



Improving the thermal performance of the New South Wales Demountable Classroom
Ben Slee

Improving the thermal performance of the New South Wales demountable classroom

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A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

Faculty of Architecture, Design and Planning,
University of Sydney

Supported by a post-graduate research scholarship from Forest and Wood Products Australia

Declaration

I declare that this thesis is my own original work and has not been submitted in any form for another degree at any other university or institution of tertiary education. Information derived from published and unpublished work of others has been acknowledged in the text and a list of references attached.

A large black rectangular box redacting the signature of Ben Slee.

Ben Slee

2019

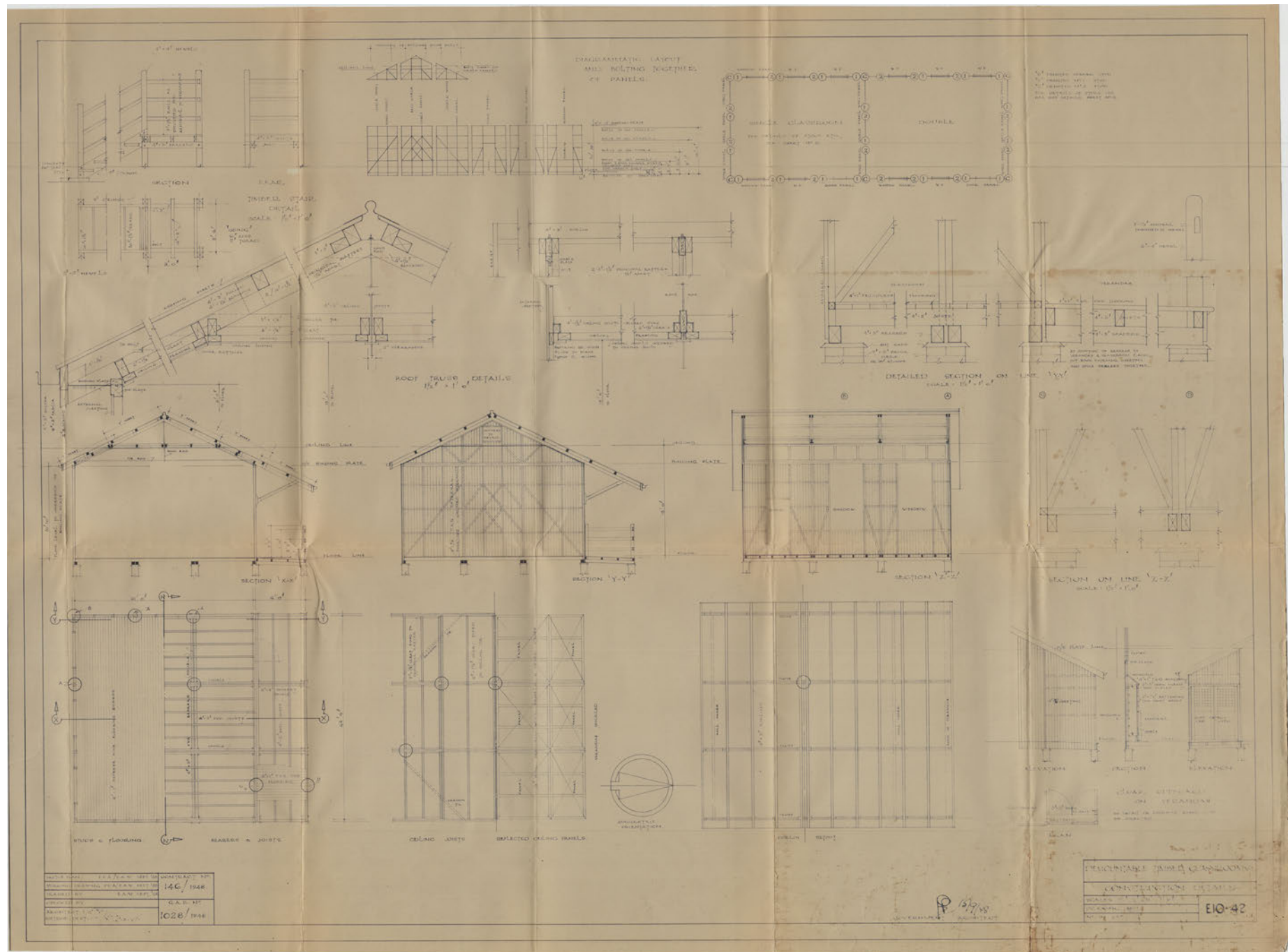
Ethics approval

These interviews were carried out in compliance with the University of Sydney ethics guidelines. Approval was granted by the Human Ethics Research Committee on the 12th of August 2014.

Human Ethics Research Committee approval project reference: 2014/544

The project was also carried out in compliance with the NSW Government Department for Education and Communities guidelines.

Project reference: SERAP 2014169



Original construction drawing for a timber "demountable classroom" dated 1948 by the New South Wales Government Architects Office (original given to the Author)

This thesis is dedicated to five people:

First to my Father, Colin, the Dean of Southwark, and to my Godmother and Aunt, Livy (Olivia), Chair of Anthropology at the London School of Economics. They lie buried next to each other at the east end of Southwark Cathedral. Neither would ever have imagined that I would embark on a PhD. I imagine them together in heaven, astonished, immensely proud, drinking plenty of fine red wine (or something stronger) and laughing an awful lot.

Second, and equally important, it is dedicated to my mother, Edith, whose constant, and often completely irrational, absolute belief in my ability to achieve things has been a source of continuous astonishment, occasionally frustration, but most importantly immense encouragement and support throughout my life, on each and every adventure, including this one.

Finally, but not least, it is for my daughter, Zoe, whose eternal happiness constantly reinvigorates me; and for Vanessa, my wife.

Improving the thermal performance of the New South Wales demountable classroom:

A design led research thesis

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NSW Demountable Classrooms. Photograph from the New South Wales Government Architects Office

The objective of the thesis is the development of socially, economically and environmentally viable proposals that will improve the thermal performance of the NSW Demountable Classroom and the thermal comfort of the people and communities who use them in any of the climates across the state.

The problem is significant because around 6000, or 12%, of all government classrooms in the state are Demountable Classrooms. The NSW Demountable Classroom was designed 50 years ago and was intended to, and continues to, provide the NSW government with a system of physical infrastructure that allows schools to expand and contract in response to population fluctuation as well as providing emergency accommodation at times of need in any of the diverse climates across NSW. However, they are commonly regarded as offering inferior “temporary” teaching spaces due, in particular, to the perception of their internal environmental quality.

The thesis understands buildings, including the NSW Demountable Classroom, as intrinsically complex systems that exist within other complex environmental, social and economic systems. Therefore there can be no single optimal solution to the challenges raised by function, climate or social context and therefore no simple route to find ‘the

solution’. This thesis adopts a research methodology that is integrative; which accepts implicitly that there is no single optimal answer or solution for a problem consisting of so many indeterminate and interrelated variables. The methodology understands the value of, and permits the integration of, sociological and scientific paradigms of thought, and what they can contribute to the search for solutions to complex problems.

The thesis has methodologically intersecting parts. By analysing existing documentary evidence, interviews and physical surveys, the first part of the thesis determines that central to the poor perception of these economically, socially and potentially environmentally efficient buildings is their poor thermal performance.

The thesis develops an overall strategy, and specific “Solution Sets”, for improving the thermal performance of the NSW Demountable Classrooms and the thermal comfort of those who use them. A computer simulation model is used to understand the performance of the existing classroom buildings in five climates representative of the diverse climates in NSW. The same model is used to evaluate the performance of the “Solution Sets”.

The thesis concludes that the NSW Government, in collaboration with local communities, can employ

simple strategies, identified in this thesis, to create high performance, adaptable and low carbon classroom buildings at a low cost. The analysis also suggests that by integrating the process of refurbishment into a constructivist pedagogy the entire school community can be engaged in, and learn, from the refurbishment process and continue to learn from the refurbished classrooms.

This is a very brief synopsis of the thesis intended to help communicate the purpose and findings of the project to specialists and non-specialists alike in an accessible and interesting format.

The NSW Demountable Classroom is a lightweight building and provides a useful example for exploring how lightweight construction can be improved so that it creates comfortable, low energy, 'high performance' buildings in a wide variety of climates.

There are 6000 demountable classrooms in NSW. That is 12% of all NSW government classrooms

'Demountables' are universally regarded as second rate.

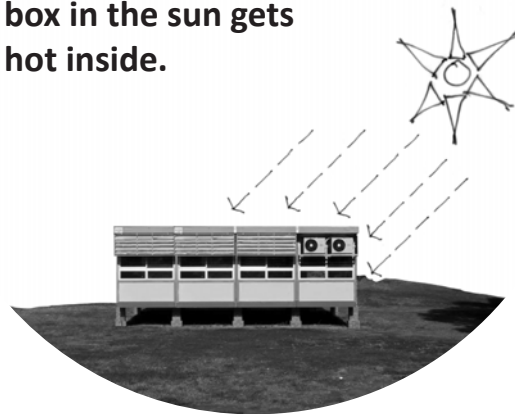
The 6000 NSW demountable classrooms represent an asset worth more than \$840

million based on the cost of replacing them with permanent classrooms.

But NSW Demountable Classrooms are able to move! And so they can be used multiple times to accommodate changing needs in schools across the state.



It is hardly a surprise that a tin box in the sun gets hot inside.



For thousands of years humans have built buildings to modify their local environment and make it more comfortable.

We live in a climate where outside is almost always comfortable.

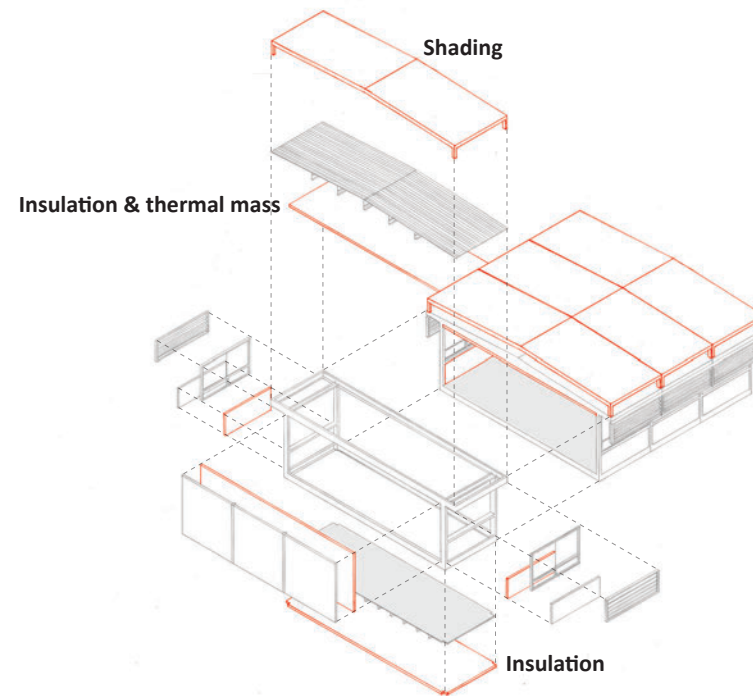
But now we build buildings that make the inside less comfortable than outside – and then attach a machine to the outside to fix that problem.

