below) is a 7-storey office building occupied by

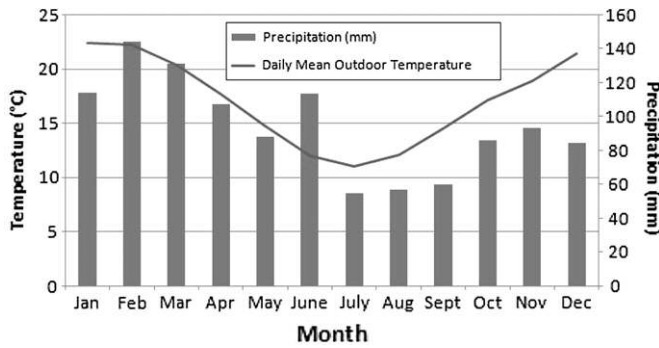


Fig. 1. Climatology of the case study building site [adapted from 31].

academic and administrative staff from a university Faculty of Business and Economics. This building forms part of a larger study and since it is co-located with a conventionally NV building occupied by the same organisation, makes it an ideal field study. As depicted in Fig. 2, the north and south perimeter zones consist of MM cellular offices with operable windows separated by a central open-plan office zone with full-time air-conditioning. Automated high and low external louvres provide natural ventilation to each floor, with adjustable internal grilles to control airflow, supplemented by user-operable windows with additional solar shading features over the northern (sun-facing) windows (Fig. 3a and b present the building as photographed from the north and south, respectively). Indoor temperature and outdoor weather sensors prompt the Building Management System (BMS) to switch (or 'change-over') into AC mode whenever a temperature greater than 25 °C is sensed within any zone. During AC mode, internal temperatures are maintained at 24 °C ( $\pm 1$  °C) as defined in the building's algorithm. BMS switch-over to NV is conditional when external meteorological conditions and the indoor thermal climate fall into an acceptable zone for the occupants. Fig. 4a and b show examples of the subjects' offices monitored throughout the study, indicating the location of the datalogger in relation to the occupant's workspace. As shown in Fig. 5, panels located at the entrance of each corridor indicate the current NV/AC mode of operation of each zone. By viewing these panels, building users know whether their office in their respective zone is in AC or NV mode. It should be noted that during NV mode, occupants are able to operate their windows. Whilst the building is in AC mode, windows can only be opened after the AC system has been active for at least 5 min.

### 2.3. Data collection and analysis

Simultaneous objective (indoor and outdoor climate) and subjective (self-assessed comfort perceptions) measurements were

collected throughout this study. Dataloggers were randomly located throughout the building to record air temperature, globe temperature and relative humidity at 5 min intervals throughout the study. The study was conducted over twelve months (March 2009–April 2010) to represent the full cycle of the seasons. Air velocity was measured during each questionnaire session using a handheld hot-wire anemometer (TSI VelociCalc). Loggers were placed within 1 m of the occupants' workstation to characterise the immediate thermal environment experienced by the occupant under normal working conditions. Outdoor weather observations were obtained from a nearby automatic weather station. The building's AC/NV mode status and indoor temperature records were collected from the BMS after the study had finished.

#### 2.3.1. Comfort questionnaires

Paper-based subjective comfort questionnaires were delivered to each participant in their normal workstation. Derived from ASHRAE-sponsored field experiments [34], the questionnaires were used to record occupant perceptions of their thermal environment on a 'right-here-right-now' basis. Subjects were asked to assess their thermal sensation along the ASHRAE 7-point scale, which included the possibility of fractional votes placed between two comfort categories. Thermal acceptability was addressed as a binary 'acceptable' or 'unacceptable' response with thermal preference being assessed on the 3-point McIntyre scale [35], wherein occupants listed if they preferred to be 'warmer', 'cooler' or 'no change'. The air movement questions focused on air movement acceptability as it related to the air speed. Subjects registered if the air velocity was 'acceptable' or 'unacceptable' and their reason, whether it was 'too low', 'too high' or 'enough' air movement. Subjects were also asked if they preferred 'more' or 'less air movement' or 'no change'. Standardised self-assessed clothing garment (clo) and metabolic activity checklists [36,37] within the subjective comfort questionnaires allowed the calculation of various comfort indices using ASHRAE's WinComf software [38], including Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD). Lastly, a section was added for the researcher to identify the location and mode of operation for each participant's office at the time of each questionnaire.

### 3. Results

Due to the ethical processes involved with the project, subject participation was purely voluntary, as is the case for many thermal comfort field studies. Whilst the initial response rate was low, representing approximately one third of the total building population, this is still comparable to field studies cited in the literature, such as [8]. Any bias in the results are likely to be negligible, however should be taken into consideration when drawing conclusions from this

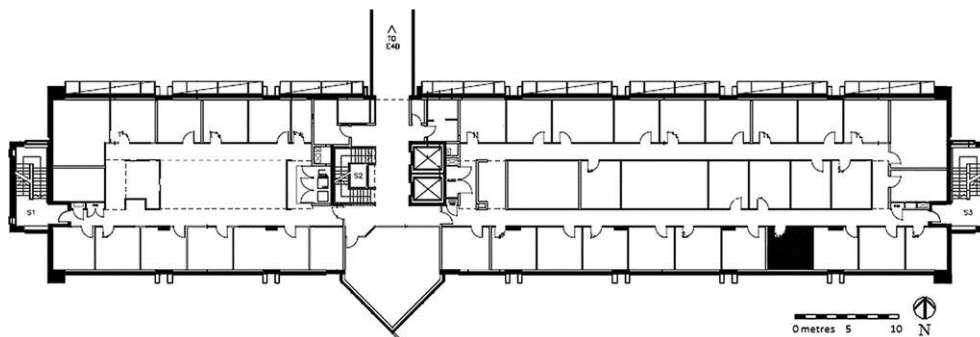


Fig. 2. Typical floor plan of the commerce building (shaded area indicates the location of the office in Fig. 4a and b).



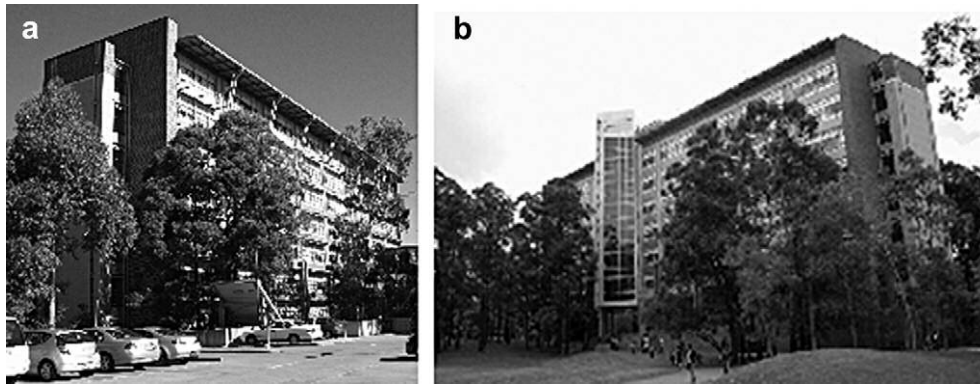


Fig. 3. The case study building as viewed from the a) North facade and b) South façade.

study. Nonetheless, a sample of 60 occupants was recruited for this study. A total of 1359 comfort questionnaires were completed (with an average of 23 responses per subject) during normal occupied office hours (0800–1800 h), with representative coverage of both genders (643 males and 716 females). At the time of each survey, the operational mode of each respective occupant's zone was noted, i.e. AC or NV mode via the AC display panel located at the entrance of each corridor (see Fig. 5). These were later verified using the building's BMS data wherein the status of each mode was logged in 5 min intervals across the duration of the study. The North and South perimeter offices switch between both AC and NV modes and the Central core is provided with constant air conditioning. Therefore, the Central zone has not been included in the following analyses because it does not operate under mixed-modes. It should be noted that, since the data was binned before plotting, linear regression analyses were therefore weighted according to the sample size within each degree bin (Figs. 6–10).

### 3.1. Thermal environment

Indoor operative temperatures calculated from the workstation dataloggers reveal the range of temperatures occupants experienced within the building. Fig. 6 below demonstrates the indoor operative and concurrent outdoor temperatures recorded throughout the study. It clearly demonstrates the internal environment (in both North and South zones) rarely exceeds an indoor operative temperature of 25 °C, suggesting the building's algorithm works well to maintain indoor temperatures within the 5 °C band (20 °C–25 °C) programmed into it. The graph in Fig. 6 represents the

average indoor operative temperature plotted against each 1 °C outdoor temperature bin. All internal temperatures that were recorded within the limits of each degree of outdoor temperature, i.e. between 21.5 and 22.49 °C, were counted and the average indoor operative temperature was calculated and plotted against its corresponding degree bin. Despite demonstrating significant correlations with the outdoor temperature, (AC Mode:  $p = 0.000$ ; NV Mode:  $p = 0.0018$ ), Fig. 6 suggests that outdoor temperatures only explained half of the variability in indoor operative temperatures in NV mode ( $R^2 = 48\%$ ) compared to those in AC mode ( $R^2 = 83\%$ ). This is likely due to the broader range of temperatures allowed during AC mode operation as opposed to the very narrow range of outdoor and indoor temperature conditions required for natural ventilation.

Table 1 below summarizes the key comfort parameters measured throughout this study. Two sample  $t$ -tests were performed to find any significant differences between each mode. Whilst the average air velocity, indoor operative temperature and relative humidity were relatively unchanged between the two modes, observed thermal sensations, i.e. Actual Mean Vote (AMV), during NV mode (0.43) were found to be significantly higher than those in the AC mode (0.19,  $p = 0.001$ ). Correspondingly, the average clo values reported within NV mode (0.50) were significantly lower than those recorded during AC mode (0.57,  $p = 0.000$ ) suggesting most people found the building to be slightly warmer during periods of natural ventilation possibly due to the increased indoor temperatures needed for the BMS algorithm to switch into AC mode. Due to these increases in indoor temperatures within NV mode, PMV and PPD values were also significantly different between the two modes. The average PMV was significantly higher



Fig. 4. a) Typical layout of occupant offices monitored throughout the study (office located in south zone as indicated in Fig. 2 above) and b) shows the location of the datalogger in relation to the occupant's workspace.

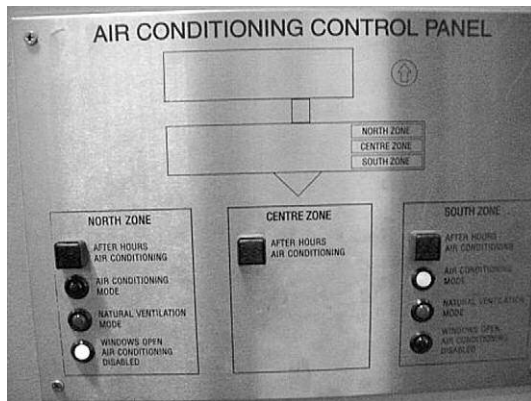


Fig. 5. Air-conditioning control panel located at the entrance of each corridor.

during AC mode ( $-0.15$ ) compared to the average PMV within NV mode ( $-0.32$ ,  $p = 0.000$ ). Consequently, PPD values between these two modes were also different, with AC mode generating a slightly lower percentage of dissatisfied peoples (12%) compared to those in NV mode (14%,  $p = 0.0015$ ). Actual Percentage Dissatisfied (APD) is derived from the ratio of occupants who found the immediate thermal environment unacceptable over those who found it to be acceptable. During AC mode, 27% of participants surveyed were dissatisfied with the thermal environment, whereas only 19% of subjects expressed dissatisfaction during times of natural ventilation. These values were found to be much higher than the calculated PPD values. Whilst these AMV and PMV results still represent neutral thermal sensation votes (between  $-0.5$  and  $+0.5$ ), they suggest that the switching of the building from one mode to the other may cause changes in how the occupants perceive their thermal environment. Accordingly, this paper will only focus on the results from the analysis of indoor operative temperature, and Actual and Predicted Mean Votes between each mode.

### 3.2. Actual vs. Predicted Mean Votes

Fig. 7 illustrates the range of individual thermal sensations recorded throughout the study in both modes (labelled as AMV) on which participants rated their level of comfort across a 7-point scale (ranging from Cold ( $-3$ ) through Neutral ( $0$ ) to Hot ( $+3$ )). It should be noted that participants were able to register votes in between each of the 7 comfort categories, e.g. if the subject placed a tick half way between Neutral ( $0$ ) and Slightly Warm ( $+1$ ), the vote was regarded as  $+0.5$ . Diamonds represent all individual

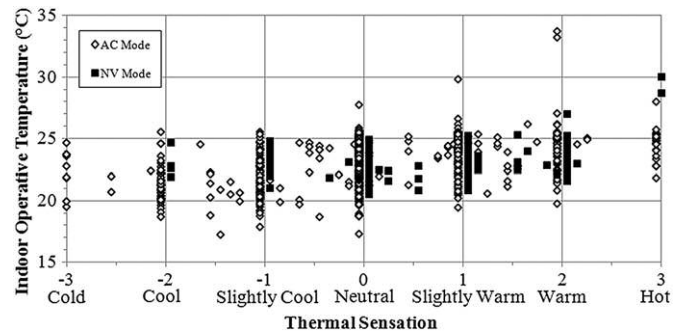


Fig. 7. Indoor operative temperature plotted against individual Actual Mean Vote (AMV) values recorded during AC mode (diamonds) and NV mode (squares).

comfort votes recorded during AC mode, and squares represent those measured in NV mode. In order to investigate how comfort was affected in a building that switches from AC to NV conditions and vice versa, it was necessary to perform separate statistical analyses for each mode. Figs. 8–10 present the average thermal sensation votes found within each  $1^\circ\text{C}$  wide indoor operative temperature bin. Indoor operative temperature represents a calculated index of air temperature, radiant temperature and air speed. All votes that were recorded within the limits of each degree were counted and the average response was calculated and plotted against its corresponding degree bin. Since the data was binned, linear regression analyses were weighted according to the sample size in each degree bin to ensure any outliers representing small sample sizes had relatively little effect on the slope of the model.

The graph in Fig. 8 presents weighted linear regressions of both observed thermal sensation votes (AMV) and those predicted using Fanger's PMV index on indoor operative temperature [1]. There are strong positive relationships for both AMV ( $R^2 = 95\%$ ) and PMV ( $R^2 = 97\%$ ) responses against the indoor operative temperature ( $p = 0.000$ ). AMV and PMV responses were then separated according to mode to investigate any differences between AC and NV modes.

The graphs in Fig. 9a and b present the results for AC mode and NV mode respectively. All correlations against the indoor operative temperature were found to be significant ( $p < 0.05$ ) showing strong positive relationships ( $R^2$  values ranged from 76% to 97%). Whereas the observed AMV values in Fig. 9a conform very well to the PMV-PPD model, there is a clear difference between thermal sensation and operative temperature during NV mode. The PMV model in Fig. 9b fails to predict thermal comfort when the building is in NV mode. Whilst eliciting strong correlations for AMV ( $R^2 = 76\%$ ,  $p = 0.003$ ) and PMV ( $R^2 = 91\%$ ,  $p = 0.000$ ) responses, the gentle gradient for observed AMV values suggests occupants were able to adapt across a fairly broad range of indoor operative temperatures

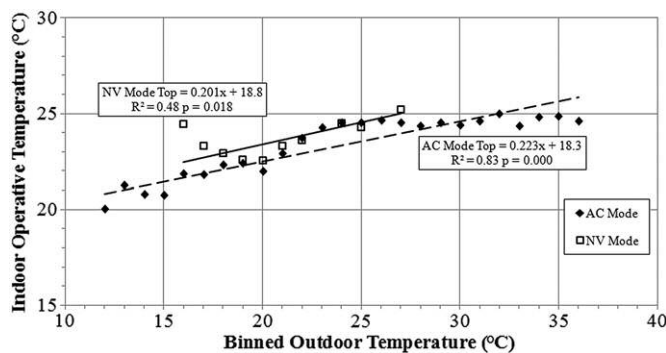


Fig. 6. Binned outdoor temperatures plotted against average concurrent indoor operative temperature ( $T_{op}$ ) for AC mode (dashed line with diamonds) and NV mode (solid line with squares).

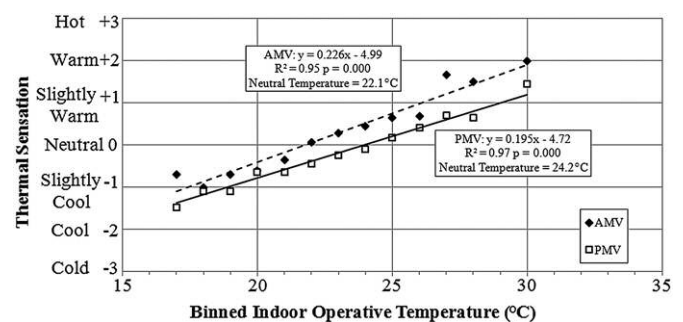


Fig. 8. Average observed (AMV – dashed line with diamonds) and predicted (PMV – solid line with squares) thermal sensation votes plotted against binned indoor operative temperature for both AC and NV modes of building operation.

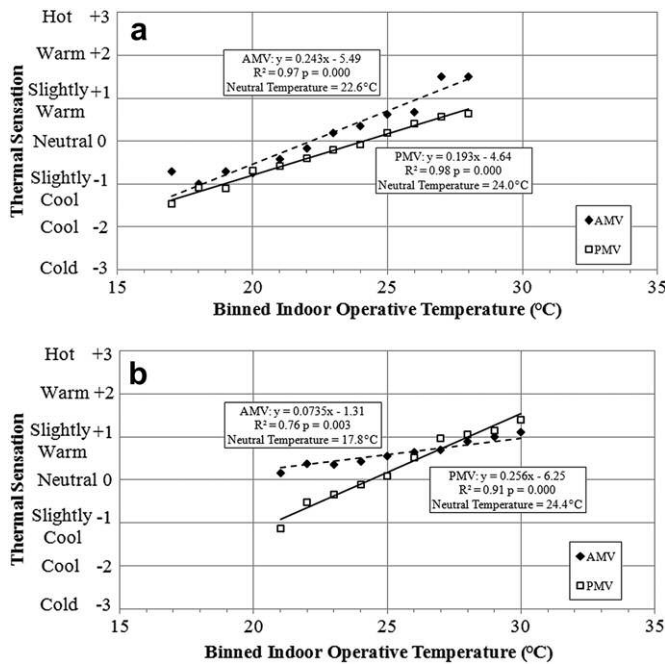


Fig. 9. Average observed (AMV – dashed lines with diamonds) and predicted (PMV – solid line with squares) thermal sensation votes plotted against binned indoor operative temperature for a) AC mode and b) NV modes of building operation.

but their thermal sensations seem to be permanently displaced into the 'slightly warm' region.

Fig. 10 below evidences the effects of adaptation during NV mode of building operation. As the slope of the line reaches zero, i.e. indicating negligible change in sensation across the entire range of indoor operative temperatures, then the occupants must be accommodating these diverse temperatures through a suite of 'adaptive opportunities' [4]. Consequently, as the AMV votes recorded during AC mode were well matched with those predicted using the PMV model and their regression coefficient is further away from zero compared to their NV counterparts, then the occupants are not adapting to the diverse temperatures experienced within this mode as well as their NV counterparts. Additionally, Fig. 10 also demonstrates the differences in thermal sensations between these two modes beyond what the thermal environmental conditions would suggest. Within AC mode, a +1 PMV environment elicited much 'warmer-than-neutral' thermal sensations compared to the same thermal environment during NV mode, suggesting thermal perceptions were affected by the

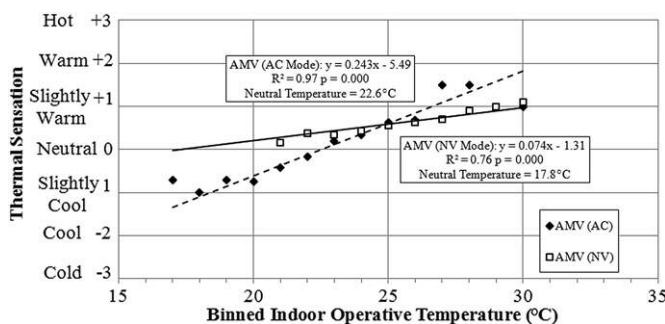


Fig. 10. Average observed (AMV) thermal sensation votes plotted against binned indoor operative temperature for AC mode (dashed line with diamonds) and NV mode (solid line with squares).

Table 1  
Summary of study variables and calculated indices for AC and NV modes.

Variable	AC mode (n = 804)	NV mode (n = 294)	Significance
Indoor Operative Temperature (°C)	23.29 °C	23.13 °C	$p = 0.175$
Relative Humidity (%)	52.8%	52.1%	$p = 0.403$
Air Velocity (m/s)	0.09 m/s	0.10 m/s	$p = 0.01^*$
Clothing Insulation (clo)	0.57	0.50	$p = 0.000^*$
Metabolic Rate (met)	1.20	1.22	$p = 0.05$
Self-Assessed Productivity (%)	−1.16%	0.90%	$p = 0.000^*$
Calculated Indices			
Actual Mean Vote (AMV)	0.19	0.43	$p = 0.000^*$
Actual Percentage Dissatisfied (APD)	27%	19%	NA
Predicted Mean Vote (PMV)	−0.15	−0.32	$p = 0.000^*$
Predicted Percentage Dissatisfied (PPD)	0.12	0.14	$p = 0.015^*$
Neutral Temperature (°C)	22.6 °C	17.8 °C	NA
Effective Temperature (ET*)	23.36 °C	23.19 °C	$p = 0.158$
Standard Effective Temperature (SET*)	24.03 °C	23.34 °C	$p = 0.000^*$

\*Indicates a significant difference with a  $p$ -value < 0.05.

building's mode of operation beyond biophysical heat balance differences.

#### 4. Discussions

The MM building operates as a passive NV building between the indoor operative temperatures of 20–25 °C. Demonstrated in Figs. 6 and 7, the BMS algorithm ensures comfortable conditions between these extremes, with internal temperatures rarely rising above 25 °C (some exceptions due to excessive solar heat gains on the north). If a temperature above 25 °C is sensed by the building's BMS sensors in any particular zone, air conditioning switches on for that zone, trimming indoor temperatures back towards the 24 °C set point ( $\pm 0.5$  °C). This is reflected in Table 1, suggesting occupants tend to feel slightly warmer leading up to an NV-AC mode switch-over event.

Figs. 8–10 present the key findings of this research, showing fundamental differences between the observed thermal sensation votes (AMV) and those predicted using Fanger's PMV-PPD model (PMV). Fig. 8 highlights the different neutral temperatures calculated from each model. On average, the AMV neutral temperature was 2.1 °C cooler than the PMV predictions. Both the observed and predicted thermal sensation votes show very strong correlations with the indoor operative temperature during AC mode (as shown in Fig. 9a, PMV:  $R^2 = 98\%$ ,  $p = 0.000$ ; AMV:  $R^2 = 97\%$ ,  $p = 0.000$ ). Both models successfully describe occupant comfort within this mode. Fig. 9b suggests that differences in thermal perception were also apparent between these two modes. During AC mode of operation, a +1 PMV (slightly warm) environment elicited significantly warmer-than-neutral thermal sensations than the same thermal environmental conditions under NV mode, suggesting thermal perceptions were affected by the building's mode of operation over-and-above any differences in actual thermal environmental conditions. By viewing the AC display panel (Fig. 5) upon entering the respective corridor to their office, occupants know the current mode of operation, either AC or NV. These findings suggest that once they are aware that the building has switched to NV mode, their expectations of the thermal environment change to correspond with changes in their degree of freedom to open their windows. It is also likely that the ratio of outdoor ventilation to air velocity would be greater under NV mode than in AC mode, so it is possible that improved thermal comfort under NV mode could have resulted from cross-modal



interactions between air quality and thermal comfort. Whilst previous studies reflect building-by-building comfort temperatures, such as de Dear and Brager [28] and Nicol and Humphreys [12], Fig. 10 clearly shows the adaptive model is best suited to explain occupant comfort during times of natural ventilation within the same building. When operating in AC mode, Fanger's PMV-PPD model shows good correlations with observed thermal sensations.

The adaptive comfort standards defined in ASHRAE Standard 55 [2] and EN15251 [3], based on the respective works of de Dear and Brager [28] and Nicol and Humphreys [12], were established as an alternative to PMV-PPD for NV buildings. Ongoing debates suggest the adaptive comfort standard should be applied as an operating guideline for the NV mode of MM buildings. Figs. 6 and 7 clearly show that interior temperatures can be allowed to float within the more energy-efficient acceptability limits of the adaptive comfort standard and still ensure comfortable conditions for the occupants. When temperatures reach the maximum limits then HVAC systems can be turned on in a limited way to ensure temperatures stay within the adaptive comfort standard limits (rather than switching to the narrow set points of a centrally-controlled AC building). Within the context of the American and European adaptive standards, results from this study favour EN15251's application of the adaptive comfort model instead of the PMV-PPD to MM buildings when they are operating in NV mode.

## 5. Conclusions

This paper investigates how occupant comfort is affected in a building that switches between AC and NV environments, i.e. in a MM building. Current international comfort standards still embody black-and-white definitions of AC and NV buildings. If a building is AC, then it typically doesn't have operable windows. According to ASHRAE Standard 55 [2] if a building is NV, then it doesn't have any mechanical cooling/heating systems, but typically has operable windows. However, the real world is not so simple. The most current version of ASHRAE Standard 55-2010 misclassifies MM buildings as AC and in doing so, not only limits the operation of such buildings to the more restrictive PMV-PPD range of indoor thermal conditions, but fails to maximise the energy saving potential of MM buildings. By comparing both observed and predicted thermal sensation votes recorded in AC and NV modes, the adaptive comfort model was found to be applicable to the MM building, especially during times of natural ventilation. In evaluating the current definition and scope of the adaptive comfort standards in ASHRAE 55-2010 and EN15251-2007, this paper provides evidence that MM buildings could in fact be defined as NV, with operable windows and supplemental cooling/heating during peak periods. Whilst this study represents one particular change-over MM case study in Sydney, Australia, many other types of MM buildings exist around the world, e.g. concurrent (where air-conditioning and operable windows are utilised in the same space and at the same time) and zoned (when passive and mechanical strategies occur at the same time but in different zones within the building). These findings help shed light as to how MM buildings, especially with change-over control strategies, should be categorised in future comfort standards. However, as more MM buildings are likely to be built in the future, more field studies (using different control strategies and in different climates) are needed to fully understand how MM ventilation affects occupant comfort and whether a new MM comfort standard should be established.

## Acknowledgements

This project was funded in part by an Australian Research Council Discovery Grant (DP0880968). We are enormously grateful

to Kerry Russell and the University's Office of Facilities Management for assistance in gathering data. We would like to express our appreciation to all the participants who gave their time to respond to our questionnaires.

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### **Paper 4.3. The Validity of Contemporary Post-Occupancy Evaluation Methods**

**Status:** Submitted May 2012; Deuble, M.P and de Dear, R.J. (2012) ‘Is it hot in here or is it just me? Validating the post-occupancy evaluation’, *Intelligent Buildings International* (Refer to Appendix P for corresponding emails)

**Journal Impact Factor:** Not applicable – new journal (started in 2009)

#### *4.3.1. Paper Overview*

Data gathered from the preceding studies (Papers 4.1 and 4.2) were used to investigate the differences in occupant satisfaction and comfort perceptions between each case study building, as well as between the POE and comfort questionnaires. Results from the POE surveys presented in Paper 4.1 suggest high levels of occupant dissatisfaction, especially in the MM building. In order to test the validity of these results, parallel thermal comfort studies were conducted to investigate the differences in occupant satisfaction and comfort perceptions between these two questionnaires. Instrumental measurements of each building’s indoor environment reveal that occupants tended to over-exaggerate their POE comfort responses. Analysis of thermal satisfaction and acceptability in each building indicate that occupants of the NV building were more tolerant of their thermal environment despite experiencing significantly warmer temperatures than their MM counterparts. In discussing these results, along with participant comments and anecdotal evidence from each building, this paper contends that POE does not accurately evaluate building performance, suggesting occupants can and do use POE as a vehicle for complaint about general workplace issues, unrelated to their building. In providing a critical review of current POE methods, this paper aims to provide recommendations as to how they can be improved, encouraging a more holistic approach to building performance evaluation.

# Is It Hot In Here Or Is It Just Me? Validating the Post-Occupancy Evaluation

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# Is It Hot In Here Or Is It Just Me? Validating the Post-Occupancy Evaluation

Journal:	<i>Intelligent Buildings International</i>
Manuscript ID:	12-IB046-RA.R1
Manuscript Type:	Research Article
Keywords:	Post-Occupancy Evaluation, Thermal Comfort, Performance Evaluation, Occupant Comfort, Indoor Environmental Quality

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**Abstract**

Historically, post-occupancy evaluation (POE) was developed to evaluate actual building performance, providing feedback for architects and building managers to potentially improve the quality and operation of the building. Whilst useful in gathering information based on user satisfaction, POE studies have typically lacked contextual information, continued feedback and physical measurements of the building’s indoor climate. They therefore sometimes over-exaggerate poor building performance. POEs conducted in two academic office buildings: a mixed-mode (MM) and a naturally-ventilated (NV) building located within a university in Sydney Australia, suggest high levels of occupant dissatisfaction, especially in the MM building. In order to test the validity of the POE results, parallel thermal comfort studies were conducted to investigate the differences in occupant satisfaction and comfort perceptions between these two questionnaires. Instrumental measurements of each building’s indoor environment reveal that occupants tended to over-exaggerate their POE comfort responses. Analysis of thermal satisfaction and acceptability in each building indicate that occupants of the NV building were more tolerant of their thermal environment despite experiencing significantly warmer temperatures than their MM counterparts. In discussing these results, along with participant comments and anecdotal evidence from each building, this paper contends that POE does not accurately evaluate building performance, suggesting occupants can and do use POE as a vehicle for complaint about general workplace issues, unrelated to their building. In providing a critical review of current POE methods, this paper aims to provide recommendations as to how they can be improved, encouraging a more holistic approach to building performance evaluation.

**Keywords:** Post-occupancy evaluation (POE), occupant satisfaction, adaptive thermal comfort, forgiveness factor, thermal acceptability

## 1. Introduction

*“Two buildings much alike in dignity, in fair Sydney, where we lay our scene...”<sup>1</sup>*

The main purpose of any building is to provide a safe and comfortable environment that neither impairs the health of its occupants nor hinders their performance. Buildings are primarily designed and built for their intended occupants, but in many cases this is done without much consideration of the buildings end-users' needs or preferences ([Vischer, 2001; Way and Bordass, 2005](#)). As a result, many occupants do not understand how to operate their building which can often lead to high levels of discontent (Leaman and Bordass, 2007). As building managers and designers continually strive to improve occupant satisfaction and productivity by ensuring comfortable and healthy working conditions, post-occupancy evaluation (POE) represents a systematic quality assurance process towards these ends.

POE is a global and rather general term for a variety of types of field studies in built environments based on assessing the responses, behaviour and perceptions of a building's occupants. In the past, POEs have been viewed as a means to measure the performance of a building from the occupant's perspective in a systematic and rigorous manner after they were built and occupied for some time ([Preiser et al., 1988; Preiser, 2001a; BCO, 2007](#)). Used extensively worldwide, POE studies aim to investigate whether buildings are performing as intended/designed. In effect, they provide 'feedback' to the architects and building managers on potential areas for improvement ([Vischer, 2004; Bordass and Leaman, 2005b](#)). They are often targeted towards the users' perception of the building rather than actual building performance metrics, such as energy consumption, temperature and humidity, lighting, noise, etc

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<sup>1</sup> Adapted from William Shakespeare's Romeo and Juliet, Act 1, Prologue

(Zimring and Reizenstein, 1980; Hartkopf et al., 1986; Preiser, 1995; Derbyshire, 2001; Nicol and Roaf, 2005). There are, however, many differing definitions of what constitutes POE. Within this paper, the authors define POE as a process of evaluating the performance of a building after it has been built and occupied for some time (Preiser et al., 1988). However, this paper argues that POEs should not only involve feedback from the building users, but also include the use of instrumental data, such as the measurement of indoor environmental quality (IEQ) indicators. Therefore, this paper aims to critically examine the validity of POE as a measure of a building's performance through user perceptions by comparing the results from POEs and thermal comfort studies conducted in two academic office buildings in Sydney, Australia. In analysing forgiveness factors and thermal sensation votes, along with occupants' comments, these results suggest that participants use POE surveys as a conduit for general complaint which may have nothing to do with the building in question.

***1.1. Post-Occupancy Evaluation: An Evolutionary Background***

Before we can effectively critique POE methods it is instructive to review the context in which they were originally developed. Up until the 1950s, systematic information on building performance from the occupants' perspective was not easily accessible. Following the rapid expansion of architectural projects in the UK in the 1960s, the Royal Institute of British Architects (RIBA, 1962) identified the need to gather and disseminate information and experience on the requirements of building users. The RIBA called for the study of buildings in use, from both the technical and cost points of view, as well as in terms of design (RIBA, 1962; Cooper, 2001; Derbyshire, 2001). The RIBA's Handbook of Architectural Practice and Management



(1965) was instrumental in defining the sequence of stages related to building construction, including briefing/programming, design, specification, tendering, completion and use ([Cooper, 2001; Preiser and Vischer, 2005; Preiser and Nasar, 2008](#)). This report also incorporated a final stage to the building life-cycle called 'feedback'. Within this stage, architects were advised to inspect their completed buildings after they had been built as a means of improving service for future clients ([Preiser, 2001b; Bordass and Leaman, 2005a](#)). Thus, the concept of 'POE' was born from this need to provide feedback to building managers on the performance of their building after completion ([Derbyshire, 2001; BCO, 2007](#)). Despite RIBA's best efforts, POE was largely ignored by the design and construction industry in the UK because of its potential to deliver evidence to clients about under-performance or just plain building design (Cooper, 2001; Hadjri and Crozier, 2009). [Following the large number of housing studies in the 1970s and 1980s in the USA](#), POE has steadily gained credibility as a mechanism of scientific inquiry for user satisfaction within buildings ([Preiser, 1995; Vischer, 2001; Bordass and Leaman, 2005a](#)). [However](#), it wasn't until the 1990s that the UK construction industry realised the true potential and value of POE as a significant development in architectural research (Cooper, 2001).

[Over the past 30 years, numerous adaptations and improvements have been made to POE methods \(Preiser and Vischer, 2005\)](#). The term POE was originally intended to reflect that assessment taking place after the client had taken occupancy of a building ([Preiser, 2001a; Zimring and Rosenheck, 2001](#)). Early descriptions focused on POE as a stand-alone practice aimed at understanding a building from the users' perspective ([Preiser, 2001a; Bordass and Leaman, 2005a; Preiser and Vischer, 2005](#)), and often included aspects of architectural design, technical performance, indoor climate, occupant satisfaction and environmental impact ([Zimring and Reizenstein,](#)

180; Hartkopf et al., 1985; Vischer and Fischer, 2005; Loftness et al., 2006; Gonchar, 2008). POEs are generally classified into three main types, as identified in Preiser et al., (1988): (1) Indicative POEs involve walk-through observations as well as selected interviews which typically raise awareness of the major strengths and weaknesses of a particular building's performance; (2) Investigative POEs carry out more in-depth evaluations and often comply with particular building performance standards or guidelines on a given building type. One of the most commonly found type of POEs, these provide a thorough understanding of the causes and effects of issues in building performance; and (3) Diagnostic POEs provide very detailed information about the buildings performance. These evaluations gather physical environmental data which are then correlated with subjective occupant responses (Preiser et al., 1988; Preiser, 2001a). However, more recent applications of POEs, especially in office buildings, fail to recognize the limitations of POE studies. Despite more recent POE discussions having emphasized the need for a more holistic and process-oriented approach to evaluating building performance (Preiser, 2001a; Vischer, 2001; Preiser and Vischer, 2005; Vischer, 2008a; Meir et al., 2009), such notions are yet to be transformed into practice.

1.2. Uses and Misuses of Post-Occupancy Evaluations in Buildings

Over the past four decades, POE has become a widely used tool in evaluating building performance (Preiser et al., 1988; Preiser, 1995; Riley et al., 2009). Since the early studies on the housing needs of disadvantaged groups in the 1970s (Bechtel and Srivastava, 1978; Vischer, 1985), POEs have broadened their scope to applications in various other building types, such as, healthcare facilities (McLaughlin, 1975; Cooper et al., 1991; Carthey, 2006; Leung et al., 2012), residential buildings (e.g.

[CABE, 2007; Gupta and Chandiwalla, 2010; Stevenson and Leaman, 2010](#)), [educational buildings \(e.g. Baird, 2005; Watson, 2005; Loftness et al., 2006; Turpin-Brooks and Viccars, 2006; Riley et al., 2010; Zhang and Barrett, 2010\)](#), and [commercial/office buildings \(e.g. Leaman and Bordass, 1999; Leaman and Bordass, 2001; Zagreus et al., 2004; Bordass and Leaman, 2005c; Vischer, 2005; Abbaszadeh et al., 2006; Leaman and Bordass, 2007; Leaman et al., 2007\)](#). Apart from providing designers with feedback, numerous researchers [\(e.g. Preiser, 2001b; Vischer, 2001; Whyte and Gann, 2001; Bordass and Leaman, 2005a; Loftness et al., 2006; Turpin-Brooks and Viccars, 2006; Preiser and Nasar, 2008; Hadjri and Crozier, 2009; Loftness et al., 2009; Riley et al., 2010\)](#) suggest a number of other plausible benefits of POE, including: (1) improving commissioning process; (2) definition of user requirements; (3) improving management procedures; (4) providing knowledge for design guides and regulatory processes; and (5) targeting of refurbishment.

Notwithstanding these benefits, many barriers to conducting POEs have [also](#) been identified [\(Cooper, 2001; Vischer, 2001; Zimmerman and Martin, 2001; Zimring and Rosenheck, 2001\)](#). The extensive discussion of these problems suggests a growing frustration with the lack of progress towards POE becoming a mainstream activity in the process of building procurement [\(Hadjri and Crozier, 2009; Meir et al., 2009\)](#). The more commonly identified barriers to the widespread adoption of POE include cost, fragmented incentives and benefits within the procurement and operation processes, potential liability for designers, engineers, builders, and owners, lack of agreed and reliable indicators, time and skills [\(Bordass et al., 2001; Cooper, 2001; Vischer, 2001; Zimmerman and Martin, 2001\)](#). Moreover, Zimmerman and Martin (2001) suggest that standard practice in the facility delivery process does not recognise the concept of continual improvement or any ongoing involvement on the

part of the designers. Despite one of the primary goals for conducting POEs is to enable designers to revisit their designs, improve their skills and produce more efficient buildings, the idea of continual improvement via feedback has lacked emphasis in both the North American and UK contexts ([Derbyshire, 2001](#); [Preiser, 2001b](#); [Preiser and Vischer, 2005](#)). Whilst many agree with these barriers, there are still some challenges in the use of contemporary POE methods (Preiser and Vischer, 2005), especially in commercial office buildings. From the literature, three key issues in the POE method have been identified: ‘lack of context’; ‘lack of feedback’ and the ‘lack of instrumental data’ ([Hartkopf et al., 1986](#); [Vischer, 2001](#); [Jarvis, 2009](#); [Loftness et al., 2009](#)). It should be noted that the following issues are predominantly focused on POE studies conducted in office buildings.

1.2.1. Lack of Context:

Traditionally, POE has been viewed as a final, one-off process as the term ‘post’ reflects only that time after a building was completed ([Bordass and Leaman, 2005a](#); [Preiser and Vischer, 2005](#)). Yet, POE is not the end phase of a building project; rather it is an integral part of the building delivery process ([Federal Facilities Council, 2001](#); [Preiser, 2001b](#); [Vischer, 2001](#)). The technique should be used more regularly to ensure buildings continue to deliver at their intended design specifications and, in return, appropriate levels of satisfaction among the end-users ([Preiser, 2001b](#); [Preiser and Nasar, 2008](#); [Vischer, 2008a](#); [Riley et al., 2010](#)). Much literature suggests POE should be cyclical in nature rather than simply providing a final feedback component in the occupancy phase (e.g. [Preiser, 1995](#); [Bordass et al., 2001](#); [Cohen et al., 2001](#); [Vischer, 2001](#).

POE practice has mainly focused on assessing specific cases ([Federal Facilities Council, 2001; Turpin-Brooks and Viccars, 2006](#)). Even when evaluators have been able to create databases of findings, they have often been used to benchmark single cases rather than to develop more general conclusions ([Zimring and Rosenheck, 2001; Baird, 2011](#)). POE studies [involving office buildings often](#) lack the contextual information in which the building was built and occupied. Prior to moving into their new building or space, occupants could already harbour distrust of management ([Vischer, 2001; Vischer and Fischer, 2005; Vischer, 2008b](#)). Workers may also have high expectations that are not met when balanced against the possible constraints of an existing building that limits the creation of effective workspace ([Schwede et al., 2008](#)). Ultimately, the uncertainty generated by moving to a new building or space affects employee's perception of their environment ([Vischer, 2005; Vischer and Fischer, 2005](#)). If left unresolved, these attitudes and predispositions are likely to carry forward into the new workspace. As such, the actual impact a building has on its users remains unaccounted for in the analysis and interpretation of the results. Many discussions have risen for the evaluation of a building prior to occupation ([Federal Facilities Council, 2001; Preiser and Vischer, 2005](#)). Leaman et al., (2010) suggest that building performance studies should seek and reveal the context behind the building, i.e. occupants' personal history and attitudes towards the building. These psychosocial factors play an important role in determining people's concerns with their environment (Vischer, 1986; Chigot, 2005; Vischer and Fischer, 2005; Turpin-Brooks and Viccars, 2006) and may well affect their perception of the building. Furthermore, the consideration of occupants' demands and experience in the design process helps to achieve more positive design outcomes (Vischer, 1985; Fischer et al., 2004; Vischer, 2005; Schwede et al., 2008).

1.2.2. Lack of Feedback (Or Has the Loop Become A Noose?):

Improvement of building performance requires the identification of positives and negatives through rapid feedback ([Cohen et al., 2001](#); [Bordass and Leaman, 2005b](#)). The UK's Building Use Studies (BUS) in the 1990s launched the Post-occupancy Review of Buildings and their Engineering (PROBE) project ([Cohen et al., 2001](#); [Cooper, 2001](#); [Derbyshire, 2001](#); [Fisk, 2001](#)). In conducting POE studies for a wide range of non-domestic buildings, the PROBE project helped develop a standardised POE method; accumulating a wide range of studies around the world into a homogenized database against which future POE studies could be benchmarked ([Bordass et al., 2001](#); [Leaman and Bordass, 2001](#)). Following these landmark PROBE studies, POE advocates stressed the need to close the loop between building managers and the building's end-users (NCEUB, 2004; Building Research and Information, 2005). In agreement, Leaman and Bordass (2001) suggest the provision of a knowledge base of lessons learned from users in completed projects should be utilised to either improve spaces in existing buildings or form a programming platform for future buildings ([Leaman and Bordass, 2001](#); [Zimmerman and Martin, 2001](#); [Preiser and Schramm, 2002](#)). Ten years on, however, there is evidence to suggest that a lack of communication and feedback still exists amongst these parties (Preiser and Vischer, 2005; Thomas, 2010).

POE has lost its initial aim to close the loop between building designers/managers and the occupants ([Jaunzens et al., 2003](#); [Jarvis, 2009](#); [Leaman et al., 2010](#)); suggesting the loop has now become the noose. To date, occupants still remain a largely untapped source of information to building managers and, as such, are rarely involved in the stages of building construction and commission (Zagreus et al., 2004). Due to this lack of involvement, many occupants do not understand how to

operate nor occupy their building, which often leads to high levels of discontent. Consequently, as Cohen et al., (2001) suggests, occupants will blame 'negative' workplace feelings on the physical environment as a way of voicing their dissatisfaction. Furthermore, occupants will often resort to using the POE as a means to report problems in the workplace, e.g. uncomfortable conditions, poor lighting or ventilation, lack of control, and even bullying which is not measured in POEs ([Loftness et al., 1989; Preiser, 2001b; Vischer, 2004; Vischer and Fischer, 2005; Turpin-Brooks and Vickers, 2006](#)).

### 1.2.3. Lack of Instrumental Data:

POEs were originally intended to provide information regarding the in-use performance of a building using instrumental data ([Hartkopf et al., 1986; Vischer, 1986; Ventre, 1988; Loftness et al., 1989; Vischer and Fischer, 2005](#)). The landmark PROBE studies [in the UK](#) set the benchmark as to how such studies should be conducted ([Loftness et al., 2009; Meir et al., 2009](#)). These studies relied on three evaluation components: Energy Assessment and Reporting Methodology (EARM); BUS occupant questionnaire; and an air pressure test (Cohen et al., 2001). Subsequent use of these tools, however, has focused more on occupant satisfaction with the building, thereby relying on more subjective criteria ([Federal Facilities Council, 2001; Fisk, 2001; Turpin-Brooks and Vickers, 2006; Jarvis, 2009; Leaman et al., 2010](#)). While many agree such metrics are more easily assessed than alternatives, such as productivity or health (Leaman and Bordass, 1999), it is often argued that occupant satisfaction is not a meaningful measure for judging building performance ([Hartkopf et al., 1985; Hartkopf et al., 1986; Heerwagen and Diamond, 1992; Leaman et al., 2010](#)). Despite providing a first-hand account of how the building is affecting the

occupants, such assessments are susceptible to bias. Since POEs don't account for any psychosocial or contextual (non-physical) factors that may affect occupants in the workplace, participants' responses may be either positively or negatively biased. Sometimes known as the 'Hawthorne effect', the behaviour or responses of an individual or group will often change to meet the expectations of the observer/researcher (Roethlisberger and Dickson, 1939).

The use of such measures therefore presents a specific challenge: respondents' subjective assessments of their environment might be affected by non-building-related factors ([Ventre, 1988](#); [Zagreus et al., 2004](#); [Jarvis, 2009](#); [Loftness et al., 2009](#)). Many aspects of building performance are readily quantifiable, such as lighting, acoustics, temperature and humidity, durability of materials, amount and distribution of space, etc. ([Hartkopf et al., 1985](#); [Hartkopf et al., 1986](#); [Preiser, 2001a](#)). Despite this, POEs typically do not obtain instrumental measurements of indoor building environmental conditions, potentially leading to unsubstantiated complaints against a building's indoor environment. In order to get a complete picture of a building's actual performance from a technical and occupants' perspective, the subjective data from occupant feedback surveys needs to be correlated against the quantitative data measured from physical monitoring (Vischer, 1986; Ventre, 1988; Turpin-Brooks and Vickers, 2006; Choi et al., 2010; Gupta and Chandiwalla, 2010). Several researchers, however, argue there are inherent difficulties in matching user's subjective responses with objective environmental data (Vischer, 1986; Vischer and Fischer, 2005; Jarvis, 2009; Loftness et al., 2009). POEs often record occupant perceptions of thermal comfort on past seasonal events [occurring](#) 3 to 12 months before the survey was administered. In order to achieve a successful correlation between the occupants' thermal comfort ratings and the internal thermal environment of the building, the



surveys need to be conducted on a 'right-here-right-now' basis for the results to be reliable. However, Vischer (1993) also suggests that humans draw on experience outside the immediate time-frame of the present to make their summary judgements of comfort conditions. Instruments, on the other hand, are temporally limited to sampling actual building conditions as a snapshot or over a prolonged period of time. By adopting a more diagnostic approach to POEs the temporal and calibration limitations on instrument-based data collection can be avoided. Furthermore, measurements of building systems performance can be carried out as a follow-up procedure to help understand the meaning behind the feedback yielded by users on their perceptions of building conditions (Vischer, 1986; Vischer, 2001; Vischer and Fischer, 2005).

## 2. Methods

### 2.1. Sydney's Climate

Located on the eastern coast of Australia, the Sydney metropolitan region (34°S, 151°E) is characterised by a moderate sub-tropical climate. Influenced from complex elevated topography surrounding the region to the north, west and south and due to close proximity to the Tasman Sea to the east, Sydney avoids the high temperatures commonly associated with more inland regions of the same latitude (BoM, 1991). In regards to summer, the months of December to February can be described as warm-to-hot with moderate-to-high humidity peaking in February to March. Within the winter months of June to August, Sydney experiences cool-to-cold winters. The two case study buildings are located within a suburban tertiary educational institution, approximately 16km north-west of Sydney's central business district (33° 46' S, 151° 6' E). As shown in Figure 1, seasonal variations range from

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mean summer daily maximum temperatures of 26-28°C, a mean winter daily maximum of 17°C and an annual mean daily maximum of 22-23°C. Mean minimum daily temperatures range from 5-8°C in winter, to 17-18°C over the summer months, with an annual daily minimum temperature of 11-13°C (BoM, 2011). Given the city's seasonal variations, Sydney's climate is well suited to natural ventilation. For much of the year, thermal comfort indoors can be easily achieved through simple passive design principles and various adaptive behaviours employed by the occupants, such as opening/closing windows, adjusting their clothing or by change of position (Aggerholm, 2002; Rowe, 2003).

**Figure 1.** Climatology of the case study building site (adapted from BoM, 2011)

**2.2. Case Study Buildings**

Two academic office buildings were selected for this study. The mixed-mode (MM) building was commissioned in 2006 and has a total usable floor area of 6541 m<sup>2</sup>. The naturally-ventilated (NV) building was built in the 1960s and covers an area of approximately 5808 m<sup>2</sup>. Since both buildings were located on the same university campus, occupied by the same organisation with comparable occupancy densities of 0.03 occupants/m<sup>2</sup>, they make for an ideal field study. Due to both buildings having North-South orientations, the North-facing facades are directly irradiated from the Sun, creating warmer internal temperatures than the South-facing perimeter zones:

1. Mixed-Mode Building: presented in Figures 2a and 2b, this 7-storey academic office building features operable windows on all North and South perimeter cellular offices. These are separated with an air-conditioned (AC) central open-plan office zone. Automated high and low external louvres provide natural ventilation to each floor, with adjustable internal grilles to control

airflow, supplemented with user-operable windows (Figure 2b). As depicted in Figure 2a, the building also features additional solar shading over the northern (sun-facing) windows. Indoor temperature and outdoor weather sensors prompt the Building Management System (BMS) to switch into AC mode whenever a temperature greater than 25°C is sensed within any zone. During AC mode, internal temperatures are maintained at 24°C (+ 1°C) as defined in the building's algorithm. BMS switch-over to NV mode is conditional when external meteorological conditions and the indoor thermal climate fall into an acceptable zone for the occupants. Around 200 academic and administrative staff from economics and finance disciplines occupy this building.

**Figure 2a)** The MM building as viewed from the north facade featuring operable windows with external solar shading devices on north-facing windows

**Figure 2b)** User-operated windows and internal grilles in the North and South perimeter offices of the MM building

2. Naturally-Ventilated Building: illustrated in Figures 3a and 3b, the NV building features occupant-operated windows with a narrow floor plate traversed by a central corridor with single- and dual-occupant cellular offices on either side. Unlike the MM building, there is no centralised heating or cooling systems, with the exception to those offices with individual window air-conditioner units (as seen in Figure 3a). Figure 3b illustrates that occupants often resort to using portable fans and heaters throughout the year for additional cooling in summer and/or heating in winter. The building's total population of 200 occupants is composed of academic and administrative staff

as well as post-graduate students from a variety of science-related disciplines, such as environmental science, physics, geology and mathematics.

**Figure 3a)** The NV building as viewed from the north facade featuring occupant-operated windows with some individual air-conditioner units

**Figure 3b)** Occupants often use portable fans or heaters in conjunction with operable windows for additional cooling/heating throughout the year

**2.3. Measurements**

Simultaneous objective (indoor and outdoor climate) and subjective (self-assessed comfort perceptions) measurements were collected throughout this study. Dataloggers were randomly located throughout each building to record air temperature, globe temperature and relative humidity at 5 minute intervals throughout the study. The study was conducted over twelve months (from March 2009 to April 2010) to represent the full cycle of the seasons. Air velocity was measured during each questionnaire session using a handheld thermal anemometer (TSI VelociCalc). Loggers were placed within 1 m of the occupants’ workstation to characterise the immediate thermal environment experienced by the occupant under normal working conditions. Outdoor weather observations were obtained from a nearby automatic weather station. The building’s AC/NV mode status and indoor temperature records were collected from the BMS after the field campaign had finished.

**2.4. Questionnaires and Data Analysis**

Two separate questionnaires were used in this study, i.e. the BUS post-occupancy evaluation and ‘right-here-right-now’ thermal comfort questionnaire:

1. Post-Occupancy Evaluation: The 3-page BUS POE questionnaire (Usable Buildings Trust, 2008; BUS, 2009) features numerous 7-point scales with space for commentary covering all variables relating to occupant satisfaction, e.g. thermal, visual and acoustic comfort, indoor air quality, perceived health and productivity, as well as overall satisfaction with the workplace. Combinations of these scores enable the calculation of various comfort and satisfaction indices, including the ‘forgiveness factor’, unique to the BUS survey. The forgiveness factor is derived as a ratio of Overall Comfort score to the average of the scores for the six environmental factors: Lighting Overall, Noise Overall, Temperature Overall in both winter and summer, and Air Overall in both winter and summer. This index purports to quantify the user’s tolerance of the environmental conditions in the building, with values greater than unity taken to indicate occupants being more tolerant, or ‘forgiving’, of a building’s thermal environmental conditions (Leaman and Bordass, 2007).

These questionnaires, in accordance to the original BUS methodology, were delivered in person to each occupant within the building. To preserve occupant anonymity, participants placed their completed questionnaires inside a blank, sealed envelope which was collected at the end of the same day.

2. Thermal Comfort Questionnaires: Paper-based subjective comfort questionnaires were used to record occupant perceptions of their thermal environment on a ‘right-here-right-now’ basis. Subjects were asked to assess their thermal sensation (Actual Mean Vote) on the ASHRAE 7-point scale, which included the possibility of fractional votes placed between two comfort categories. Thermal acceptability was addressed as a binary ‘acceptable’ or ‘unacceptable’ response whereas thermal preference was assessed on the 3-

point McIntyre scale (McIntyre, 1980), on which occupants listed if they preferred to feel ‘warmer’, ‘cooler’ or ‘no change’. In terms of air movement, subjects registered if the air velocity was ‘acceptable’ or ‘unacceptable’ and their reason: whether it was ‘too low’, ‘too high’ or ‘enough’ air movement. Subjects were also asked if they preferred ‘no change’, ‘more’ or ‘less’ air movement. Standardised self-assessed clothing garment (clo) and metabolic activity checklists (ASHRAE, 2001; ISO, 2003) within the subjective comfort questionnaires allowed the calculation of various comfort indices using ASHRAE’s WinComf software (Fountain and Huizenga, 1997), including Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD). Lastly, a section was added for the researcher to identify the respondents’ location and mode of operation for each participant’s office at the time of each questionnaire. This information was used to match the questionnaire responses with the instrumental measurements.

**3. Results**

In order to show the differences between each building based on both subjective (occupant satisfaction) and objective measurements (instrumental measurements), it is instructive to compare both buildings’ performance under similar weather conditions. POEs were conducted in each building between March and April 2009 and 2010 to reflect occupants’ perceptions of thermal comfort and other IEQ performance through the previous winter-summer cycle. Thermal comfort field studies were conducted simultaneously in both buildings from October 2009 to April 2010 in which the outdoor weather conditions were comparable to those from the previous summer period (2008-2009).

### 3.1. Summertime Thermal Environment

Presented in Figure 4 are the concurrent indoor temperatures recorded at the time when each comfort questionnaire was administered across both buildings throughout the study (October 2009 to April 2010). As illustrated, the data in Figure 4 highlights discrepancies between the internal operative temperatures within these buildings during the study period. The NV building experienced significantly warmer indoor temperatures (average = 25.4°C,  $p = 0.000$ ) compared to the MM building over the same period (average = 23.8°C). Recorded during occupied office hours (8am to 6pm), the average daily outdoor air temperature of 24.4°C was typical for Sydney's summer months. Figure 4 indicates internal temperatures within the NV building tracking changes in the outdoor weather conditions. Temperatures in the MM building ranged from 21-25°C in accordance with the BMS algorithm switching into AC mode whenever average indoor air temperatures reach a 25°C trigger temperature. In contrast, temperatures inside the NV building varied between 20-30°C. Internal temperatures in the NV building exceed the 25°C threshold on 27 days during the study, which equates to over 50% of all occupied office hours. Thus, objectively, the NV building is significantly warmer than the MM building during summer months.

**Figure 4.** Summertime thermal environment recorded for the MM and the NV building (October 2009 to April 2010). Each data point corresponds to days in which thermal comfort questionnaires were administered

### 3.2. Occupant Satisfaction: POE vs. Thermal Comfort

POEs were delivered face-to-face on a Tuesday morning to all occupants within each building, as recommended by the BUS (2009) methodology. This was done to ensure the best possible response rates. In total, 163 POE questionnaires were

distributed in the MM building and 120 in the NV building<sup>2</sup>. With a 53% response rate, the MM building returned 86 completed questionnaires (39 male, 47 female), and 81 (38 male; 43 female) were completed from the NV building (68% response rate).

Incomplete responses were omitted from the subsequent analysis. The thermal comfort variables are measured using a 7-point scale with 4 as the mid-point; scores greater than 4 express satisfaction and scores lower than 4 express dissatisfaction. Calculated as the percentage of scores less than 4 to the total number of scores recorded. Table 1 shows the percentage of dissatisfaction votes for each of the thermal comfort variables, i.e. temperature in summer, ventilation in summer, noise, lighting, perceived productivity, comfort overall and forgiveness factor.

The values in Table 1 demonstrate that occupants of the MM building rated their building quite poorly in terms of thermal comfort with over half the study population (55%) registering dissatisfaction with overall comfort. Similarly, 58% and 57% of subjects surveyed found the temperature and ventilation in summer to be unacceptable respectively. Fewer people were dissatisfied with temperature and ventilation in the NV building (28% and 25% respectively). In terms of overall lighting, noise and perceived productivity, both buildings scored similar percentages of occupant satisfaction. Values greater than 1 on the forgiveness factor index are taken to indicate that occupants may be more tolerant, or ‘forgiving’ of the conditions (Leaman and Bordass, 2007). Therefore, the forgiveness factor of the NV building (1.14) suggests that occupants were more prepared to forgive the buildings’ less-than-ideal conditions, as opposed to their MM counterparts (forgiveness factor = 0.99).

<sup>2</sup> Questionnaires were administered to all occupants located on floors 6, 7 and 8 in the NV building between March and April 2009. A separate follow-up study was conducted in March 2010 using the rest of the occupants (located on floors 2 to 5).



**Table 1.** Forgiveness factor and dissatisfaction percentages of variables in the POE for the MM and NV building

Sixty subjects were recruited from each building for the summer thermal comfort field studies. In total, 713 ‘right-here-right-now’ questionnaires were collected from the MM building (average of 15 per day), and 607 were collected from the NV building (average of 13 per survey day). In order to analyse these results against comparable conditions in each building, Actual Percentage Dissatisfied (APD) and Predicted Percentage Dissatisfied (PPD) based on Fanger’s heat-balance comfort model (1970) were plotted against binned indoor operative temperature. As mentioned previously, PPD values were calculated based on the PMV equation using ASHRAE’s WinComf software (Fountain and Huizenga, 1997). APD was derived as the percentage of thermal sensation votes greater than +1.5 and less than -1.5 recorded within the limits of a 1°C indoor operative temperature bin, e.g. 21.5 to 22.49°C, against the total number of votes for each corresponding bin. Those votes registered outside  $\pm 1.5$  were regarded as expressing dissatisfaction (as described by (Fanger, 1970)). Figures 5a and 5b below show the results of these analyses for the MM and NV building respectively. Since the central zone in the MM building is constantly AC and does not have the capability to operate under natural ventilation, it was not included in the following analyses. Furthermore, when APD equals 100% this indicates that all subjects surveyed voted their thermal sensation to be greater than  $\pm 1.5$  units outside thermal neutrality. Conversely, APD is ‘zero’ when all subjects’ thermal sensations were between the votes of *slightly warm* (+1) to *slightly cool* (+2) on the ASHRAE 7-point scale of thermal sensation.

As illustrated in Figure 5a, occupants of the MM building were found to be quite dissatisfied with the thermal environment. Observed levels of thermal

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dissatisfaction (APD) were greater than or equal to those predicted on the basis of actual environmental conditions using the PMV-PPD model at modest indoor temperatures, i.e. 22 to 26°C. This suggests that occupants found these temperatures to be overwhelmingly unacceptable despite PPD values falling at or below the 10-20% dissatisfied threshold. In contrast, the NV building results indicate PPD levels, on average, higher than the APD values registered by occupants (Figure 5b). Fewer occupants expressed dissatisfaction compared to the PPD levels for temperatures ranging from 19 to 25°C, indicating that, despite the much warmer indoor environmental conditions with PPD levels well above the recommended 20% margin, occupants still voted these temperatures as acceptable.

These results also highlight fundamental differences between occupants of these two buildings. Even under similar thermal conditions, occupants of the NV building, on average, registered lower APD values compared to those in the MM building. For instance, at an indoor operative temperature of 23°C, 15% of occupants in the MM building were thermally dissatisfied, whereas all subjects surveyed in the NV building at the same temperature voted the indoor thermal environment as satisfactory. Again, at an indoor operative of 25°C, only 8% of the subjects surveyed in the NV building recorded thermal sensations outside the band of thermal acceptability ( $\pm 1.5$ ), whereas in the MM building, 18% of occupants surveyed expressed thermal dissatisfaction.

**Figure 5.** Average APD and PPD recorded in **a)** the MM building (above) and **b)** the NV building (below)

### 3.3. Thermal Acceptability

The preceding analyses inferred acceptability from the sensation scale, and in doing so, afforded comparisons between observed thermal dissatisfaction and that predicted in the same setting by Fanger's PPD (1970). A more direct approach on our subjective comfort questionnaires used a binary item, i.e. was the thermal environment simply 'acceptable' or 'unacceptable'? The numbers of 'acceptable' and 'unacceptable' votes recorded in each indoor operative temperature bin were tallied (Figures 6a and 6b). As shown in Figure 6a, a higher percentage of occupants in the MM building voted the thermal environment as 'unacceptable' compared to those in the NV building (shown in Figure 6b). Within the MM building, over 20% of occupants surveyed found the indoor temperature to be unacceptable, even at moderate temperatures, e.g. 20-26°C. In contrast, Figure 6b demonstrates that fewer occupants (as low as 5%) in the NV building found the indoor temperature to be unacceptable. Between temperatures of 20-25°C, over 80% of the study population in the NV building found these temperatures to be acceptable. Not surprisingly, the number of 'unacceptable' votes recorded in both buildings increased under warmer indoor conditions. Interestingly, even at similar indoor temperatures of 26°C, the NV building recorded 90% acceptability (grey bars), whereas the MM building recorded just over 70%.

**Figure 6.** Percentage of thermal acceptability votes registered in **a)** the MM building (above) and **b)** the NV building (below)

## 4. Discussion

Despite indoor operative temperatures in the MM building being significantly cooler than the NV building (Figure 4), the subjects' POE responses reflect lower

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3 levels of satisfaction (40-50%) with the thermal environment. Objectively, the thermal  
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5 environment in the NV building appears significantly worse than the adjacent MM  
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7 building. On average, temperatures in the NV building during the summer months  
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9 were 2°C warmer than the MM building. As shown in Figure 4, the MM building  
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11 rarely exceeds the 25°C threshold due to the building switching into AC mode when  
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13 indoor temperatures are greater than 25°C. But despite these less-than-ideal  
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15 conditions, occupants of the NV building reported moderate levels of satisfaction  
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17 (around 80%) and this was borne out by their forgiveness levels (1.14) compared to  
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19 their MM counterparts (0.99).  
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23 In regards to the results from the thermal comfort studies, occupants'  
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25 perceptions of comfort and thermal acceptability were quite different between these  
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27 buildings. Even though indoor environmental conditions experienced within the NV  
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29 building were less-than-ideal, Actual Percentage Dissatisfied (APD) were, on average,  
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31 lower than the predicted PPD values. In comparison, occupants of the MM building  
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33 registered much higher APD levels than the PPD values predicted using Fanger's  
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35 heat-balance model. Despite temperatures within the MM building being constrained  
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37 during summer between 20-25°C, occupants expressed significantly greater levels of  
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43 Although outside the stated scope of this paper, the results also highlight  
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45 another important issue regarding the use of subjective and objective building  
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47 performance metrics. According to ASHRAE Standard 55 (2010), the PMV-PPD  
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49 model is used to evaluate the thermal environment of AC buildings. The adaptive  
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51 comfort standard, as an alternative to the PMV-PPD model, is restricted in scope to  
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53 NV or 'free-running' buildings (de Dear and Brager, 2002; Nicol and Humphreys,  
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55 2010). This paper demonstrates the complexities of relying solely on subjective  
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indicators of building performance, e.g. APD and acceptability or POE in general. Many building guidelines and comfort standards recommend the use of objective criteria, such as temperature and PMV-PPD to assess a building's thermal environment. However, this study has shown that PPD results significantly underestimated the observed levels of thermal dissatisfaction in one building (MM case study), and overestimated them in another (NV building). If purely assessed using Fanger's PMV-PPD model (1970), as expressed in ASHRAE 55-2010, the MM building would be deemed comfortable as indoor operative temperatures fell within the 80% acceptability PPD limits. The NV building, however, would be deemed uncomfortable as indoor operative temperatures were well above the upper limit of 25°C. Despite this, the APD results in Figure 5b suggest the NV occupants found the thermal environment to be quite acceptable across a broad range of indoor operative temperatures (20-25°C). Occupants of the MM building expressed greater levels of thermal dissatisfaction (i.e. higher APD values in Figure 5a) across the same range of temperatures. The better than predicted acceptability scores in the NV building have been discussed in terms of forgiveness factors and adaptive opportunities, suggesting occupants of both buildings are exhibiting some degree of thermal adaptation to their indoor environment (de Dear and Brager, 1998; de Dear and Brager, 2002). However, both case study buildings possess similar degrees of occupant-orientated environmental control, or adaptive opportunities (Baker and Standeven, 1996) to control air movement/ventilation (operable windows) and lighting (shades, artificial lighting). The only difference is that the MM building uses centralised HVAC whenever indoor temperatures exceed the 25°C trigger temperature. From these findings, it is apparent that occupants' acceptability of the thermal environment is influenced by their expectations as suggested by the adaptive hypothesis (de Dear and

[Brager, 2002](#)). Considering only 71% of occupants in the MM building found the thermal environment to be acceptable as opposed to 85% of occupants surveyed in the NV building, it therefore seems that something extra other than thermal adaptation (Brager and de Dear, 1998) is required to explain the worse-than-expected acceptability in the MM building.

**4.1. Analysis of Occupants’ Comments and Anecdotal Evidence**

Occupant-based comments and anecdotal evidence are considered important contextual information in POE studies ([Bordass and Leaman, 2005b](#); [Moezzi and Goins, 2011](#)). Since the comparison of quantitative IEQ survey data often lacks the context and complexity of user experiences, text responses can be analysed to provide a deeper understanding of the POE results ([Baird, 2011](#); [Moezzi and Goins, 2011](#); [Baird et al., 2012](#)). Especially in situations when the results of the POE may not match the physical environmental data, as is the case presented in the MM building, such data can be used to verify the validity and reliability of both the subjective and objective results. Many POE questionnaires, such as the BUS POE, offer subjects the option to give their own comments regarding particular IEQ variables. Other surveys, such as the Occupant IEQ Satisfaction Survey developed by CBE ([Zagreus et al., 2004](#); [CBE, 2012](#)), offer a more detailed response from the participants. Using similar keyword and phrase extraction methods employed by Moezzi and Goins (2011), text responses were analysed and compared between each building to validate their respective POE results in Table 1.

Occupants’ comments from the POE were grouped according to those featuring keywords or phrases related to temperature, ventilation, noise and lighting. The results and list of words used to identify negative comments, or ‘complaints’,

relating to each category across both case study buildings are presented in Table 2. In total, 167 complaints were recorded for the MM building and 108 for the NV building. Since the NV building predominantly relies on natural ventilation, its users are prone to complain about uncomfortable working conditions, especially during summer and winter. As expected, 'temperature' was the most common complaint within the NV building with 56% of comments using phrases such as: "too hot" and "too cold". However, within the MM building, temperature was the second most reported problem with 31% of the comments. "Noise from outside" and "from colleagues" was frequently reported within both buildings, especially in the MM building wherein it was the most common complaint (38% of the total; 64 comments). Noise complaints were only mentioned 25 times (23%) within the NV building. The MM building, in comparison to the NV building, also recorded more comments relating to lighting, i.e. "too much glare" (15% and 9% respectively) and ventilation, i.e. "ventilation" and "draught" (MM: 16%; NV: 12%).

**Table 2.** List of keywords and phrases used to identify complaints in each category.

These results shed light on a common theme evident in many recent POE studies in NV and MM buildings. Buildings with natural ventilation capabilities are often hotter in summer, colder in winter and contain more glare (Leaman and Bordass, 2007). Many studies reveal air movement, temperature, glare and noise as the most common causes for dissatisfaction in green buildings ([Abbaszadeh et al., 2006](#); [Brager and Baker, 2009](#); [Moezzi and Goins, 2011](#); [Baird and Dykes, 2012](#)). However, while these results demonstrate potential areas of improvement and lessons to be learned in future green building construction, they also illustrate that occupants can potentially use POE as a conduit to complain. Participants in both buildings expressed lengthy

complaints, often incorporating emotional language into their responses. Occupants predisposed to complain, either due to contextual (e.g. work-related) or physical (e.g. temperature) factors will exaggerate poor building performance ([Loftness et al., 2009; Vischer, 2009; Baird and Dykes, 2012; Baird et al., 2012](#)). Whereas the MM case study building was deemed comfortable on objective criteria, its occupants felt compelled to complain about the building's [performance, particularly its thermal environment](#). Furthermore, the discrepancies between occupants' thermal satisfaction and acceptability and the POE results suggest the building may not be the problem. This begs the question: how much does the POE get influenced by non-building contextual factors?

Whilst purely based on anecdotal evidence and occupants' comments, it is interesting to note the faculty occupying this contentious MM building. [While both buildings are occupied by staff from the same organisation at the same location, there are clearly differences in the occupants' expectations and attitudes of the thermal environment](#). We speculate that the [occupants of the MM building](#) are dissatisfied due to a number of non-building-related factors. The building is occupied by academic and administrative staff from a variety of business and economics departments, including accounting and finance, actuarial studies, and business studies. Responsible for one of the University's largest student populations, the staff to student ratio for this faculty is the lowest in the entire University. As a result of these high teaching workloads, staff morale within this building is commonly acknowledged to be quite low compared to the NV building which is occupied by various science departments, such as geology, physics, environmental sciences and astronomy. Prior to moving into their new MM building, the business and economics departments occupied a conventional AC building. They were deeply distrustful of management and



suspicious of the motives behind the new building's partial air conditioning (mixed-mode). Additionally, given the initial teething problems with the MM building due to deficient commissioning, these occupants were predisposed to respond to the POE questionnaire in a strongly negative mood. Figure 4 suggests these initial technical glitches in the MM system had been corrected. Nonetheless, the occupants' perceptions of their MM building remain coloured by their negative first impressions.

#### *4.2. Recommending an Improved Methodology for Conducting Building Performance Studies*

Since inception, POE has taken several approaches varying from highly technological methodologies involving physical environmental data ([e.g. Hartkopf et al., 1986; Sanders and Collins, 1995; Vischer and Fischer, 2005; Turpin-Brooks and Viccars, 2006; Loftness et al., 2009; Choi et al., 2010](#)), to socio-psychological interests where more subjective parameters are employed to evaluate building performance ([e.g. Vischer and Fischer, 2005; Abbaszadeh et al., 2006; Leaman et al., 2007; Brown and Cole, 2009](#)). However, such studies are more commonly based on an 'investigative' approach utilising qualitative interviews and questionnaires ([Preiser, 1995; Preiser, 2001a](#)). The POE results from this paper raise concerns about the validity of adopting a single approach. When compared with more objective data collected in each building, i.e. temperature, thermal satisfaction and acceptability, the different results from each building were inconsistent. Therefore, POEs alone do not adequately evaluate [the overall performance of a building, nor the extent to which the building meets the needs of its end-users \(Vischer, 2009\)](#). In order to provide a better understanding of how occupants use and interact with their building, this paper recommends more holistic and robust performance evaluations [that incorporate](#)

physical environmental data with subjective occupant responses (Ventre, 1988; Preiser, 2001a; Vischer, 2001; Loftness et al., 2009).

Because POEs have commonly focused on building user feedback, much of the information received is negative in nature (Vischer, 2001). Hence, one of the challenges of POEs going forward is to identify a reasonable system of informed weighting of user feedback; allowing data to be interpreted according to balanced positive and negative categories (Preiser, 2001b; Vischer, 2001). Preiser (2001a) suggests more ‘diagnostic’ POE approaches can combat this problem. These types of POE provide a highly sophisticated and detailed assessment enabling the correlation between physical environmental measures with subjective occupant response measures (Hartkopf et al., 1986; Preiser, 2001a; Preiser and Vischer, 2005). Socio-cultural observation and functional comfort surveys would be further enhanced by the monitoring and analysis of scientific data on ‘real-time’ workplace environmental conditions, e.g. thermal, acoustic and visual comfort; occupants’ satisfaction and behaviour; as well as, physiological and psychological comfort (Preiser and Vischer, 2005; Turpin-Brooks and Vickers, 2006; Vischer, 2008b; Meir et al., 2009). This information could be used to gauge any adjustments needed in the controls or environmental settings of the workplace, but also verify users’ problems with the indoor environment/building performance; thus enabling systematic and reliable feedback (Vischer, 2008a; Loftness et al., 2009).

In summary, whilst a number of alternative methods are available, it is clear that ‘one size does not fit all’ especially in regards to the physical, psychological and psychosocial influences on workplace satisfaction. Several studies have demonstrated that a combined approach POE using more than one tool of assessment can enhance the understanding of a building’s performance (Hartkopf et al., 1986; Vischer and

Fischer, 2005; Turpin-Brooks and Viccars, 2006; Loftness et al., 2009; Choi et al., 2010). A more holistic POE, combining objective building performance data and subjective satisfaction ratings, may in fact offer a more valid and reliable evaluation of a building's success.

## 5. Conclusions

Over the last four decades, a large number of POEs have been conducted in a variety of different building types, using a wide range of methods, goals and frameworks. However, despite the potential of POE to have a positive effect on subsequent building delivery and management, the full potential has not yet been realised. In its current form, POE remains a superficial assessment of building performance; merely providing a face-value assessment of buildings by their occupants. Used in isolation, POE surveys may not be a fair reflection of the building's actual performance, i.e. energy consumption/efficiency and IEQ indicators. Since such studies don't typically obtain parallel instrumental measurements of these variables, e.g. indoor climate, they lack an objective benchmark against which poor satisfaction ratings can be verified.