Why is it that it is often more comfortable, more productive, to teach under that tree than inside that classroom?

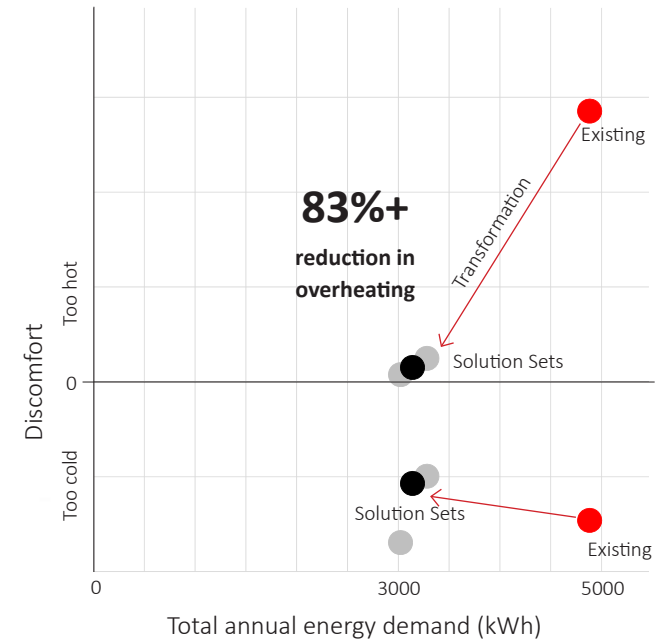
Imagine if we created buildings that are great to teach in and great teachers.

Imagine if our classrooms could show us how to create buildings that are as simple and intelligent; as efficient, economic and socially inclusive as that tree.

This project explores the thermal performance of the NSW Demountable classroom in five climates representative of the diverse range of climates found across NSW.



The project sets out to find simple and low cost solutions to improving the thermal performance of the NSW Demountable Classroom and, as a consequence, the thermal comfort of those who use them.



It is possible to practically eliminate overheating discomfort and significantly reduce energy demand for these classrooms using a combination of simple strategies (Solution Sets).

Solution sets



(Ex) Existing situation



(02) **Solution Sets 02, 04 and 05**
(04) Additional Insulation and thermal mass to the building envelope.
(05)



(11) **Solution Sets 11**
Existing + Fly-roof



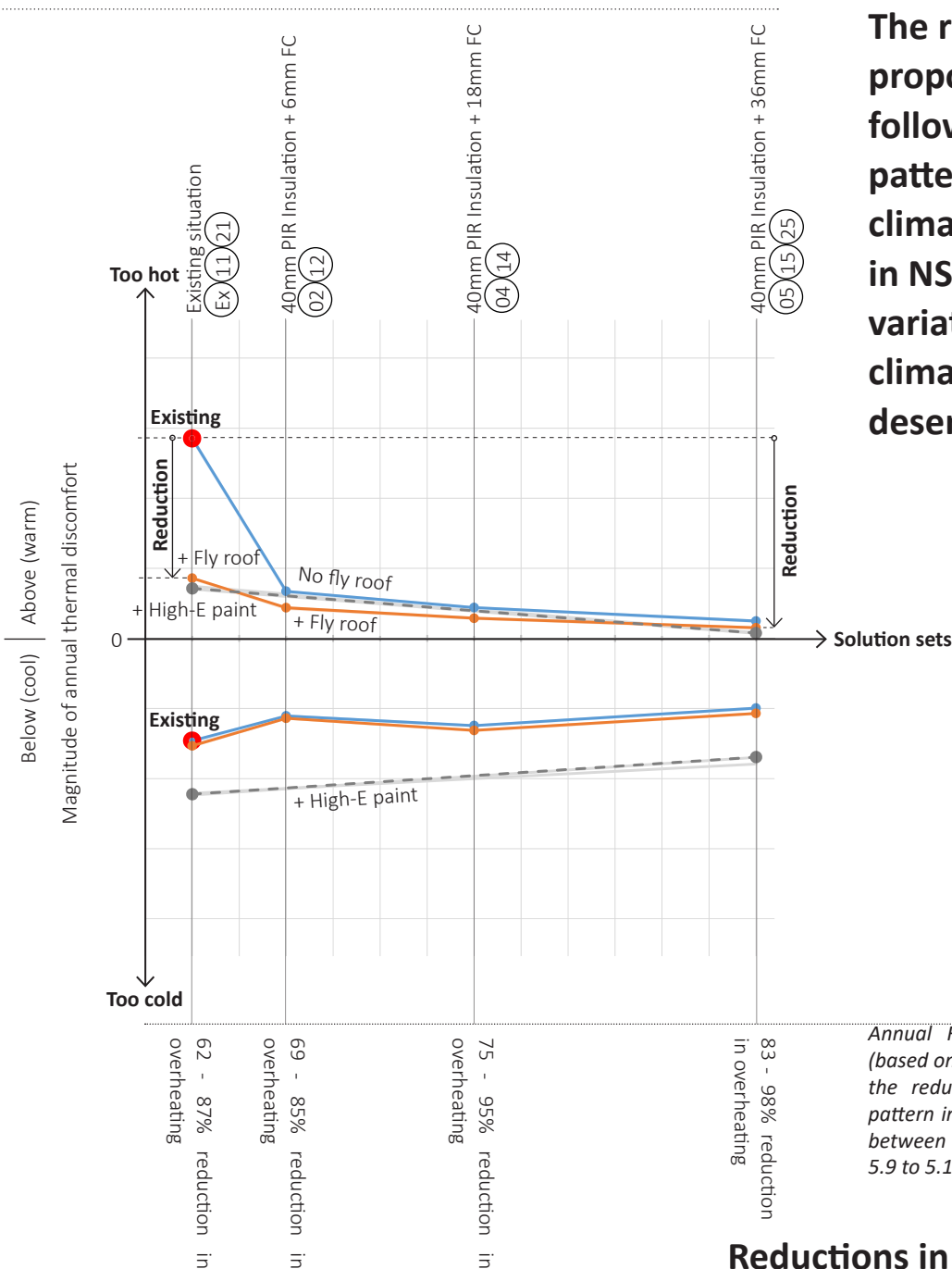
(12) **Solution Sets 12, 14 and 15**
(14) Fly-roof with additional Insulation and thermal mass to the building envelope.
(15)



(21) **Solution Set 21**
High-E coating



(25) **Solution Set 25**
High-E coating with additional Insulation and thermal mass to the building envelope.



The response to the proposed interventions follows the same pattern in all of the five climate types found in NSW (sub-tropical, variations of temperate climates and hot dry desert climates).

Reductions in thermal discomfort

Solution sets



(Ex) Existing situation



(02) **Solution Sets 02, 04 and 05**
(04) Additional Insulation and thermal mass to the building envelope.
(05)



(11) **Solution Sets 11**
Existing + Fly-roof



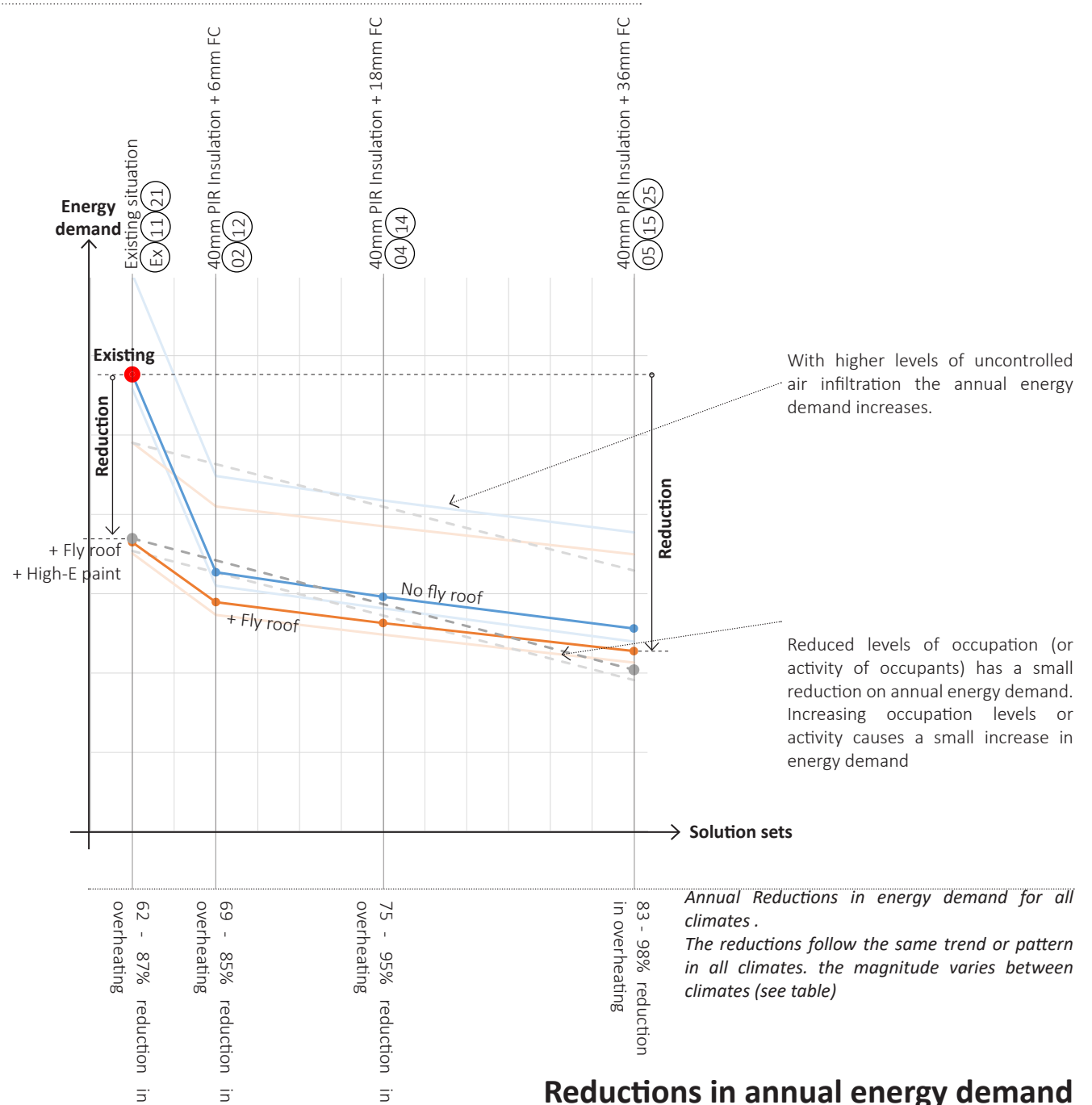
(12) **Solution Sets 12, 14 and 15**
(14) Fly-roof with additional Insulation and thermal mass to the building envelope.
(15)



(21) **Solution Set 21**
High-E coating

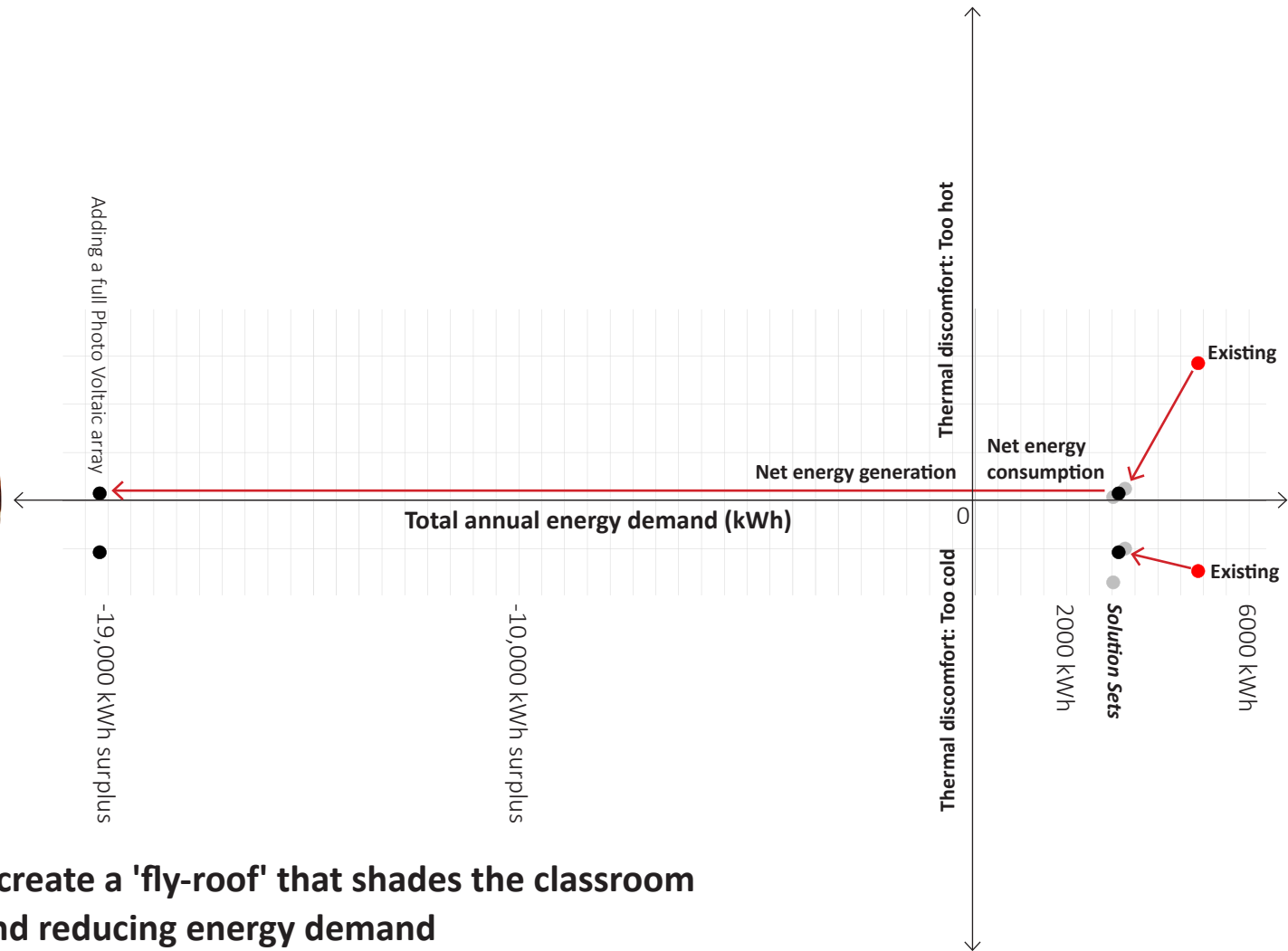


(25) **Solution Set 25**
High-E coating with additional Insulation and thermal mass to the building envelope.



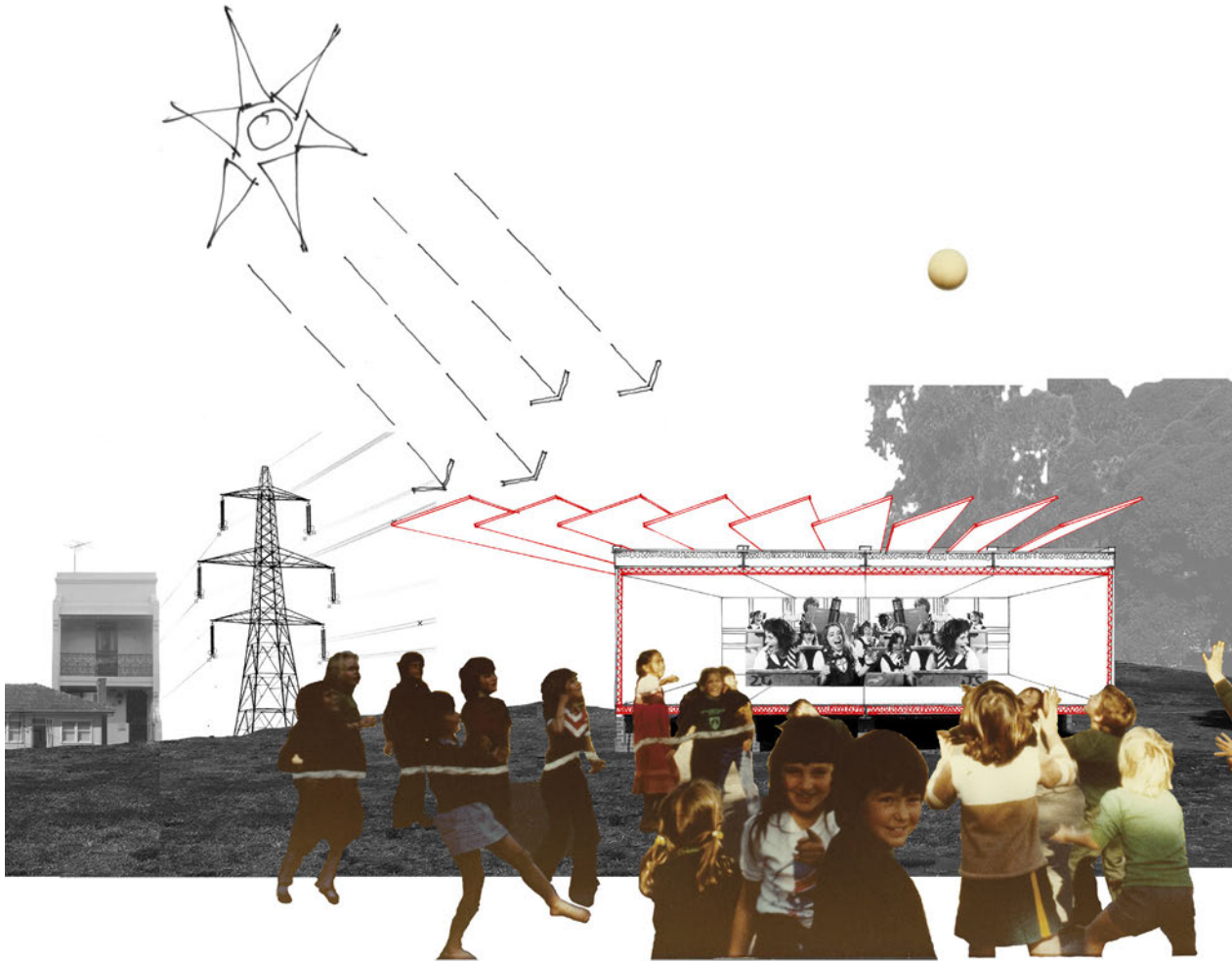
Reductions in annual energy demand

The addition of an array of Photo-Voltaic panels turns the NSW Demountable Classroom into a small green power station for the community



The photo-voltaic panels will create a 'fly-roof' that shades the classroom improving thermal comfort and reducing energy demand

Potential to be a net energy generator



The NSW Demountable Classroom re-imagined as a zero-carbon, energy positive, comfortable and inspirational building

There are three important findings:

1. The response to the proposed interventions follows the same pattern in all of the five climate types found in NSW (sub-tropical, variations of temperate climates and hot dry desert climates).
2. It is important to 'defend' the whole building, and not just the windows, from the sun. i.e. shade the whole building or use a High-E coating (paint).
3. It doesn't require very complicated or very large interventions to make a big difference

Term	Abbreviation	Definition
Units		<i>Metric (SI) units have been used throughout this thesis</i>
Adaptive comfort		Adaptive comfort is a concept that describes how people's perception of comfort changes primarily as a consequence of recent weather conditions. During warmer weather the environments we consider to be 'cool' will be a higher temperature to environments we consider to be 'cool' during colder weather (ASHRAE 55, 2013, Humphreys and Nicol, 1998).
Comfort		Comfort is defined by ASHRAE and CIBSE (with reference to ASHRAE) as "that condition of mind that expresses satisfaction with the environment. (CIBSE Guide A, 2015, ASHRAE, 2013)
Environmental performance		Environmental Performance considers the performance holistically in the context of overall sustainability. According to the United Nations, and others, Sustainability is constituted of three independent and mutually reinforcing 'pillars' (UN General Assembly 60/1, 2005): • Environmental • Social • Economic In this context Environmental performance considers the operational energy demand and associated pollution (including green house gasses) of the building, the energy demand and pollution created by the construction or fabrication and maintenance of the building (embodied energy or CO₂-e), the impact of the building on its surrounding environment and eco-system during construction or deployment, use and after it has been removed. Environmental performance also considers the how the building influences the social and economic activities of the society in which it operates and the environmental consequences of these aspects of sustainability.
		Continued....

Term	Abbreviation	Definition
Degree-Hours		A 'Degree-Hour' is the number of degrees above or below the comfort zone multiplied by the number of hours the temperature is at that level outside the comfort zone. For periods inside the comfort zone the number of hours is multiplied by one.(See part 2.4).
Internal Air Quality	IAQ	Internal Air Quality (IAQ) describes the condition of the air in a space and whether or not it adversely affects people in the space. Poor IAQ will result from inadequate ventilation which will, in turn, raise the level of CO ₂ in the space adversely affecting concentration. Other factors are the level of indoor air pollutants such as chemicals (off-gassing), microbes from mould etc, and dust. Good IAQ may enhance the health, concentration and enjoyment of those who use a space (Daisey et al., 2003).
Internal Environmental Quality	IEQ	Internal Environmental Quality (IEQ) is a holistic concept that describes the internal environment and how well it maintains the comfort and well-being (health) of people in that environment. The desired or appropriate IEQ will be different in different situations, for instance a library, classroom or restaurant (CIBSE Guide A, 2015). When considering IEQ four main factors are included: • Light • Air quality • Acoustics • Thermal comfort (Mendell and Heath, 2005, Soccio, 2014)
NSW Demountable Classrooms		These are portable modular classrooms that were manufactured by the New South Wales Government in the late 1960's (the Mk 1 version) and early 1980's (the Mk 2 version).
Portable, Modular, Relocatable, Pre-fabricated (Prefab), Demountable classrooms		Portable, prefabricated modular classrooms that can be relocated exist in states across Australia and throughout the world. The terms are generally interchangeable and dependent on local vernacular language. In NSW the relocatable classrooms used by the NSW Government are called 'Demountables'.
		Continued....