The aim of this paper was intended to illustrate how supplementary instrumental measurements of a building's indoor climate could lead to a fundamental reinterpretation of POE results in office environments. Whilst the study only looked at two office buildings from a tertiary education institution in Sydney, Australia, it highlights the need for a more robust and holistic approach to building performance evaluation that includes both objective and subjective data. However, this does not require a re-invention of the wheel. POE is simply one of a suite of tools to measure building performance and should be used in conjunction with other methods to

evaluate all aspects of a building; including the social, psychological and physical. It is the authors view that the combination of objective building performance data and subjective satisfaction ratings may offer a more valid and reliable evaluation of a building's success.

6. Acknowledgements

7. References

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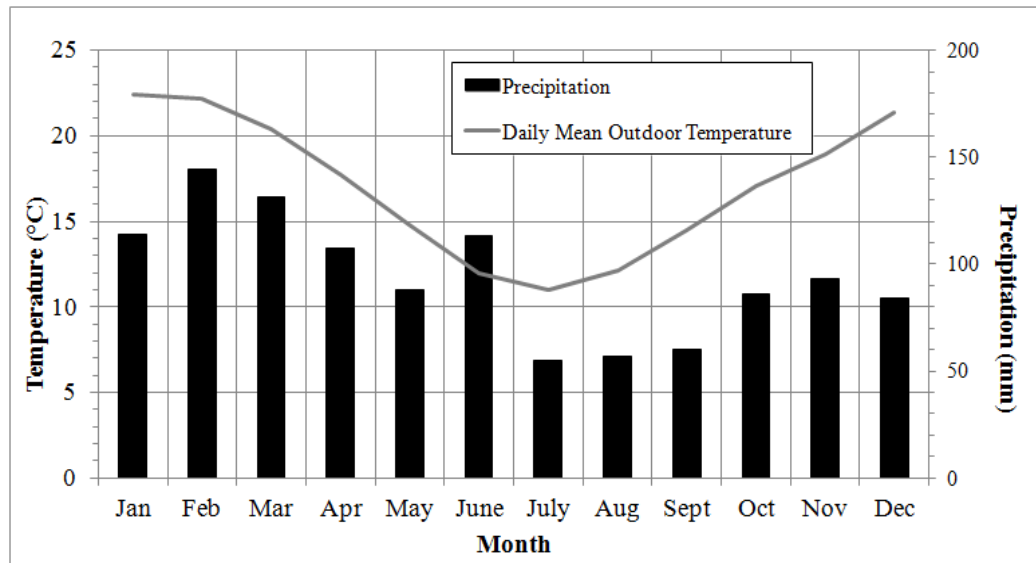
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**Acknowledgements**

This project was funded in part by an Australian Research Council Discovery Grant (DP0880968). We are enormously grateful to Adrian Leaman for permission to use the BUS questionnaire under license and his assistance in data analysis. We would also like to thank the University’s Office of Facilities Management for their support. Finally, and most importantly, we express our appreciation to all the building occupants who responded to the questionnaires.

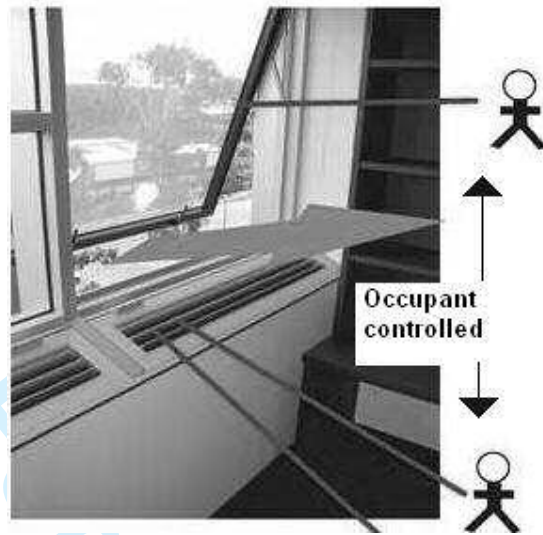
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**Figure 1.** Climatology of the case study building site (adapted from BoM, 2011)



**Figure 2a)** The MM building as viewed from the north facade featuring operable windows with external solar shading devices on north-facing windows



**Figure 2b)** User-operated windows and internal grilles in the North and South perimeter offices of the MM building

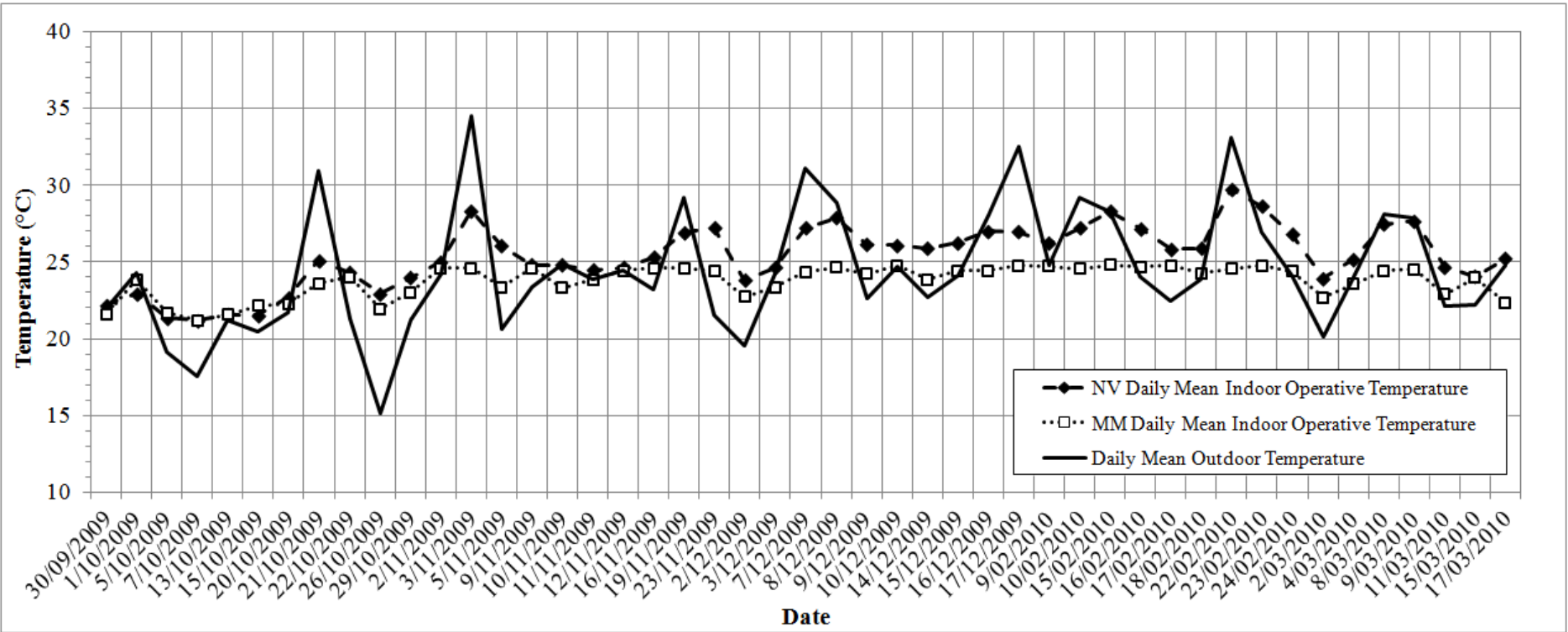


**Figure 3a)** The NV building as viewed from the north facade featuring occupant-operated windows with some individual air-conditioner units



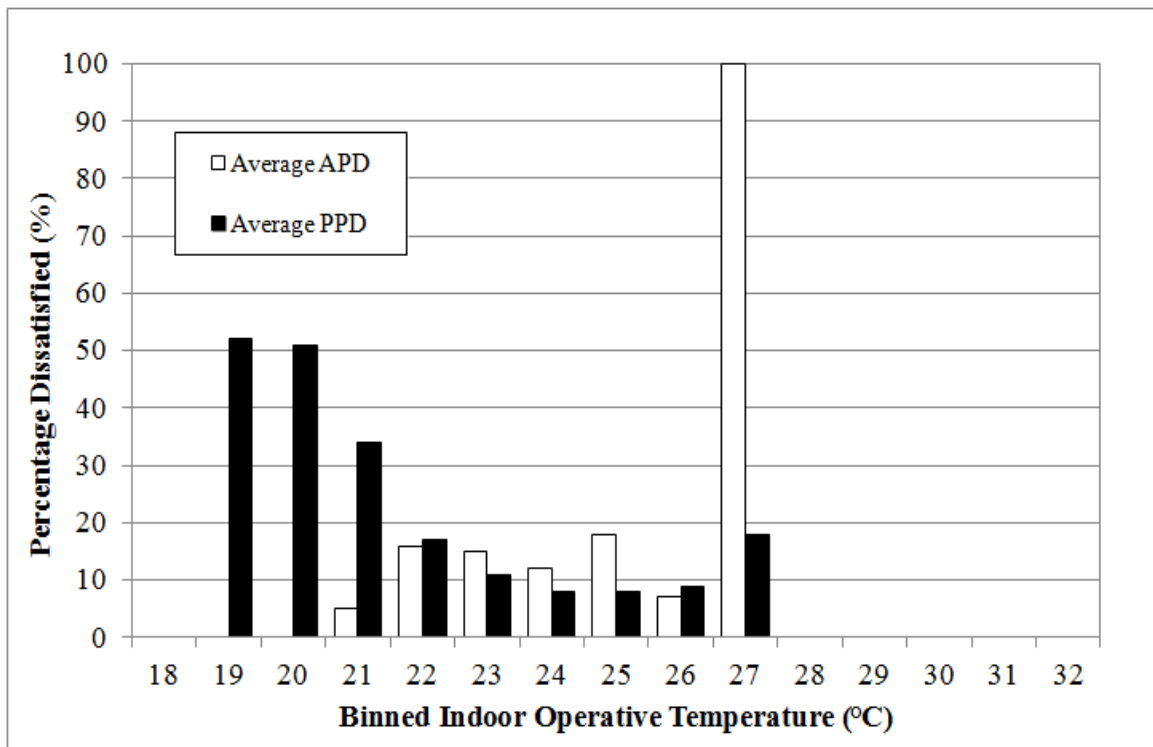
**Figure 3b)** Occupants often use portable fans or heaters for additional cooling/heating throughout the year





**Figure 4.** Summertime thermal environment recorded for the MM and the NV building (October 2009 to April 2010). Each data point corresponds to days in which thermal comfort questionnaires were administered





**Figure 5a)** Average APD and PPD recorded in the MM building

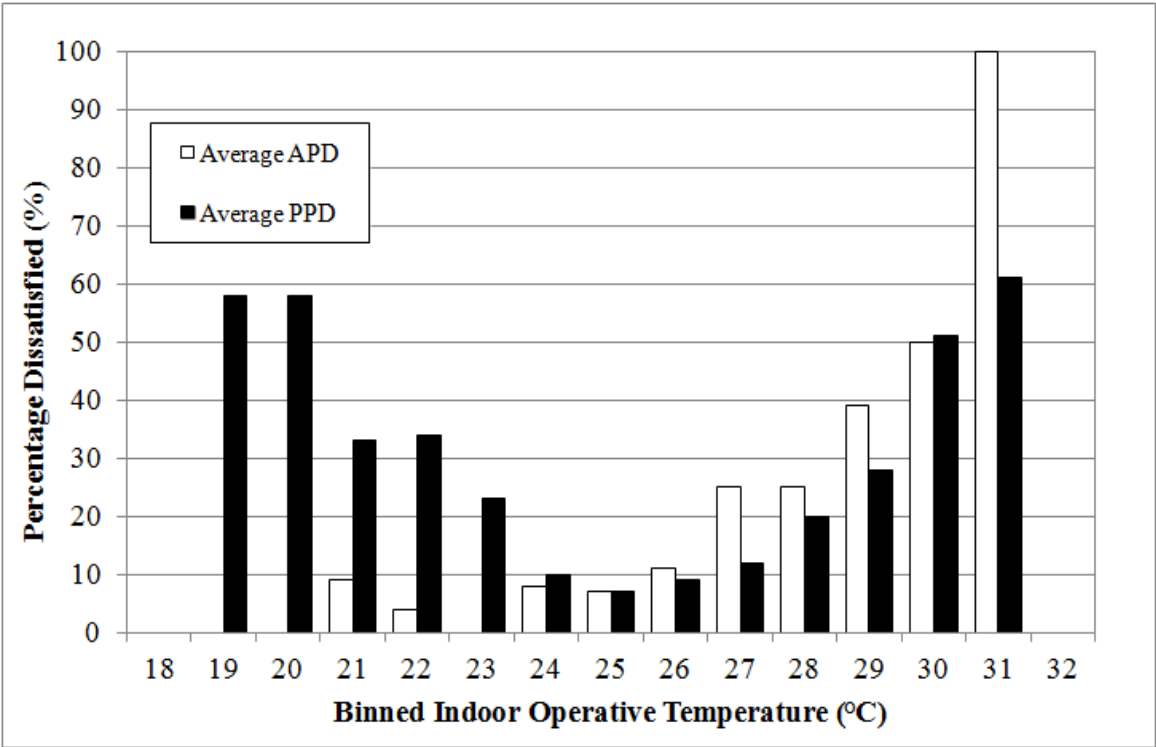
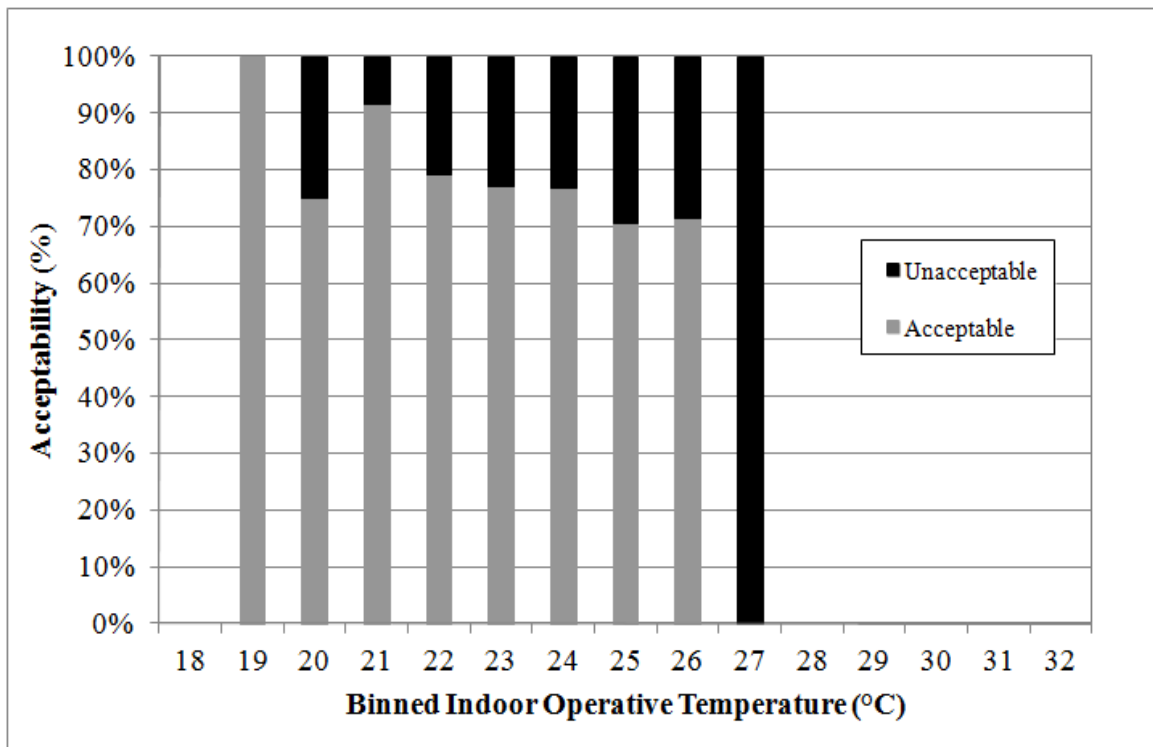


Figure 5b) Average APD and PPD recorded in the NV building



**Figure 6a)** Percentage of thermal acceptability votes registered in the MM building

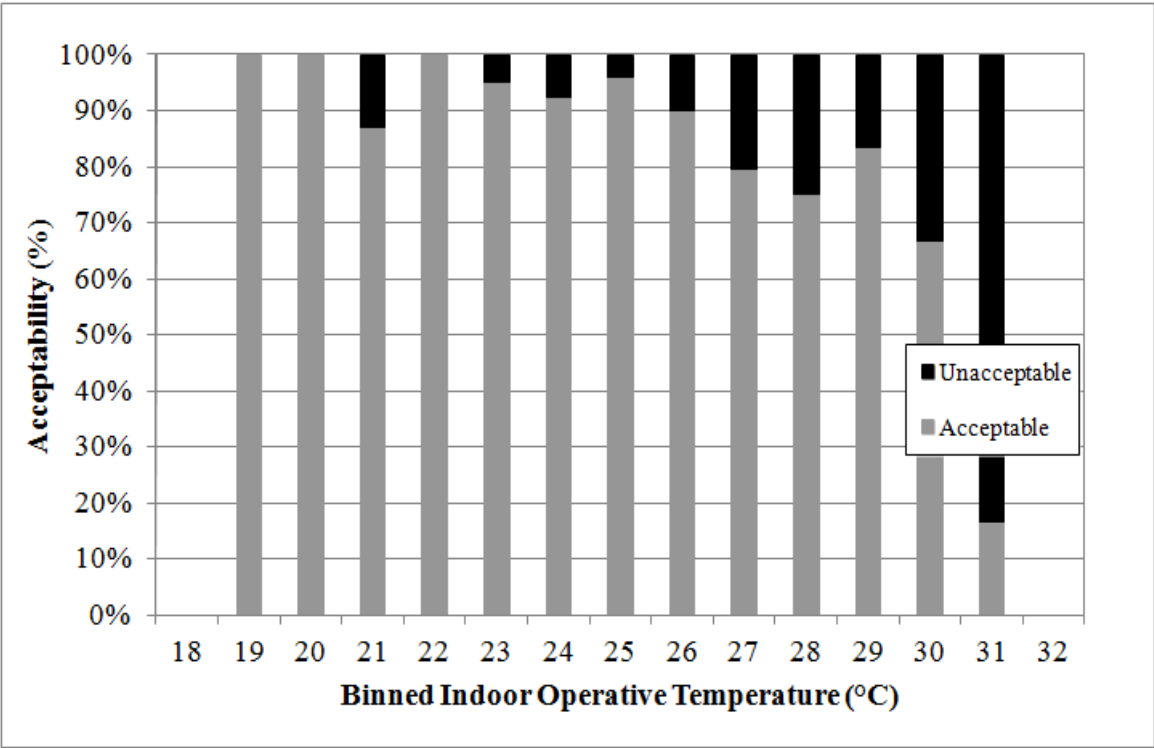


Figure 6b) Percentage of thermal acceptability votes registered in the NV building

**Table 1.** Forgiveness factor and dissatisfaction percentages of variables in the POE for the MM and NV building

Variable	Dissatisfaction (%)	
	MM (n = 86)	NV (n = 81)
Temperature in summer	58	28
Ventilation in summer	57	25
Comfort overall	55	44
Lighting overall	16	23
Noise overall	35	38
Perceived productivity	33	58
Forgiveness factor	0.99	1.14

**Table 2.** List of keywords and phrases used to identify complaints in each category.

Category	Keywords and Phrases	MM Building (n = 167)	NV Building (n = 108)
Temperature	Hot, cold, heat, temperature, air-conditioning	51 (31%)	60 (56%)
Ventilation	Air, ventilation, draught, humidity	27 (16%)	13 (12%)
Noise	Noise, outside, students, talking	64 (38%)	25 (23%)
Lighting	Glare, lighting, window, blinds,	25 (15%)	10 (9%)

#### **4.4. Results and Discussions Summary**

The preceding sections of this chapter, i.e. Paper 4.1, Paper 4.2 and Paper 4.3, present the results, as well as the discussions and conclusions of each study in turn. Whereas each study, and its resulting paper, covers specific aims and objectives related to its topic, several overarching themes emerge from this ensemble. These themes: cultivating environmental attitudes in green buildings (i.e. the ‘green occupant’ phenomenon), engineering comfort expectations, and incorporating occupants into building design, are interrelated across each paper. In highlighting these themes, this section discusses the key findings of each paper and how they fit within the broader context of the thesis.

##### *4.4.1. Cultivating Environmental Attitudes*

The first paper in this thesis (Paper 4.1) investigates how environmental attitudes relate to occupants’ forgiveness of green buildings. Substantial savings in terms of energy consumption and GHG emissions can be realised through the construction of ‘green’ buildings (GBCA, 2008). However, the difficulty in optimising energy efficiency within green buildings involves the attitudes or behaviour of the occupants. Browne and Frame (1999) suggest that in order for green buildings to work effectively and maximise their climate change mitigation potential, their occupants need to think and act in a way that complements the buildings’ green design intent. In other words, green buildings need green occupants (Browne and Frame, 1999). Prior to this study, the level of pro-environmentalism within buildings had never been investigated; this study was the first to use the NEP scale (Dunlap and van Liere, 1978; Dunlap et al., 2000) in conjunction with the BUS POE questionnaires (BUS, 2009) to explore the relationship between environmental attitudes and occupant satisfaction within MM and NV buildings.

Green buildings are often promoted as offering higher quality, more comfortable and more productive environments for their occupants (e.g. Huizenga et al., 2003). Whilst there is little empirical evidence in the literature to support this notion, previous studies suggest green buildings lead to higher levels of occupant satisfaction (e.g. Abbaszadeh et al., 2006; Leaman and Bordass, 2007; Paul and Taylor, 2008; Brager and Baker, 2009). Paul and Taylor (2008) compared occupants' comfort perceptions and overall satisfaction with the workplace between a green (NV) and conventional (AC) building located in Australia's south-eastern region of Albury-Wodonga. This region's climate is characterised as having hot dry summers and cool winters. Their study, conducted across an Australian summer season (December 2000 to February 2001), revealed that thermal environments perceived to be warm, i.e. those occurring in the green building, caused lower levels of satisfaction than those environments perceived as cool or thermally comfortable (typical of conventional AC buildings) (Paul and Taylor, 2008). On this basis, the warmer summertime thermal environment of the NV building, compared to the cooler indoor temperatures found in the MM building (Figure 4.1.3 in Paper 4.1, page 103) should have elicited warmer comfort perceptions and lower occupant satisfaction. However, both buildings were, in general, poorly received by their occupants in terms of occupant satisfaction, thermal comfort and perceived productivity (Deuble and de Dear, 2010). Despite the differences between each buildings' physical thermal environment, the average forgiveness factor for occupants in the NV building was significantly higher than that of their MM counterparts (Table 4.1.1 in Paper 4.1, page 104). This is consistent with an emerging trend in Australian green buildings noted by Leaman et al. (2007), and suggests that occupants of the NV building were more tolerant of the less-than-ideal conditions experienced in their building than their MM building counterparts.

Leaman and Bordass (1999) interpret the 'forgiveness factor' as a measure of how far people can stretch their comfort zone by overlooking and accepting inadequacies of their building's



thermal, acoustic and visual environments. The higher forgiveness scores typically found in 'green-intent' or 'green' buildings are often attributed to their occupants having some degree of personal environmental control (Leaman and Bordass, 2007). Furthermore, this tolerance of less-than-ideal indoor environments could also indicate that occupants may have an understanding of, and connection with, the outdoor climate by virtue of the building's design (Kwok and Rajkovich, 2010; Baird, 2011b). Both case study buildings in this thesis afforded their occupants similar degrees of occupant-orientated environmental control, or 'adaptive opportunities' (Baker and Standeven, 1996) to control air movement/ventilation (operable windows) and lighting (shades, artificial lighting). The only difference was that the MM building resorted to centralised HVAC whenever and wherever indoor temperatures exceeded the 25°C trigger temperature.

In acknowledging that neither overall occupant satisfaction nor personal environmental control can explain these findings, we are left to consider another covariate to this relationship; environmental attitudes as measured with the NEP (Dunlap et al., 2000). The NV building's occupants had significantly higher mean NEP scores than their counterparts in the MM building (Table 4.1.1 in Paper 4.1, page 104). Employment in environmentally-inclined disciplines is considered a major determinant of NEP scores (Ewert and Baker, 2001). When categorised into either environmental or non-environmental science academic disciplines, the non-environmental science academics of the NV building measured similar levels of environmental attitudes (NEP scores) as the occupants of the MM building. Despite this, however, the forgiveness factors of occupants in the MM building remained significantly lower than that of the non-environmental occupants in the NV building (Table 4.1.2, page 104). These results suggest that occupants of the NV building, regardless of their academic discipline or environmental orientation, were more forgiving of their building. The linear regression model shown in Figure 4.1.4 (Paper 4.1, page 104) supports the hypothesis that the

‘green’ building users were more prepared to overlook and forgive less-than-ideal conditions than their ‘brown’ (non-green) counterparts.

This correlation could be the result of what environmental psychologists refer to as place identity: the conception of the self or personal identity that has been constructed on the basis of the place to which the individual belongs (Proshansky et al., 1983; Lalli, 1992; Bonaiuto et al., 1996; Devine-Wright and Clayton, 2010). This concept is not to be confused with place attachment, which is a person’s emotional or affective bonds to a place caused by the long-term connection with a certain environment within which that person becomes accustomed to its surroundings (Hidalgo and Hernandez, 2001; Lewicka, 2011). Place identity theory predicts that those people who feel empathetic towards the environment would be more likely to identify with a green building and, therefore, more likely to have a positive evaluation of the building’s indoor environmental conditions (McCunn and Gifford, 2012). On the other hand, environmental empathy would be negatively correlated with place identity in conventional AC buildings, and, in turn, result in a less positive evaluation of the workplace environment in such a building. In support of this notion, Monfared and Sharples (2011) suggest that occupants’ disengagement with the building’s green identity can affect their satisfaction with the building. Given the higher levels of pro-environmental attitudes and forgiveness factors observed in the ‘greener’ NV building (Paper 4.1), these occupants are more likely to identify themselves as being ‘green’, and therefore form a connection with the ‘greenness’ of their building.

The findings from Paper 4.1 highlight how occupant attitudes and expectations play an important role in the way green buildings are designed, built and received. Whilst it has not been determined if occupants of green buildings are more actively engaged in sustainable behaviours than those in conventional AC buildings, this study suggests that green occupants

are best suited to green buildings. Given the study presented in Paper 4.1 did not focus on pro-environmental behaviour but rather the attitudes that presumably drive them, it is nonetheless important to understand the key aspects of the physical environment or behavioural context which influence individuals to participate in pro-environmental behaviours. Currently, there is little evidence to suggest that green design in office buildings has a positive effect on employee engagement (i.e. job satisfaction, perceived productivity and organisational commitment) or on environmental attitudes and behaviours (McCunn and Gifford, 2012). Needless to say, the results from Paper 4.1 indicate that occupants' environmental attitudes can and do affect their forgiveness of green buildings.

It is suggested that occupants with greater environmental beliefs and concern are able to appreciate and tolerate green buildings if their design-intent matches their own altruistic behaviour and pro-environmental motivations. In other words, green occupants are able to forgive the less-than-ideal conditions inside green buildings because they perceive themselves, and the building, as a co-operative partnership working towards a common solution to environmental problems, such as climate change mitigation. Already we are seeing successful examples of these strategies working in different ways. Many multinational corporations have established themselves as being committed to environmental issues and green building designs. These companies understand the role buildings must play to counteract climate change and preserve the environment for future generations. As a means of broadcasting their company's 'green' reputation, headquarters are often accommodated within some of the world's iconic green buildings (as rated by rating tools, e.g. LEED in the US, BREEAM in the UK, and Green Star in Australia). Such corporations maintain their 'green image' through the selective employment of occupants pre-disposed to work in green buildings because of their environmental attitudes. By understanding how their

environmental attitudes match the building's green design features, such occupants can achieve high levels of satisfaction and forgiveness for the building.

Given the urgency to mitigate climate change, it has become apparent that people's attitudes, and the behaviours associated with them, can be shifted. Whilst buildings take years to build or months to retrofit, the path to altering people's expectations of the built environment presents another, potentially more accessible strategy. Many behaviour change programs within the US and Canada have discovered the power of social norms, i.e. the customary rules that govern behaviour in groups and societies, to induce energy conservative and pro-environmental behaviours (Schultz et al., 2007). This study acknowledges that the forgiveness of green buildings can be cultivated, and given the multitude of sustainable and pro-environmental behaviour literature, there is great potential for occupants to be 're-educated' about the role buildings play in addressing global climate change (e.g. Berkhout et al., 2006; Schultz et al., 2007; Griskevicius et al., 2008; Nolan et al., 2008; Allcott, 2011; McKenzie-Mohr, 2011; Stern, 2011). Perhaps the most notable example of this is Japan's Cool Biz campaign. In their attempts to help mitigate climate change and reduce the country's GHG emissions by 6% by 2010, Japan's Ministry of the Environment (MOE, 2006) widely encouraged businesses and the general public to set office air-conditioners at 28°C during summer (Koike, 2006). As a part of this campaign, the MOE promoted 'Cool Biz', encouraging business people to wear cool and comfortable clothes to work efficiently in offices where thermostats were set at around 28°C. Following acceptance by the majority of companies and people, it was estimated that during the summer months of June through to August 2005, electricity demand was reduced by 210 million kWh; and accordingly, emissions were reduced by 460,000 t CO<sub>2</sub> (Koike, 2006; IPCC, 2007).

The need to develop sustainable lifestyles and attitudinal and behaviour change is central to achieving sustainability in the built environment (Jackson, 2005). Environmental psychology, sociology, occupational psychology, and marketing can all play a role in understanding the drivers for pro-environmental behaviours (Kollmuss and Agyeman, 2002; McKenzie-Mohr, 2011). Clearly there is ample scope for further research in this area, with multidisciplinary teams of psychologists, building and environmental scientists, facility managers, and marketing experts collaborating to identify, design, implement and test interventions for pro-environmental attitudes and behaviours by building occupants. In doing so, such initiatives will not only communicate the necessity of creating a culture of sustainability and resource conservation among a building's occupants, but also develop the building's true 'green' potential.

#### *4.4.2. Engineering Occupant Expectations and Perceptions of Control*

In investigating how MM ventilation affects occupant comfort, Paper 4.2 represents one of only a handful of thermal comfort field studies conducted within MM buildings. MM buildings represent a combination of both AC and NV buildings: reduced energy consumption compared with centrally-controlled HVAC systems and the greater range of acceptable temperatures associated with natural ventilation through occupant-controlled windows. Despite increasing interest in such ventilation strategies, little is known about the effects of MM ventilation on thermal comfort, especially in commercial office settings. Furthermore, topical debates regarding whether international adaptive comfort standards should be applicable to MM buildings remain unresolved. Whereas the global ACS in ASHRAE Standard 55 (ASHRAE, 2010) precludes MM buildings, its European counterpart, EN15251 (CEN, 2007) allows the more flexible ACS to be applied to MM buildings during times when they are employing natural ventilation. This study, therefore, aimed to test whether the adaptive comfort model can be applied to MM buildings during NV mode.

Thermal sensations registered by the occupants (AMV) and those predicted based on Fanger's heat-balance equation (PMV) (1970) recorded in both AC and NV modes were compared. As illustrated in Figure 4.2.9a in Paper 4.2 (page 114), the thermal sensation votes show very strong correlations with the indoor operative temperature during AC mode. This suggests that within this mode, occupants act as passive recipients of the thermal environment; when operative temperature increases, they tend to feel warmer. It should be noted that these results were compatible to when all thermal sensations (predicted and observed) recorded in both modes were combined (Figure 4.2.8 in Paper 4.2, page 113). In addition, the range of thermal sensations was equal amongst the observed and predicted values. However, whereas the PMV values in NV mode again show high correlation with the indoor operative temperature, the observed AMV values do not match this correlation (Figure 4.2.9b in Paper 4.2, page 114). The gentler gradient found between the AMV values and indoor operative temperature suggests that occupants were more adapted to the thermal environment. Moreover, the thermal sensations predicted by the PMV model ranged from -1 (*slightly cool*) as the lowest to +1.5 (*slightly warm to warm*) as the highest. Across the same range of temperatures, the occupants' thermal sensations registered between the regions of 0 (*neutral*) to +1 (*slightly warm*) suggesting they were able to adapt to the indoor environment by availing themselves of the adaptive opportunities, such as opening/closing their window; adjusting their clothing, and/or shifting their expectations (Brager and de Dear, 1998).

Adaptive comfort theory predicts that the gradient of the relationship between thermal sensation and indoor operative temperature is inversely related to the adaptability of the subjects. In other words, as adaptability increases the gradient approaches zero (horizontal). Figure 4.2.10 in Paper 4.2 (page 114) demonstrates the role of occupants' psychological and behavioural adaptations in manipulating thermal perceptions between AC and NV mode. During times when the building was employing air-conditioning, an indoor operative

temperature of 27°C (a PMV = +1 (*slightly warm*) environment) elicited significantly ‘warmer-than-neutral’ thermal sensations than the same thermal environmental conditions within NV mode. Even at a temperature of 21°C, the average AMV value recorded by occupants in NV mode was neutral (0.16) whereas in AC mode, the average observed thermal sensation was significantly cooler (-0.42). Whereas this difference (0.58) is only about half of a thermal sensation unit (0.5), these findings suggest that thermal perceptions were affected by the building’s mode of operation over-and-above the objective indoor climatic conditions. Comparable to previous studies reflecting differences in comfort temperatures on a building-by-building basis (e.g. Busch, 1992; de Dear and Brager, 2002; Nicol and Humphreys, 2002), the resulting linear regression model fitted to observed thermal sensations (AMV) (Figure 4.2.10 in Paper 4.2, page 114) clearly shows the adaptive model is best suited to explain occupant comfort during times of natural ventilation within the same building. In relation to the differences in scope between the ASHRAE and European comfort standards, the findings presented in Paper 4.2 favour EN15251’s application of the adaptive comfort model instead of PMV-PPD to MM buildings when they are operating in NV mode. During AC mode, Fanger’s PMV-PPD model (1970) displayed good correlations with observed thermal sensations (AMV).

Apart from justifying the inclusion of MM buildings within the ACS of ASHRAE’s Standard 55-2010, this study further highlights the complexity of comfort perception and psychological adaptations in MM environments. According to Table 4.2.1 in Paper 4.2 (page 114), there were no significant differences between the thermal environments of each mode. Across the entire 12 months in which this study was conducted, the average indoor operative temperature recorded in AC mode ( $23.3 \pm 1.8^{\circ}\text{C}$ ) was, in fact, very close to that for NV mode ( $23.1 \pm 1.2^{\circ}\text{C}$ ). Additionally, the average air velocity during both modes remained very similar as well ( $0.10 \pm 0.05 \text{ m/s}$ ) (Table 4.2.1, Paper 4.2, page 114). Despite the limitation in

expressing differences between two modes on the basis of average values, the only physical variable that changed appreciably was clothing insulation. Occupants, on average, wore significantly less clothing ( $\text{clo} = 0.50$ ) during natural ventilation than when the building was in AC mode ( $\text{clo} = 0.57$ ). This difference of 0.07 clo (equivalent to a short sleeve T-shirt; or the difference between long trousers and shorts for men, or between a dress and knee-length skirt for women) suggests occupants felt warmer in NV mode and cooler in AC mode. This finding is further supported by the significantly warmer AMV value recorded in NV mode (0.43) compared to AC mode (0.19). Understandably, as indoor temperatures are allowed to rise during NV mode to prompt switch-over to AC mode (shown in Figure 4.2.6 in Paper 4.2, page 113), occupants would actively remove items of clothing in order to maintain thermal neutrality. Considering the negligible differences in the thermal environment of each mode, there is no reason to suggest the occupants would sense the need to remove or add clothing during these events. Nonetheless, while these differences are possibly reflected in the discrepancy between observed (AMV) and predicted (PMV) thermal sensations in both modes (Figures 4.2.9a and 4.2.9b, Paper 4.2, page 114), it is suggesting that contextual effects, such as shifting expectations and perceived control may indeed influence thermal comfort.

Despite negligible difference in the actual indoor environment, the occupants' thermal sensations/perceptions within the MM building differed between AC and NV modes of operation (Table 4.2.1 in Paper 4.2, page 114). Whilst difficult to pinpoint the actual cause of this phenomenon, it is speculated that the occupants' expectations and the ability to control their windows (or at least knowledge of this ability once the building was in NV mode) are the reasons why thermal sensations during NV mode were more adaptive compared to those in AC mode (Figure 4.2.10 in Paper 4.2, page 114). By viewing the AC display panel (Figure 4.2.5 in Paper 4.2, page 113) upon entering their respective corridor to their office, occupants



are aware of their office's current mode of operation, either AC or NV. When the building switched into NV mode occupants located in the North and South perimeter zones are then able to open their windows for additional ventilation. Once the occupants knew they had control of their windows during NV mode, their expectations of the thermal environment shifted to allow for a greater range of acceptable indoor temperatures which could be accommodated through use of their operable windows. It is also likely that the ratio of outdoor ventilation to air velocity would be greater during natural ventilation than air-conditioning; so it is entirely possible that improved thermal comfort under NV mode resulted from cross-modal interactions between air quality and thermal comfort (Deuble and de Dear, 2011). However, since these variables were not recorded during this study, this potential relationship could not be confirmed.

Within the present study (Paper 4.2), there is evidence to support the effects of psychological adaptation, i.e. expectations and perceived control, on thermal comfort. Psychological adaptation refers to an altered perception of, or response to, the thermal environment, resulting from one's thermal experiences and expectations (Auliciems, 1981; Fountain et al., 1996). Brager et al. (2004) suggest that subjects with greater access to control actively shift their expectations to become more tolerant of, and potentially prefer, conditions previously considered to be thermally uncomfortable. Similarly, Pacuik (1989) proposed that *perceived* control (expectation) was one of the strongest predictors of thermal comfort and satisfaction. The resulting divergence between observed and PMV-predicted comfort found within NV mode (Figures 4.2.9b and 4.2.10 in Paper 4.2, page 114) can be ascribed to shifting comfort expectations (de Dear and Brager, 2002). Indeed, the role of personal control on expectation and thermal response has important implications in MM buildings. Within the context of the AC mode, it is plausible that occupants have come to expect thermal constancy and even the slightest departure away from that expectation is sufficient to prompt complaint (de Dear,

2007). Given the indoor temperatures prevailing during times of natural ventilation are more closely correlated with outdoor climatic conditions than in centrally AC buildings, occupants come to expect the indoor thermal environment to match the outdoor weather conditions, especially during NV mode. Considering the NV mode affords greater degrees of thermal control to its occupants than to those of AC buildings, it is this sense of control that leads to more relaxed expectations and greater tolerance of the thermal excursions typical of buildings featuring natural ventilation and operable windows (Brager et al., 2004).

Certainly, the maintenance of indoor climates accounts for a substantial component of energy end-use, and therefore, GHG emissions in the buildings sector. However, when building occupants are offered adequate adaptive opportunities, e.g. operable windows, the psychological dimensions of comfort (i.e. expectation and control) hold as much promise for mitigating climate change in the buildings sector as the more frequently mentioned technical GHG abatement options of the building envelope and HVAC systems found in the literature (IPCC, 2007; Levine et al., 2007; Urge-Vorsatz et al., 2007). Although the potential of human thermal adaptation to indoor climates was recognised as highly relevant to energy savings, the IPCC (2007) focused its attention on market transformation that didn't account for adjustments to lifestyles or comfort levels. Nonetheless, it is becoming increasingly clear that simply shifting building thermostat settings to be closer to outdoor temperatures, without resorting to expensive retrofits to the building envelope or HVAC systems, can have a profound effect on energy consumption and the associated GHG emissions. For example, by shifting the thermostat set-point in a conventionally AC office building in Melbourne one degree higher (from 22°C to 23°C), Ward and White (2007) measured a 14% reduction in HVAC energy consumption on identical summer days. These findings are significant considering HVAC energy typically accounts for up to 40-50% of total commercial building energy end-use. Therefore, by changing comfort expectations of the building occupants away

from static HVAC set-points to more adaptive indoor temperatures that follow the natural swings in the prevailing outdoor weather, such efficiency measures can be readily applied across much of the existing building stock, and not just new construction and refurbishments. However, the time taken for occupants to adapt to variable indoor temperatures after they have been acclimatised to static HVAC environments remains to be seen.

#### *4.4.3. Incorporating Occupants into Building Design*

The complexity of occupant expectations and attitudes with respect to indoor thermal environments are also echoed in the final paper of this thesis (Paper 4.3). This study tested the validity of contemporary POE methods through comparisons with thermal comfort studies conducted in the MM and NV buildings, and in doing so, provides recommendations as to how occupant-centred building performance evaluations can be enhanced. The POE has been taken as a means to evaluate actual building performance. However, recent applications of these tools have relied on more subjective criteria, such as occupant satisfaction, to evaluate building performance. This paper argues that due to a lack of contextual information, continued feedback and physical (instrumental) measurements of the building's indoor environment, contemporary POE methods potentially over-exaggerate poor building performance and as such, provide a superficial assessment of the buildings' occupants.

The indoor and outdoor climates for each building were measured over the duration of this study (between March 2009 and April 2010). Not surprisingly, the NV building experienced significantly warmer indoor temperatures than the MM building during Sydney's summer months (Figure 4.3.4 in Paper 4.3, page 162). On average, temperatures in the MM building were 2°C cooler than in the NV building, emphasising the effect of the MM building's AC switch-over trigger temperature. Although more modest temperatures were recorded in the MM building, results from the POEs conducted in both buildings (outlined in Paper 4.1)

demonstrate higher levels of occupant dissatisfaction in the MM building compared to the NV building (Table 4.3.1 in Paper 4.3, page 167). Previous studies indicate that building users often perceive NV buildings as too hot and AC buildings as too cold, in summer (Leaman and Bordass, 2007; Baird et al., 2012). Despite the less-than-ideal conditions experienced in the NV building, its occupants reported moderate levels of satisfaction (around 80%) and this can be understood with reference to their higher forgiveness factor compared to their MM counterparts (Table 4.3.1 in Paper 4.3, page 167).

From parallel ‘right here, right now’ thermal comfort studies conducted in both buildings, it was found that occupants’ perceptions of comfort and thermal acceptability not only differed between these buildings but so too did their POE and thermal comfort results. According to Fanger’s PMV-PPD model (1970), as expressed in ASHRAE 55-2010, the indoor environmental conditions experienced in the NV building would be deemed uncomfortable as indoor operative temperatures were well above the upper limit of 25°C (Figure 4.3.4 in Paper 4.3, page 162). Despite this, the occupants’ actual percentage dissatisfied (APD) in the NV building was, on average, lower than the PPD values predicted using Fanger’s heat-balance model (Figure 4.3.5b in Paper 4.3, page 164). In comparison, occupants of the MM building registered greater levels of thermal dissatisfaction (i.e. higher APD values in Figure 4.3.5a in Paper 4.3, page 163) than those predicted using PMV-PPD across the same range of temperatures. Despite summertime temperatures within the MM building being constrained between 20-25°C, occupants expressed significantly greater levels of thermal discomfort. According to the analyses shown in Figure 4.3.6a in Paper 4.3 (page 165), within the MM building, over 20% of occupants surveyed found the indoor temperature to be unacceptable, even at moderate temperatures, e.g. 20-25°C. In contrast, Figure 4.3.6b in Paper 4.3 (page 166) demonstrates that under similar environmental conditions, fewer occupants (as low as 5%) in the NV building found the indoor temperature to be unacceptable. In agreement with

other POE studies, these findings suggest that the NV occupants were more tolerant and accepting of the thermal environment, despite experiencing significantly warmer temperatures than their MM counterparts (Leaman and Bordass, 2007; Baird, 2011b).

It is evident from this paper that objective criteria, such as temperature and PMV-PPD, are not the only determinants of comfort. Occupants can be a useful and inexpensive source of information about IEQ (Peretti and Schiavon, 2011). The comparison of occupant-based comments and anecdotal evidence offer the invaluable, but often overlooked context and complexity of user experiences (Bordass and Leaman, 2005b; Moezzi and Goins, 2011). From the list of keywords and phrases related to temperature, ventilation, noise and lighting (Table 4.3.2 in Paper 4.3, page 168), 167 complaints were recorded for the MM building and 108 for the NV building. As reinforced by the physical instrumental measurements (Figure 4.3.4 in Paper 4.3, page 162), over 50% of comments gathered from the NV building complained about the “temperature”. Within the MM building, “temperature” was the second most reported problem (31%), with “noise from outside” and “from colleagues” as the most common complaints (38%). These results shed light on a common theme emerging from many recent POE studies in NV and MM buildings. Many studies reveal air movement, temperature, glare and noise as the most common causes for dissatisfaction in green buildings (Abbaszadeh et al., 2006; Brager and Baker, 2009; Moezzi and Goins, 2011; Baird et al., 2012). From their analysis of occupants’ comments and satisfaction scores across 47 POE studies, Baird and Dykes (2012) found that negative comments (i.e. complaints) were moderately correlated with lower satisfaction scores and positive comments were correlated with higher satisfaction scores. While the results in Paper 4.3 demonstrate potential areas of improvement and lessons to be learned in future green building construction, they also suggest that the building may not be the problem. This begs the question: how much does the POE get influenced by non-building contextual factors?

Within building performance studies, it is not uncommon to find gaps between the designer's expectations and built outcomes (Leaman et al., 2010). Whereas the MM case study building was deemed comfortable on objective criteria, its occupants felt the need to complain about the building's performance. These results indicate that occupants predisposed to complain, either due to contextual (e.g. work-related) or physical (e.g. temperature) factors will over-exaggerate poor building performance. The discrepancies between thermal satisfaction and acceptability between the POE and thermal comfort results (in Paper 4.3) further supports the hypothesis that occupants can and do use POEs as a vehicle for complaint about general workplace issues, unrelated to their building. Much of the information generated by POE is inherently subjective and often negative (Vischer, 2002; Baird and Dykes, 2012). Many researchers have advocated more robust POE approaches, thereby providing a highly sophisticated and detailed assessment that enables the triangulation between physical environmental measures and subjective occupant appraisals (Preiser, 2002; Preiser and Vischer, 2005; Turpin-Brooks and Vickers, 2006). More importantly, Paper 4.3 stresses the importance of educating occupants about design decisions and intent, comfort provision, as well as the environmental consequences of their actions (Brown and Cole, 2009). In doing so, such induction programs may play a valuable role in improving comfort and calibrating green building occupants' expectations.

#### **4.5. Synthesis**

In light of findings from Papers 4.1, 4.2 and 4.3, it is apparent that green buildings, i.e. MM and NV buildings, can perform well. However, the success (or failure) of these buildings, and their performance, are ultimately determined by their occupants. Buildings are primarily designed and built for their intended occupants, however in many cases this is done without explicit consideration of the buildings end-users' needs or preferences (Way and Bordass, 2005). As a result, many occupants do not understand how to operate their building,

which can often lead to high levels of discontent (Leaman and Bordass, 2007). In order for green buildings to perform effectively in the context of a low-carbon future, a shift is required from conceptualising the occupant as a passive recipient of the indoor thermal environment, to the inhabitant that interacts and plays a more active role in the maintenance and performance of their building (Brager and de Dear, 1998; Cole et al., 2008; Brown and Cole, 2009).

Within this thesis, the term ‘green’ occupant is used to describe building users who are in-tune with their building’s performance and understand the role green buildings can play in mitigating climate change. Collectively, the overarching themes of environmental attitudes, occupant comfort expectations, and incorporating occupants into building design, underscore the importance of occupant engagement within commercial office buildings. At its pinnacle, occupant engagement describes a building-wide culture in which empowered building occupants are aware of and accountable for their own energy and water use, and waste disposal. However, occupant engagement can also encompass the process of creating that culture – including decisions made by architects and engineers as well as building managers, employers, and other stakeholders. The findings from Papers 4.1, 4.2 and 4.3 clearly identify the need to change people’s attitudes, expectations and behaviours towards green buildings to better reflect the design-intent of the building. Furthermore, these studies suggest that the use of occupant engagement strategies, such as, providing feedback, transforming social norms, occupant education and empowerment, will enable building users to become ‘green’ occupants.

There are many reasons why buildings don’t perform as well as expected, however, the hardest-to-manage reason for longer-term performance gaps is the way people live and work in their buildings. Individual occupants and the choices they make, such as opening/closing

windows, overriding automated systems, leaving appliances on, etc directly affect the building's energy performance. While it is estimated that 20-50% of energy use in buildings can be attributable to occupant behaviour (Janda, 2011), building users are unaware of the energy they use and its overall impact on the building's energy consumption. Within each of the papers presented, it is apparent that building designers need to incorporate features that allow the building to be operated properly. The use of adequate feedback systems and effective communication can provide meaningful real-time consumption information which helps the building managers and occupants understand how their choices affect energy use.

Constant communication between the building owners, their managers and occupants is another important part of occupant engagement. However, in order to be effective, such communication needs to be contextualised, direct and visually engaging. All three papers hinge on the idea that environmental attitudes can be cultivated using a variety of environmental psychology and behaviour change principles, e.g. changing social norms through community-based social marketing (CBSM) (McKenzie-Mohr, 2011). CBSM involves intensive, interactive work and two-way feedback at the community level and focuses on simple and incremental changes in habits, setting measurable short- and long-term goals and tracking progress (McKenzie-Mohr, 2000). The connection of energy consumption data and daily habits through visual displays can be a powerful tool in transforming social norms within the context of commercial buildings. Moreover, competitions and financial incentives can also provide a social context in which people will track their energy and water use and make public commitments to changing habits (Driedger, 2011).

As organisations begin closely tracking occupants' habits and occupants start to be more aware of their own energy consumption, people can start to be held accountable for less sustainable behaviours. At its core, occupant engagement is about occupant empowerment.



As building owners begin to set energy performance goals through green building rating tools, such as NABERS and Energy Star (both of which are based on actual measured building performance), tenant companies and their employees also need to be on board with building-wide goals. Each paper highlights the need for occupants to be more involved with their building's performance and operation. While education campaigns and seminars were held for the occupants of the MM building upon its completion, these were largely unattended. As such, the occupants did not know how to effectively and efficiently use the building. Considering the high levels of occupant dissatisfaction within this building, the papers provide an impetus for greater educational and empowerment strategies within green buildings. If these buildings are contracted to sustain high levels of energy, water, IEQ or IAQ performance, the occupants need to feel empowered and connected with their building. Greater knowledge of the building's design features and how they operate will achieve effective, long-term occupant engagement programs and strategies, thus creating a building-wide culture of sustainability and 'green' occupants.

#### **4.6. Limitations**

This chapter presented the main results in the form of three papers that have been published in, or submitted to peer-reviewed journals. Limitations of the methods used in this thesis can now be discussed.

##### *4.6.1. Instrumentation and Data Collection*

Dataloggers were placed within one metre of the subject's workstation to accurately measure the immediate thermal environment. Occupant's desks were typically located next to the window (with their back being in direct sunlight, especially for offices on the Northern façade). Every attempt was made to ensure the black globe sensors attached to the dataloggers were not in direct sunlight; any erroneous indoor temperature measurements were

hence attributed to sunlight directly hitting the sensor. The heights and location of the dataloggers were repeatedly checked during questionnaire sessions and HOBO data uploads. However, there is no guarantee that the dataloggers were not mishandled over the course of the study, which may have influenced the indoor climate measurements.

#### *4.6.2. Sample Size and Response Rates*

Considering both case study buildings used in this thesis have populations of over 200 occupants it was important to recruit a large number of participants for each study. Notwithstanding attempts to ensure statistically significant sample sizes and response rates within each building, it is plausible that the results may not accurately describe the entire building population. In regards to the thermal comfort studies, 60 participants were recruited from each building, representing approximately 30% of the total occupant population in each building. These limited participant sample sizes can be attributed to difficulties in obtaining permission from the building occupants to participate in the study. As such, thermal comfort responses reported in this research may not be representative of the entire building.

In total, 163 POE and NEP questionnaires were distributed in the MM building with 86 completed questionnaire sets (39 male, 47 female) being collected, representing a response rate of 53%. Within the NV building, 120 POE and NEP questionnaires were delivered<sup>6</sup> and 69 were completed (30 male, 39 female) to achieve a 57% response rate. Incomplete responses were omitted from the samples during routine quality assurance processing. While the POE methodology calls for at least 50% of the building population (BUS, 2009), these response rates were sufficient for the purposes of benchmarking the results against the Australian green building BUS database.

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<sup>6</sup> Questionnaires were administered to all occupants located on floors 6, 7 and 8 in the NV building between March and April 2009. A separate follow-up study was conducted in March 2010 using the rest of the occupants (located on floors 2 to 5).

#### *4.6.3. Questionnaire Data*

Subjective questionnaires such as the POE, NEP and thermal comfort questionnaires are potentially prone to bias, depending on the methods and context in which the questionnaires are conducted. Since there was no way to directly influence or control for psychosocial or contextual (non-physical) factors that affect occupants in the workplace, participants' responses may be either positively or negatively biased due to their high susceptibility to observation-bias, otherwise known as the 'Hawthorne effect' (Franke and Kaul, 1978; Sonnenfeld, 1985). In this regard, the Hawthorne effect would be considered when the behaviour or responses of an individual or group change to meet the expectations of the observer/researcher (Roethlisberger and Dickson, 1939; Landsberger, 1958; Parsons, 1974).

The subjective thermal comfort questionnaires were used to record occupant perceptions of thermal comfort within their workspace. Considering these questionnaires were initially piloted to reduce participant confusion, the researcher was on-hand to answer any questions. As standardised clothing and metabolic activity checklists were simplified to include typical office-based work garments, it is possible that deviations around these values may exist due to the varying definitions of clothing garments and metabolic activity.

#### *4.6.4. Context of the Study*

Given that the case studies used in this research were academic office buildings located at MQ, the results and conclusions presented in this chapter (Papers 4.1, 4.2 and 4.3) are limited to these particular buildings in the context of Sydney, Australia. Whilst it is plausible that some results may be applicable to non-academic MM and NV office buildings and their occupants, by no means can the results of these studies be regarded as universal.

Furthermore, since the majority of data collected was during Sydney's summer months, the results were mainly focused on the use of air-conditioning for cooling purposes.

#### **4.7. Chapter Summary**

Comprised of three papers that have been published in, or submitted to, peer-reviewed journals, this chapter presented the key findings and discussions from each study (i.e. Papers 4.1, 4.2 and 4.3) within the broader context of the thesis. In discussing the overarching themes of these papers, i.e. cultivating environmental attitudes, engineering comfort expectations and incorporating occupants into building design, their findings clearly demonstrate the need for greater occupant engagement and involvement within commercial buildings. Each study highlighted significant differences between occupants' thermal responses under different indoor environmental conditions, suggesting people's environmental attitudes and expectations affect their perception of thermal comfort and satisfaction. The development of 'green' occupants, especially in green buildings, necessitates that building users are more in-tune with their building's performance and function. Through the use of feedback and energy tracking mechanisms, communication and social norms, occupant empowerment and knowledge, the process of and result of engaging occupants with their buildings will not only communicate the necessity of creating a culture of sustainability and resource conservation among building occupants, but also highlight the building's true 'green' potential. The final chapter presents some concluding remarks and recommendations for future research.

## **Chapter 5. Conclusions**

In order to maximise the climate change mitigation potential within commercial buildings, the right balance between building design, occupants, their comfort expectations and environmental attitudes is paramount. This thesis provides evidence to further support expanding the scope of comfort provision and building performance evaluation in green buildings to encompass a wide range of behavioural, psychological and contextual aspects. Building on previous work in the field, the research extends the psychological dimensions of thermal comfort and building occupancy studies to account for the contextual influences at play in NV and MM buildings, such as attitudes, expectations, and personal control. In doing so, this research provides evidence of how pro-environmental attitudes and comfort expectations are associated with occupants' satisfaction, experience and interaction with buildings and their indoor environmental conditions. This final chapter addresses the aims and objectives of each study and how they were achieved, and also, makes recommendations for future research.

### **5.1. Summary of Aims and Objectives Addressed in This Thesis**

This thesis evaluated how occupant expectations and environmental attitudes relate to thermal comfort and occupant satisfaction within the context of low-energy indoor thermal environments, as found in MM and NV buildings. Corresponding to a specific study and journal paper, three main topics were covered in this thesis, i.e. environmental attitudes and occupant satisfaction in green buildings (Paper 4.1); thermal comfort in MM buildings (Paper 4.2); and, the validity of contemporary POE methods (Paper 4.3). The research objectives of each study and how they were addressed throughout this thesis are summarised below:

### *5.1.1. Environmental Attitudes and Occupant Satisfaction in Green Buildings*

The study presented in Paper 4.1 addressed each of the following research objectives:

1. By conducting POEs within two ‘green’ buildings, i.e. a MM and a NV building, this study aims to evaluate the occupants’ ‘forgiveness factor’ in relation to their thermal environment.

Upon analysing the indoor climatic and outdoor weather conditions for the MM building (identified as Building E4A in Section 3.2.1) and the NV building (identified as Building E7A in Section 3.2.2), both buildings were found to exhibit some degree of dependence of their indoor temperature on outdoor weather conditions. However, in comparison to the MM building, the NV building experienced significantly warmer indoor temperatures throughout the study. Furthermore, the range of temperatures experienced in the NV building was far greater than in the MM building due to the latter’s BMS algorithm switching to AC mode whenever indoor temperatures reached 25°C. The BUS POE questionnaires were used to measure the levels of occupant satisfaction and ‘forgiveness factor’ within each building. Both buildings were generally rated poorly by the occupants on the POE, especially the MM building; however a higher forgiveness factor was recorded in the NV building. Considering the forgiveness factor quantifies the extent to which building occupants can accept the building’s indoor environmental conditions, this suggests that occupants of the NV building were more forgiving of their building’s less-than-ideal indoor climatic conditions than their counterparts in the MM building. From these case studies, it would seem that objective thermal conditions within a building are not the sole determinants of occupant satisfaction with thermal conditions, and that contextual factors may also be relevant. Earlier published building occupancy studies have alluded to occupants’ ability to control their indoor environmental conditions as the primary cause for the higher forgiveness scores found in ‘green’ buildings. However, given both case study buildings offer their occupants similar

degrees of adaptive opportunities, i.e. operable windows, we are left to explore another possible factor that may be associated with the higher forgiveness factors observed in the ‘greener’ NV building.

2. Through the use of the NEP questionnaire, this study investigates occupants’ levels of environmental attitudes within the MM and NV buildings. It is hypothesised that broadly pro-environmental attitudes are associated with the stronger ‘forgiveness factors’ towards indoor thermal environmental performance often reported in green building POE studies in the research literature.

The NEP environmental attitude scale was supplemented with the POE to measure the occupants’ level of pro-environmental attitudes within both buildings (outlined in Section 3.3.1). Occupants of the NV building had significantly higher levels of environmental attitudes (NEP) than the occupants of the MM building. To eliminate any potential bias in the NEP scores, occupants from the NV building were separated according to academic discipline, i.e. those associated with environmental science (labelled the ‘Eco’ group) and those associated with non-environmental science, e.g. Physics, Mathematics, Astronomy, etc. (labelled the ‘Control’ group). Whilst the average NEP score for the ‘Eco’ group was significantly higher compared to occupants of the MM building, the ‘Control’ occupants measured similar NEP scores to their MM counterparts. Subsequently, occupants in the MM building recorded significantly lower levels of forgiveness than those recorded in both staff groups of the NV building. Therefore, it appears that pro-environmental attitudes are related to occupants’ satisfaction and tolerance of the thermal environments found within green buildings. Furthermore, in order for green buildings to maximise their climate change mitigation potential, their occupants need to think and act consistently with the building’s

design-intent; the aphorism that green buildings need green occupants has been supported by these case studies.

Paper 4.1 demonstrated a strong positive relationship between environmental attitudes and forgiveness factors, suggesting that pro-environmental or ‘green’ occupants were more forgiving of their building, especially those featuring aspects of green design. Despite criticisms of their building’s IEQ, the ‘green’ building users were more prepared to forgive less-than-ideal indoor conditions than their ‘brown’ (or ‘less green’) counterparts. As the NV building is ‘greener’ than the MM building, the occupants of the former share a higher tolerance of their building’s performance, supporting the hypothesis that pro-environmental attitudes are closely associated with the stronger ‘forgiveness factor’ often observed in green buildings. Admittedly, the direction of causality remains moot and requires further investigation, but this study nonetheless amplifies how occupants’ environmental attitudes play an important role in the way green buildings are perceived by their occupants.

#### *5.1.2. Thermal Comfort in Mixed-Mode Buildings*

The research objectives listed below were addressed in Paper 4.2:

1. This study aims to understand how MM ventilation affects occupant comfort by comparing both observed and predicted thermal sensation votes recorded in AC and NV modes. In doing so, this study will test whether the adaptive comfort model can be applied to MM buildings, especially during times of natural ventilation.

Between March 2009 and April 2010, a longitudinal thermal comfort field study was conducted within the MM building using a variety of objective (indoor and outdoor climate conditions) and subjective (‘right here, right now’ comfort questionnaires) methods (outlined in Section 3.3.2). Within AC mode, the relationship between observed (AMV) thermal



sensations and indoor operative temperature was strongly consistent with the PMV values. However, during times of natural ventilation, the occupants' AMV values did not conform to the PMV values, suggesting occupants were more adaptive to the building's indoor thermal environment when the building was operating under NV mode. During AC mode, warmer indoor operative temperatures were found to elicit much '*warmer-than-neutral*' thermal sensations than the same environmental conditions experienced during NV mode, suggesting the occupants' subjective thermal comfort perceptions were affected by the building's mode of operation over and above the objective indoor climatic conditions. These discrepancies suggest that psychological adaptations, such as attitudes, expectations and control, may influence occupants' comfort perceptions, especially within a building that switches between AC and NV environments. Given the opportunity to control their windows more readily during NV mode, occupants' expectations of the thermal environment apparently relaxed to accept a greater range of indoor temperatures. Hence, the engineering of comfort expectations away from conventional AC environments and towards more weather and seasonally-responsive indoor temperatures, along with occupant-operated control strategies, hold great promise for the successful mitigation of climate change and enhanced energy efficiency of both new and existing commercial buildings.

2. In evaluating the current definition and scope of the adaptive comfort standards in ASHRAE 55-2010 and EN15251-2007, the implications of this research are discussed in the context of whether adaptive comfort standards for NV buildings should be applied to MM buildings.

Despite its most recent revisions, ASHRAE's Standard 55 (ASHRAE, 2010) still restricts the application of the ACS to MM buildings, even if they are operating under a 'free-running' or NV mode. According to ASHRAE, buildings using/equipped with mechanical cooling

systems, as is the case for MM buildings, are currently (mis)classified as AC. The strict interpretation of this standard in MM buildings not only limits their operation to the more restrictive PMV-PPD range of indoor thermal conditions, but also fails to maximise their energy saving and GHG mitigation potential. On the other hand, the European standard EN15251 (CEN, 2007) permits the more flexible adaptive comfort model to be applied to MM buildings when they are operating under a NV mode. This study's comparison of both observed and predicted thermal sensation votes recorded in AC and NV modes found that the adaptive comfort model was applicable to the MM building, especially during times of natural ventilation. The findings provide evidence that MM buildings should be defined as NV buildings, with operable windows and supplemental cooling/heating during peak periods, favouring EN15251's scope of applying the adaptive comfort model instead of PMV-PPD to MM buildings whilst operating in NV mode. Not only does this study illustrate the inadequacy of relying on PMV-PPD models to describe occupant comfort in MM buildings, but it sheds light on how MM buildings, especially those featuring change-over control strategies, should be categorised in future revisions to the relevant thermal comfort standards, in particular ASHRAE 55-2010.

#### *5.1.3. The Validity of Contemporary Post-Occupancy Evaluation Methods*

The third study, outlined in Paper 4.3, addressed each of the following objectives:

1. By comparing the results from the POE and thermal comfort field studies in the MM and NV buildings, this study aims to test the validity of assessing building performance using the POE method.

Following the POE results in the first study (Paper 4.1), simultaneous thermal comfort field studies were conducted during the summer months (between October 2009 and April 2010) in the MM and NV buildings. Occupant satisfaction results from the POEs and thermal

comfort studies were compared and analysed to test the effectiveness of POE methods in evaluating building performance. Upon comparison, indoor operative temperatures within the NV building, recorded at the time thermal comfort questionnaires were delivered, were significantly warmer than the MM building during the summer months. Despite experiencing cooler, theoretically more comfortable temperatures, POE responses for subjects of the latter reflect lower overall levels of satisfaction with the thermal environment. In contrast, occupants of the NV building reported higher levels of overall satisfaction, and forgiveness factors, towards the thermal environment, compared to their MM counterparts. This ‘ground-truthing’ research design suggests that contemporary POE methods, such as BUS and CBE, do not provide reliable evaluations of actual building performance. Instead, they generate a face-value assessment of the occupant’s subjective satisfaction ratings towards the building, which can be biased by factors exogenous to the building and its services. In the present study, additional statistical analyses were performed by triangulating instrumental objective and subjective POE measurements.

2. Occupant satisfaction and thermal acceptability levels, along with participants’ comments and anecdotal evidence, were analysed between each method to examine how POEs may generate over-exaggerated responses of poor building performance.

In contrast to the subjective POE results mentioned above, APD and PPD values from the thermal comfort studies were analysed to compare thermal satisfaction and acceptability within both buildings during exposure to comparable indoor operative temperatures. Observed levels of thermal dissatisfaction (APD) in the MM building were greater than those predicted on the basis of actual environmental conditions after transformation with the PMV-PPD model (PPD). In contrast, occupants of the NV building recorded significantly lower APD values than the PPD values predicted from the instrumental data. It also appears that

occupant perceptions of comfort and thermal acceptability differed between these two buildings. Despite experiencing much warmer indoor environmental conditions, occupants of the NV building expressed higher levels of satisfaction and acceptability with their thermal environment across a broad range of indoor temperatures (i.e. 22 to 26°C) compared to occupants of the MM building.

Since completion of the MM building, many of its occupants have expressed discontent with the building's performance. The analysis of occupants' POE comments found that 'temperature', 'noise' and 'ventilation' were the most common complaints among the occupants of both buildings, especially those in the MM building. When interpreted alongside concurrent instrumental measurements of each building's indoor climate, this evidence suggests that these occupants were using the POE as a conduit to complain about general workplace issues. The discrepancies between the MM and NV buildings, as well as the POE and thermal comfort results, further exemplifies how non-building related factors, e.g. staff morale and job (dis)satisfaction, may influence occupants' comfort perceptions of, and satisfaction with, their workplace's thermal environment. Furthermore, this study emphasises the importance of using a combination of both objective and subjective building performance metrics to evaluate a building.

3. Finally, this study makes recommendations as to how these tools can be improved, encouraging a more holistic approach to building performance evaluation.

Based on a critical review of the POE literature, this study identified three key issues relating to the validity of typical POE methods: their omission of contextual information, lack of feedback, and lack of instrumental data (Section 2.3.2). It is apparent that POE surveys in isolation do not provide a true reflection of a building's actual performance, but rather a

superficial assessment of its occupants. Considering typical POE studies do not obtain parallel instrumental measurements of the buildings' indoor climate, they lack an objective benchmark against which poor satisfaction ratings can be validated. Despite encouragements from the POE research literature to include occupants into every facet of the building life-cycle (from planning to commission), building users are routinely omitted from these stages which can potentially lead to feelings of mistrust and discontent towards their building and its managers. Moreover, the orientation/education of occupants on building design, thermal comfort and environmental control, as well as the environmental consequences of their actions, can play a valuable role in improving occupant comfort and "calibrating" expectations of green buildings.

## **5.2. Future Research**

This thesis addressed many topical issues in the fields of thermal comfort and building performance. Specifically, it has presented findings that have increased our understanding of how occupants' environmental attitudes are associated with their tolerance of, and satisfaction with, green buildings; thermal comfort during different modes of operation in MM buildings; as well as the validation of contemporary POE methods. Answering the research questions of this thesis leads to asking several new questions which prompt the need for future research to further expand our understanding of these issues within the context of occupants' attitudes and expectations to the indoor thermal environment:

The aphorism that green buildings work best with green occupants opens up new avenues of research enquiry. This thesis was the first to use the NEP questionnaire in conjunction with a POE to analyse the correlation between the levels of pro-environmentalism and occupant satisfaction in a green building. However, one other study has very recently presented similar findings focusing on occupants' environmental attitudes and forgiveness factors (Lakeridou

et al., 2012). Bearing in mind that both of these studies were conducted in specific contexts, future studies across a wider range of different buildings ('green' and 'non-green') located in different climates are needed to confirm the link between environmental attitudes and forgiveness factors. Future studies should aim to measure building occupants' environmental attitudes using psychologically-based questionnaires, surveys and interviews, the level of occupant satisfaction and forgiveness towards the building's performance, as well as physical measurements of the building's performance. In doing so, the causal direction of the relationship between environmental attitudes and occupant satisfaction in buildings can be better understood. However, the big research question left begging by these tantalising results is whether attitude change can lead to behavioural change within green buildings? The exploration of this issue might also extend to other aspects of IEQ, e.g. thermal comfort, air quality and productivity, as the link between pro-environmentalism and occupant satisfaction within green buildings is further explored. More research would also be needed to investigate the differences between occupants of 'green' vs. 'non-green' buildings.

One of the key barriers to the uptake of MM ventilation has been the contradiction of international comfort standards. This research provides an impetus towards changing the current scope and definition of the ACS in ASHRAE Standard 55-2010 to include MM buildings when they are operating in natural ventilation mode; following the adaptive standard in EN15251-2007. In doing so, the application of adaptive BMS control algorithms within both existing and future MM buildings will help reduce energy consumption in buildings and allows the variation of comfort temperatures during times of natural ventilation. However, more research still needs to be carried out to bring about a more justified revision of the standard to include MM buildings into ASHRAE's ACS instead of relying on the more conventional black-and-white definitions of 'AC' vs. 'non-AC'. As more MM buildings are likely to be built in the future, more field studies sampled from a variety of

different climate zones, and across all possible MM design/control strategies, i.e. change-over, concurrent and zoned systems, are essential to understanding how MM ventilation affects occupant comfort and whether a new MM comfort standard should be established.

Further research addressing the limitations in current POE methods is required to develop more robust and holistic building performance evaluations. Future building occupancy studies should encourage the use of POE tools in conjunction with other methods to evaluate all aspects of building performance, such as the social, psychological and physical aspects. Collaboration is therefore needed among building owners, managers and academia to resolve this complex issue with a view to creating a more holistic method for conducting these studies in future buildings. This, however, requires studies to be conducted in many buildings from many different climates and contexts to ensure the creation of a validated and reliable set of building performance measures and metrics. Only then can more reliable building performance studies, wherein assessments of occupant satisfaction along with energy consumption, indoor temperature, thermal comfort, psychosocial factors and forgiveness, be undertaken.

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## **Appendix**

## **Appendix A: Post-Occupancy Evaluation Study Human Ethics and Final Report Approval**

29 August 2008

Mr Max Paul Deuble  
79 Macquarie Street  
Chatswood NSW 2067

Reference: **HE22AUG2008-D06019**

Dear Mr Deuble

**FINAL APPROVAL**

Title of project: ***Building E4A Post Occupancy Evaluation***

Thank you for your recent correspondence. Your responses have satisfactorily addressed the outstanding issues raised by the Committee. You may now proceed with your research.

Please note the following standard requirements of approval:

1. Approval will be for a period of twelve months. At the end of this period, if the project has been completed, abandoned, discontinued or not commenced for any reason, you are required to submit a Final Report on the project. If you complete the work earlier than you had planned you must submit a Final Report as soon as the work is completed. The Final Report is available at <http://www.ro.mq.edu.au/ethics/human/forms>
2. However, at the end of the 12 month period if the project is still current you should instead submit an application for renewal of the approval if the project has run for less than five (5) years. This form is available at <http://www.ro.mq.edu.au/ethics/human/forms>. If the project has run for more than five (5) years you cannot renew approval for the project. You will need to complete and submit a Final Report (see Point 1 above) and submit a new application for the project. (The five year limit on renewal of approvals allows the Committee to fully re-review research in an environment where legislation, guidelines and requirements are continually changing, for example, new child protection and privacy laws).
3. Please remember the Committee must be notified of any alteration to the project.
4. You must notify the Committee immediately in the event of any adverse effects on participants or of any unforeseen events that might affect continued ethical acceptability of the project.
5. At all times you are responsible for the ethical conduct of your research in accordance with the guidelines established by the University (<http://www.ro.mq.edu.au/ethics/human>).

If you will be applying for or have applied for internal or external funding for the above project **it is your responsibility** to provide Macquarie University's Research Grants Officer with a copy of this letter as soon as possible. The Research Grants Officer will not inform external funding agencies that you have final approval for your project and funds will not be released until the Research Grants Officer has received a copy of this final approval letter.

Yours sincerely

*F. The*

Dr Margaret Stuart  
Director of Research Ethics  
Chair, Ethics Review Committee [Human Research]  
cc. Associate Professor Richard De Dear



8 December 2009

Mr Max Paul Deuble  
79 Macquarie Street  
Chatswood  
NSW 2067

**Reference: HE22AUG2008-D06019**

Dear Mr Deuble,

**FINAL REPORT APPROVED**

**Title of project: Building E4A Post Occupancy Evaluation**

Your final report has been received and approved, effective 8 December 2009. The Committee is grateful for your cooperation and would like to wish you success in future research endeavours.

Yours sincerely

Dr Karolyn White  
Director of Research Ethics  
Chair, Ethics Review Committee (Human Research)

Cc: Dr Paul Beggs, Environment and Geography

## **Appendix B: Building Use Studies Questionnaire License Agreement**



## Definitions

### Questionnaire:

The work produced by the Licensor

### Territory :

Australia

### Period :

One year

**Term:** The full term of copyright and all renewals and extensions.

**Rights:** The non-exclusive right by licence, to utilise the questionnaire in the agreed material format for the purposes defined.

**Study building :** The building to which the licence applies, normally named in Further Details below.

### Further details :

Study of Commerce Building, Macquarie University, North Ryde Campus, Sydney.

PhD under supervision.

BUS job-number 934

## Licence agreement

This is a questionnaire licence agreement between:

Adrian Leaman, Building Use Studies

*The Licensor*

and:

Max Deuble, MacQuarie University

*The Licensee*

concerning the method/s:

### Building Use Studies 2-page occupant questionnaire 2008 Probe or Workplace version

The licensors as owners of the copyright of the title agree to grant the rights to the licensee subject to these terms and conditions.

1. The licensor as beneficial owner grants the licensee rights throughout the territory for the period.
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4. If a survey is undertaken, the licensee undertakes to lodge the data file of the survey with Building Use Studies subject to full confidentiality in agreed computer file format..
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11. If a translation is undertaken, the licensee undertakes to carry out the translation under supervision from the licensor and to release the resulting translation file to Building Use Studies.