Term	Abbreviation	Definition
Thermal Comfort		Thermal comfort is defined by ASHRAE and CIBSE (with reference to ASHRAE) as “that condition of mind that expresses satisfaction with the [thermal] environment. (CIBSE Guide A, 2015, ASHRAE, 2013)
Thermal Performance		Thermal performance refers to the whole building and describes how well (good) or poorly (bad) the building moderates the external thermal environment to maintain thermal comfort inside. The concept includes energy demand used to maintain thermal comfort with high energy demand being considered poor performance and low energy demand considered to be good performance.
Temperature:		
Air Temperature	T-air	Air temperature is the dry-bulb temperature (CIBSE Guide A, 2015)
Radiant Temperature	T-rad	Radiant temperature is the mean temperature of the surfaces in a space (CIBSE Guide A, 2015)
Operative temperature	T-op	The Operative temperature is generally taken to be the mean of the air temperature and the radiant temperature and is the best measure of the temperature, or sensation, experienced by people. (CIBSE Guide A, 2015, de Dear and Brager, 1998)
Outdoor temperature	T-od T-out	The air temperature outside.
Computer simulation models		
Calibration (modelling)		Calibration is the process by which the input parameters of a computer model are ‘tuned’ to make sure that the output from a computer model match, as closely as possible, data collected empirically from the building the model is intended to replicate (ASHRAE, 2009)(p.19.24)
Sensitivity (of model)		Sensitivity describes, or illustrates, how the modification of input parameters to the model changes the results generated by the model (see section 2.5) (Macdonald, 2002).
Uncertainty (in model)		Uncertainty describes the levels, or boundaries, of confidence around the results of the model (see section 2.5) (Macdonald, 2002).

Continued....

Term	Abbreviation	Definition
Validation (modelling)		Validation is the process of demonstrating that the software and the algorithms and assumptions embedded in the software provide results that can be considered to be accurate (ASHRAE Standard 140, 2017, Judkoff and Neymark, 1995, Fumo, 2014). The process is commonly referred to as the BESTEST method which has been incorporated into the ASHRAE standard 140 (Judkoff and Neymark, 1999, Judkoff and Neymark, 1995).
Abbreviations		
Air Changes per Hour	ACH	The number of times the total volume of air in the space is changed per hour.
Carbon Dioxide equivalent	CO2-e	There are large number of gasses that contribute to global warming and each gas makes a different contribution to the problem, sometimes referred to as the “Global Warming Potential’ or GWP. CO2-e expresses the global warming potential of all these gasses in terms of the quantity of Carbon dioxide that would cause the same Global Warming Potential as the gas that is emitted (Department for climate change, 2013) (Appendix 1).
Education Facilities Standards and Guidelines	EFSG	https://efsg.det.nsw.edu.au/ The standards and guidelines for schools produced by the NSW Department of Education.
	MET	A unit of measurement for the physical activity of a person relative to the activity of a person seated at rest (CIBSE Guide A, 2015). To obtain the actual energy output of the person the MET value needs to be multiplied by the energy output of the person at rest, (normally taken as 58.2 W/m ²) and the surface area of the person (normally 1.8m ² for an adult man).
Nationwide House Energy Rating Scheme	NatHERS	http://www.nathers.gov.au/ The Nationwide House Energy Rating Scheme (NatHERS) is a star rating system (out of ten) that rates the energy efficiency of a home, based on its design.
	NSW	New South Wales

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First I must thank my wife, Vanessa, for her tolerance, forbearance, economic support and encouragement as I struggled with the strictures of an academic institution and a PhD.

Second I must thank Professor Richard Hyde for encouraging me to embark on a PhD, and continuing to support and guide me however energized our arguments, however obstinate I became, or disenchanted with the project. It is his enduring faith that has enabled me to do this and I am eternally grateful to him for it. I understand that he recently told a colleague of mine that I am “untrainable”. I hope that this thesis demonstrates to him that he has taught me a great deal since the day I walked into his office and he agreed to undertake a research project, into thermal mass, with someone who had never done research, someone who thought a literature review had something to do with William Shakespeare.

Third, I must thank Associate Professor Bill Martens whose calm, phlegmatic support guided me past several procedural problems and enhanced my appreciation and understanding of statistics. He is also the only person I have ever met with an office that appears to be more chaotic than my own.

Fourth, I must thank Professor Mathew Aitchison and Associate Professor Glen Hill for their faith in me and their calm encouragement and guidance, for accepting and engaging with the underlying premise of this thesis rather than trying to mould it into their own theoretical world view. Without them I would have given up. Particular thanks must go to Glen Hill for his eternally sympathetic and excellent editing.

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Figure 0.1: Demountable Classrooms
from the NSW Government Architects Office

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0.1 Overview

This thesis sets out to investigate how the utility and environmental performance of the New South Wales Demountable Classroom can be significantly improved in terms of both the environmental quality of the teaching environment and the overall carbon footprint of the classroom typology. To achieve this the thesis focussed on improving the thermal comfort of the people who use the classrooms and reducing the carbon emissions associated with the energy used to maintain comfort.

0.2 Background

This thesis developed out of an interest in how lightweight construction systems could be used to create comfortable and energy efficient buildings in warm and hot climates, specifically the warm and hot climates of Australia.

There appears to be a paradox in the way in which we build and use buildings that becomes starkly apparent in climates such as those found on the East coast of Australia: We live in a climate where outside it is almost always comfortable, at least during the day. For thousands of years humans have built buildings to modify their local environment and make it more comfortable. But now the opposite seems to happen: we build buildings that make us less comfortable than we would be outside; and then we attach machines to the outside of our buildings to try and solve the problem we have created.

Why is it that it is often more comfortable to sit under the tree outside a building than inside the same building?

The academic literature exploring the ontology of comfort is vast. There is also a significant body of work exploring the thermal performance and properties of building fabric and construction systems. This thesis developed out of a desire to thread a line connecting the two: to build on both so that our understanding of comfort and the way in which we encounter and experience the thermal world might inform and direct the way we build buildings and the materials we choose to build them with. Expressed at its most naïve and idealistic the objective was, and continues to be, to understand how we can create buildings that are as simple and intelligent; as efficient, economic and socially inclusive as that tree.

The precursor to this thesis was a project exploring the use of thermal mass in lightweight buildings,* and attempting to understand how much thermal mass is needed to achieve thermal comfort (Slee and Hyde, 2015). Part of that project used small test cell buildings provided by our partner CSR and Derek Munn. Towards the end of the project a discussion took place about the limitations of the test cell buildings and it was suggested that the New South Wales Demountable Classroom would be a useful vehicle for exploring the ideas our experiments were investigating at a larger scale and in a variety of climates.

**A project that was also supported by Forest and Wood Products Australia with CSR as an Industry Partner*

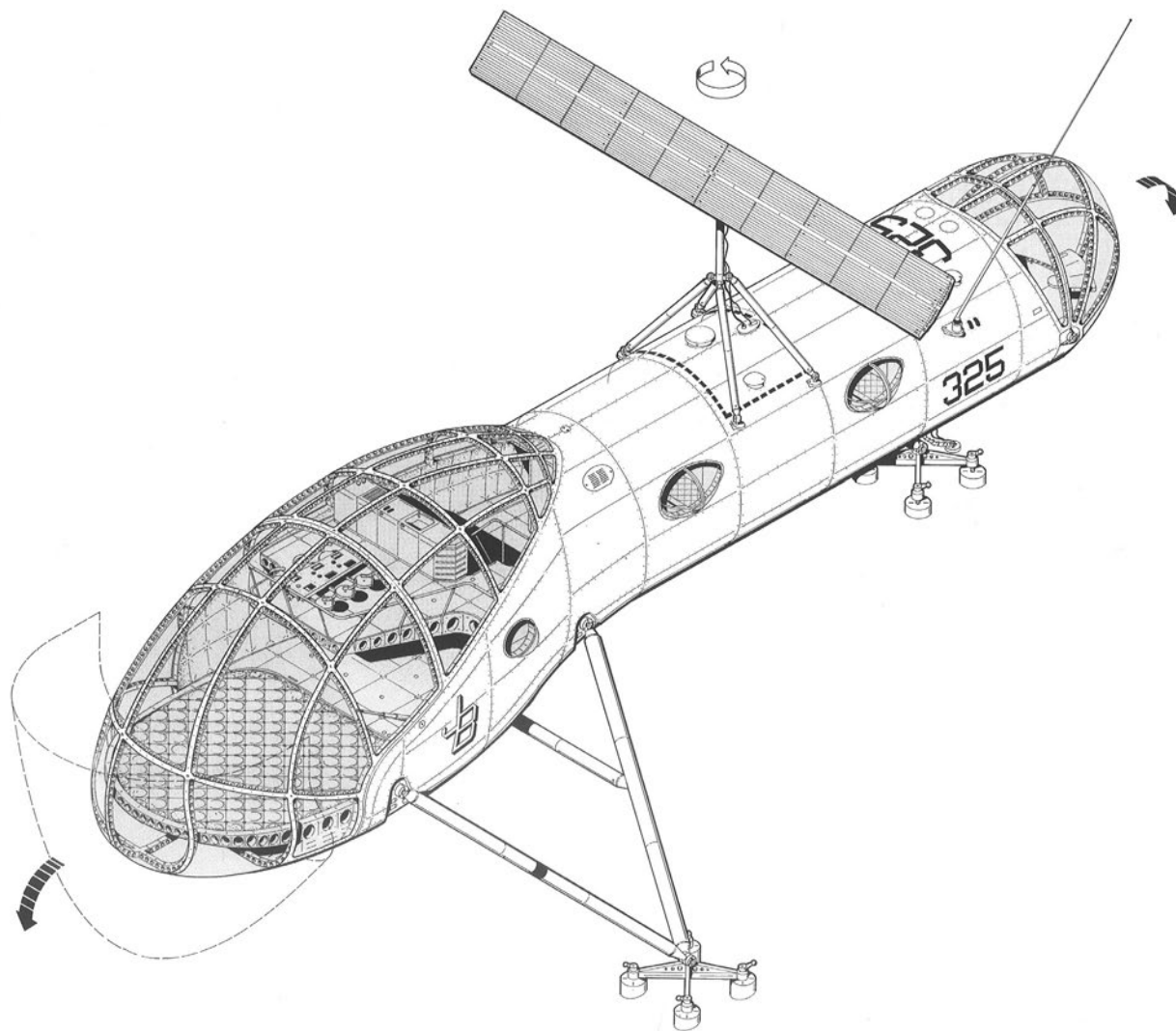


Figure 0.2: Vehicle, 1980 by Jan Kaplicky and Future Systems
(Rogers and Margolius, 2015)

The NSW Demountable is an ideal experimental device because it is a standard design and of lightweight construction. It is relatively easy to transport. It exists in multiple climates and the programme of occupation and use is almost identical in all situations because it is defined by the school day and term times. The clothing of those in the classrooms is also almost identical. So many potential variables are ‘controlled’ by the program of building itself rather than those designing the experiment. The classrooms also present some challenges. There are complex and occasionally contentious questions that arise around undertaking research projects that involve children. There are challenges finding funding in order to modify the classrooms and monitor them.