More details are available of the approach on:  
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Signed:

**Adrian Leaman**

Digitally signed by Adrian Leaman  
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email=adrianleaman@usablebuildings.co.uk, c=GB  
Date: 2008.06.26 07:38:59 +01'00'

Adrian Leaman, Building Use Studies

Signed:



Max Deuble, MacQuarie University

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## **Appendix C: Post-Occupancy Evaluation Occupant Consent Email**

**Name of Project:** Building E4A and E7A Post-Occupancy Evaluation Study

Dear occupants,

You have been invited to participate in a Post-Occupancy Evaluation (POE) study of your building. This study forms part of my PhD studies and will be conducted in Buildings E4A and E7A to provide a comparison between green office buildings. It is well known that the thermal environment within Building E7A can be quite uncomfortable throughout the year, especially in summer and winter. Since the completion of Building E4A, many occupants have expressed discontent with the building's performance. After talks with the University's Office of Facilities Management (OFM) and Sustainability Office, we have been encouraged to conduct a POE of these buildings to identify the cause, strength and solutions to these problems. Some of you may be aware that your building is currently undergoing another study – the Thermal Comfort Study, focussing on occupant thermal comfort within mixed-mode and naturally-ventilated buildings. This POE is entirely independent of the Thermal Comfort Study and is in no way related.

These types of studies have been conducted all around the world, including Australia, and their results have been widely collected and collated into a database often used to benchmark new studies against other building performance studies. The results from this study will in turn help demonstrate how the occupants feel about their building. These responses are used to generate an overall occupant evaluation on the performance of this building and will be benchmarked across a wide range of national and international studies, with specific consideration given to how your building rates in comparison to other green buildings, particularly within Australia. Participation is strictly voluntary, however the more participants the better the results. This study will help Macquarie University highlight any problems the building occupants have with the building, which can be used for the design and planning of current and future building projects.

This study is being conducted by the following researcher to meet the requirements for the Doctor of Philosophy degree:

Max Deuble, PhD student,  
Department of Environment and Geography (Faculty of Science)  
Phone: 02 9850 8396 Email: [max.deuble@students.mq.edu.au](mailto:max.deuble@students.mq.edu.au)

Under the supervision of:

Paul Beggs, Senior Lecturer,  
Department of Environment and Geography (Faculty of Science)  
Phone: 02 9850 8399  
Email: [pbeggs@els.mq.edu.au](mailto:pbeggs@els.mq.edu.au)

Associate Investigator:

Adrian Leaman, Managing Director,  
Building Use Studies, Ltd  
Phone: +44 20 7287 1147  
Email: [adrianleaman@usablebuildings.co.uk](mailto:adrianleaman@usablebuildings.co.uk)

The questionnaires will be handed out to all occupants in the morning of **Tuesday the 23<sup>rd</sup> of March**. The questionnaires will take 5 MINUTES to fill in (longer if you add comments). The surveys will be collected, in person, by Max Deuble at the end of the day at **4:30pm**. Thank you in advance for your help.

This is an anonymous survey, so any information or personal details gathered in the course of this study are confidential. No individual will be identified in any publication of the results and only the researchers listed above will have access to the data. The results obtained from this research will be made into a report which will be emailed to all building occupants in the form of a PDF attachment. If you have any questions or concerns please contact any of the researchers above.

The ethical aspects of this study have been approved by the Macquarie University Ethics Review Committee (Human Research). If you have any complaints or reservations about any ethical aspect of your participation in this research, you may contact the Committee through the Research Ethics Officer (telephone [02] 9850 7854, fax [02] 9850 8799, email: [ethics@mq.edu.au](mailto:ethics@mq.edu.au)). Any complaint you make will be treated in confidence and investigated, and you will be informed of the outcome.



## **Appendix D: Environmental Attitudes Questionnaire**

## Environmental Attitude Questionnaire

Listed below are statements about the relationship between humans and the environment. For each one, please indicate whether you **STRONGLY DISAGREE**, **MILDLY DISAGREE**, are **UNSURE**, **MILDLY AGREE** or **STRONGLY AGREE** with it:

	<b>Strongly Disagree</b>	<b>Mildly Disagree</b>	<b>Unsure</b>	<b>Mildly Agree</b>	<b>Strongly Agree</b>
1. We are approaching the limit of the number of people the earth can support	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
2. Humans have the right to modify the natural environment to suit their needs	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
3. When humans interfere with nature it often produces disastrous consequences	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
4. Human ingenuity will ensure that we do NOT make the earth unliveable	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
5. Humans are severely abusing the environment	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
6. The earth has plenty of natural resources if we just learn how to develop them	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
7. Plants and animals have as much right as humans to coexist	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
8. The balance of nature is strong enough to cope with the impacts of modern industrial nations	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
9. Despite our special abilities humans are still subject to the laws of nature	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
10. The so-called 'ecological crisis' facing humankind has been greatly exaggerated	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
11. The earth is like a spaceship with very limited room and resources	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
12. Humans were meant to rule over the rest of nature	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
13. The balance of nature is very delicate and easily upset	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
14. Humans will eventually learn enough about how nature works to be able to control it	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>
15. If things continue on their present course, we will soon experience major ecological catastrophe	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>	<input type="checkbox"/>

## **Appendix E: Post-Occupancy Evaluation Study Instructions Sheet**

## BUILDING E4A AND E7A POST-OCCUPANCY EVALUATION STUDY

Thank you for participating in the Building E4A and E7A Post-Occupancy Evaluation (POE) study.

As you may know, building E7A is one of Macquarie University's oldest buildings. Being a naturally-ventilated building, the thermal environment can be quite uncomfortable throughout the year, especially during summer and winter. Building E4A, on the other hand, is a newly built building for Macquarie University determined to promote itself as the way of the future, i.e. green buildings. However, since completion, many occupants have expressed discontent with the building's performance, but as yet the University cannot understand the cause of these problems. The University's Office of Facilities Management (OFM) and Sustainability Office have encouraged that both these buildings undergo an occupancy evaluation to identify the strength of this discontent and possible solutions.

Post-occupancy evaluation studies are conducted all around the world and their results are used to help demonstrate how the occupants feel about their building. The responses are used to generate an overall occupant evaluation on the performance of this building, which will be benchmarked across a wide range of national and international studies, with specific consideration given to how building E4A and E7A rate in comparison to other green buildings, particularly within Australia. This study will in turn help Macquarie University highlight any problems the building occupants have with the building, which can be used for the design and planning of future building projects.

This survey is strictly anonymous, and no individual will be identified in any publication of the results. The results obtained from this research will be made into a report which will be emailed to the building occupants in the form of a PDF attachment. Please read and follow the instructions written below carefully:

1. Please fill out the Post-Occupancy Evaluation and Environmental Attitude questionnaires. These should only take 5 MINUTES to complete (longer if you add comments).
2. Once you have completed the questionnaires, please place them into the envelope provided and seal it off.
3. Leave the envelope in a prominent place so the researcher, Max Deuble, can collect it at **4:30pm** TODAY. If you will not be in your office at this time then please leave the envelope under your door and he can collect it at the end of the day.
4. Thank you in advance for your help.

Sincerely,  
Max Deuble

## **Appendix F: Thermal Comfort Study Human Ethics and Final Report Approval**

16 October 2008

Mr Max Deuble  
79 Macquarie Street  
Chatswood  
NSW 2067

Reference: **HE26SEP2008-D06064**

Dear Mr Deuble

### FINAL APPROVAL

**Title of project: "Occupant comfort in naturally-ventilated and mixed-mode spaces within air-conditioned office buildings"**

Thank you for your recent correspondence. Your response has addressed the issues raised by the Committee and you may now proceed with your research.

Please note the following standard requirements of approval:

1. Approval will be for a period of twelve (12) months. At the end of this period, if the project has been completed, abandoned, discontinued or not commenced for any reason, you are required to submit a Final Report on the project. If you complete the work earlier than you had planned you must submit a Final Report as soon as the work is completed. The Final Report is available at: [http://www.research.mq.edu.au/researchers/ethics/human\\_ethics/forms](http://www.research.mq.edu.au/researchers/ethics/human_ethics/forms)
2. However, at the end of the 12 month period if the project is still current you should instead submit an application for renewal of the approval if the project has run for less than five (5) years. This form is available at [http://www.research.mq.edu.au/researchers/ethics/human\\_ethics/forms](http://www.research.mq.edu.au/researchers/ethics/human_ethics/forms). If the project has run for more than five (5) years you cannot renew approval for the project. You will need to complete and submit a Final Report (see Point 1 above) and submit a new application for the project. (The five year limit on renewal of approvals allows the Committee to fully re-review research in an environment where legislation, guidelines and requirements are continually changing, for example, new child protection and privacy laws).
3. Please remember the Committee must be notified of any alteration to the project.
4. You must notify the Committee immediately in the event of any adverse effects on participants or of any unforeseen events that might affect continued ethical acceptability of the project.
5. At all times you are responsible for the ethical conduct of your research in accordance with the guidelines established by the University [http://www.research.mq.edu.au/researchers/ethics/human\\_ethics/policy](http://www.research.mq.edu.au/researchers/ethics/human_ethics/policy)

If you will be applying for or have applied for internal or external funding for the above project **it is your responsibility** to provide Macquarie University's Research Grants Officer with a copy of this letter as soon as possible. The Research Grants Officer will not inform external funding agencies that you have final approval for your project and funds will not be released until the Research Grants Officer has received a copy of this final approval letter.

Yours sincerely

*f. r.*  


**Dr Margaret Stuart**  
**Director of Research Ethics**  
**Chair, Ethics Review Committee (Human Research)**

**Cc: Associate Professor Richard de Dear, Department of Physical Geography**

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ETHICS REVIEW COMMITTEE (HUMAN RESEARCH)  
LEVEL 3, RESEARCH HUB, BUILDING C5C  
MACQUARIE UNIVERSITY  
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**Ethics Secretariat: Ph: (02) 9850 6848 Fax: (02) 9850 4465 E-mail: [ethics.secretariat@vc.mq.edu.au](mailto:ethics.secretariat@vc.mq.edu.au)**

[http://www.research.mq.edu.au/researchers/ethics/human\\_ethics](http://www.research.mq.edu.au/researchers/ethics/human_ethics)

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## Final Report Approved - Deuble (HE26SEP2008-D06064)

1 message

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**Ethics Secretariat** <ethics.secretariat@mq.edu.au>

Wed, Nov 24, 2010 at 3:25 PM

To: max.deuble@students.mq.edu.au

Cc: paul.beggs@mq.edu.au

Dear Mr Deuble,

FINAL REPORT APPROVED

Title of project: 'Occupant Comfort in Naturally-Ventilated and Mixed-Mode Spaces Within Air-Conditioned Office Buildings' (RefHE26SEP2008-D06064)

Your final report has been received and approved, effective 24 November 2010. The Committee is grateful for your cooperation and would like to wish you success in future research endeavours.

Yours sincerely

Dr Karolyn White  
Director of Research Ethics  
Chair, Human Research Ethics Committee



## **Appendix G: Thermal Comfort Study Occupant Consent Email**

## Participant Information/Consent Email

**Name of Project:** Occupant Comfort within Mixed-Mode and Naturally-Ventilated Office Buildings

Within Australia, energy used for heating, ventilation and air-conditioning (HVAC) still accounts for 50% of greenhouse gas emissions within the commercial building sector. Low-energy, green buildings are rapidly emerging because they can provide comfortable working conditions for the occupants whilst reducing energy consumption, and hence greenhouse gas emissions. As Building E7A predominantly uses natural ventilation it consumes less energy than the conventional air-conditioned buildings on campus. However, whilst occupants prefer having control over their own thermal environment by using operable windows, they often do not appreciate the uncomfortable conditions likely to occur during extreme conditions. Building E4A, on the other hand, utilises mixed-mode ventilation; working as a naturally ventilated structure with operable windows, the building is capable of switching into an air-conditioned building when outdoor weather conditions make the naturally ventilated option untenable for the occupants. After talks with the University's Deputy Vice-Chancellor, Paul Bowler, under encouragement from the University's Office of Facilities Management (OFM) and the University's Sustainability Office, approval has been obtained from the Dean and Heads of Departments within this building to invite you to participate in a study investigating how occupants achieve thermal comfort within mixed-mode and naturally-ventilated buildings.

The purpose of this study is to examine thermal comfort issues in an accurate and conclusive fashion within both buildings. In comparing both buildings, this project will highlight recommendations of such spaces and the justification of their design into new buildings and for the refurbishment of existing building stock.

Secondly, as there are no international thermal comfort guidelines for mixed-mode spaces due to a lack of empirical research on which such guidelines could be based, this study will help develop a model of thermal comfort that takes account of occupant behaviour, as people utilise spaces of different comfort conditions within the same building.

This study is being conducted by the following researcher to meet the requirements for the Doctor of Philosophy degree. If you have any questions or concerns please contact any of the researchers below:

Max Deuble, PhD student  
Department of Environment and Geography (Faculty of Science)  
Phone: 02 9850 8396 Email: [max.deuble@students.mq.edu.au](mailto:max.deuble@students.mq.edu.au)

Under the supervision of:

Paul Beggs, Senior Lecturer,  
Department of Environment and Geography (Faculty of Science)  
Phone: 02 9850 8399 Email: [pbeggs@els.mq.edu.au](mailto:pbeggs@els.mq.edu.au)

The approach of this project is to select 30-60 participants from a series of typical locations from different zones within both buildings: North, South and Central. Upon participation, office spaces will be equipped with unobtrusive sensors to record indoor climatic data such as temperature, mean radiant temperature, humidity and air speed throughout the year (these instruments SHOULD NOT interfere with the daily activities of the occupants). This data will be matched with questionnaire responses to stationary indoor climate data (measured using a mobile thermal comfort 'Sputnik' instrument periodically throughout the year, i.e. a couple of visits per week) and concurrent outdoor weather data. Questionnaires are designed to record the occupants' perceptions of thermal comfort within their office spaces and SHOULD NOT take longer than ONE MINUTE to complete.

Any information or personal details gathered in the course of this study are confidential and no individual will be identified in any publication of the results. Only the researchers listed above will have access to the data.

Reply to this email will be regarded as consent. All those involved in this study will be emailed an executive summary (maximum length 5 pages) of the research findings.

The ethical aspects of this study have been approved by the Macquarie University Ethics Review Committee (Human Research). If you have any complaints or reservations about any ethical aspect of your participation in this research, you may contact the Committee through the Research Ethics Officer (telephone [02] 9850 7854, fax [02] 9850 8799, email: [ethics@mq.edu.au](mailto:ethics@mq.edu.au)). Any complaint you make will be treated in confidence and investigated, and you will be informed of the outcome.

## **Appendix H: Thermal Comfort Study Background Questionnaire**

# THE COMFORT STUDY



Gender: **Male** ☐ **Female** ☐

Age: < 20 ☐ 20-30 ☐ 30-40 ☐ 40-50 ☐ 50-60 ☐ 60-70 ☐ 70+ ☐

1. How long have you been working in building E4A?

< 3 months		3 to 6 months		6 months to 1 year		> 1 year	
------------	--	---------------	--	--------------------	--	----------	--

2. What type of building did you work in prior to this one?

Air-Conditioned		Naturally Ventilated (operable windows)	
-----------------	--	---	--

3a) Was this building located in Sydney? **Yes** ☐ **No** ☐ 3b) If 'No', where was it located?

4. On average, how many **hours per week** do you work at this job? \_\_\_\_\_ Hours at work

5. On average, how many **hours per day** do you sit at your work area? \_\_\_\_\_ Hours per day

6a) Please **tick** where you are presently using **air-conditioning**? 6b) If selecting 'Other', please specify where: \_\_\_\_\_

At home, bedroom		At home, living room		In car		Other	
------------------	--	----------------------	--	--------	--	-------	--

7. During the **summer** season, please tick how often you use each of the following in **your office**:

	Frequently	Occasionally	Rarely	Never	N/A
Portable fan					
Open/close window					
Open/close door					
Draw blinds/shades					
Remove clothing					
Open/close air vent					
Other (please specify): _____					

8. During the **winter** season, please tick how often you use each of the following in **your office**:

	Frequently	Occasionally	Rarely	Never	N/A
Portable heater					
Open/close window					
Open/close door					
Draw blinds/shades					
Add clothing					
Open/close air vent					
Other (please specify): _____					

**Appendix I: Thermal Comfort ‘Right Here, Right Now’  
Questionnaire (summer/winter)**

# COMFORT STUDY – RIGHT HERE, RIGHT NOW

1. Please **tick the scale** below at the place that best represents how **YOU FEEL RIGHT NOW**? You may tick between two categories, if you wish.

Cold      Cool      Slightly Cool      Neutral      Slightly Warm      Warm      Hot

2. Is the thermal environment **acceptable** to you?

Acceptable ☐ Unacceptable ☐

4. How do you **feel right now** about the **air movement** in your room?

If unacceptable, why?	
Low air movement	
High air movement	
If acceptable, why?	
Less air movement	
Enough air movement	
High air movement	

3. **Right now I would prefer** to be:

Warmer ☐ No Change ☐ Cooler ☐

5. Right now I would prefer:

More Air Movement	
No Change	
Less Air Movement	

6. Has your **window** been **opened today**?

Yes ☐ No ☐

7. What activities have you been engaged in during the preceding hour?

	Sitting quietly	Sitting typing	Standing still	On your feet working	Walking around	Driving a car
Last 10 minutes						
The 10 minutes preceding that?						
The 10 minutes before that?						
The half hour before that?						

8. Compared to normal, please estimate how you feel your **productivity** has increased or decreased **today**, by ticking where you feel appropriate on the scale below?

-40%      -30%      -20%      -10%      0      +10%      +20%      +30%      +40%  
or more      or more

9. Have you made any **adjustments** to your **clothing** ensemble **within the last 15 minutes**? Yes ☐ No ☐

10. As you know, the amount of clothing we wear affects our thermal comfort. Please **indicate** whether you are **wearing any** of the items listed below (0 = not wearing item; 1 = summer/light-weight item; 2 = winter/heavy-weight item):

<b>Footwear:</b>	Socks	0 - 1 - 2	Shoes	0 - 1 - 2	Pantyhose	0 - 1 - 2
<b>Midlayer:</b>	Short-sleeved shirt	0 - 1 - 2	Long-sleeved shirt	0 - 1 - 2	Dress	0 - 1 - 2
	Pants or slacks	0 - 1 - 2	Shorts	0 - 1 - 2	Skirt	0 - 1 - 2
<b>Outerlayers:</b>	Sweater	0 - 1 - 2	Vest	0 - 1 - 2	Jacket	0 - 1 - 2
<b>Other items:</b>		0 - 1 - 2		0 - 1 - 2		0 - 1 - 2

11. Which of the following have you **used today** to **control** the thermal environment within your **office**? For those you have used can you please list the **order** in which they were **used**?

Device	Yes	No	Order
Portable fan/heater			
Open/close window			
Open/close door			
Draw blinds/shades			
Remove/Add clothing			
Open/close air vent			
Other			

For Office Use			
<b>D:</b>			
<b>T:</b>			
<b>G:</b>	0	1	
<b>W:</b>	0	1	
<b>C:</b>	0	1	
<b>L:</b>	N	S	C
	E	W	
<b>M:</b>	AC	NV	

THANK YOU FOR YOUR TIME

## **Appendix J: Healthy Buildings 2009 Conference Paper**

Deuble, M. and de Dear, R. (2009) 'Do green buildings need green occupants', *Proceedings of the Healthy Buildings 2009 Conference*, Syracuse, NY, USA, 13-17 September 2009

## Do Green Buildings Need Green Occupants?

Max Deuble<sup>1\*</sup> and Richard de Dear<sup>2</sup>

<sup>1</sup>Macquarie University, Sydney NSW 2109, Australia

<sup>2</sup>University of Sydney, Sydney NSW 2006, Australia

\*Corresponding author's email: [mdeuble@els.mq.edu.au](mailto:mdeuble@els.mq.edu.au)

### SUMMARY

Mixed-mode: these words are synonymous with the world's emergent 'green' buildings, heralded as low carbon buildings of the future. While the technical efficiency of such buildings is important, the well-being, productivity, (dis)comfort, general satisfaction of the occupants, as well as environmental attitudes and beliefs, is in itself, necessarily important. Post-occupancy evaluations for occupant satisfaction, and New Ecological Paradigm questionnaires, measuring levels of environmental concern, were conducted between March and April 2009 in two academic office buildings at Macquarie University. Upon analysis, significantly higher environmental attitudes were present for occupants possessing greater tolerance of their building's thermal environment. This paper hypothesises that occupants valuing their building highly possess greater pro-environmental attitudes compared to those valuing their building poorly, and thus provides evidence supporting the link between environmental attitudes and occupant satisfaction within green buildings.

### KEYWORDS

Green buildings, Post-occupancy evaluation, New Ecological Paradigm, Environmental attitudes

### INTRODUCTION

Twentieth century office buildings generally provided static temperatures for all occupants using centralised heating, ventilation and cooling (HVAC) technology. Adaptive comfort studies (de Dear and Brager, 1998; de Dear and Brager, 2002) have identified the need for greater occupant control in personal preferences of their thermal environment, thus widening the acceptable range of temperatures, and ultimately achieving higher levels of occupant satisfaction (Leaman and Bordass, 2007). Low-energy green buildings advocate this shift of environmental control towards the occupants (Brager et al., 2004). Whereas occupants prefer the adaptive opportunities provided by green-intent buildings, i.e. those with natural ventilation capabilities, opposed to the sealed façade and air-conditioned (AC) alternative, they do not expect the thermally variable and sometimes uncomfortable conditions during unusually hot weather. Notwithstanding occasional discomforts, many post-occupancy evaluation (POE) studies suggest that green building users are prepared to forgive such conditions provided they possess a modicum of environmental control (de Dear and Brager, 2002; Leaman and Bordass, 2007; Brager and Baker, 2008).

The New Ecological Paradigm (NEP) (a revision of the New Environmental Paradigm) Scale is a 15-item questionnaire, consisting of 8 pro-NEP and 7 anti-NEP items, that simply measures degrees of endorsement (from low to high) of an ecological worldview (Dunlap et al., 2000; Dunlap, 2008). After worldwide applications into environmental psychology, there is broad consensus that the NEP represents a valid and reliable scale for measuring levels of ecological beliefs (Cordano et al., 2003). Despite its extensive use, the scale has not been used in conjunction with POE studies and could potentially identify the link between successful occupancy of green buildings and environmental attitudes. Thus this paper investigates the hypothesis that green buildings need green occupants by comparing POE and NEP results of two green buildings at Macquarie University (MQ).



## METHODS

Sydney (34°S, 151°E), located on the southeast coast of Australia, can be described as having a humid sub-tropical climate, experiencing warm-to-hot summers combined with moderate-to-high humidity, peaking in February to March. Winters are mild and temperate, and an annual rainfall of 1200mm, distributed evenly throughout the year. Sydney's climate is ideally suited to mixed-mode (MM) buildings.

In this study, two academic staff buildings from MQ were selected, both having North-South orientations, whereby North facades are directly irradiated from the Sun during the day, indicating warmer temperatures than the South. The buildings used were E4A, a MM building (in Photo 1) commissioned in 2006, and NV building E7A (in Photo 2), built in the late 1960s. Building E4A consists of operable windows with MM cellular offices along north and south perimeter zones separated by AC central open-plan office space. Indoor temperature and outdoor weather sensors prompt the Building Management System (BMS) to switch to AC mode when the average temperature increases above 25°C. Occupants are mainly academics and administrative staff from various Economic and Finance departments. Correspondingly, building E7A features occupant-operated windows with narrow floor plate consisting of a central corridor with single and dual occupant cellular offices on either side. Academic staff, post-graduate students and administrative staff from a variety of Environment and Geography disciplines, occupy this building.

Photo 1. MQ, Building E4A (North facade)



Photo 2. MQ, Building E7A (North facade)



Between March and April 2009, two questionnaires were distributed to all staff in both buildings. Firstly, the three-page Building Use Studies (BUS, 2009) POE using 7-point Likert scales with space for commentary, covers variables relating to occupant satisfaction, e.g. thermal, visual and acoustic comfort, indoor air quality, perceived health and productivity, and general acceptance of the workplace. BUS (2009) further details the BUS methodology. Secondly, the Environmental Attitudes questionnaire is a 15-item version of the NEP Scale, using 5-point response scales ranging from Strongly Disagree to Strongly Agree, with higher scores on the scale from 1 (low) to 5 (high) indicating greater levels of environmental concern. All scales were converted to a NEP score by summing each item response and dividing by the total number of items in the scale. Results were analysed using MiniTab statistical software.

Dataloggers randomly located throughout each building recorded air temperature at 5 minute intervals throughout the study. Outdoor air temperature was measured over the same period at a nearby automatic weather station, with BMS data from the survey period was collected from the Office of Facilities Management (OFM).

## RESULTS

From temperatures averaged across all dataloggers, it was established that building E7A experienced significantly warmer temperatures (mean = 24.5°C,  $p = 0.000$ ) over the study period than building E4A (mean = 24.1°C) (Figure 1). Temperatures inside each building were far greater than the surrounding outdoor air temperature (mean = 20.6°C). As a NV building, temperatures inside E7A closely match changes in outdoor weather conditions, whereas building E4A, experienced a narrower temperature range, possibly due to the use of HVAC as temperatures rose towards the 25°C cooling set-point.

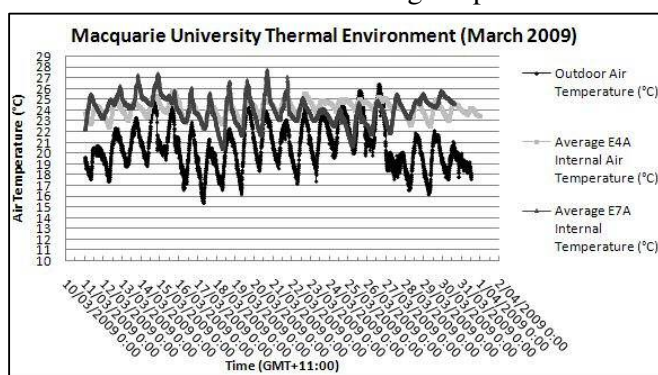


Figure 1. Indoor and outdoor thermal environments measured over the study period.

In total, 180 POE and NEP questionnaires were distributed in building E4A and 40 in building E7A. 95 (43 male, 52 female) were completed from E4A (53% response rate), and 28 (11 male; 17 female) from E7A (70% response rate). To ensure quality assurance, incomplete or fraudulent responses were omitted from the samples. POE responses were benchmarked against the Australian BUS database (as summarised in Table 1). Both buildings generally measure poorly, ranking well below Australian benchmarks. While E7A appears worse than E4A, the only significantly different variable in the study was perceived productivity ( $p = 0.000$ ).

Table 1. A summary of POE and NEP results for buildings E4A and E7A.

Study Variable	E4A (n = 92)	E7A (n = 28)	Significance
Forgiveness Factor	0.99	1.04	$p > 0.05$
Comfort Index	-0.39	-0.70	$p > 0.05$
Satisfaction Index	0.02	-0.10	$p > 0.05$
Perceived Productivity	-5.34	-10.71	$p = 0.000$
NEP	3.69	4.04	$p = 0.005$

NEP questionnaire items were tested for internal consistency and were found to have strong coefficient alphas ( $\alpha = 0.82$ ) suggesting good internal consistency. E7A had a significantly higher mean NEP score (4.04,  $p = 0.005$ ) than E4A (3.96), plausible for environmentally educated academics. Interestingly, the NEP score for E4A is relatively high for occupants associated with economics, finance and business studies.

## DISCUSSION

Upon comparison, with higher temperatures recorded in E7A, it is reasonable to assess that perception of productivity at temperatures up to 28°C was significantly lower than E4A. Nonetheless, occupants in both buildings have often complained about indoor temperatures in the summer months, particularly on the north facade. This anecdotal feedback is consistent with a more systematic pattern emerging in Australian green buildings that have undergone the BUS POE (Leaman et al., 2007). In comparing 22 green-intent buildings against 23 conventional HVAC office buildings, Leaman et al (2007) reported that green buildings were perceived as hotter in summer and cooler in winter. Green-intent buildings, such as E4A and E7A, are designed to perform this way. In comparing 'forgiveness' scores, a variable derived by dividing scores for the variable 'comfort overall' by the average of the summary variables for temperature in summer and winter, ventilation/air in summer and winter, noise and

lighting, it was possible to compare the results in Table 2, from Leaman et al., (2007), to find that E4A is poorly received by its users (forgiveness = 0.99). Comparatively, building E7A measured significantly higher NEP scores indicating greater tolerance to perceived thermal variance (forgiveness = 1.04), concluding consistency with green-intent buildings in the BUS database.

Table 2. Forgiveness scores by ventilation type: Australian BUS building database (n = 45).

Study Variable	Green-intent (NV, ANV, MM)	AC	E4A (MM)	E7A (NV)
Forgiveness Factor	1.02	0.99	0.99	1.04
n	22	23		

Note: Higher values indicate occupants more tolerant or 'forgiving' of the conditions. Building types include natural ventilation (NV), advanced natural ventilation (ANV), mixed-mode (MM) and air-conditioning (AC).

## CONCLUSIONS

POE instruments appear to measure building occupants as much as they evaluate the quality of a building's indoor environments. Green buildings have greater thermal variations than their AC counterparts, in which centralised HVAC provides static indoor temperatures to all occupants all-year round. This paper suggests green building users are more forgiving of their building, consistent with the hypothesis that green occupants are needed for green buildings. While this study only represents two green buildings at MQ, with current focus being directed towards the well-being and satisfaction of green building users, more research is needed to identify the link between occupant satisfaction and environmental attitudes.

## ACKNOWLEDGEMENTS

We are enormously grateful to Adrian Leaman for permission to use the BUS questionnaire under license and his assistance in data analysis. We would also like to thank Riley Dunlap for his valuable comments and encouragements, and Macquarie University's OFM, especially Kerry Russell, for their support. Finally, and most importantly, we express our appreciation to all the building occupants who responded to the questionnaires.

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## **Appendix K: ANZAScA 2009 Conference Paper**

Drake, S., de Dear, R., Alessi, A. and Deuble, M. (2009) 'Occupant comfort in naturally ventilated and mixed-mode spaces within air-conditioned offices', *Proceedings of the 43<sup>rd</sup> Annual ANZAScA Conference 2009: Performative Ecologies in the Built Environment - Sustainability Research Across Disciplines*, Launceston, Tasmania, Australia, 25-27 November 2009

# Occupant comfort in naturally ventilated and mixed-mode spaces within air-conditioned offices

Scott Drake<sup>1</sup>, Richard de Dear<sup>2</sup>, Angela Alessi<sup>1</sup> and Max Deuble<sup>3</sup>

<sup>1</sup>University of Melbourne, Melbourne, Australia

<sup>2</sup>University of Sydney, Sydney, Australia

<sup>3</sup>Macquarie University, Sydney, Australia

## ABSTRACT:

Contemporary concerns for improving environmental performance in buildings have led to an increased interest in natural ventilation either on its own (NV) or in combination with air-conditioning (mixed mode – MM) as an alternative to traditional HVAC systems. HVAC systems are widely used because they avoid many of the problems encountered with NV or MM – noise, dust, insects, odours, temperature extremes – and readily conform to steady state conditions of thermal comfort. However it is possible that NV or MM can provide improved indoor air quality precisely through variations associated with external climate conditions. This paper introduces an ARC funded project evaluating comfort conditions in MM spaces, using field studies from two buildings. The first, a University campus building in Sydney, offers MM perimeter offices with air-conditioned central spaces, while the second, a commercial building in Melbourne, offers a series of MM spaces that can be used by workers from adjacent air-conditioned office spaces. The aim of the project is to evaluate the feasibility of using MM either in place of or in association with traditional HVAC systems. The outcomes of the project will be used to elaborate the justifications for inclusion of NV spaces and/or NV periods within contemporary office environments. This paper presents preliminary results of the field work at each location.

Conference theme: Human

Keywords: Thermal comfort, Mixed-mode buildings, Hybrid ventilation

## INTRODUCTION

Current practices in office buildings generally provide standardised indoor climates for all occupants using heating, ventilation and cooling (HVAC) technology. Typically adopting a building-centred, energy-consuming approach focused on creating constant, uniform-neutrality conditions, the primary purpose of HVAC systems is to provide acceptable indoor air quality and thermal comfort aiming for an optimum 'steady-state' temperature setting based upon Fanger's PMV-PPD model (Fanger 1970). This 'static' approach to thermal comfort was intended to maximise safety and comfort. In contrast, a person-centred approach would purposely provide variability across time and space (Brager and de Dear 1998). Spatially, thermally differentiated areas would be designed to allow for individual thermal requirements. Temporally, indoor temperatures would gradually drift towards outdoor conditions in a way that would enable and encourage adaptations such as clothing changes and use of operable windows.

Recent studies (Baker and Standeven 1996; Humphreys and Nicol 1998; Rowe 2004; Humphreys et al. 2007; Rijal et al. 2007) have made the case for greater environmental variation inside buildings, either via user adjustments to windows, shade devices, etc or by adaptive algorithms that more closely match HVAC set-points to prevailing outdoor temperatures. The 'adaptive' thermal comfort model (Humphreys and Nicol 1998; Humphreys et al. 2007) has advocated the shift towards variable indoor environmental conditions, underlying an essential aspect of sustainable building design, i.e. providing thermal comfort while reducing energy use and associated greenhouse gas emissions. Within conventional air-conditioned (AC) buildings, the HVAC system contributes to over half the energy and emissions required for building operation (AGO 1999). The move towards sustainability involves decreasing the reliance on active systems and pursuing more passive strategies of building design. One alternative is natural ventilation (NV) with occupant-controlled windows, however, while people may prefer a high degree of 'adaptive' opportunities (Baker and Standeven 1996; Brager et al. 2004) they do not appreciate the thermally uncomfortable conditions likely to occur in NV buildings during unusually hot or cold weather conditions. As a result, building architects and engineers are exploring 'mixed-mode' (MM) ventilation as a way of combining the best features of NV and AC buildings (Brager 2006; Brager and Baker 2008).

### Mixed-mode Buildings

The basic philosophy of MM or 'hybrid' ventilation is to maintain a satisfactory indoor environment by alternating between and combining natural and mechanical systems to avoid the cost, energy penalty and consequential environmental effects of full year-round air conditioning (Brager 2006; Lomas et al. 2007). These buildings provide good air quality and thermal comfort using NV and operable windows whenever the outdoor weather conditions are favourable but revert to mechanical systems for HVAC whenever external conditions make the NV option untenable for occupants.

Existing international comfort standards, e.g. the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard-55 (ASHRAE 2004), ISO 7730 (ISO 2006) and pr-EN 15251 (CEN 2007) mainly cover thermal comfort conditions under steady state conditions based on laboratory experiments. Field studies (Humphreys and Nicol 1998; Nicol and Humphreys 2002; Rowe 2004; Nicol and Humphreys 2009) have led to the inclusion of an Adaptive Comfort Standard (ACS) serving as an alternative to the PMV-based method for free-

running, i.e. NV buildings (ASHRAE 2004). However, the scope of the ACS option is heavily constrained to naturally conditioned, occupant-controlled spaces in which thermal comfort conditions of the space may be heavily influenced primarily by operable windows which open to the outdoors and which can be readily adjusted by the occupants of the space. When mechanical cooling systems are provided for the space, the ACS is not applicable (Nicol and Humphreys 2002; Turner 2008). The potential flexibility offered by the standard is not available to hybrid buildings, which may operate in a passive, natural ventilation mode preferentially, and equipped with only supplemental cooling and heating for peak periods; or that control airflow using a building energy management system (BEMS) rather than occupant intervention; or to spaces where operable elements are not connected to the outdoors, must therefore resort to the more restrictive PMV-PPD method as a result (Turner 2008).

By comparing field studies in two recent commercial and institutional buildings from Melbourne and Sydney, this paper investigates thermal comfort conditions within NV or MM spaces located within traditionally AC buildings. The buildings used for this study are Macquarie University's (MQ) Commerce building (Building E4A) at North Ryde in Sydney and the National Australia Bank (NAB) building at Docklands in Melbourne.

### **Thermal Comfort: The Adaptive Concept and Mixed Mode Spaces**

Thermal comfort is currently defined within two internationally recognized standards, the ASHRAE and British Standard BS EN ISO 7730 as "that condition of mind which expresses satisfaction with the thermal environment" (ASHRAE 2004). So the term describes a person's psychological state taking into account a range of environmental and personal factors. Generally air temperature, humidity, air velocity clothing and metabolic activity are the common variables to be considered, however other comfort factors like a sense of relaxation and freedom from worry and pain should be considered (Darby and White 2005). These aspects represent a major impact on a person's thermal comfort, what de Dear defines as "perceptual relativity", i.e. when people interact with their environment (de Dear 2004). Established by ASHRAE Standard 55 (2004), "reasonable comfort" considers 80% of occupant satisfaction as a reasonable limit for the minimum number of people who should be thermally comfortable in an environment. However, occupant comfort complaints are the biggest routine operational problem in business administration, "if one person is too hot, someone else nearby is too cold, and tomorrow both complaints may be reversed" (Opitz 2008). In fact people employ adaptive strategies to cope with their thermal environment like removing clothing, change in posture, choice of heating, opening windows or moving to non-AC areas.