An idea had been formed and an investigation began.

It soon became apparent that the NSW Demountable Classroom is a fascinating and radical building typology in its own right. Created in the late 1960’s to provide a lightweight, relocatable classroom system that could be, was and is, used to create “instant schools”, it was created several years before the iconic “Instant Cities” of Archigram (Archigram) (Figure 0.3) or the extraordinary prefabricated, relocatable, light-weight structures of Jan Kaplicky and Future Systems (Rogers and Margolius, 2015) (Figure 0.2). The classroom system has outlasted many permanent buildings built at the same time and since then. It is a building typology that continues to do what it was originally designed to do very well. It is also a building typology that engages with and is constrained by a range of significant social,

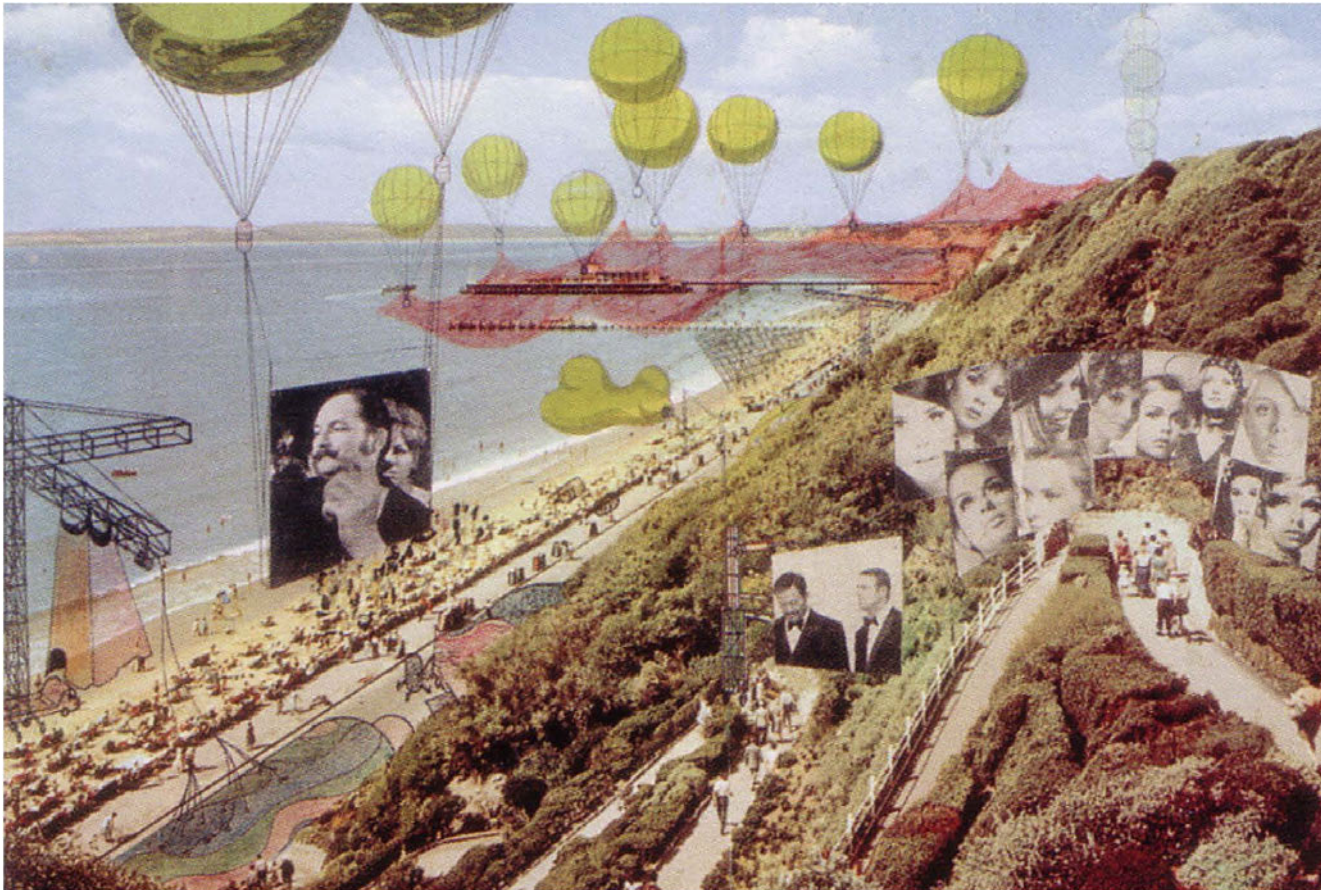


Figure 0.3: Instant City visits Bournemouth (1969 - 1970)

This is an iconic project in the canon of twentieth century architecture that proposes a vision of a relocatable urban infrastructure. Independently, but at the same time, the NSW Demountable Classroom, now perhaps an "anti-icon", was being designed, fabricated and used to create relocatable, instant, urban infrastructure for education across the state of NSW.
(Archigram)

economic and environmental issues. It is a building type that is often regarded as second rate, or obsolete, by the communities it serves for a range of reasons, including its aesthetics, its thermal performance and its intentional impermanence:

"Demountables have been the subject of incessant criticism throughout the Inquiry. [in] the absence of air conditioning they are too hot; their insubstantial character detracts from the appearance and confirmed identity of a school."
(Vinson et al., 2002)

Thus this project developed from being focussed on the performance of building fabric in relation to comfort isolated from any specific context, to a project that engages with the complexities of the social, economic and environmental context of the NSW Demountable Classroom. This complexity, and the interconnectedness of the associated problems, is the essence of Architecture. Understanding and solving the problem of the thermal performance of these classroom buildings helps to build our contextual understanding, and knowledge, of the problem, potential solutions, and the strategies or methods that can be used to solve such complex problems, at the heart of which are people, because buildings, and architecture, are for people.

0.3 Objective

This thesis set out to understand how the 6000 Demountable Classrooms across the state of New South Wales (NSW) can be transformed to improve the thermal performance of the buildings and the thermal comfort of those who use them.

The problem is complex and engages with social, economic and environmental issues of sustainability and pedagogy. The perception of social value, politics, aesthetics and their impermanence all play a part (Vinson et al., 2002). The thermal performance of the NSW Demountable Classroom has a profound impact on both the perception and utility of these classrooms. Understanding and resolving the problem of thermal performance in the NSW Demountable Classroom is significant. Thus the research question emerges:

How can these buildings be modernised to improve their thermal performance and the thermal comfort of the those who use them?

The objective of this research project is to develop socially, economically and environmentally viable proposals that will improve the thermal performance of the classroom buildings and the thermal comfort of those who use them. This, in turn, will help reduce the energy demand of those classrooms and so reduce the associated CO₂-e emissions and overall environmental footprint of the NSW Demountable Classrooms.



Figure 0.4: Demountable Classrooms, Carringbah
(Photograph by the author)

There is an assumption within practice and guidance that if something, a solution, is 'good' then lots of that thing, or solution, must be 'better'. Within the research literature there are many papers that seek to 'optimise' the building envelope: to find the ideal construction for a particular climate based on some form of cost-benefit analysis. Rather than seeking an ideal or 'optimal' solution, or accepting the premise that more of a good thing must be better, this thesis asks "how much is enough?", or, "how much do we need?" to significantly improve the thermal performance of the classrooms.

0.4 An introduction to the research approach

The author of this thesis is an Architect trained in the tradition of enquiry and problem solving that is centred on people. A tradition that is holistic encompassing social, technical and aesthetic inquiry, knowledge and proposition (Vitruvius, 25 BC (Circa) Trans. 1826, BPRU, 1972, Rowe, 1987). The approach to the research adopted in this thesis is founded in this tradition of inquiry and understanding of the problem, eloquently articulated and deconstructed by Schon (Schön, 1983) in 'The Reflective Practitioner' and Rowe (Rowe, 1987) in 'Design Thinking'.

The thesis understands buildings, including the NSW Demountable Classroom, as intrinsically complex systems that exist within other complex environmental, social and economic systems. Therefore there can be no single optimal solution to the challenges raised by function, climate or social context and therefore no simple route to find 'the solution' (BPRU, 1972, Rowe, 1987, Schön, 1983, Blackmore, 2011).

As a consequence, this thesis has adopted a research methodology that embraces the complexity and multi-faceted nature of the problem of the performance of the NSW Demountable Classroom and how that problem might be solved.

This thesis uses the tension between the analytical and abstract approach embodied by the scientific paradigm,

and the synthetic and contextual approach embodied by the design methodology, to explore the problem of thermal performance in the NSW Demountable Classroom.

Dong et al (2015) argue that design thinking is based on “cumulative knowledge building”; that only by moving between the abstract and the particular, the contextual, is it possible to come to understand a problem. It is through this continual abstraction and contextualisation of ideas that knowledge is created (Schön, 1983, Owen, 1998, Maton, 2013, Dong et al., 2015). It is a dynamic and temporal intellectual process described by Schon as a ‘reflective conversation’ (Schön, 1992, Schön, 1983).

Buchanan (1992) argues that the traditional research paradigms fragment knowledge into ever smaller and more specialised domains and so lose their connection with the “real” world. The goal of science is to understand how things work, and in order to do this it fragments problems into ever smaller pieces in order to isolate and separate variables. The designed paradigm sets out to construct an integrated and connected knowledge base. Design puts things together to understand what they can become. Again, in the words of Buchanan, the concern of design is

“to connect and integrate useful knowledge from the arts and sciences alike, but in ways that are suited to the problems and purposes of the present. Designers, are exploring concrete integrations of knowledge that will combine theory with practice for new productive purposes” (Buchanan, 1992).

The design methodology is ecumenical rather than dogmatic. It embraces and explores multiple means for exploring and gathering knowledge. In 1969 The Royal College of Art (RCA, 1969) argued that design is the third methodology for research while Buchannan called it “the new liberal art for technological culture”. The methodologies and world views of the humanities and science are both useful and intrinsic to design thinking. Design seeks to integrate and synthesise in order to apply knowledge, and through application, understand more.

“all disciplines build knowledge bases.There is no single means, and the multiplicity strengthens the results.” (Owen, 1998)

This thesis uses the tension between the pragmatic context in which the problem is founded, the abstract ideas and scientific methodologies it uses to understand those problems, and the pragmatism required to find ways of applying those theoretical ideas in the physical (real) world of NSW schools to develop an understanding of how the performance of the NSW Demountable Classroom can be improved from a social, environmental and economic perspective. The research is applied and contextual.

Rowe (1987, p.56) explains the (design) research process in the following stages:

- i. The representation of the problem through the structuring and re-structuring of the problem
- ii. The generation of solutions
- iii. The evaluation of the candidate solutions

Schon describes this process as the reflective conversation: the framing and re-framing of the problem, moving from the global to the particular to the global, and from exploration to commitment to further exploration in order to understand the implications of the proposed intervention.

The overall structure of this thesis adopts the following process:

- The development of a rigorous analysis and confirmation of the problem (the framing or structuring of the problem)
- An exploration of potential solutions (the generation of solutions)
- The testing and evaluation of these solutions

The thesis concludes by reflecting on and discussing the intended, and un-intended, implications of the solutions that have been proposed and the opportunities these create for further investigation.

0.5 Methodology

This thesis developed out of an interest in how lightweight construction systems could be used to create comfortable and energy efficient buildings in warm and hot climates, specifically the warm and hot climates of Australia. This thesis explores the problem through the context of the NSW Demountable Classroom. The NSW Demountable Classroom is a lightweight building that is ubiquitous in all of the wide range of climates that exist across the state of NSW.

The thesis understands buildings, including the NSW Demountable Classroom, as intrinsically complex systems that exist within other complex environmental, social and economic systems (Blackmore, 2011, BPRU, 1972). Therefore there can be no single optimal solution to the challenges raised by function, climate or social context and therefore no simple route to find ‘the solution’.

As a consequence, this thesis has adopted a research methodology that embraces the complexity and multi-faceted nature of the problem of the performance of the NSW Demountable Classroom and how that problem might be solved. The overall structure of the thesis adopts the following process, and, as a consequence has methodologically intersecting parts that oscillate between qualitative and quantitative analytical methods. The research is applied and contextual.

i. The development of a rigorous analysis

Chapter 1 provides an analysis of the NSW Demountable Classroom based on a variety of documentary evidence, observations and interviews. The Thesis adopts the Building Performance Research Unit’s framework of ‘Building Systems’ (BPRU, 1972) in order to explore how different social, physical and environmental elements of these classrooms operate and interact, and their relationship with the original and current objectives or purpose of these classrooms. Section 1.2 describes this framework in more detail. The chapter concludes that the thermal performance of the NSW Demountable Classrooms, or at least communities’ perception of their thermal performance, is a significant problem.

ii. Problem confirmation

Chapter 2 uses the information collected in Chapter 1 to construct a computer simulation model to enable a quantitative analysis of the thermal performance of the existing NSW Demountable Classrooms in five climates from across New South Wales. A detailed description of the methodology used for this is set out in Chapter 2. The five climates are considered to be representative of the broad range of conditions the NSW Demountable Classroom encounters across the state.

iii. Exploration of potential solutions found in literature

Chapter 3 and Chapter 4 use an analysis of existing literature to explore potential solutions to the problem of poor thermal performance in lightweight buildings.

iv. The testing and evaluation of those solutions

Chapter 5 and Chapter 6 The final chapters of the thesis use the digital simulation model to to analyse the performance of the various strategies that have been proposed. The quantitative results of this analysis are discussed in both a quantitative and a qualitative context.

0.6 Data collection methods and sources

In order to undertake both the qualitative analysis on Chapter 1 and the quantitative analysis in Chapter 2 of the NSW Demountable Classrooms evidence was collected from a variety of documentary sources and compared to evidence from observation (physical surveys) and from interviews. This section describes the methods used and reasons for the collection of documentary evidence

0.6.1 Media

Relevant newspaper articles were provided by, and collected from, a number of sources in order to understand the broad public narrative that surrounds the NSW Demountable Classroom. The Department for Education provided a series of newspaper articles they had collected that were relevant to the NSW Demountable classrooms.

Searches were undertaken on the Factiva database and the ProQuest database of Australian Newspapers using a variety of search keywords including

‘Demountable Classroom’

‘Demountable Classrooms’

‘Demountable Classroom’ AND ‘Comfort’

‘Classroom’ AND ‘Comfort’

‘Classroom’ AND ‘Heat’ AND ‘Comfort’

The search term 'NSW' was added to these searches to narrow the down to articles relevant to NSW.

In addition, the Author has taken part in a number of radio interviews on ABC Radio stations. During these interviews the themes of 'inadequate', 'substandard' and 'uncomfortable' classrooms were repeated (Bisset, 2015, Slee, 2015, Slee, 2017a, Slee, 2017b, Slee, 2017c).

0.6.2 NSW Hansard

Hansard is the record of debate in the NSW Parliament (Hansard NSW). A study of Hansard provides an insight into how politicians have represented their own views, and the views of their constituents, about the NSW Demountable Classroom over the last 50 years. Hansard records the position (e.g. Minister for Education) or name (e.g. Mr Park, Member for Tamworth) but does not list the political affiliation (Political Party). What is clear is that Ministers have consistently defended the need for and use of these classrooms while those in opposition have criticised the classrooms, initially because there were not enough and later for their quality.

The Hansard NSW website explains that

'Hansard is the written record of proceedings and debates in Parliament. It is a verified and accurate record rather than strictly verbatim transcript. Repetitions and redundancies are omitted, obvious mistakes are corrected, and interjections omitted unless responded to by the principal speaker.'

The Hansard website has a database that can be searched using keywords. A keyword search for 'Demountable Classrooms' was undertaken for debates in both houses which generated 295 results between 1974 and 2014 inclusive. These Hansard entries for these results were read and entries that dealt with the utility, provision, quality, cost, environmental performance and internal comfort of these classrooms were highlighted and summarised for reference in the thesis.

0.6.3 Academic literature and reports

Academic literature and formal reports provide a more formal, rigorous and evidence based source of information about the performance of the NSW Demountable Classroom, when it is considered from various perspectives, compared to the opinions expressed in the media and in Parliament. Academic literature also provides evidence of a broader context for the purpose, utility and operation of the NSW Demountable Classrooms in relation to research in other States, the whole of Australia and internationally. The literature reviewed pedagogy, thermal comfort, industrial construction systems and the broader theoretical framework for the discussion.

The search for literature began with discussions with people who had already undertaken research in these areas. This led to a number of detailed published literature reviews as well as individual papers.

Further searches for both literature reviews and relevant articles were undertaken using keyword searches in Google Scholar, Science Direct and Scopus.

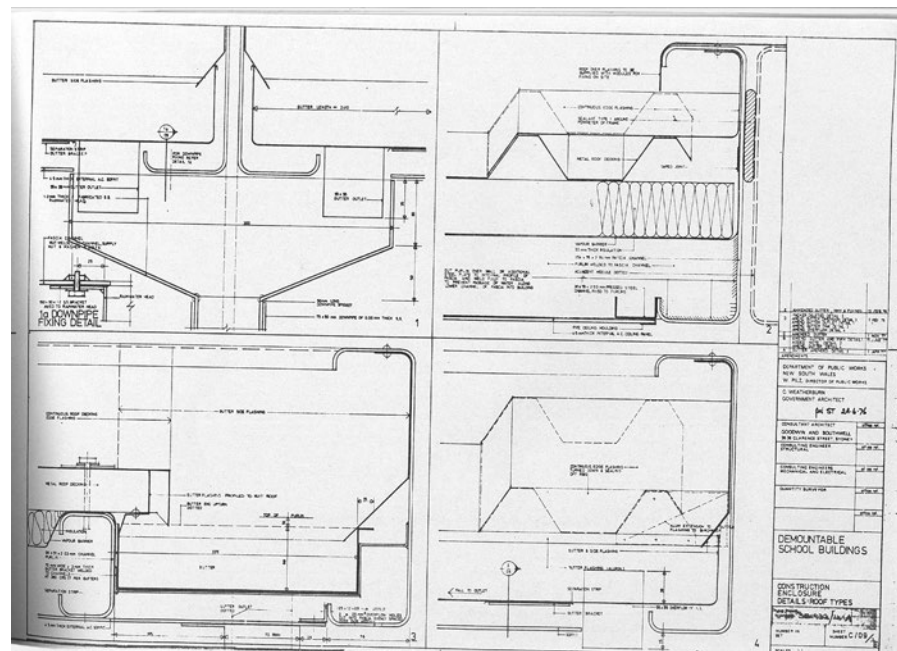
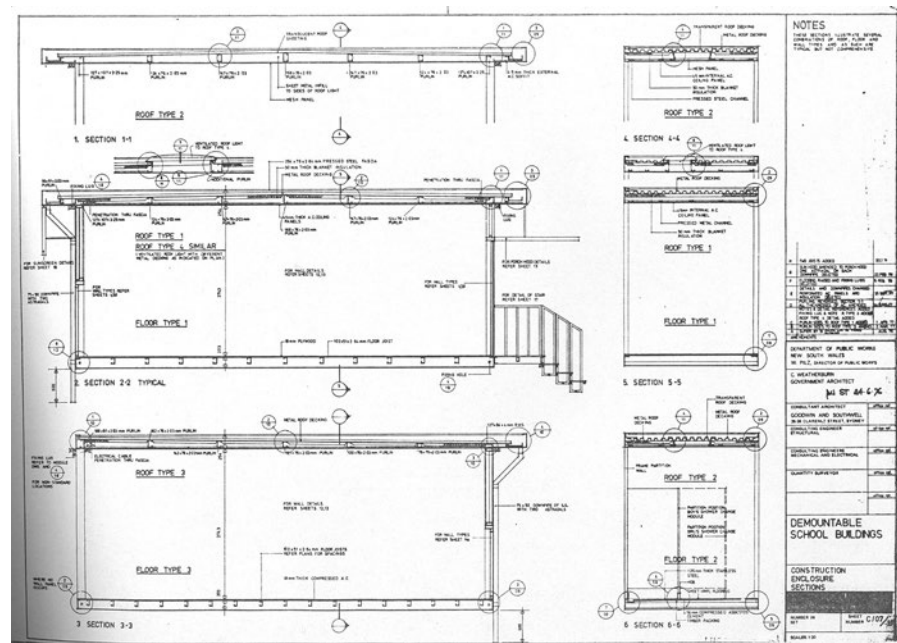


Figure 0.5: Examples of original construction drawings

Examples of original construction drawings: G.A. sections (above) and eaves details (below) of Mk 1 NSW Demountable Classrooms from the NSW Government Architects Office construction drawings. (NSW Government Architects Office, 1976 (circa))

Apparently useful references within literature reviews, theses, papers and reports were followed up using the academic databases listed above. Where the academic literature databases failed to reveal source documents searches in Google were employed as well as assistance from the University Librarians.

In some cases reports and pamphlets were provided by serendipity. A contact in the Department for Education provided a copy of 'Public School Architecture in New South Wales' by Underwood (1972). This is a very useful pamphlet that was reprinted from 'NSW Builder'. The publication date is unclear and no other record of the document has been found. The RIBA published a report titled 'Better places for learning' while the thesis was being written (RIBA, 2016). This report contained a number of references that led to many additional references.

Other documents or reports were suggested by interviewees as we discussed the history of the NSW Demountable Classrooms. These were followed up independently.

0.6.4 Original drawings and specifications

The NSW Government Architects Office was approached and provided copies of the original drawings for both the Mk. 1 and Mk. 2 classroom systems (Figure 0.5) (NSW Government Architects Office, 1983, NSW Government Architects Office, 2001, NSW Government Architects Office, 1976 (circa)). These provide detailed construction information and illustrate the variety of layouts and typologies that the designers envisaged. In

The construction of the Mk. 2 classroom is similar but slightly larger overall in plan.