The debate between the heat-balance and the adaptive approach has dominated the development of thermal comfort science in recent years (Nicol and Humphreys 2002). The thermal comfort standard used by ASHRAE is based on experiments in climate chambers initiated by Fanger in the 60s. This approach combines the theory of heat transfer with physiological thermoregulation to determine different comfort temperatures for people in a specific environment: individuals studied in tight controlled situations. The adaptive approach, on the other hand, is based on field studies demonstrating that people are more tolerant of temperature changes than laboratory studies suggest. In fact, people act consciously and unconsciously to affect the heat balance of the body, what is called behavioural thermoregulation. In this way, comfort is normally achieved in a wider range of temperatures than predicted by ASHRAE standards (Heschong 1979; Nicol and Humphreys 2002). As Heschong (1979) interestingly points out comfort is a relationship between thermal content and human imagination. As humans we are capable of adapting to most thermal experiences but mostly we are in need of variations to avoid "thermal boredom" (Kwok 2000).

According to Humphreys and Nicol (1998), straightforward applications of the Fanger equation underestimates human adaptability to indoor climate by about 50% leading to excessive energy use and inappropriate design (Humphreys and Nicol 1998). The adaptive approach to thermal comfort is based on the findings of surveys that focus on gathering data about the thermal environment and the simultaneous thermal response of the individuals in real situations, keeping researcher intervention to a minimum, as achieved in our Melbourne and Sydney case studies. The fundamental assumption of this approach is expressed by the adaptive principle: "if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort" (Nicol and Humphreys 2002). Both Angela and Max are conducting observations that have already given indications related to people's adjustments to their environment. For example, at the NAB, there is a frequency of people entering the tea pot room indicating the need for a break from their work but also that the need to enter a different thermal environment; hence seeking relaxation as well as fresh air. There is a clear association between the comfort conditions and people's actions that links comfort temperatures to the context in which individuals find themselves. Research at the NAB looks into people's behaviour and how they move into the NV tea pot area from their AC office space, what they do and where they come there. Patterns of movement and various chosen activity will reveal physical and psychological adaptations providing indications about the space and its comfort acceptability.

Comfort has both a spatial and a temporal dimension, as users respond to different weather or different activities by adjusting clothing levels, temperature settings, window openings or by moving to another space (Hawkes 1997). The option for people to react to a specific thermal situation reflects the opportunities to adapt to their environment and the possibility to achieve good levels of comfort. Well designed spaces should be able to provide different thermal conditions in the one location (Ong 1997). Ong suggests the need for heterogeneous conditions reflecting the complexity of our sensory experience, allowing users to seek various environmental conditions according to their particular needs at a given time. In this respect, the NAB is the only building in Australia that includes a key innovative design, the MM space<sup>1</sup>, and integrating natural ventilation within AC commercial buildings.

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<sup>1</sup> Mixed-mode refers to a hybrid approach to space conditioning using a combination of natural ventilation from operable windows, manually or automatically controlled, and mechanical systems, i.e. air distribution and refrigeration equipment for cooling. The NAB is the only one in Australia with this particular system (CBE, 2005).



### CASE STUDY 1: NATIONAL AUSTRALIA BANK, DOCKLANDS, MELBOURNE

The National Australia Bank (NAB) building was the first new commercial building built as part of the reconstruction of Melbourne's Docklands. As one of the largest single tenant commercial buildings in Australia, with 140,000 m<sup>2</sup> of office space suitable for around 4000 employees, the building features a series of MM spaces along the Northern façade, giving users the possibility to choose between active mechanical air-conditioning (AC) or natural ventilation (NV), depending on outdoor weather conditions.

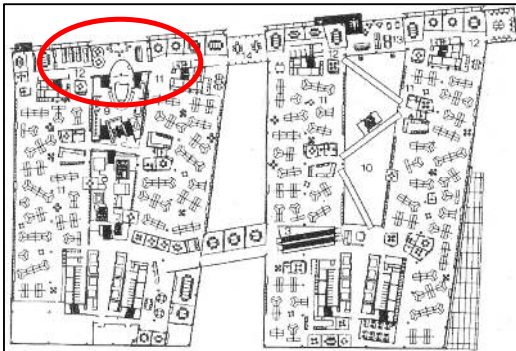


Figure 1: Plan, National Australia Bank Melbourne

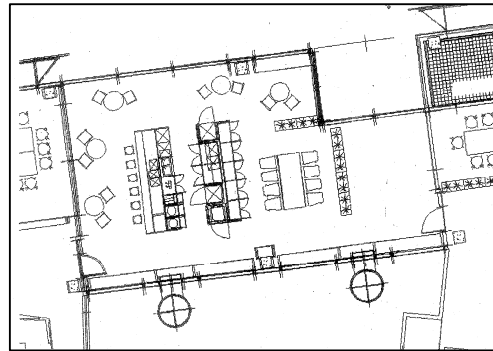


Figure 2: Plan of the North End Tea Point, Level 6

The study at NAB focussed on a single space, level 6 Northern Tea point (figure 2), as part of the MM north façade. In this zone the hybrid ventilation system allows workers to switch between air-conditioning and MM using the control panel (figure 3). The MM spaces provide a unique setting to investigate people's response to NV within AC environments.



Figure 3: The control panel



Figure 4: Overview of the room and the instruments

The methodology used includes quantitative data collection, with instruments monitoring temperature, mean radiant temperature, relative humidity (RH), air-velocity and radiation (Figure 4). Two people counters were used to determine the population of the room at 5 minute intervals. This data will be complemented by qualitative data from questionnaires and field work observations of user behaviour in the space, to be conducted for a period of one week four times throughout the year (corresponding to the seasons).

### CASE STUDY 2: MACQUARIE UNIVERSITY COMMERCE BUILDING, SYDNEY

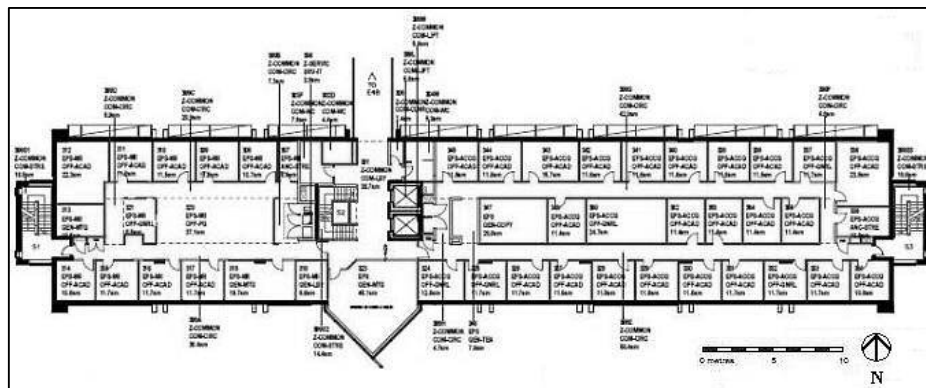
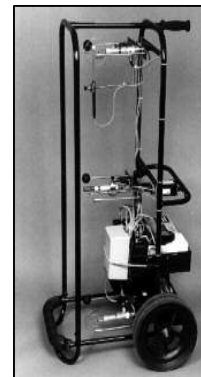


Figure 5: Commerce Building Typical Floor Plan

Macquarie University's (MQ) North Ryde campus is located within the Sydney metropolitan region. Commissioned in 2006, the Commerce building is a 7-storey office building occupied by academic and administrative staff. Consisting of MM cellular offices with operable windows along north and south perimeter zones separated by AC central open-plan office space, the entire façade is built on a louvre system featuring external solar shading over the northern windows (Figure 5). Automated high and low external louvres provide natural ventilation to each floor, with adjustable internal grilles to control airflow, supplemented by user-operable windows. Indoor temperature and outdoor weather sensors prompt the Building Management System (BMS) to switch into AC mode whenever a peak temperature greater than 25°C is sensed in any zone. During AC mode, internal temperatures are maintained at 24°C ( $\pm 1.5^\circ\text{C}$ ) as defined in the building's algorithm. BMS switch-over to NV is conditional when external meteorological conditions and the indoor thermal climate fall into an acceptable zone for the occupants

Dataloggers randomly located throughout the building record air temperature and relative humidity at 5 minute intervals throughout the study. Outdoor weather conditions were collected from a nearby automatic weather station, and BMS data was collected from the University's Office of Facilities Management (OFM). Field studies used mobile observations to supplement continuous monitoring of occupant workplaces, using the thermal comfort 'sputnik' system (Figure 6). These provided detailed thermal comfort measurements for air temperature; mean radiant temperature, relative humidity, and air speed at a height of 0.6m within each occupied zone. Standardised comfort questionnaires were used to record occupant perceptions of thermal comfort within their workspace, including standardised clothing garment and metabolic activity check lists allowing the calculation of various comfort indices, e.g. Predicted Mean Vote (PMV), Effective Temperature (ET\*) and Standard Effective Temperature (SET\*), etc. (ASHRAE 2004). Statistical analyses were performed using Minitab statistical software.

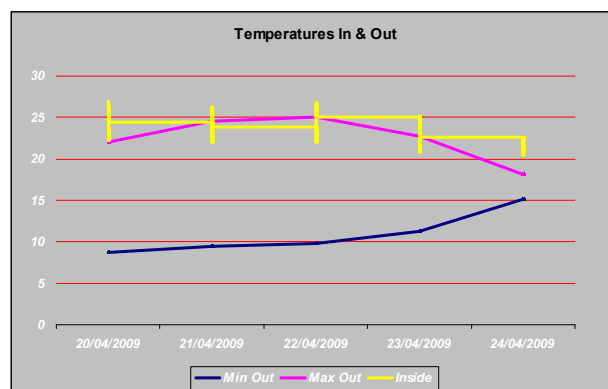


**Figure 6: 'Sputnik' thermal comfort system used for the Sydney MM field study**

#### 1A) PRELIMINARY RESULTS: NATIONAL AUSTRALIA BANK, MELBOURNE

The survey was conducted on the 29<sup>th</sup> April 2009 between 10:30 am and 3 pm. The people counters established that an average of 200 entries per day with 100 occurring between morning tea and lunch time. Most people entered the room at least twice per day, which means that only 66 people (33%) were in the room at the time of surveying. Thirty people volunteered to answer the survey, a response rate of just below half. The average age of respondents was 33 years with 43% females and 56% males. The majority of people surveyed, 73%, have been working at NAB for more than one year and 97% of them worked previously in an AC office mainly in Melbourne.

Throughout April, outdoor temperatures ranged between a minimum of 7°C and a maximum of 32°C. During the week of observations, from the 20<sup>th</sup> to 24<sup>th</sup> April, the average outdoor temperature was 16°C, quite typical for autumn in Melbourne as temperatures were often in the mid-20s (Figure 7). Internal temperatures during this same period ranged between 23-25°C.



**Figure 7: Outside temperature maximum and minimum and inside temperature**

As seen in Figure 8 workers declared on average that they were neutral to slightly cool (4.34). However for all of them the thermal environment was acceptable and for 87% there was no need for change even if 13% would have liked the room to be warmer. Furthermore, 70% declared that there was no need for any change in the air-movement but 26% would have liked more air movement. However 94% didn't open the window during the day of the survey. When people were asked how the temperature was at that particular moment, 70% answered that it was ok and for 23% it was perfect. The majority of people surveyed declared they didn't adjust their clothing level 15 minutes prior to answering the survey. Only 13% stated they did. Most subjects wore similar clothing ensembles, 60% wore pants/skirt, shirt, socks/pantyhose and shoes. The addition of a vest/cardigan was declared by 40% of respondents. When asked to describe the room, half of respondents indicated that the room was full of light, while nearly a quarter stated that the room was full of fresh air and a good place to work. Interestingly, 33% of the answers pointed out that the room was warmer than the rest of the office while 16% of the answers indicated that it was cooler than the rest of the office. The predominant activity conducted in the space is simply having a break or getting away from the work desk. 10% of respondents indicated that they were there to enjoy the view. Use of the kitchen facilities is also significant, with many respondents having lunch or coffee.



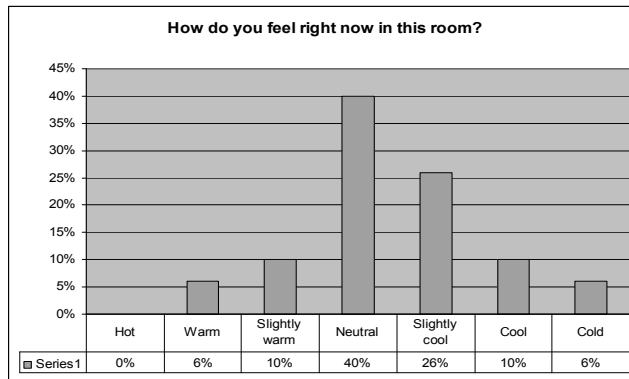


Figure 8: Likert scale analysis: How do you feel now in this room?

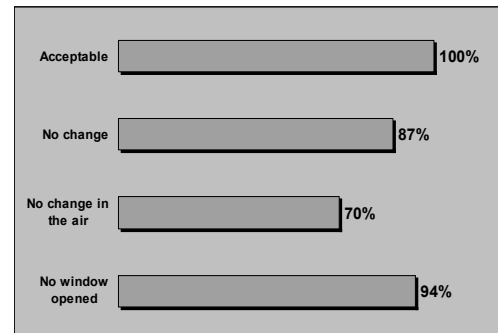


Figure 9: Response rates

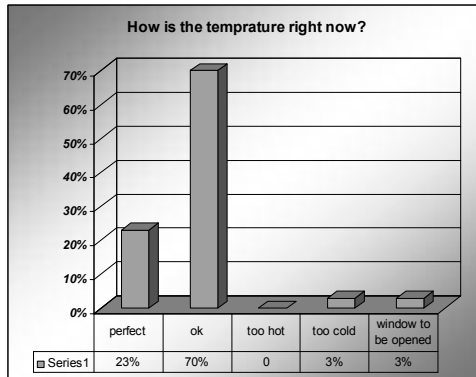


Figure 10: Response rates

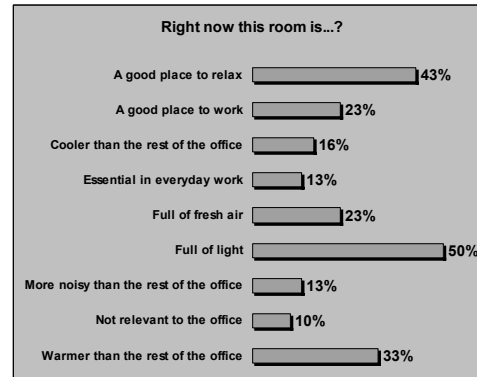


Figure 11: Response rates

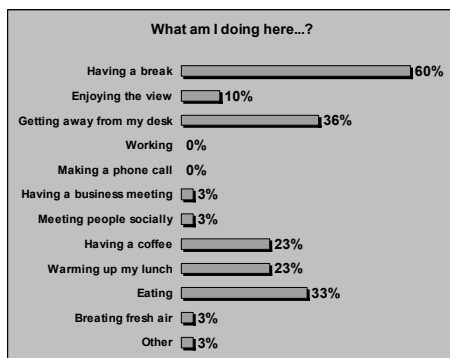


Figure 12: Response rates

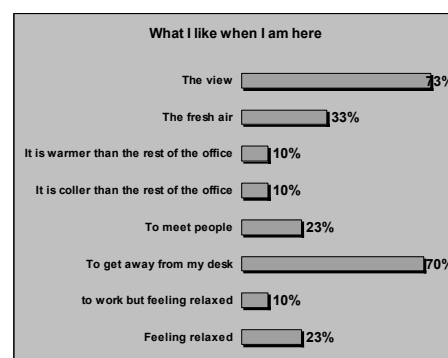


Figure 13: Response rates

When asked about the qualities of the space, the view was the most frequent response, followed closely by the fact that the room was simply an alternative to their usual work station. One third of respondents indicated that they liked the fresh air, while nearly a quarter appreciated the social aspect of meeting other workers. Several indicated that the space provided a place where they could feel more relaxed, either with or without bringing work. Interestingly, ten percent of respondents considered the space warmer than the rest of the office, while the same number considered the space cooler. This is above what would be expected of a normal PMV/PPD response, possibly indicating responses to the different mix of air and mean radiant temperature.

The benefits of the MM system in this space is difficult to separate from other qualities of the space; the view, the kitchen facilities, the social aspect, the chance to relax somewhere away from the pressures of work at the desk. However, since many respondents regarded the room as being slightly warmer or slightly cooler than at their desk indicates that the variation from desk temperatures is important, giving workers a break from the constant conditions of AC, and possibly encountering a different mix of air and mean radiant temperatures. That many respondents regarded the air as being 'fresh' indicates a perception of qualitative difference in the nature of air being breathed, whether due to its temperature, humidity, air speed, oxygen content, or other (e.g. odours). What may be significant here is the opportunity to enjoy indoor air quality conditions that are different to those encountered at the workstation.

#### 1B) PRELIMINARY RESULTS: MACQUARIE UNIVERSITY COMMERCE BUILDING, SYDNEY

Figure 14 below shows daily outdoor temperatures recorded during this period plotted against internal temperatures measured from the HOBO dataloggers and averaged across each zone. Between March to June there was a steadily decline in outdoor temperatures as the study shifted from autumn into the winter months, and each zone mirrors

these changes (typical for a NV building). Based on one-way ANOVA statistical analyses, the average outdoor temperature of 14.7°C was significantly cooler ( $p = 0.000$ ) than average temperatures for the North (22.6°C), Central (22.4°C) and South (20.9°C) zones. As expected, the north façade experienced significantly warmer temperatures than Central and South zones, whereas temperatures in the South zone were significantly less than in Central offices. The variability of these temperatures is also worth noting. The Central zone experienced less variability than the perimeter due to constant air-conditioning throughout these zones. In contrast, the variability in northern offices was greater than the southern zone. These temperature ranges are due to the use of HVAC when temperatures rise towards the 25°C cooling set-point and drop towards the 18°C heating set-point, which explains why temperatures rarely exceed these extremes. The northern façade is also susceptible to high solar heat gains from office windows, suggesting the blips present in the data.

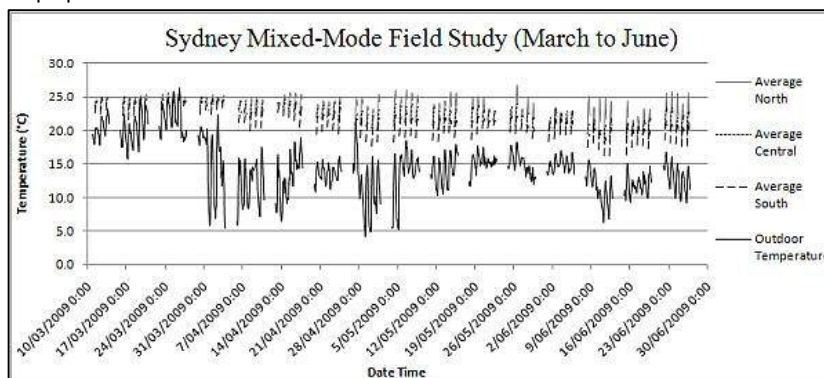


Figure 14: Internal Temperatures for the Sydney field study (Weekdays between March and June 2009)

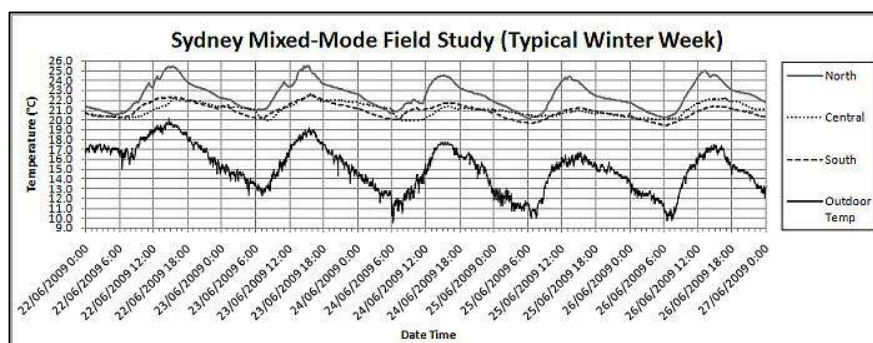


Figure 15: Internal temperatures for the Sydney study showing effects of AC to NV switch-over

In order to show what happens to indoor temperatures during AC to NV switch-over, a typical week in the study period was chosen (as shown in Figure 15 above). During NV mode, temperatures are allowed to rise towards the 25°C cooling set-point at which time; AC mode turns on, automatically shutting the windows and stabilises the internal temperatures to around 24°C ( $\pm 1.5^\circ\text{C}$ ). These events are present in Figure 15 when the temperatures peak at 25°C during the middle of the day.

Over 100 questionnaires have been conducted with representative samples of both genders (37 males and 63 females) for Sydney's field study. Clothing insulation (clo) values were recorded using a standardised check-list of typical office clothing items (ASHRAE 2004). The average clo value for females (0.78) was significantly higher than males (0.62,  $p = 0.002$ ). Clo values were also plotted against outdoor and indoor temperatures for any significant relationships. This data was binned into degrees and thus analysed using weighted linear regressions. The clo relationship with outdoor temperatures was non-significant ( $p > 0.05$ ), however, Figure 16 below illustrates a significant negative clo relationship with indoor temperatures ( $p = 0.000$ ). With  $R^2 = 89.1\%$ , this suggests that indoor temperatures have a strong influence on the amount of clothing insulation worn by the building occupants. As indoor temperatures increase, occupants will remove items of clothing.

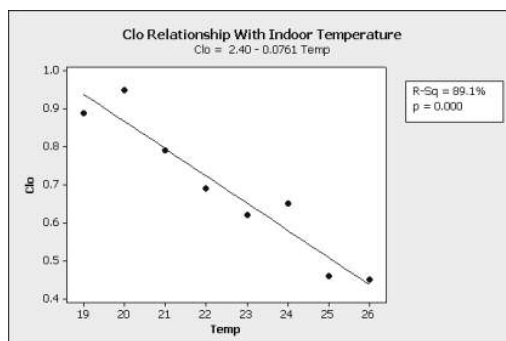


Figure 16: Clothing insulation relationship against indoor temperature for Sydney MM field study

On the basis of AC/NV mode at the time of the questionnaire, it was possible to compare responses during each mode of operation, i.e. AC and NV modes. Table 1 below highlights some of the key study variables being investigated throughout this study. The only significant difference found was Actual Mean Vote (AMV) wherein participants rated their level of comfort across a 7-point Likert Scale (ranging from Cold (-3) through Neutral (0) to Hot (+3)). Within AC mode, the average AMV was neutral (-0.02), which is significantly cooler ( $p = 0.01$ ) than the average AMV during NV mode (0.80). This suggests most people found the building to be slightly warmer during NV mode compared to AC mode, possibly due to the increased indoor temperatures needed for the NV algorithm to start. Other variables did not achieve any significant levels of difference. Thermal preference was significantly different. People did not want the thermal environment changed during AC mode (2.16) whereas during NV mode, occupants preferred to be cooler (1.73). Temperatures were significantly different which can be verified by Figure 15 above which demonstrates that when the building is in NV mode, indoor temperatures will rise until the 25°C cooling set-point.

**Table 1: Comfort data summaries for Sydney MM field study**

Study Variable	AC Mode (n = 81)	NV Mode (n = 25)	Significance
AMV	-0.02	0.80	$p = 0.01$
Acceptability	1.75	1.73	$p > 0.05$
Preference	2.16	1.73	$p = 0.02$
Clo	0.73	0.68	$p > 0.05$
Productivity	-0.5%	0%	$p > 0.05$
PMV	-0.25	0.19	$p > 0.05$
Temperature	21.9	24.0	$p = 0.03$

## DISCUSSIONS

As shown in Figures 16 and 17, internal temperatures are clipped at 25°C as this is the peak temperature zones can experience before the BMS switches into AC mode. Before this transition, office spaces will gradually increase in temperature due to increased solar loads, particularly in the North zone, which experiences significantly warmer temperatures than both the Central and South zones. Up till this point, occupant comfort is said to be neutral, as judging from the summary data present in Table 1 above. However, what isn't clear is what happens when the building activates the HVAC system. Currently the building's MM ventilation algorithm, upon a temperature greater than 25°C has been sensed; the air-conditioning system will lower and maintain temperatures around 24°C ( $\pm 1.5^\circ\text{C}$  depending on concurrent outdoor weather). As can be illustrated in Figure 15 above, there is a lag effect after an AC mode switch-over event. This may be due to inconsistencies depending on the position of the BMS sensors, but overall it takes 30 minutes to reach optimal temperature. Comfort votes taken before and after these periods propose that occupants tend to feel warmer leading up to AC mode operation as internal temperatures are allowed to rise towards the 25°C set-point. Correspondingly, as highlighted in Table 1, the average AMV when the building was in NV mode is slightly warmer than neutral (1.17).

When the building switches into AC mode, internal temperatures are maintained at around 24°C. Contrastingly, the average AMV whilst AC mode was in operation was neutral (0.00) which suggests that occupants preferred these conditions (Rowe 2004; Brager and Baker 2008). However, while PMV values during both these modes do not suggest any significant differences (both -0.25 and 0.19 are within the limits of a Neutral vote), more conclusive evidence is needed to define occupant perceptions of the thermal environment whilst the building switches between AC and NV mode. A meaningful analysis would be to investigate any differences in clo values through both operation modes. The Sydney field study relies heavily on the temporal effects of thermal comfort, especially as this building is capable of switching between modes various times during a day. While the majority of the data presented here was collected in typical winter months, i.e. Figure 14 shows that outdoor temperatures rarely rose above 20°C between April and June, what can be expected during summer months occurred during March in Figure 15, in which high outdoor temperatures, often above 20°C will force the building into AC mode as internal temperatures during these periods exceed the building's natural ventilation limits.

Not only do indoor environments influence clothing choices but so too does the outdoor weather (Morgan and de Dear 2003; De Carli et al. 2007). For NV buildings, occupants tend to change their clothing according to external conditions as the building more closely matches the prevailing outdoor temperatures. However, as Figure 16 demonstrates, occupant clo values are only moderately related to indoor temperatures and not outdoor conditions. Perhaps there is a difference in these relationships when the building is in AC mode and when it is in NV mode. As yet, there is not enough conclusive data to suggest these correlations, but this may be highlighted later on in the study.

## CONCLUSION

The two case studies presented here adopt different approaches to mixed mode ventilation, with the NAB building offering mixed mode ventilation in a break-out area adjacent to workspaces, and the Commerce building using mixed mode ventilation within workspaces. While these two approaches have necessitated slightly different methodologies for evaluating thermal comfort, it is clear that there are benefits in each of these approaches over a traditional air-conditioning system. Of particular interest are the points of change from one mode to another, either spatially, as with the NAB building, or temporally, as with the Commerce building. Comparison between the different comfort conditions in each case study will form a future component of this project, but for now what is evident is that steady-state models are inadequate for describing thermal comfort conditions in mixed mode buildings, and that new temporal and spatial models need to be developed.

## ACKNOWLEDGEMENTS

The project has been funded by an ARC (Australian Research Council) Discovery Grant. We are grateful to Kerry Russell and Macquarie University's Office of Facilities Management (OFM) and to Angelina Andonovski and John Hurren at NAB Docklands for their support and assistance in gathering data for these projects. We would like to extend our appreciation to all participants who have given their time to complete surveys and questionnaires.

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## **Appendix L: Windsor 2010 Conference Paper**

Deuble, M. and de Dear, R. (2010) ‘Green occupants for green buildings: The missing link?’, *Proceedings of the 2010 Windsor Conference: Adapting to Change: New Thinking on Comfort* Windsor, London, UK, Network for Comfort and Energy Use in Buildings, <http://nceub.org.uk>, 9-11 April 2010

## **Green Occupants for Green Buildings: The Missing Link?**

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### **Summary**

This paper follows the results of recent post-occupancy evaluation surveys within two office buildings at Macquarie University, Sydney Australia. Supplemented with an environmental attitudes questionnaire, based upon the New Ecological Paradigm (Dunlap et al. 2000), it was found that occupant satisfaction levels are positively associated with environmental beliefs. Occupants with higher levels of environmental concern were more tolerant of their building, particularly those featuring aspects of green design, such as naturally-ventilated façades and operable windows. Despite their criticisms of the building's indoor environmental quality, the 'green' occupants were prepared to overlook and forgive less-than-ideal conditions more so than their 'brown' (non-green) counterparts. Drawing upon these results, statistical analyses of the association between environmental beliefs and occupant satisfaction in this paper support the hypothesis that broad environmental attitudes are closely associated with the stronger 'forgiveness factor' often observed in green-intent buildings.

### **Keywords**

Green buildings, Post-occupancy evaluation (POE), Forgiveness factor, New Ecological Paradigm (NEP)

### **Introduction**

Many adaptive comfort studies (Humphreys and Nicol 1998; Nicol and Humphreys 2002) have called for greater indoor environmental variability, either via user adjustments to operable windows, shade devices, etc or automated controls shifting heating, ventilation and air-conditioning (HVAC) set-points in sync with weather and seasonal variations outdoors. This shift towards greater indoor climatic variability is integral to many sustainable building designs. Buildings featuring natural ventilation capabilities are typically defined nowadays as green-intent buildings. Many studies (Abbaszadeh et al. 2006; Leaman and Bordass 2007; Brager and Baker 2009) have found occupants are more favourably disposed to green buildings than their conventional energy-intensive predecessors. It is now widely accepted that occupants prefer more adaptive opportunities inside their buildings than the sealed façade, air-conditioned (AC) designs of last century (Baker and Standeven 1996). Leaman and Bordass (2007) observed in their extensive database of post-occupancy evaluation (POE) studies that occupant satisfaction scores for green-intent buildings tend to be higher than those in conventional AC buildings. Despite occupants preferring greater adaptive opportunities, they do not necessarily *expect* the thermal excursions that sometimes occur in naturally-ventilated (NV) buildings, especially in hot weather. Recent POE studies suggest that, notwithstanding occasional discomforts, occupants

of green buildings tend to forgive these shortcomings provided they can exercise a modicum of indoor environmental control (Leaman and Bordass 2007). Coined as the 'forgiveness factor', derived by dividing 'comfort overall' scores by the average of the variables for temperature in summer and winter, ventilation/air in summer and winter, noise and lighting, this variable describes how people extend their comfort zone by overlooking and allowing for inadequacies of their thermal environment (Leaman et al. 2007). Although many green buildings tend to be hotter in summer, colder in winter and contain more glare from the sun and sky than their conventional AC alternatives, the occupants tend to be more forgiving. This toleration of moderate discomfort suggests that people may have an understanding of and a connection to the outdoor climate by virtue of the buildings design. Leaman and Bordass (2007) suggest increased knowledge of the adaptive opportunities in buildings yields a greater likelihood of reduced discomfort.

### ***Environmental Attitudes, Behaviours and The New Ecological Paradigm (NEP)***

In recent decades, there has been a growing awareness of the problematic relationship between modern industrialised societies and the physical environments on which they depend (Dunlap 2008). With the emergence of pervasive environmental problems such as climate change, researchers have started exploring how to quantify public sentiment on these issues. The New Ecological Paradigm (NEP) scale, a revision of the New Environmental Paradigm, is a 15-item questionnaire consisting of 8 pro-NEP and 7 anti-NEP items. It measures strength of endorsement (from low to high) of an ecological worldview (Dunlap et al. 2000). After extensive application across diverse studies, a broad consensus is emerging in the environmental psychology literature that the NEP represents a valid and reliable scale for measuring levels of ecological beliefs and behaviours (Cordano et al. 2003). To date, however, the NEP scale has not been used in building occupant studies.

## **Methods**

### ***Sydney's Climate***

The Sydney metropolitan region is located on the eastern coast of Australia (34°S, 151°E) and is characterised by a moderately temperate climate. Influenced from complex elevated topography surrounding the region to the north, west and south and due to close proximity to the Tasman Sea to the east, Sydney avoids the high temperatures commonly associated with more inland regions as well as the high humidity of tropical coastal areas (BoM 1991). The summer months of December to February can be described as warm-to-hot with moderate-to-high humidity peaking in February to March. Between June and August, Sydney experiences cool-to-cold winters. Macquarie University (MQ) is located in Sydney's North Ryde, 16km north-west of Sydney's CBD (33° 46' S, 151° 6' E). Seasonal variations are fairly consistent with the greater metropolitan region with a mean summer daily maximum temperature of 26-28°C, a mean winter daily maximum of 17°C and an annual mean daily maximum of 22-23°C. Mean minimum daily temperatures range from 5-8°C in winter, to 17-18°C over the summer months, with an annual daily minimum temperature of 11-13°C (BoM 2007). Given the city's yearly seasonal variations, Sydney's climate is well suited to mixed-mode (MM) buildings.

### ***Case Study Buildings***

Two academic staff buildings from MQ were selected for this study, both having North-South orientations, with North facades directly irradiated from the Sun, creating warmer internal temperatures than the South-facing perimeter zones. The



sample buildings consisted of a MM building (see Photo 1) commissioned in 2006, and a NV building (see Photo 2) built in the late 1960s.

The MM building features operable windows on all perimeter cellular offices along North and South facades separated by an AC central open-plan office zone. Indoor temperature and outdoor weather sensors drive the Building Management System (BMS) to switch to AC mode when average indoor temperatures increase above 25°C. Occupants are mainly academics and administrative staff from economics and finance departments. The NV building features occupant-operated windows and a narrow floor-plate traversed by a central corridor with single- and dual-occupant cellular offices on either side. Academic staff, administrative staff and post-graduate students from a variety of environment-related disciplines occupy this NV building.



**Photo 1:** MQ, MM building (North façade) featuring operable windows with external solar shading devices on north-facing windows



**Photo 2:** MQ, NV building (North façade) featuring occupant-operated windows with some individual air-conditioner units

### ***Measurements***

Throughout the study, dataloggers have been randomly located within each building to record air temperatures, globe temperatures and relative humidity at 5 minute intervals. These were placed within 1 metre of the occupants' workstation to characterise the immediate thermal environment experienced by the occupant whilst working. In addition to indoor climate measurements, outdoor air temperature was also recorded over the same period at a nearby automatic weather station. Concurrent BMS data from the survey period was collected from the University's Office of Facilities Management (OFM).



### **Questionnaires**

Between March and April 2009 (the Austral autumn), two questionnaires were distributed to all staff in both buildings:

1. The three-page Building Use Studies (BUS 2009) POE uses 7-point Likert scales with space for commentary, covering variables relating to occupant satisfaction, e.g. thermal, visual and acoustic comfort, indoor air quality, perceived health and productivity, and general acceptance of the workplace. BUS (2009) further details the BUS methodology. Combinations of these scores enable the calculation of BUS comfort and satisfaction indices, as well as the forgiveness factor (defined earlier).
2. The Environmental Attitudes questionnaire is a 15-item version of the NEP Scale (Dunlap et al. 2000), using 5-point response scales ranging from *Strongly Disagree* to *Strongly Agree*, with higher scores on the scale from 1 (low) to 5 (high) indicating greater levels of environmental concern. All scales were converted to a NEP score by summing each item response and dividing by the total number of items in the scale. Results were analysed using MiniTab statistical software.

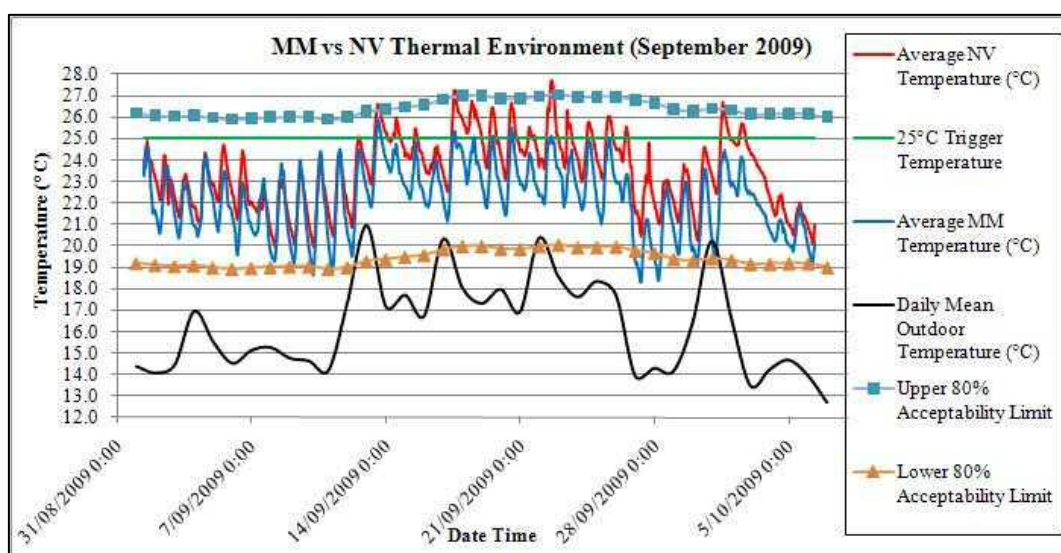
### **Results**

#### ***Thermal Environment***

In order to show the differences between each building based on objective measurements, i.e. internal temperature, it is instructive to show how both buildings perform under the same weather conditions. Building occupant studies are generally conducted in summer, hence it was necessary to obtain temperature data from September 2009 to reflect similar conditions to when the questionnaires were administered 6 months prior. From temperatures averaged across all dataloggers, it was established that the NV building experienced significantly warmer temperatures (average = 23.5°C,  $p = 0.000$ ) than the MM building over the same period (average = 22.2°C). Figure 1 below highlights the discrepancies between the internal temperatures within these buildings. Temperatures inside each building were far greater than the surrounding outdoor air temperature throughout the day (mean = 16.3°C,  $p = 0.000$ ). As a NV building, internal temperatures closely match changes in outdoor weather conditions, whereas the MM building contained its indoor temperatures within a narrower band.