The refurbishment process takes place in a secure prison yard. No cameras are permitted in the works yard and so all notes were recorded by hand in a sketchbook following the traditional process of architectural surveys (Figure 0.6). Dimensions were taken using a metal measuring tape. The author (an Architect) visited Cessnock Corrective Services on two occasions. There were a number of classroom units being refurbished, each in different stages of deconstruction or reconstruction. These ranged from the bare primary steel frame, the steel frame plus the welded steel infill structure to support the wall panels, roof and floor. The installation of intermediate layers within the walls, roof and floors and the cladding to the internal and external surfaces being fixed and finished, including painting. In addition to the classroom units undergoing refurbishment the yard contains a store for the materials used in the refurbishment of the classroom units. This enabled the Author to confirm the specification of the various components.

0.6.6 Interviews

Interviews were undertaken with a variety of people familiar with the design, maintenance and operation of the NSW Demountable Classroom system. The purpose of the interviews was to gather knowledge and perspectives embedded within the administrative systems that surround the Classrooms are that are not expressed publicly.

The information and knowledge garnered can be compared to other sources if information to corroborate or contradict it. The information can also open new avenues for enquiry, exploring perspectives or functional attributes that may not have been apparent otherwise.

The open ended interviews are recorded in Appendix A and have been anonymised. Participants in the interviews were selected because of their particular expertise. They were often found at the suggestion and introduction of other interviewees due to their expertise or experience with an aspect of the design, maintenance, management or administration of the NSW Demountable Classroom as a civil servant, either currently or in the past. The interviewees have experience of managing Demountable Classrooms stretching over 35 years. In total 8 people were interviewed in 5 separate interviews.

Interview process

The interviewees were invited to take part on the basis of recommendations. An initial introduction to the Department for Education led to informal discussions and a variety of additional introductions. Following these informal discussions, a formal process of invitation and record was introduced. Potential participants were emailed inviting them to take part. The email explained

- Who or how they had been recommended for participation.
- An outline of the purpose of the project
- An explanation of why they, in particular, might be able to contribute to the project

Each email or letter was a personal invitation containing information relevant to the interviewee. After the interviewee agreed to take part in principle a time for the interview was arranged and the semi-structured interview questions were emailed to the participant. Formal agreement to take part (a signed document) was obtained either prior to the interview or at the beginning of the interview.

The interviews were conducted face to face in a discursive, fairly informal, semi-structured manner ensuring that topics were covered but also creating the opportunity to explore lines of thought, knowledge or recollections that emerged during the discussion. The interviews took place with individuals (2) or pairs (3). The author took notes during the discussion and these notes were typed up and sent to the interviewees for comment. The final versions of the interview notes are in Appendix A.

Interview structure

The interviews were structured around the History (past), Present and Future of the NSW Demountable Classroom. Under each heading the author identified a series of questions based on the initial research that had been conducted. This included reading various reports, academic papers and informal discussions with various people who were, or had been, connected with the NSW Demountable Schools program.

The final part of the interview, the Future, was based on a SWOT analysis (Strengths, Weaknesses, Opportunities, Threats) in the context of the concept of obsolescence (see part 1.9). This created the opportunity for a wide-ranging discussion.

Anonymity

It was the view of experienced researchers within the University and the Ethics team that the interviews should be anonymised.

0.7 Limitations

The limitations for this project are centred on the simulation strategy that has been adopted, the climates and sites chosen and the methodology for defining and evaluating comfort. These issues are discussed in more detail in Chapter 2 and Chapter 5.

Simulation strategy

The thesis identifies four methodologies or strategies for modelling the performance of buildings, and the effect of various interventions to those buildings, in different climates. These methodologies range from the fundamentally empirical, to the calibrated simulation model, to the use of digital simulation models for comparative analysis.

For this project the first two approaches present a number of significant challenges in terms of the time frames required to collect appropriate and useful empirical data, the range of climates considered, the physical distances between potential sites, and the difficulty of accessing classrooms that are in use. The difficulty of undertaking a robust calibration process is discussed at length by Raftery et al (2011a, 2011b), Sun and Reddy (2006) and Mustafarj et al (2014). These challenges are exacerbated by the range of climates considered in this project and the number and magnitude of proposed modifications to the Demountable Classroom buildings.

The third strategy, a carefully constructed digital simulation model, offers the significant advantage of speed, but at the cost of the loss of calibrating the base case model against empirical data. This may be considered a significant limitation (Westphal and Lamberts, 2005). Others argue that a simulation model validated to the appropriate standards (ASHRAE Standard 140, 2017, IBPSA, 2018) produces results that are “assumed to be accurate enough to be considered valid” (Fumo, 2014). There are a large number of research projects that adopt this position (See Table 2.2 for examples).

The choice of approach depends on many factors, in particular the ability to access or collect empirical data, the time and resources available for the study and the purpose of the study (ASHRAE, 2009, Fumo, 2014). For this study the third approach, the carefully constructed digital simulation model, has been chosen in preference to the calibrated model because it was not possible to obtain useful empirical data; the limited time available for the study; and, because the level of modifications proposed and range of climates considered mean that almost all of the models would be considerably different from any original calibrated base case model. This reduces the value of the base case model and can reduce the credibility of the entire simulation (Sun and Reddy, 2006).

All models are a simplification of reality, imperfect and contain uncertainty (ASHRAE Standard 140, 2017). One of the significant simplifications in any model is the definition of how the building is used. In reality

people, teachers, classes and schools use classrooms in many different ways and so no model can be accurate or universally representative of reality, it is always an approximation. Junghans and Bae (2016) and Hopfe (2009, Hopfe and Hensen, 2011) argue that this uncertainty should be expressed and articulated within the simulation results.

It is argued that where the simulation model is intended to be used to explore the relative impact of these parametric modifications and the impact of climate on the thermal performance of the classroom building, rather than to develop absolute values, that this form of study is valid. In this thesis the model is used for this form of comparative analysis (ASHRAE, 2009, Fumo, 2014, Brotas and Nicol, 2017, Smith et al., 2012 and others).

Choice of climates and sites

The climate types within the state of New South Wales range from Sub-Tropical in the north East, to Desert in the West, to Cool and Warm Temperate climates in the South East and a range of other climate types in between.

Every site has particular micro-climatic quirks. This thesis has chosen to use five specific sites, one within each of five different climate zones from across the state, to represent the broad range of climates that actually exist. It is considered that the results from the simulations in these climates will indicate the probable performance of the Demountable Classrooms in any of the locations they are likely to encounter.

Comfort

The definition of comfort and how, or whether, we are able to predict comfort for different groups of people in different circumstances is an area of ongoing and productive research (Humphreys et al., 2007, de Dear et al., 2013, Parkinson and de Dear, 2015). Comfort is clearly a subjective, dynamic and temporal experience that is influenced by a range of both subjective and environmental factors. For this project the Adaptive Comfort Model has been adopted as set out by De Dear and Candido in a paper discussing comfort in naturally ventilated buildings in New South Wales (de Dear and Candido, 2012).

In the discussion and analysis of the results of the simulations (Chapter 5) the thesis explores the implications of the Adaptive Thermal Comfort protocol on the results and how other current research might offer an alternative interpretation of the results.

0.8 The thesis structure

Chapter 1 is an exploration of the history and purpose of the NSW Demountable Classroom using a qualitative analysis based on documentary evidence, including original drawings and survey information, and interviews. Chapter 1 concludes by identifying the research question.

Chapter 2 sets out a quantitative methodology for analysing the thermal performance of the existing Demountable Classrooms in five different climates from across NSW using a digital simulation model. The purpose of this analysis is to understand if the conclusions of the qualitative analysis are justified and, further, to identify possible causes of the problems with thermal comfort and thermal performance.

Chapter 3 defines an overall strategy to solve the problem identified in Chapters 1 and 2 by discussing three alternatives: The replacement of the existing Demountable Classrooms with a new design, a “deep” refurbishment, or a low cost strategy that can be carried out on-site and in-situ.

Chapter 4 uses existing research literature to explore various technical solutions and combinations of solutions, “Solution Sets” (Hyde et al., 2009), that maybe employed to improve the thermal performance of the NSW Demountable Classroom in the context of the social, economic and environmental issues identified previously.

Chapter 5 uses the simulation model developed in Chapter 2 to evaluate the effect of these Solution Sets on the thermal performance of the NSW Demountable Classrooms in the five representative climates. Chapter 5 then discusses the results of these simulations in more detail and explores the impact of using different criteria for controlling the heating, cooling and ventilation of the classrooms, based on current research literature. The chapter concludes by evaluating the integration of photo-voltaic panels to offset the energy demand of the air-conditioning system, the likely financial costs associated with the Solution Sets and the impact they will have on the relocate-ability of the modular classrooms.

Chapter 6 is the conclusion and reviews the findings, their significance and the opportunities they create for further research. The thesis concludes by arguing that, because the thermal performance of the classrooms is, perhaps, the least complicated of the problems they face, but has a significant impact on the perception of the classrooms by the communities who use them, and because it can be solved, the process of solving it creates an opportunity to engage with many of the other social challenges the classrooms and communities face.

The NSW Demountable Classroom: An analysis of a radical building typology

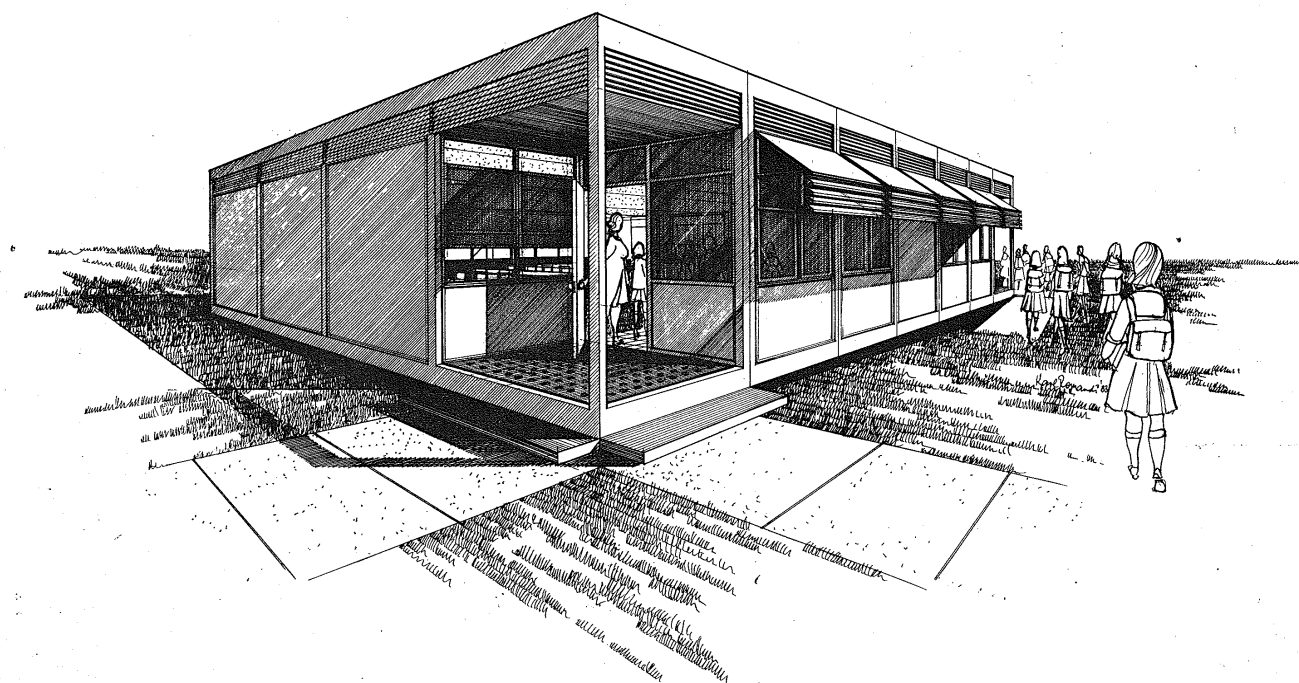


Figure 1.1: Original perspective of a Mk 2 NSW Demountable Classroom

Perspective of a Mk 2 Demountable Classroom from the NSW Government Architects Office construction drawings circa 1983

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1.1 Introduction

The NSW Department for Education and Training possesses around 6,000 Demountable Classrooms accounting for 12% of all NSW state government classrooms (Department for Education and Training, 2010). The Demountable Classroom was originally designed in the late 1960's, referred to here as the Mk 1 classroom, with a modified version manufactured in the 1980's, referred to here as the Mk 2 classroom. The objective of the original NSW Demountable Classroom was to provide the NSW government with an easily re-locatable and adaptable classroom building that would allow the government to respond to changing school populations, demographics and local disasters such as bushfire, floods or arson (Underwood, 1972). These standard buildings are expected to provide an adequate learning environment across all of New South Wales' diverse climates that range from cool temperate, to hot and dry (desert), to hot and humid (sub tropical).