Figure 1 indicates that internal temperatures within the MM building rarely exceed 25°C due to the BMS switching into AC mode whenever average temperatures reached the 25°C trigger temperature. Less than 10% of occupied office hours (i.e. 8am-6pm weekdays) within this building experienced indoor temperatures greater than 25°C. In contrast, temperatures inside the NV building varied between 20-28°C. Internal temperatures in the NV building exceeded the 25°C threshold almost 50% of all occupied office hours.

Using a 7-day running average of daily mean outdoor temperatures, Figure 1 also presents the 80% thermal acceptability band limits derived from the ASHRAE Standard 55 adaptive comfort model (ASHRAE 2004). These indicate the suggested range of internal operative temperatures that should not be exceeded within the occupied zone (de Dear 2007). As seen in Figure 1 below, average temperatures inside the NV building exceeded the upper limit of acceptable adaptive comfort on four separate occasions in September. In contrast, the MM building never exceeds these limits; in fact indoor temperature only exceeded the 25°C trigger temperature on one occasion.



**Figure 1:** Indoor and outdoor thermal environments comparing the NV and MM buildings (September 2009)

### *POE and NEP Analysis*

In total, 163 POE and NEP questionnaires were distributed in the MM building and 40 in the NV building. With a 53% response rate, the MM building returned 86 completed questionnaires (39 male, 47 female), and 29 (13 male; 16 female) were completed from the NV building (73% response rate). Incomplete or suspect responses were omitted from the samples in a basic quality assurance check. POE responses for both buildings were benchmarked against the Australian BUS database (as summarised in Table 1). The NEP questionnaire items were tested for internal consistency and were found to have strong coefficient alphas ( $\alpha = 0.82$ ) suggesting good internal consistency.

As shown in Table 1 (below), both buildings generally measure poorly in regards to the POE summary variables. The NV building appears worse than the MM building in most summary variables; it was found that the average forgiveness factor (FF) was significantly higher than that for the MM building, with FF scores greater than 1.0 indicating greater levels of tolerance. The NV building had a significantly higher mean NEP score (4.04,  $p = 0.005$ ) than the MM building (3.69), plausible for environmentally educated academics. Interestingly, the NEP score for the MM building is relatively high for occupants associated with economics, finance and business studies as scores greater than 3.0 generally indicate pro-environmental attitudes.

**Table 1:** A summary of POE and NEP results for the MM and NV buildings

Study Variable	MM (n = 86)	NV (n = 29)	Significance
Forgiveness Factor	0.99	1.17	$p = 0.019$
Comfort Index	-0.39	-0.70	Not sig.
Satisfaction Index	0.02	-0.10	Not sig.
Perceived Productivity	-5.34	-10.71	$p = 0.000$
NEP	3.69	4.04	$p = 0.005$

In order to analyse environmental attitudes and their relation with forgiveness factors within each building, it was important to isolate a control group that would not be biased towards any environmental or building-related concepts. Administrative staff within both buildings undertake various clerical duties and management aspects for

their respective faculties. Since they are not considered to have academically inclined responsibilities, these groups were considered separate from the buildings' academic staff (summarised in Table 2).

Within the NV and MM buildings, administrative staff had slightly lower levels environmental concern compared to the academic staff within the building. Also, both groups were significantly different in regards to their FF, with the academics scoring higher levels of tolerance for each building. Table 2 indicates that the administrative staff of the NV building had significantly higher NEP scores (3.21) than those located inside the MM building (2.66,  $p = 0.016$ ). Correspondingly, the same group measured higher degrees of forgiveness (NV = 0.89, MM = 0.74,  $p = 0.004$ ).

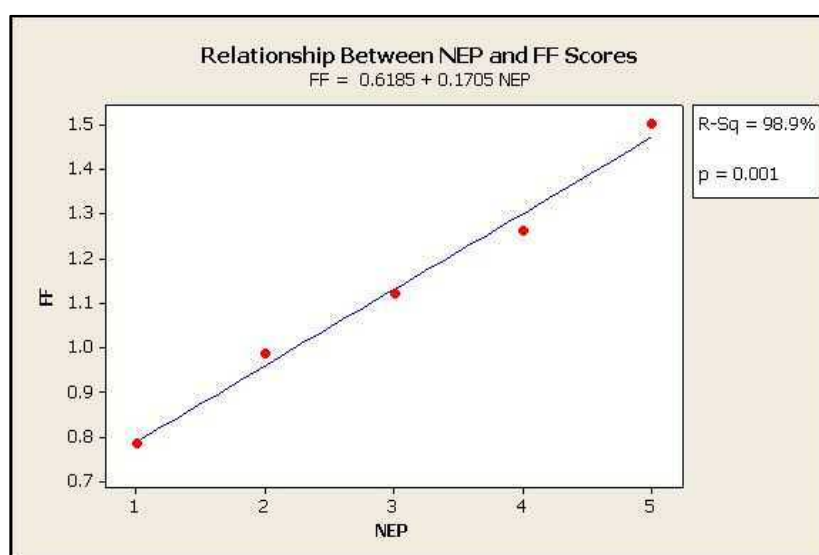
**Table 2:** Analysis of Forgiveness Factor and NEP results for the MM and NV buildings

Study Variable	MM Academic (n = 64)	NV Academic (n = 22)	Significance
Forgiveness Factor	1.02	1.14	$p = 0.017$
NEP	3.80	4.20	$p = 0.000$

Study Variable	MM Admin (n = 13)	NV Admin (n = 7)	Significance
Forgiveness Factor	0.74	0.89	$p = 0.004$
NEP	2.66	3.21	$p = 0.016$

Since the NEP questionnaire items are measured across a 5-point Likert scale, responses were binned according to their item response (from low to high, 1 to 5). Weighted according to the number of FF samples within each NEP bin, a linear regression model was fitted to test any correlation between NEP and FF scores for these two case study buildings. As illustrated in Figure 2, there is a strong positive relationship between environmental attitudes and forgiveness factors ( $R^2 = 98.9\%$ ,  $p = 0.001$ ) suggesting higher levels of environmental beliefs yielded higher levels of tolerance.



**Figure 2:** Relationship between NEP and FF scores for both study buildings.

## Discussions

With higher temperatures recorded in the NV building (Figure 1), it is reasonable to expect that perception of productivity at temperatures up to 28°C would be significantly lower than a MM building. Occupants in both buildings have often

complained about indoor temperatures in summer months, particularly on the north façade. This anecdotal feedback is consistent with a trend emerging from Australian green buildings that have undergone the BUS POE (Leaman et al. 2007). In comparing 22 green-intent buildings against 23 conventional HVAC office buildings, Leaman et al (2007) reported that green buildings were perceived as hotter in summer and cooler in winter. Green-intent buildings, such as the NV and MM buildings in this study, are *expected* to perform this way. In comparing the ‘forgiveness’ scores from Leaman et al (2007) (summarised in Table 3 below) to those results in Table 1 (above), it was found that the MM building is poorly received by its users (forgiveness = 0.99, equal to that of conventional AC buildings in Australia). Contrastingly, the NV building measured significantly higher NEP scores indicating greater tolerance to perceived thermal variance (forgiveness = 1.17), consistent with other green-intent buildings already in the BUS database.

**Table 3:** Forgiveness scores by ventilation type: Australian BUS building database (n = 45)

Study Variable	Green-intent (NV, ANV, MM)	AC	MM (MQ)	NV (MQ)
Forgiveness Factor	1.02	0.99	0.99	1.17
n	22	23		

Note: Higher values indicate occupants more tolerant or ‘forgiving’ of the conditions. Building types include natural ventilation (NV), advanced natural ventilation (ANV), mixed-mode (MM) and air-conditioning (AC).

The correlation of NEP and FF scores shown in Figure 2 supports the hypothesis that green building users are more prepared to overlook and forgive less-than-ideal conditions than their ‘brown’ (non-green) counterparts suggesting there is a possible link between occupant satisfaction and environmental attitudes. Whilst the NEP Scale was originally designed to measure environmental concern of the general public, with both samples containing tertiary-educated participants there is a limit to what can be drawn from these results. Nonetheless, it amplifies how occupant attitudes and expectations play an important role in the way green-intent buildings are designed, built and received.

## Conclusions

Green buildings have greater thermal variations than their AC counterparts, in which centralised HVAC provides static indoor temperatures to all occupants all-year round. This paper suggests green building users are more forgiving of their building, consistent with the hypothesis that green buildings need green occupants. Whilst the study only represents two green buildings at MQ, it highlights the increasing awareness to the psychological dimensions of occupant adaptation, such as attitudes, expectation and control. Given the urgency to mitigate global warming, it has become apparent that people’s attitudes, and the behaviours they entail, can be manipulated. Whilst buildings take years to build and even months to retrofit, the path to altering people’s expectations of the built environment presents the low-lying fruit. According to this study, the forgiveness of green buildings can be cultivated. Given the multitude of sustainable and pro-environmental behaviour literature, there is great potential for occupants to be ‘re-educated’ about the role buildings play in addressing global climate change. The emergent practical applications of adaptive building design calls for the clear communication of intent by designers to the users and building managers to ultimately assist in the transition to an energy efficient, low-carbon future.

## Acknowledgements

We are enormously grateful to Adrian Leaman for permission to use the BUS questionnaire under license and his assistance in data analysis. We would also like to thank Riley Dunlap for his valuable comments and encouragements, and Macquarie University's OFM, especially Kerry Russell, for their support. Finally, and most importantly, we express our appreciation to all the building occupants who responded to the questionnaires.

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## **Appendix M: Co-Author Statement of Contribution**


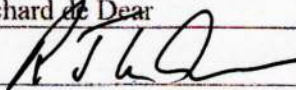
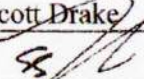
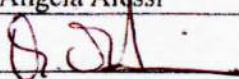


## Statement of Co-Author Contribution

**Publication title and date of publication:**

Drake, S; de Dear, R; Alessi, A and Deuble, M (2010) 'Occupant comfort in naturally ventilated and mixed-mode spaces within air-conditioned offices', *Architectural Science Review*, 53(3): 297-306

For this paper, each author's role was integral to the paper's final publication. The paper was divided into two separate case studies: the NAB Docklands case study, undertaken by Scott Drake and Angela Alessi; and the Macquarie University commerce building case study, undertaken by Richard de Dear and Max Deuble. Scott Drake and Richard de Dear were both responsible for the initial project design/concept. Before the project could officially commence, all authors met to discuss the data collection methods and survey designs. Max Deuble and Angela Alessi both undertook extensive data collection leading up to the drafting of the manuscript, each responsible for their respective case studies. Angela Alessi was also responsible for writing the sections referring to the adaptive concept and mixed-mode spaces, whereas Max Deuble wrote the introduction section on mixed-mode buildings and thermal comfort. During the writing of the manuscript, initial data analysis and results (including the graphs presented in the paper) were performed by Angela Alessi and Max Deuble. These were later discussed with, and subsequently aided by Scott Drake and Richard de Dear respectively. The discussion and conclusion sections were written by Max Deuble and Angela Alessi collaboratively. These were ultimately reviewed and edited by Richard de Dear and Scott Drake prior to submission to the journal.

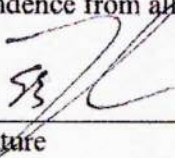
Contributor	Statement of contribution
Max Deuble	Macquarie University commerce building case study data collection; wrote introduction section on mixed-mode buildings and thermal comfort; data analysis and results; wrote discussions and conclusion sections
(Signature) 	
(Date) 19/5/11	
Richard de Dear	Initial project design/concept; discussed data collection methods; aided data analysis; and assisted Max Deuble with discussions and conclusion section
(Signature) 	
(Date) 19.5.11	
Scott Drake	Initial project design/concept; discussed data collection methods; aided data analysis; assisted Angela Alessi with discussions and conclusion section; and submission of draft manuscript
(Signature) 	
(Date) 9.5.11	
Angela Alessi	NAB Docklands case study data collection; wrote introduction section on adaptive concept and mixed-mode spaces; data analysis and results; wrote discussions and conclusion sections
(Signature) 	
(Date) 10.5.11	

By signing this document, the authors listed above have certified that:

1. they meet the criteria for authorship in that they have participated in the conception, execution, or interpretation, of at least that part of the publication in their field of expertise;
2. they take public responsibility for their part of the publication, except for the lead author who accepts overall responsibility for the publication;
3. there are no other authors of the publication according to these criteria;
4. potential conflicts of interest have been disclosed to (a) granting bodies, (b) the editor or publisher of journals or other publications, and (c) the head of the responsible academic unit, and
5. they agree to the use of the publication in the student's thesis and its publication on the Australasian Digital Thesis database consistent with any limitations set by publisher requirements.

**Principal Supervisor Confirmation**

I have sighted email or other correspondence from all co-authors confirming their certifying authorship.

SCOTT DRAKE		9.5.11
Name	Signature	Date



## **Appendix N: *Architectural Science Review* Paper**

**Status:** Published; Drake, S., de Dear, R., Alessi, A. and Deuble, M. (2010) ‘Occupant comfort in naturally ventilated and mixed-mode spaces within air-conditioned offices’, *Architectural Science Review*, 53(3): 297-306

DOI: <http://dx.doi.org/10.3763/asre.2010.0021>

**Journal Impact Factor:** Not applicable: All research papers, research notes and review articles are double-blind refereed.

# Occupant comfort in naturally ventilated and mixed-mode spaces within air-conditioned offices

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Contemporary concerns for improving environmental performance in buildings have led to an increased interest in natural ventilation (NV) either on its own or in combination with air-conditioning (mixed mode (MM)) as an alternative to traditional heating, ventilation and cooling (HVAC) systems. HVAC systems are widely used because they avoid many of the problems encountered with NV or MM – noise, dust, insects, odours, temperature extremes – and readily conform to steady-state conditions of thermal comfort. However, it is possible that NV or MM can provide improved indoor air quality precisely through variations associated with external climatic conditions. This article introduces an ARC (Australian Research Council) funded project evaluating comfort conditions in MM spaces, using field studies from two buildings. The first, a University campus building in Sydney, offers MM perimeter offices with air-conditioned central spaces, while the second, a commercial building in Melbourne, offers a series of MM spaces that can be used by workers from adjacent air-conditioned office spaces. The aim of the project is to evaluate the feasibility of using MM either in place of or in association with traditional HVAC systems. The outcomes of the project will be used to elaborate the justifications for inclusion of NV spaces and/or NV periods within contemporary office environments. This article presents preliminary results of the fieldwork at each location.

Keywords: Hybrid ventilation; mixed-mode buildings; thermal comfort

## INTRODUCTION

Current practices in office buildings generally provide standardized indoor climates for all occupants using heating, ventilation and cooling (HVAC) technology. Typically adopting a building-centred, energy-consuming approach focused on creating constant, uniform-neutrality conditions, the primary purpose of HVAC systems is to provide acceptable indoor air quality and thermal comfort aiming for an optimum ‘steady-state’ temperature setting based on Fanger’s predicted mean vote–predicted percentage of dissatisfied (PMV–PPD) model (Fanger, 1970). This ‘static’ approach to thermal comfort was intended to maximize safety and comfort. In contrast, a person-centred approach would purposely provide variability across time and space (Brager and de Dear, 1998). Spatially, thermally differentiated areas would be designed to allow for individual thermal requirements. Temporally, indoor temperatures would gradually drift towards outdoor conditions in a way that would enable and encourage adaptations such as clothing changes and use of operable windows.

Recent studies (Baker and Standeven, 1996; Humphreys and Nicol, 1998; Rowe, 2004; Humphreys *et al.*, 2007; Rijal *et al.*, 2007) have made the case for greater environmental variation inside buildings, either via user adjustments to windows, shade devices and so on or by adaptive algorithms that more closely match HVAC set-points to prevailing outdoor temperatures. The ‘adaptive’ thermal comfort model (Humphreys and Nicol, 1998; Humphreys *et al.*, 2007) has advocated the shift towards variable indoor environmental conditions, underlying an essential aspect of sustainable building design, that is, providing thermal comfort while reducing energy use and associated greenhouse gas emissions. Within conventional air-conditioned (AC) buildings, the HVAC system contributes to over half the energy and emissions required for building operation (AGO, 1999). The move towards sustainability involves decreasing the reliance on active systems and pursuing more passive strategies of building design. One alternative is natural ventilation (NV) with occupant-controlled windows; however, while people may prefer a high degree

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of 'adaptive' opportunities (Baker and Standeven, 1996; Brager *et al.*, 2004), they do not appreciate the thermally uncomfortable conditions likely to occur in NV buildings during unusually hot or cold weather conditions. As a result, building architects and engineers are exploring 'mixed-mode' (MM) ventilation as a way of combining the best features of NV and AC buildings (Brager, 2006; Brager and Baker, 2008).

## MM BUILDINGS

The basic philosophy of MM or 'hybrid' ventilation is to maintain a satisfactory indoor environment by alternating between and combining natural and mechanical systems to avoid the cost, energy penalty and consequential environmental effects of full year-round AC (Brager, 2006; Lomas *et al.*, 2007). These buildings provide good air quality and thermal comfort using NV and operable windows whenever the outdoor weather conditions are favourable but revert to mechanical systems for HVAC whenever external conditions make the NV option untenable for occupants.

Existing international comfort standards, for example, the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard-55 (ASHRAE, 2004), ISO 7730 (ISO, 2006) and pr-EN 15251 (CEN, 2007), mainly cover thermal comfort conditions under steady-state conditions based on laboratory experiments. Field studies (Humphreys and Nicol, 1998; Nicol and Humphreys, 2002, 2009; Rowe, 2004) have led to the inclusion of an adaptive comfort standard (ACS) serving as an alternative to the PMV-based method for free-running, that is, NV buildings (ASHRAE, 2004). However, the scope of the ACS option is heavily constrained to naturally conditioned, occupant-controlled spaces in which thermal comfort conditions of the space may be heavily influenced primarily by operable windows that open to the outdoors and that can be readily adjusted by the occupants of the space. When mechanical cooling systems are provided for the space, the ACS is not applicable (Nicol and Humphreys, 2002; Turner, 2008). The potential flexibility offered by the standard is not available to hybrid buildings, which may operate in a passive NV mode preferentially, equipped with only supplemental cooling and heating for peak periods; or that control airflow using a building energy management system (BEMS) rather than occupant intervention; or spaces where operable elements are not connected to the outdoors. As a result, these must therefore resort to the more restrictive PMV-PPD method (Turner, 2008). By comparing field studies in two recent commercial and institutional buildings from Melbourne and Sydney, this article investigates thermal comfort conditions within NV or MM spaces located within traditionally AC buildings. The buildings used for this study are Macquarie University's (MQ) Commerce

building (building E4A) at North Ryde in Sydney and the National Australia Bank (NAB) building at Docklands in Melbourne.

## THERMAL COMFORT: THE ADAPTIVE CONCEPT AND MM SPACES

Thermal comfort is currently defined within two internationally recognized standards, the ASHRAE and British Standard BS EN ISO 7730, as 'that condition of mind which expresses satisfaction with the thermal environment' (ASHRAE, 2004). So the term describes a person's psychological state taking into account a range of environmental and personal factors. Generally, air temperature, humidity, air velocity, clothing and metabolic activity are the common variables to be considered; however, other comfort factors like a sense of relaxation and freedom from worry and pain should also be considered (Darby and White, 2005). These aspects represent a major impact on a person's thermal comfort, what de Dear defines as 'perceptual relativity', that is, when people interact with their environment (de Dear, 2004). Established by ASHRAE Standard 55 (2004), 'reasonable comfort' considers 80% of occupant satisfaction as a reasonable limit for the minimum number of people who should be thermally comfortable in an environment. However, occupant comfort complaints are the biggest routine operational problem in business administration: 'if one person is too hot, someone else nearby is too cold, and tomorrow both complaints may be reversed' (Opitz, 2008). In fact, people employ adaptive strategies to cope with their thermal environment like removing clothing, change in posture, choice of heating, opening windows or moving to non-AC areas.

The debate between the heat balance and the adaptive approach has dominated the development of thermal comfort science in recent years (Nicol and Humphreys, 2002). The thermal comfort standard used by ASHRAE is based on experiments in climate chambers initiated by Fanger in the 1960s. This approach combines the theory of heat transfer with physiological thermoregulation to determine different comfort temperatures for people in a specific environment: individuals studied in tightly controlled situations. The adaptive approach, on the other hand, is based on field studies demonstrating that people are more tolerant of temperature changes than laboratory studies suggest. In fact, people act consciously and unconsciously to affect the heat balance of the body, which is called behavioural thermoregulation. In this way, comfort is normally achieved in a wider range of temperatures than predicted by ASHRAE standards (Heschong, 1979; Nicol and Humphreys, 2002). As Heschong (1979) interestingly points out, comfort is a relationship between thermal content and human imagination. As humans we are capable of adapting to most thermal experiences, but mostly we are in need of variations to avoid 'thermal boredom' (Kwok, 2000).

According to Humphreys and Nicol (1998), straightforward application of the Fanger equation underestimates human adaptability to indoor climate by about 50%, leading to excessive energy use and inappropriate design (Humphreys and Nicol, 1998). The adaptive approach to thermal comfort is based on the findings of surveys that focus on gathering data about the thermal environment and the simultaneous thermal response of the individuals in real situations, keeping researcher intervention to a minimum, as achieved in our Melbourne and Sydney case studies. The fundamental assumption of this approach is expressed by the adaptive principle: 'if a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort' (Nicol and Humphreys, 2002). Both Angela and Max are conducting observations that have already given indications related to people's adjustments to their environment. For example, at the NAB, there is a frequency of people entering the teapot room, indicating the need for a break from their work but also the need to enter a different thermal environment, hence seeking relaxation as well as fresh air. There is a clear association between comfort conditions and people's actions that links comfort temperatures to the context in which individuals find themselves. Research at the NAB looks into people's behaviour and how they move into the NV teapot area from their AC office space, what they do and why they come there. Patterns of movement and various chosen activities will reveal physical and psychological adaptations providing indications about the space and its comfort acceptability.

Comfort has both a spatial and a temporal dimension, as users respond to different weather or different activities by adjusting clothing levels, temperature settings and window openings or by moving to another space (Hawkes, 1997). The option for people to react to a specific thermal situation reflects the opportunities to adapt to their environment and the possibility to achieve good levels of comfort. Well-designed spaces should be able to provide different thermal conditions in one location (Ong, 1997). Ong suggests the need for heterogeneous conditions reflecting the complexity of our sensory experience, allowing users to seek various environmental conditions according to their particular needs at a given time. In this respect, the NAB is the only building in Australia that includes a key innovative design, the MM space,<sup>1</sup> and integrating NV within AC commercial buildings.

### CASE STUDY 1: NATIONAL AUSTRALIA BANK, DOCKLANDS, MELBOURNE

The NAB building was the first new commercial building built as part of the reconstruction of Melbourne's Docklands. As one of the largest single tenant commercial buildings in Australia, with 140,000m<sup>2</sup> of office space suitable for around 4000 employees, the building features a series of MM spaces along the northern façade, giving users the

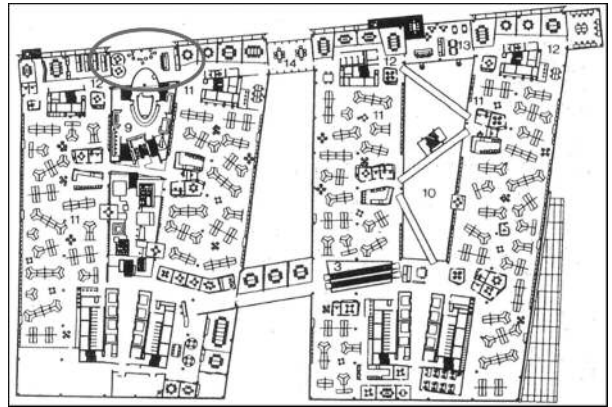


Figure 1 | Plan, National Australia Bank, Melbourne

possibility to choose between active mechanical AC or NV, depending on outdoor weather conditions (Figure 1).

The study at NAB focused on a single space, level 6 North-End Tea Point (Figure 2), as part of the MM north façade. In this zone, the hybrid ventilation system allows workers to switch between AC and MM using the control panel (Figure 3). The MM spaces provide a unique setting to investigate people's response to NV within AC environments.

The methodology used includes quantitative data collection, with instruments monitoring temperature, mean radiant temperature, relative humidity (RH), air velocity and radiation (Figures 4 and 5a–e). Two people counters were used to determine the population of the room at 5-min intervals. These data will be complemented by qualitative data from questionnaires and fieldwork observations of user behaviour in the space, to be conducted for a period of one week four times throughout the year (corresponding to the seasons).

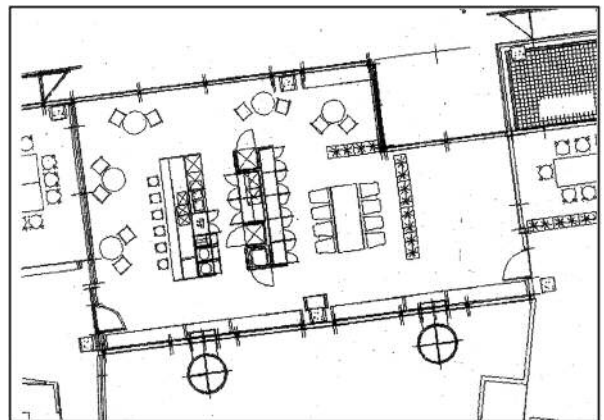


Figure 2 | Plan of the North-End Tea Point, level 6



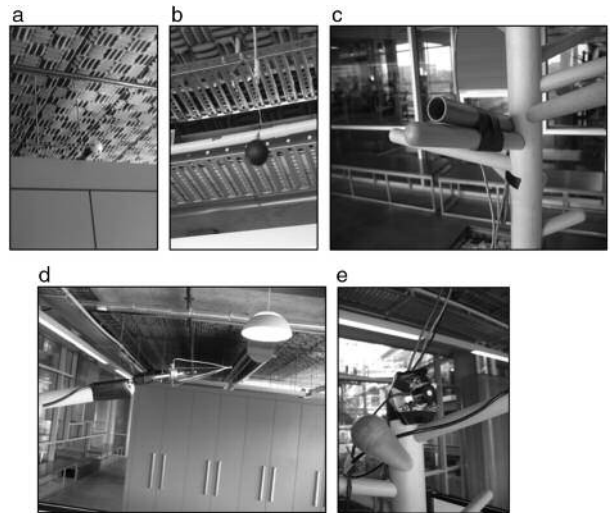
**Figure 3** | The control panel



**Figure 4** | Overview of the room and the instruments

## CASE STUDY 2: MACQUARIE UNIVERSITY COMMERCE BUILDING, SYDNEY

Macquarie University's (MQ) North Ryde campus is located within the Sydney metropolitan region. Commissioned in 2006, the Commerce building is a seven-storey office building occupied by academic and administrative staff. Consisting of MM cellular offices with operable windows along north and south perimeter zones separated by AC central open-plan office space, the entire façade is built on a louvre system featuring external solar shading over the northern windows. Figure 6 below shows the typical layout of the buildings floor plan. Automated high and low external louvres provide NV to each floor, with adjustable internal grilles to control airflow, supplemented by user-operable windows. Indoor temperature and outdoor weather sensors prompt the Building Management System (BMS) to switch into AC mode whenever a peak temperature greater than 25°C is sensed in any zone. During AC mode,



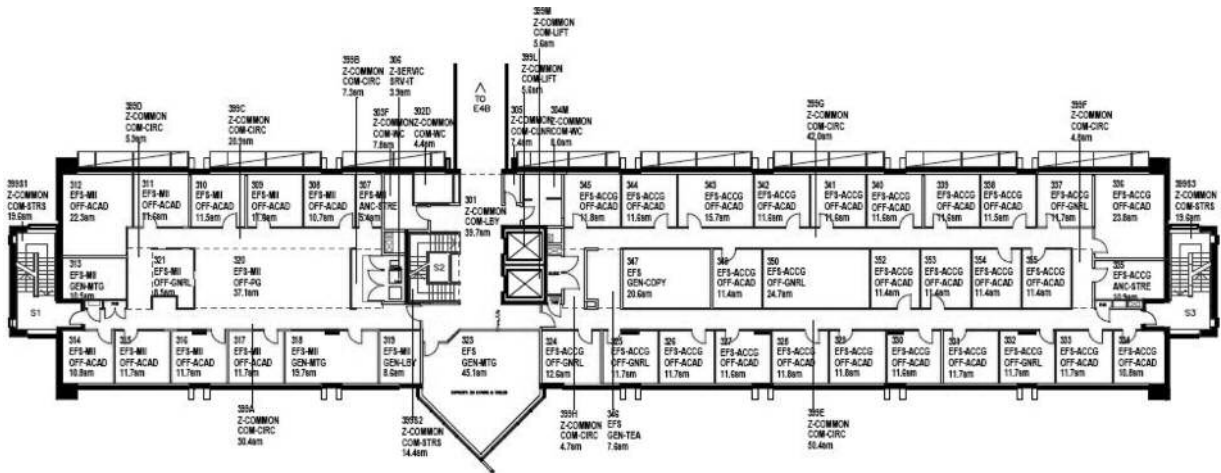
**Figure 5** | (a) Hygrometer (RH), (b) mean radiant temperature, (c) thermistor (temperature), (d) hot wire anemometer (wind speed) and (e) pyranometer (radiation)

internal temperatures are maintained at 24°C ( $\pm 1.5^\circ\text{C}$ ) as defined in the building's algorithm. BMS switch-over to NV is conditional when external meteorological conditions and the indoor thermal climate fall into an acceptable zone for the occupants. Figures 7a and 7b show the northern and southern façades of Commerce building.

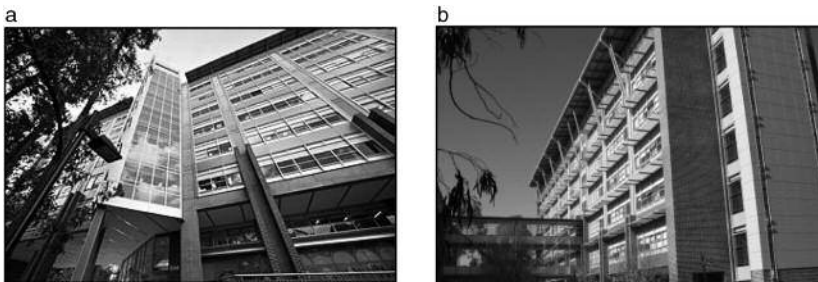
Dataloggers randomly located throughout the building record air temperature and RH at 5-min intervals throughout the study. Outdoor weather conditions were collected from a nearby automatic weather station, and BMS data were collected from the University's Office of Facilities Management. Field studies used mobile observations to supplement continuous monitoring of occupant workplaces, using the thermal comfort 'sputnik' system (Figure 8). These provided detailed thermal comfort measurements for air temperature, mean radiant temperature, RH and air speed at a height of 0.6m within each occupied zone. Standardized comfort questionnaires were used to record occupant perceptions of thermal comfort within their workspace, including standardized clothing garment and metabolic activity checklists allowing the calculation of various comfort indices, for example, PMV, effective temperature (ET\*) and standard effective temperature (SET\*) (ASHRAE, 2004). Statistical analyses were performed using Minitab statistical software.

## PRELIMINARY RESULTS, CASE STUDY 1

The survey was conducted on 29th April 2009 between 10:30 am and 3 pm. The people counters established an average of 200 entries per day, with 100 occurring between morning tea and lunchtime. Most people entered the room at least twice per day, which means that only 66



**Figure 6** | Commerce building typical floor plan



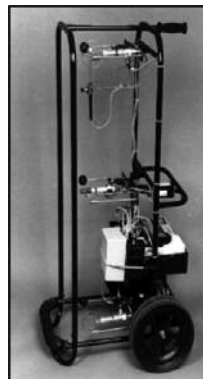
**Figure 7** | (a) Commerce building, North façade and (b) commerce building, South façade

people (33%) were in the room at the time of surveying. Thirty people volunteered to answer the survey, a response rate of just below half. The average age of respondents was 33 years with 43% females and 56% males. The majority of people surveyed, 73%, have been working at NAB for more than one year and 97% of them worked previously in an AC office mainly in Melbourne.

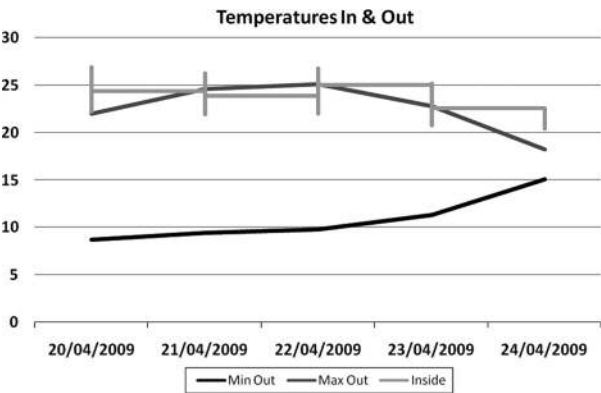
Throughout April, outdoor temperatures ranged between a minimum of 7°C and a maximum of 32°C. During the week of observations, from 20th to 24th April, the average outdoor temperature was 16°C, quite typical for autumn in Melbourne as temperatures were often in the mid-20s (Figure 9). Internal temperatures during this same period ranged between 23 and 25°C.

As seen in Figure 10, workers declared on average that they were neutral to slightly cool (4.34). However, for all of them the thermal environment was acceptable and for 87% there was no need for change even if 13% would have liked the room to be warmer. Furthermore, 70% declared that there was no need for any change in the air movement but 26% would have liked more air movement. However, 94% did not open the window during the day of the survey.

When people were asked how the temperature was at that particular moment, 70% answered that it was ok and 23% that it was perfect. The majority of people surveyed declared they did not adjust their clothing level 15min prior to answering the survey. Only 13% stated they did. Most subjects wore



**Figure 8** | 'Sputnik' thermal comfort system used for the Sydney MM field study

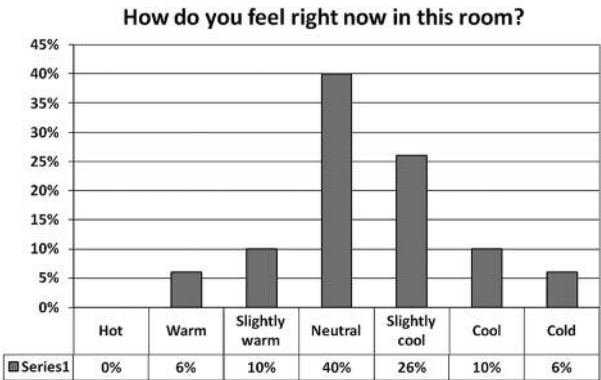


**Figure 9** | Outside temperature maximum and minimum and inside temperature

similar clothing ensembles; 60% wore pants/skirt, shirt, socks/pantyhose and shoes. The addition of a vest/cardigan was declared by 40% of respondents.

When asked to describe the room, half of the respondents indicated that the room was full of light, while nearly a quarter stated that the room was full of fresh air and a good place to work. Interestingly, 33% of the answers pointed out that the room was warmer than the rest of the office, while 16% of the answers indicated that it was cooler than the rest of the office. The predominant activity conducted in the space is simply having a break or getting away from the work desk. In all, 10% of respondents indicated that they were there to enjoy the view. Use of the kitchen facilities is also significant, with many respondents having lunch or coffee.

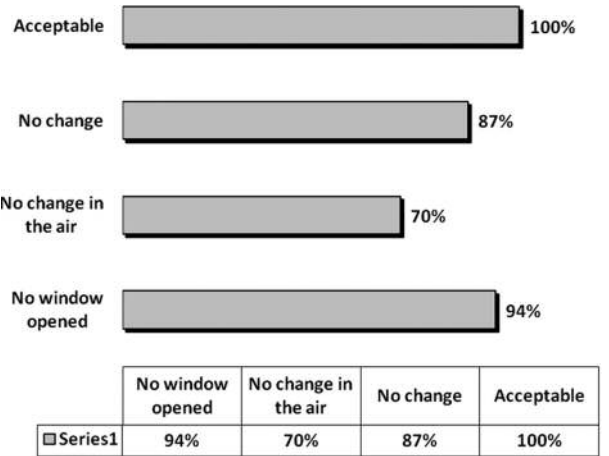
When asked about the qualities of the space, the view was the most frequent response, followed closely by the fact that the room was simply an alternative to their usual workstation. One third of respondents indicated that they liked the fresh air, while nearly a quarter appreciated the social aspect of meeting other workers. Several indicated that the space



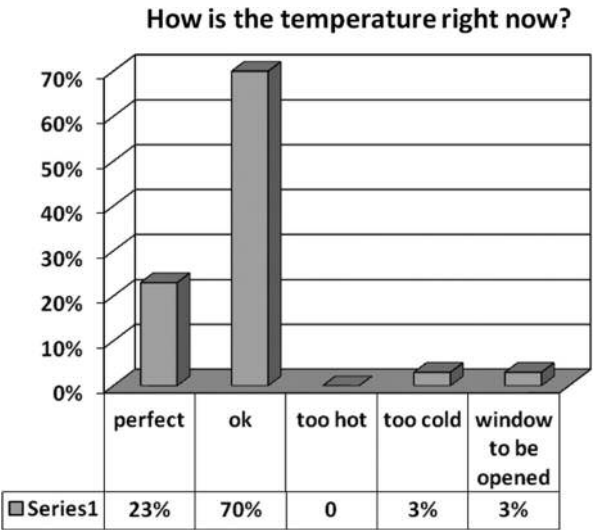
**Figure 10** | Likert scale analysis

provided a place where they could feel more relaxed, either with or without bringing work. Interestingly, 10% of respondents considered the space warmer than the rest of the office, while the same number considered the space cooler. This is above what would be expected of a normal PMV–PPD response, possibly indicating responses to the different mix of air and mean radiant temperature (Figures 11–15).

The benefits of the MM system in this space are difficult to separate from other qualities of the space: the view, the kitchen facilities, the social aspect, the chance to relax somewhere away from the pressures of work at the desk. However, since many respondents regarded the room as being slightly warmer or slightly cooler than at their desk indicates that the variation from desk temperatures is



**Figure 11** | Response rates



**Figure 12** | Response rates

### Right now this room is...?



Figure 13 | Response rates

### What I like when I am here

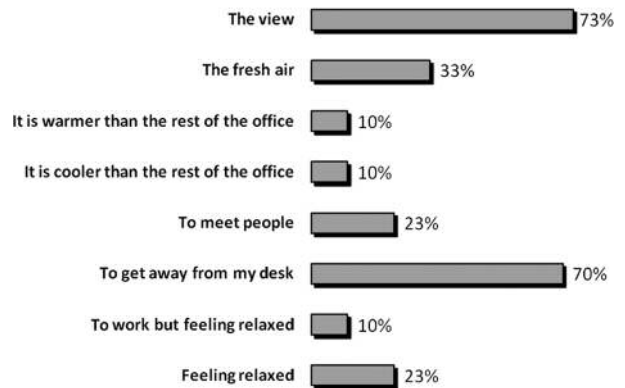


Figure 15 | Response rates

### What am I doing here...?



Figure 14 | Response rates

important, giving workers a break from the constant conditions of AC, and possibly encountering a different mix of air and mean radiant temperatures. That many respondents regarded the air as being 'fresh' indicates a perception of qualitative difference in the nature of air being breathed, whether due to its temperature, humidity, air speed, oxygen content or other (e.g. odours). What may be significant here is the opportunity to enjoy indoor air quality conditions that are different from those encountered at the workstation.

## PRELIMINARY RESULTS, CASE STUDY 2

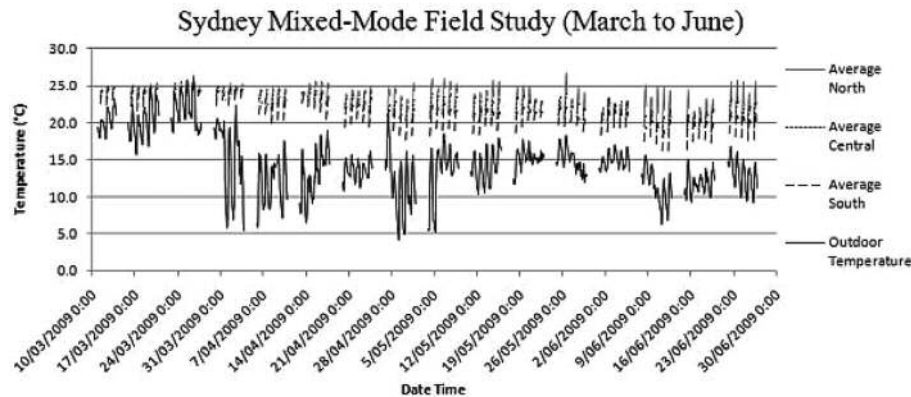
Figure 16 shows daily outdoor temperatures recorded during this period plotted against internal temperatures measured

from the HOBO dataloggers and averaged across each zone. Between March and June there was a steady decline in outdoor temperatures as the study shifted from autumn into the winter months, and each zone mirrors these changes (typical for an NV building). Based on one-way ANOVA statistical analyses, the average outdoor temperature of 14.7°C was significantly cooler ( $p = 0.000$ ) than average temperatures for the North (22.6°C), Central (22.4°C) and South (20.9°C) zones. As expected, the North façade experienced significantly warmer temperatures than Central and South zones, whereas temperatures in the South zone were significantly less than in Central offices. The variability of these temperatures is also worth noting. The Central zone experienced less variability than the perimeter due to constant AC throughout these zones. In contrast, the variability in northern offices was greater than in the southern zone. These temperature ranges are due to the use of HVAC when temperatures rise towards the 25°C cooling set-point and drop towards the 18°C heating set-point, which explains why temperatures rarely exceed these extremes. The northern façade is also susceptible to high solar heat gains from office windows, suggesting the blips present in the data.

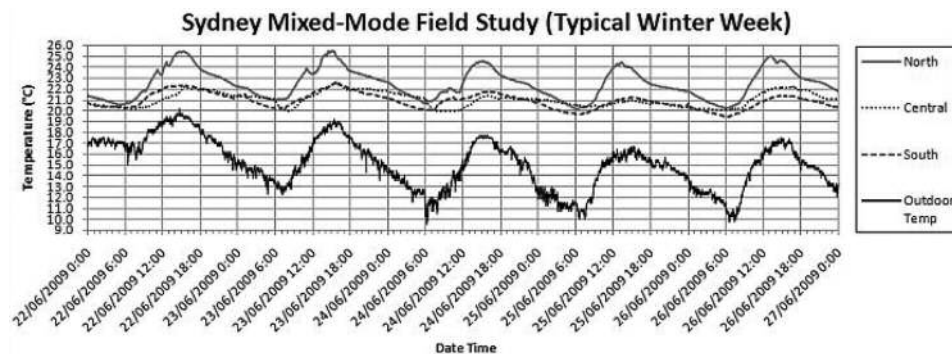
In order to show what happens to indoor temperatures during AC to NV switch-over, a typical week in the study period was chosen (as shown in Figure 17). During NV mode, temperatures are allowed to rise towards the 25°C cooling set-point at which time AC mode turns on, automatically shutting the windows, and stabilizes the internal temperatures to around 24°C ( $\pm 1.5^\circ\text{C}$ ). These events are present in Figure 17 when the temperatures peak at 25°C during the middle of the day.

Over 100 questionnaires have been conducted with representative samples of both genders (37 males and 63 females) for Sydney's field study. Clothing insulation (clo) values were recorded using a standardized checklist of typical office clothing items (ASHRAE, 2004). The





**Figure 16** | Internal temperatures for the Sydney field study (weekdays between March and June 2009)



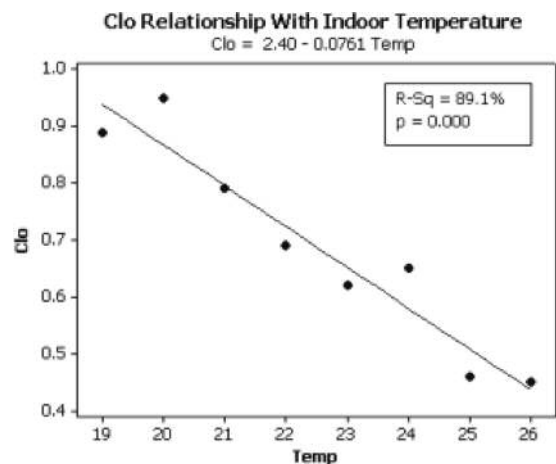
**Figure 17** | Internal temperatures for the Sydney study showing effects of AC to NV switch-over

average clo value for females (0.78) was significantly higher than for males (0.62,  $p = 0.002$ ). Clo values were also plotted against outdoor and indoor temperatures for any significant relationships. These data were binned into degrees and thus analysed using weighted linear regressions. The clo relationship with outdoor temperatures was non-significant ( $p > 0.05$ ); however, Figure 18 illustrates a significant negative clo relationship with indoor temperatures ( $p = 0.000$ ). With  $R^2 = 89.1\%$ , this suggests that indoor temperatures have a strong influence on the amount of clothing insulation worn by the building occupants. As indoor temperatures increase, occupants will remove items of clothing.

## MM FIELD STUDY

On the basis of AC/NV mode at the time of the questionnaire, it was possible to compare responses during each mode of operation, that is, AC and NV modes. Table 1 highlights some of the key study variables being investigated throughout this study. The only significant difference found was actual mean vote (AMV), wherein participants

rated their level of comfort across a seven-point Likert scale (ranging from cold (−3) through neutral (0) to hot (+3)). Within AC mode, the average AMV was neutral



**Figure 18** | Clothing insulation relationship against indoor temperature for Sydney

**Table 1** | Comfort data summaries for Sydney MM field study

Study variable	AC mode (n = 81)	NV mode (n = 25)	Significance
AMV	-0.02	0.80	$p = 0.01$
Acceptability	1.75	1.73	$p > 0.05$
Preference	2.16	1.73	$p = 0.02$
Clo	0.73	0.68	$p > 0.05$
Productivity	-0.5%	0%	$p > 0.05$
PMV	-0.25	0.19	$p > 0.05$
Temperature	21.9	24.0	$p = 0.03$

(-0.02), which is significantly cooler ( $p = 0.01$ ) than the average AMV during NV mode (0.80). This suggests that most people found the building to be slightly warmer during NV mode compared to AC mode, possibly due to the increased indoor temperatures needed for the NV algorithm to start. Other variables did not achieve any significant levels of difference. Thermal preference was significantly different. People did not want the thermal environment changed during AC mode (2.16), whereas during NV mode occupants preferred to be cooler (1.73). Temperatures were significantly different: this can be verified by Figure 17, which demonstrates that when the building is in NV mode, indoor temperatures will rise until the 25°C cooling set-point.

## DISCUSSION

As shown in Figures 16 and 17, internal temperatures are clipped at 25°C as this is the peak temperature zones can experience before the BMS switches into AC mode. Before this transition, office spaces will gradually increase in temperature due to increased solar loads, particularly in the North zone, which experiences significantly warmer temperatures than both the Central and South zones. Up till this point, occupant comfort is said to be neutral, as judging from the summary data present in Table 1. However, what is not clear is what happens when the building activates the HVAC system. Currently, the building's MM ventilation algorithm, upon a temperature greater than 25°C, has been sensed; the AC system will lower and maintain temperatures around 24°C ( $\pm 1.5^\circ\text{C}$  depending on concurrent outdoor weather). As can be illustrated in Figure 17, there is a lag effect after an AC mode switch-over event. This may be due to inconsistencies depending on the position of the BMS sensors, but overall it takes 30min to reach optimal temperature. Comfort votes taken before and after these periods propose that occupants tend to feel warmer leading up to AC mode operation as internal temperatures are allowed to rise towards the 25°C set-point.

Correspondingly, as highlighted in Table 1, the average AMV when the building was in NV mode is slightly warmer than neutral (1.17).

When the building switches into AC mode, internal temperatures are maintained at around 24°C. In contrast, the average AMV while AC mode was in operation was neutral (0.00), which suggests that occupants preferred these conditions (Rowe, 2004; Brager and Baker, 2008). However, while PMV values during both these modes do not suggest any significant differences (both -0.25 and 0.19 are within the limits of a neutral vote), more conclusive evidence is needed to define occupant perceptions of the thermal environment while the building switches between AC and NV mode. A meaningful analysis would be to investigate any differences in clo values through both operation modes. The Sydney field study relies heavily on the temporal effects of thermal comfort, especially as this building is capable of switching between modes various times during a day. While the majority of the data presented here were collected in typical winter months, that is, Figure 16 shows that outdoor temperatures rarely rose above 20°C between April and June, what can be expected during summer months occurred during March in Figure 17, in which high outdoor temperatures, often above 20°C, will force the building into AC mode as internal temperatures during these periods exceed the building's NV limits.

Not only do indoor environments influence clothing choices, but so too does the outdoor weather (Morgan and de Dear, 2003; De Carli *et al.*, 2007). For NV buildings, occupants tend to change their clothing according to external conditions as the building more closely matches the prevailing outdoor temperatures. However, as Figure 18 demonstrates, occupant clo values are only moderately related to indoor temperatures and not outdoor conditions. Perhaps there is a difference in these relationships when the building is in AC mode and when it is in NV mode. As yet, there are not enough conclusive data to suggest these correlations, but this may be highlighted later on in the study.

## CONCLUSION

The two case studies presented here adopt different approaches to MM ventilation, with the NAB building offering MM ventilation in a break-out area adjacent to workspaces, and the Commerce building using MM ventilation within workspaces. While these two approaches have necessitated slightly different methodologies for evaluating thermal comfort, it is clear that there are benefits in each of these approaches over a traditional AC system. Of particular interest are the points of change from one mode to another, either spatially, as with the NAB building, or temporally, as with the Commerce building. Comparison between the different comfort conditions in each case study will form a future component of this project, but for now what is evident is that steady-state models are inadequate for

describing thermal comfort conditions in MM buildings, and that new temporal and spatial models need to be developed.

extend our appreciation to all participants who have given their time to complete surveys and questionnaires.

## ACKNOWLEDGEMENTS

The project has been funded by an ARC (Australian Research Council) Discovery Grant. We are grateful to Kerry Russell and Macquarie University's Office of Facilities Management (OFM) and to Angelina Andonovski and John Hurren at NAB Docklands for their support and assistance in gathering data for these projects. We would like to

## NOTE

- 1 Mixed-mode refers to a hybrid approach to space conditioning using a combination of NV from operable windows, manually or automatically controlled, and mechanical systems, that is, air distribution and refrigeration equipment for cooling. The NAB is the only one in Australia with this particular system (CBE, 2005).

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## **Appendix O: Indoor Air 2011 Conference Paper**

Deuble, M. and de Dear, R. (2011) 'Mixed-mode buildings: A double standard in comfort',  
*Proceedings of Indoor Air 2011 Conference*, Austin, TX, USA, 5-10 June 2011

# Mixed-Mode Buildings: A Double Standard in Comfort

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## SUMMARY

This paper investigates how mixed-mode (MM) ventilation affects occupant comfort by presenting results from a longitudinal field study within an office building located in sub-tropical Sydney, Australia. The building automatically switches into air-conditioned (AC) mode whenever indoor temperatures exceed 25°C. Coincident indoor and outdoor climate measurements along with 1359 subjective comfort questionnaires were collected. Thermal sensations during natural ventilation were, on average, 2.1°C warmer than those predicted using Fanger's PMV-PPD (Fanger 1970). Differences in thermal perception were also apparent between these two modes. Within AC mode, a +1 PMV environment elicited much 'warmer-than-neutral' thermal sensations than the same environment within naturally-ventilated (NV) mode, suggesting thermal perceptions were affected by the building's mode of operation over and above the indoor climatic conditions. These discrepancies emphasize the complexity of thermal perception and the inadequacy of using PMV models to describe occupant comfort in MM buildings.

## IMPLICATIONS

ASHRAE's Standard 55 (2010) classifies MM buildings as AC buildings, and as such, limits the operation of these buildings to the more restrictive PMV-PPD range of indoor thermal conditions. EN 15251 (CEN 2007) however, allows the more flexible adaptive comfort standard to be applied to buildings operating under NV mode. Results from this study favor EN15251's application of the adaptive comfort model instead of PMV-PPD to MM buildings when they are operating in NV mode.

## KEYWORDS

*Thermal comfort, mixed-mode ventilation, comfort standards*

## INTRODUCTION

The basic concept of mixed-mode (MM) or 'hybrid' ventilation is to maintain satisfactory indoor environments by alternating between and combining natural and mechanical systems. Utilizing a naturally-ventilated (NV) or 'free-running' mode providing good air quality and thermal comfort, these buildings will revert to mechanical systems for heating, ventilation and air-conditioning (HVAC) whenever external conditions make the NV option untenable for occupants (Brager 2006). Previous studies document the disparities between steady-state and adaptive comfort models in air-conditioned (AC) and NV buildings (Humphreys and Nicol 1998), highlighting the inadequacy of static models for describing thermal comfort in 'free-running' buildings (Nicol and Humphreys 2010). However, in a building that switches between AC and NV environments which comfort model should be applied?

## Comfort Standards

International comfort standards, e.g. ASHRAE Standard 55 (ASHRAE 2010) and EN 15251 (CEN 2007) provide guidelines produced from combinations of air temperature, thermal radiation, humidity, air speed, metabolic activity and clothing to ensure thermal environmental conditions that will be acceptable to 80% or more of the occupants within a space. Earlier versions cover

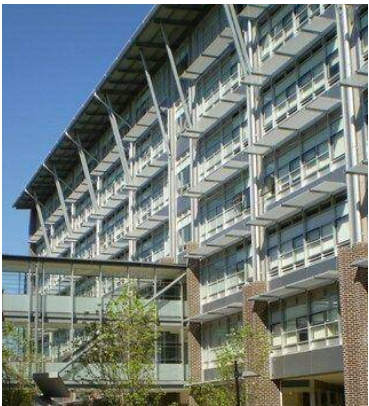


thermal comfort under steady-state conditions based on laboratory experiments; however more recent revisions have utilised global field study databases, e.g. ASHRAE and SCATS (Nicol and Humphreys 2010). Following detailed field studies from around the world, the 2004 edition of ASHRAE’s Standard 55 (2010) included an Adaptive Comfort Standard (ACS) as an alternative to the Predicted Mean Vote (PMV)-based method for free-running, i.e. NV buildings (de Dear and Brager 2002; Nicol and Humphreys 2002). At the time of ASHRAE 55-2004 going to press, insufficient studies undertaken in MM buildings meant they were excluded from the scope of the ACS (de Dear and Brager 2002). ASHRAE clarifies that when mechanical cooling systems are provided for the space, as is the case for many MM buildings, the ACS is not applicable. Thus, the potential flexibility offered by the standard is not available to MM buildings, which may operate in a passive, NV mode preferentially, equipped with only supplemental cooling and heating for peak periods; or that control airflow using a building energy management system rather than occupant intervention; or to spaces where operable elements are not connected to the outdoors, must therefore resort to the more restrictive PMV-PPD method regardless of which mode they happen to be operating under (Turner 2008).

**METHODS**  
**Sydney’s Climate**

The Sydney metropolitan region, located on the eastern coast of Australia (34°S, 151°E), is often characterised by a moderately temperate climate. Influenced from complex elevated topography surrounding the region to the north, west and south, and due to close proximity to the Tasman Sea to the east, Sydney avoids the high temperatures commonly associated with more inland regions as well as the high humidity of tropical coastal areas (Bureau of Meteorology 1991). Given the city’s very moderate yearly seasonal variations, Sydney’s climate is well suited to MM buildings.

**Case Study Building**

Macquarie University's (MQ) North Ryde campus is located within the Sydney metropolitan region. Commissioned in 2006, the Commerce building (pictured below) is a 7-storey office building occupied by academic and administrative staff from the Faculty of Business and Economics. Figure 1 below depicts the north and south perimeter zones consist of MM cellular offices with operable windows separated by a central open-plan office zone with full-time AC. Automated high and low external louvres provide natural ventilation to each floor, with adjustable internal grilles to control airflow, supplemented by user-operable windows with additional solar shading features over the northern (sun-facing) windows (Photos 1 and 2). Indoor temperature and outdoor weather sensors prompt the Building Management System (BMS) to switch into AC mode whenever a temperature greater than 25°C is sensed within any zone. During AC mode, internal temperatures are maintained at 24°C (±1.5°C) as defined in the building’s algorithm. BMS switch-over to NV is conditional when external meteorological conditions and the indoor thermal climate fall into an acceptable zone for the occupants. As shown in Photo 3, panels located at the entrance of each corridor indicate the current operation of each zone.

		
<p>Photo 1. MQ, Commerce building (North/sunny facade)</p>	<p>Photo 2. MQ, Commerce building (South facade)</p>	<p>Photo 3. AC Control Panel</p>



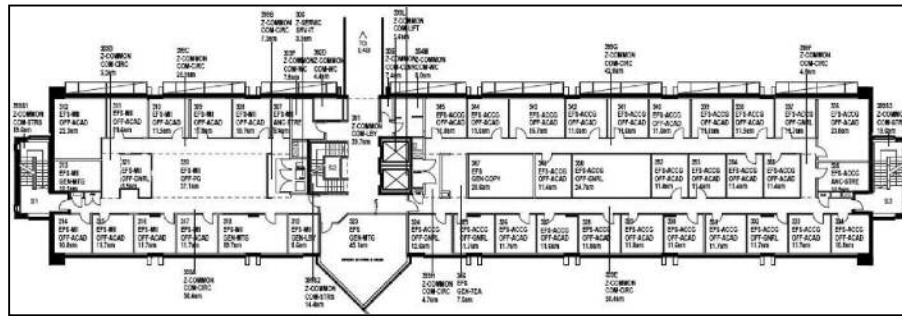


Figure 1. MQ, Commerce building, typical floor plan

## Data Collection and Analysis

Dataloggers were randomly located throughout the building to record air temperature, globe temperature and relative humidity at 5 minute intervals throughout the study (March 2009 to April 2010). Loggers were placed within 1 m of the occupants' workstation to characterise the immediate thermal environment experienced by the occupant under normal working conditions. Outdoor weather observations were obtained from the University's nearby automatic weather station, with AC/NV mode operations and indoor temperatures collected from the University's Office of Facilities Management. During the study comfort questionnaires were used to record occupant perceptions of thermal comfort within their workplace on a 'right-here-right-now' basis, which included standardized clothing garment (clo) and metabolic activity checklists. Air velocity measurements were taken using a handheld anemometer during each survey to enable the calculation of various comfort indices, including PMV, PPD, ET\* and SET\* (ASHRAE 2010).

## RESULTS

Throughout this study, a total of 1359 comfort questionnaires were administered during University occupied office hours, with representative coverage of both genders (643 males and 716 females). At the time of each survey, the operational mode of each respective occupant's zone was noted, i.e. AC or NV mode. The North and South perimeter offices switch between both AC and NV modes and the Central core is provided with constant air conditioning. Therefore, the Central zone has not been included in the following analyses because it does not operate under mixed-modes.

## Thermal Environment

Operative temperatures calculated from the dataloggers reveal the range of temperatures occupants experienced within the building. As shown in Figure 2 below, the building's algorithm works well to maintain indoor temperatures within a comfortable 5°C band (20°C to 25°C). Deviations from these limits may be due to increased solar heat gains on the north façade. Figure 2 also illustrates the range of thermal sensations (labeled as Actual Mean Vote (AMV)) wherein participants rated their level of comfort across a 7-point Likert Scale (ranging from Cold (-3) through Neutral (0) to Hot (+3)).

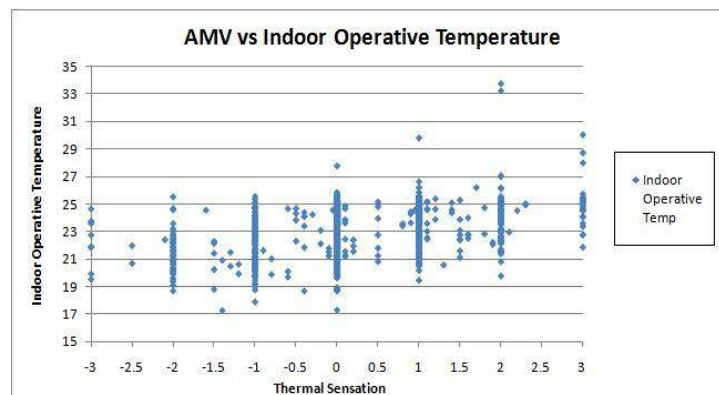


Figure 2. Relationship between Actual Mean Vote (AMV) against indoor operative temperature

Table 1 below summarizes the key comfort parameters. Two sample t-tests were performed to find any significant differences between each mode. During both modes, average AMV remained unchanged (0.4) however, average clo values reported within NV mode (0.50) were significantly lower than those recorded during AC mode (0.57,  $p = 0.000$ ) suggesting most people found the building to be slightly warmer during periods of natural ventilation possibly due to the increased indoor temperatures needed for the BMS algorithm to switch into AC mode. In contrast, PMV values were significantly lower during NV mode (-0.32) compared to those in AC mode (-0.15,  $p = 0.000$ ). Air velocities during NV mode were slightly higher (0.10m/s) than those recorded during AC mode (0.08m/s) likely due to occupants using their windows and increased air flow from the external louvres. All other variables, such as operative temperature, relative humidity and metabolic rate were not significantly different between the building's two modes of operation.

Table 1. Summary of study variables for AC and NV modes

Variable	AC Mode (n = 804)	NV Mode (n = 294)	Significance
Operative temperature	23.2°C	23.1°C	$p > 0.05$
Relative humidity	53%	52%	$p > 0.05$
Air velocity	0.08m/s	0.1m/s	$p = 0.008$
Clothing insulation	0.57	0.5	$p = 0.000$
Metabolic rate	1.2	1.2	$p > 0.05$
AMV	0.4	0.4	$p > 0.05$
PMV	-0.15	-0.32	$p = 0.000$

### Adaptive versus PMV-PPD Models

Separate statistical analyses were performed for each mode to investigate how comfort was affected in a building that switches from AC to NV conditions and vice versa. The graph in Figure 3 presents weighted linear regressions of both observed thermal sensation votes (AMV) and those predicted using Fanger's PMV (1970). There are strong positive relationships for both AMV ( $R^2 = 95\%$ ) and PMV ( $R^2 = 97\%$ ) responses against the indoor operative temperature, both yielding significant correlations ( $p = 0.000$ ). AMV and PMV responses were then separated according to mode to investigate any effects between each mode. The graphs in Figures 4 and 5 present the results for AC mode and NV mode respectively. All correlations against the indoor operative temperature were found to be significant ( $p < 0.05$ ) showing strong positive relationships.

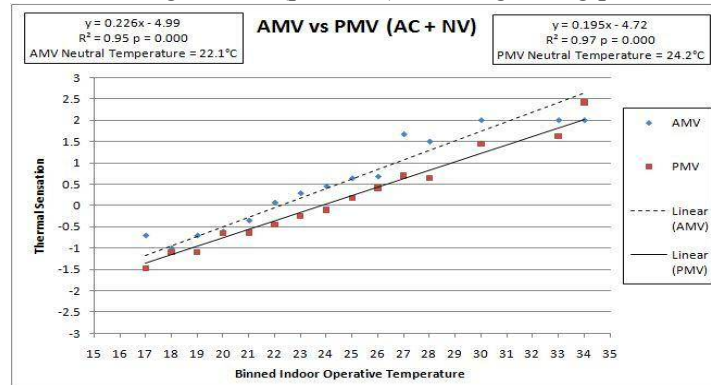


Figure 3. Observed and predicted comfort votes against indoor operative temperature

There is a clear difference among the relationships between thermal sensation and operative temperature during NV mode. As illustrated in Figure 5, the PMV model fails to predict thermal comfort whilst the building is in NV mode. Whilst eliciting strong correlations for AMV ( $R^2 = 76\%$ ,  $p = 0.003$ ) and PMV ( $R^2 = 91\%$ ,  $p = 0.000$ ) responses, the gentle gradient for observed AMV values suggests occupants were able to adapt across a fairly broad range of indoor operative temperatures but their thermal sensations seem to be permanently displaced into the 'slightly warm' region.



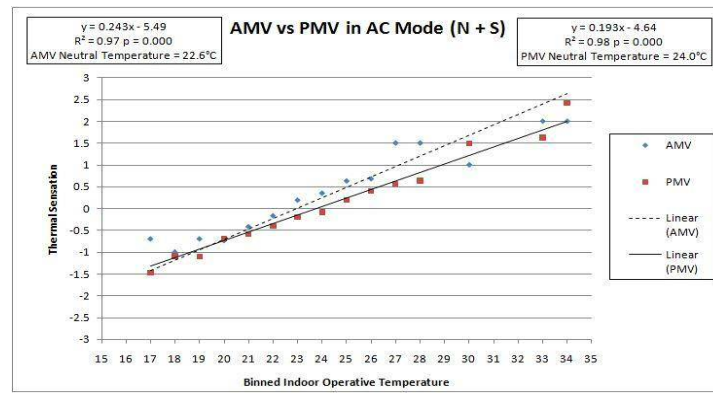


Figure 4. Observed and predicted comfort votes against indoor operative temperature for AC mode.

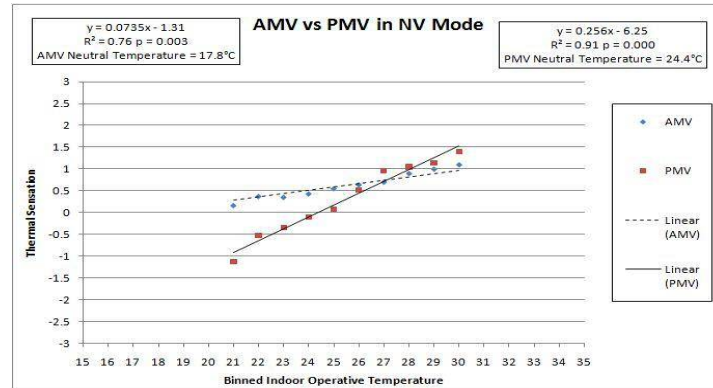


Figure 5. Observed and predicted comfort votes against indoor operative temperature for NV mode

## DISCUSSIONS

The MM building operates as a passive NV building between the indoor operative temperatures of 20–25°C. Demonstrated in Figure 2, the BMS algorithm ensures comfortable conditions between these extremes, with internal temperatures rarely rising above 25°C (some exceptions due to excessive solar heat gains on the north). If a temperature above 25°C is sensed by the building's BMS sensors in any particular zone, air conditioning switches on for that zone, trimming indoor temperatures back towards the 24°C set point ( $\pm 0.5^\circ\text{C}$ ). This is reflected in Table 1, suggesting occupants tend to feel slightly warmer leading up to an NV-AC mode switch-over event.

Figures 3 to 5 present the key findings of this research, showing fundamental differences between the observed thermal sensation votes (AMV) and those predicted using Fanger's PMV-PPD model (PMV). Figure 3 highlights the different neutral temperatures calculated from each model. On average, AMV responses were 2.1°C warmer than the PMV predictions. Both the observed and predicted thermal sensation votes show very strong correlations with the indoor operative temperature during AC mode (as shown in Figure 4, PMV:  $R^2 = 98\%$ ,  $p = 0.000$ ; AMV:  $R^2 = 97\%$ ,  $p = 0.000$ ). Both models successfully describe occupant comfort within this mode. Figures 4 and 5 highlight differences in thermal perception were also apparent between these two modes. During AC mode of operation, a +1 PMV (*slightly warm*) environment elicited significantly warmer-than-neutral thermal sensations than the same thermal environmental conditions under NV mode, suggesting thermal perceptions were affected by the building's mode of operation over-and-above any differences in actual thermal environmental conditions. It is likely that the ratio of outdoor ventilation to air velocity would be greater under NV mode than in AC mode, so it is possible that improved thermal comfort under NV mode resulted from cross-modal interactions between air quality and thermal comfort. Whilst previous studies reflect building-by-building comfort temperatures, such as de Dear and Brager (2002) and Nicol and Humphreys (2002), Figures 4 and 5 clearly show the adaptive model is best suited to explain occupant comfort during times of natural ventilation within the same building. When operating in AC mode, Fanger's PMV-PPD model shows good correlations with observed thermal sensations.

Current standards establish the ACS as an alternative to PMV-PPD for NV buildings. The ACS, as defined in ASHRAE Standard 55 (2010) and EN 15251 (2007), was based on the works of de Dear and Brager (2002) and Nicol and Humphreys (2002). Ongoing debates suggest the ACS should be applied as an operating guideline for the NV mode of MM buildings. Figures 4 and 5 clearly show that interior temperatures can be allowed to float within the more energy-efficient acceptability limits of the ACS. When temperatures reach the maximum limits then HVAC systems can be turned on in a limited way to ensure temperatures stay within the ACS limits (rather than switching to the narrow set points of a centrally-controlled AC building).

## CONCLUSIONS

If a building is AC, then it typically doesn't have operable windows. According to ASHRAE Standard 55 (2010) if a building is NV, then it doesn't have any mechanical cooling/heating systems, but typically has operable windows. These black-and-white definitions express the current view embodied in international comfort standards; however, the real world is not so simple. Current standards misclassify MM buildings as AC and in doing so, fail to maximise the energy saving potential of MM buildings. This paper provides evidence that MM buildings could in fact be defined as NV, with operable windows and supplemental cooling/heating during peak periods. Whilst this study represents one particular MM building at MQ, these findings provide an insight as to how MM buildings should be categorised in future comfort standards. However, more studies are needed to determine whether a new MM comfort standard should be established.

## ACKNOWLEDGEMENTS

This project was funded in part by an Australian Research Council Discovery Grant (DP0880968). We are enormously grateful to Kerry Russell and Macquarie University's Office of Facilities Management for assistance in gathering data. We would like to express our appreciation to all the participants who gave their time to respond to our questionnaires.

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## **Appendix P: Is It Hot In Here Or Is It Just Me? Validating the Post-Occupancy Evaluation Journal Submission Email**

**Status:** Submitted May 2012; Deuble, M.P and de Dear, R.J. (2012) ‘Is it hot in here or is it just me? Validating the post-occupancy evaluation’, *Intelligent Buildings International*

**Journal Impact Factor:** Not applicable – new journal (started in 2009)

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## Intelligent Buildings International - Manuscript ID 12-IB046-RA.R1

1 message

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**sirinath.jamieson@live.co.uk** <sirinath.jamieson@live.co.uk>

Mon, Feb 11, 2013 at 2:17  
PM

To: max.deuble@students.mq.edu.au

10-Feb-2013

Dear Mr. Deuble:

The revised version of your manuscript entitled "Is It Hot In Here Or Is It Just Me? Validating the Post-Occupancy Evaluation" has been successfully submitted online and is presently being given full consideration for publication in Intelligent Buildings International .

Your manuscript ID is 12-IB046-RA.R1.

Please mention the above manuscript ID in all future correspondence or when calling the office for questions. If there are any changes in your street address or e-mail address, please log in to ScholarOne Manuscripts at <http://mc.manuscriptcentral.com/inbi> and edit your user information as appropriate.

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Sincerely,  
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1 message

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**d.j.clements-croome@reading.ac.uk** <d.j.clements-croome@reading.ac.uk>  
To: max.deuble@students.mq.edu.au

Fri, May 11, 2012 at 4:19 PM

11-May-2012

Dear Mr. Deuble:

Your manuscript entitled "Is It Hot In Here Or Is It Just Me? Validating the Post-Occupancy Evaluation" has been successfully submitted online and is presently being given full consideration for publication in the journal, Intelligent Buildings International .

Your manuscript ID is 12-IB046-RA.

The email address for questions regarding your submission is [inbi@earthscan.c.o.uk](mailto:inbi@earthscan.c.o.uk). Please make sure that you mention the above manuscript ID in all future correspondence. If there are any changes in your street address or e-mail address, please log in to e-submission site at <http://mc.manuscriptcentral.com/inbi> and edit your user information as appropriate.

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## Fwd: Intelligent Buildings International Special POE Issue Call For Papers

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Ying Hua <yh294@cornell.edu>

Fri, May 11, 2012 at 1:12 PM

To: MAX DEUBLE <max.deuble@students.mq.edu.au>

Cc: "Derek J. Croome" <d.j.clements-croome@reading.ac.uk>

Dear Max:

I'd like to invite you to develop your abstract, titled "Is It Hot In Here Or Is It Just Me? Validating the Post-Occupancy Evaluation", into a full paper.

Here are some important requirements for the full paper development and submission:

1. Go to the Journal website: <http://www.tandfonline.com/tibi> where you will find more details of the journal and instructions for authors.
2. Length of full paper: 3000-5000 words.
3. The papers will need to be submitted through the Journal's online submission system: <http://mc.manuscriptcentral.com/inbi>.
4. Your full paper is due by July 31st, 2012.
5. All papers will undergo a double-blind refereeing process. When submitting your paper, please declare 3 preferred reviewers (editors will decide whether to use these referees).

Feel free to contact me if you have questions.

Best  
Ying

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On Thu, Apr 26, 2012 at 4:48 AM, MAX DEUBLE

<max.deuble@students.mq.edu.au> wrote:

> Dear Ying Hua,

>

> I was wondering if its still possible to submit abstracts of papers for the upcoming special issue of Intelligent Buildings International on Post-Occupancy Evaluation? I am aware the due date was 20th April 2012 however I only just received the call for papers email. I have provided a copy of the abstract of my paper in this email just in case you allow it to be accepted. If my abstract can be accepted as a paper for this special issue please let me know, because this paper is ready to be submitted to another journal before knowledge of this special POE issue of Intelligent Buildings International.

>

> Paper Title: Is It Hot In Here Or Is It Just Me? Validating the Post-Occupancy Evaluation

> Authors: Max Deuble and Richard de Dear

> Abstract: Historically, post-occupancy evaluation (POE) was developed to evaluate actual building performance, providing feedback for architects and building managers to potentially improve the quality and operation of the building. Whilst useful in gathering information based on

user satisfaction, POE studies have typically lacked contextual information, continued feedback and physical measurements of the building's indoor climate. They therefore sometimes over-exaggerate poor building performance. POEs conducted in two academic office buildings: a mixed-mode (MM) and a naturally-ventilated (NV) building located within a university in Sydney Australia, suggest high levels of occupant dissatisfaction, especially in the MM building. In order to test the validity of the POE results, parallel thermal comfort studies were conducted to investigate the differences in occupant satisfaction and comfort perceptions between these two questionnaires. Instrumental measurements of each building's indoor environment reveal that occupants tended to over-exaggerate their POE comfort responses. Analysis of thermal satisfaction and acceptability in each building indicate that occupants of the NV building were more tolerant of their thermal environment despite experiencing significantly warmer temperatures than their MM counterparts. In discussing these results, along with participant comments and anecdotal evidence from each building, this paper contends that POE does not accurately evaluate building performance, suggesting occupants can and do use POE as a vehicle for complaint about general workplace issues, unrelated to their building. In providing a critical review of current POE methods, this paper aims to provide recommendations as to how they can be improved, encouraging a more holistic approach to building performance evaluation

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> Thanks,

> --Max

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