However, communities across NSW regard the Demountable as a second rate classroom providing inadequate teaching accommodation. They have become "a pejorative" (Interview B, 2014). Professor Vinson highlighted this problem in his report on the provision of education in NSW in 2002 when he stated that:

"Demountables have been the subject of incessant criticism throughout the Inquiry. [in] the absence of air conditioning they are too hot; their insubstantial character detracts

from the appearance and confirmed identity of a school."(Vinson et al., 2002, p.89)

This statement highlights three important issues that have a bearing on the perception of these buildings. Their thermal performance is widely regarded as being inadequate. Their "insubstantial character" reinforces the perception that they are temporary and therefore inferior to permanent classroom buildings. This view is exemplified by a debate in the NSW parliament in 2003 with a motion calling for the House to acknowledge, *"that the learning environment of a permanent classroom in regional New South Wales is a better learning environment than a Demountable Classroom."* (Hansard NSW 8/09/2003). Finally, they are regarded as "ugly". An aversion to their appearance is a recurring theme that militates against their acceptance as a useful resource by communities (Gan and Backhouse, 2012, Gan and Newton, 2012b, Vinson et al., 2002). The community's perception of the quality of a school's buildings and environment is significant because, as Professor Vinson eloquently explains,

"the quality of school buildings and their surrounds can also be a potent symbol of the regard (or otherwise) in which public education is believed to be held by governments and the community" (Vinson et al., 2002)

This chapter uses documentary evidence, structured interviews (Appendix A) and physical observation to explore and understand the purpose, history, role and performance of the NSW Demountable Classroom in

communities across the state. Through this analysis the chapter will develop an understanding of the reasons the classroom typology is regarded as “second rate”.

Chapter structure

This chapter explores the performance of the NSW Demountable Classroom in relation to the 'Systems' set out using the holistic model, or framework, for understanding building performance described by the Building Performance Research Unit (BPRU, 1972).

The first part of the chapter describes the BPRU framework and how it has been adapted to structure the analysis of the existing NSW Demountable Classroom.

The following parts of the chapter explore the performance of the NSW Demountable Classroom in relation to the “systems” set out by the BPRU framework.

The penultimate part of the chapter explores the concept of obsolescence, particularly obsolescence intrinsic to the performance of the building and the social expectation and perception of that performance.

The chapter concludes by considering whether these buildings are obsolete or whether they continue to be useful. It is argued that these classrooms are actually a radical building typology that offer a highly effective solution to many of the environmental, social and economic challenges faced by Australian (and other) communities today. However, the poor thermal performance and consequential thermal discomfort of the people who use these classrooms means that they

are almost universally regarded as second rate, they have become a pejorative (Interview B, 2014).

The research question emerges from this analysis: **How can these buildings be transformed to improve their thermal performance and the thermal comfort of those who use them?**

1.2 Understanding the NSW Demountable Classroom

*“It is obvious that buildings are for people”
(BPRU, 1972)*

Buildings are an intrinsically complex system and exist within other complex environmental and social systems.

The complexity of the interrelationships, the variety and nature of the factors that must be considered and the significance of context mean that no single classical methodology can be used to understand how the building “performs”.

In their paper “Building evaluation: practice and principles” the pioneers of building evaluation research, Leaman, Stevenson and Bordass (2010) set out three perspectives that need to be considered

- Occupants, and how well their needs are met
- Environmental performance, normally energy and water efficiency
- Whether the building makes economic sense, such as value for money or return on investment

They argue that qualitative and moral considerations and information needs to be given equal weight to quantitative considerations and data.

In the concluding part of their paper Leaman et al (2010) highlight how the need for building evaluation systems has evolved over four decades since the “landmark” publication of the book “Building Performance” (BPRU,

1972) by the Building Performance Research Unit (BPRU) at the University of Strathclyde. The book sets out a model for understanding and evaluating the performance of buildings as an open ended system that should consider the design, construction and use of buildings as a single process (Figure 1.1). The model is conceived as a holistic system that contains within itself smaller systems and is itself part of a larger system. It places the needs and experience of building users at the heart of the model because, as the opening sentence explains:

“It is obvious that buildings are for people.” (BPRU, 1972)

The BPRU model has been chosen as the underlying framework for this chapter because it embraces the complexity of buildings as systems within complex social and environmental systems and tries to understand them as a series of interrelated systems. The following section explains how the BPRU model has been interpreted and used to analyse and evaluate the performance of the NSW Demountable Classroom (Figure 1.2).

The Building Performance Research Unit model

The BPRU model provides a framework for understanding, categorising and evaluating sub- and meta- systems that come together to create the whole. At its simplest the model consists of “Operative Systems” and “Evaluation Systems” (Figure 1.2).

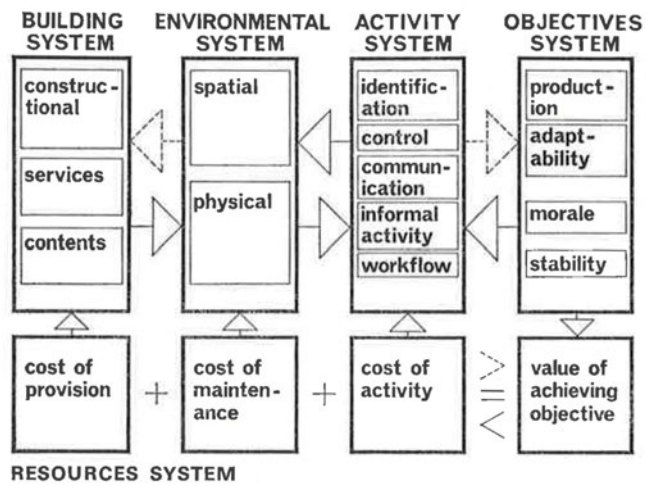


Figure 1.1: BPRU Building Performance System
(BPRU, 1972)

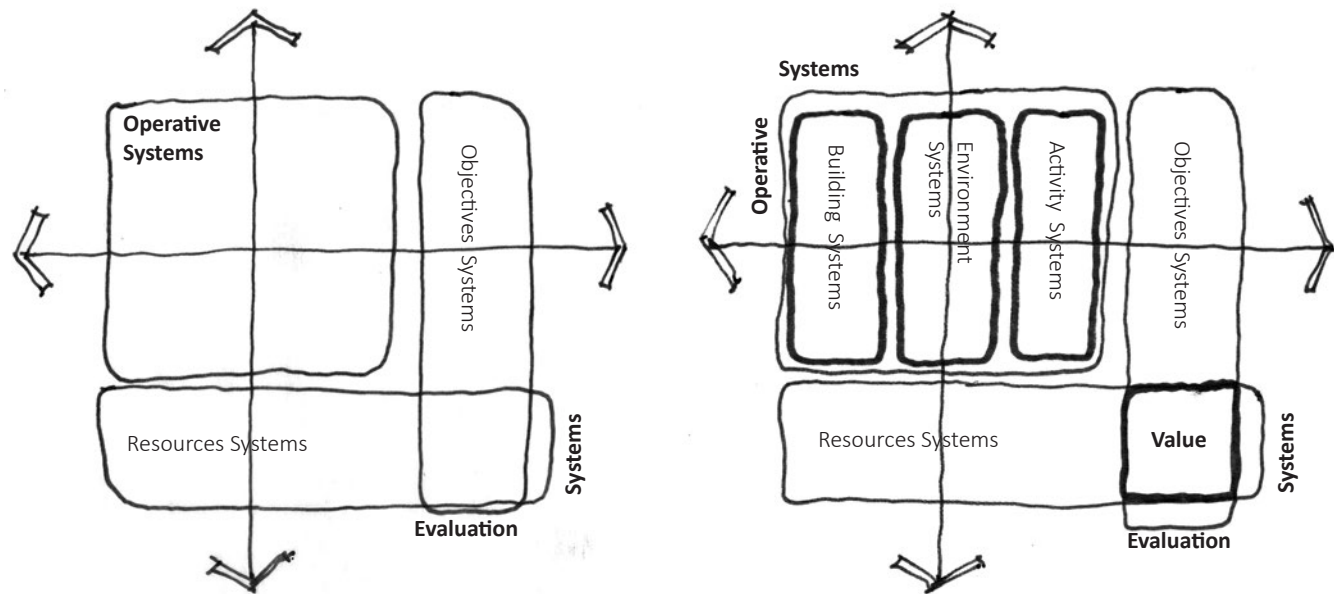


Figure 1.2: The Building Performance Research Unit model re-drawn
The Building Performance Research Unit model simplified (left) and illustrating the five primary systems (right)
(Diagrams by author)

Operative Systems are the physical and social structures, processes and activities that allow a building to exist and operate. The evaluation systems set out the objectives of the whole system (Objectives System) and the resources used to meet those objectives (Resources System).

Within the “Operative Systems” are the “Building Systems”, “Environmental Systems” and “Activity Systems”. The Building Systems deal with the fabric of the building and the method of construction, manufacture and deployment. The Environmental Systems cover the strategies that are designed to create a comfortable internal environment. The Activity Systems are the activities that take place in the building, in this case teaching and learning.

The Evaluation Systems evaluate the Operative Systems in terms of the purpose of the building as a social entity, the “Objective System”, and the means used to meet those objectives, the “Resources System”. The means, that is the Resources System, includes social, environmental and economic costs and benefits. Thus the framework creates a means of understanding the economic, social and environmental value of the building.

It is important to recognise that the BPRU model provides a framework that is flexible and so adaptable rather than a rigid taxonomic methodology. Like all frameworks it contains within it a particular perspective, in this case arguably a utilitarian perspective, that omits the essential poetic quality of architecture articulated by

“delight” in the Vitruvian triad of “firmness, commodity and delight” (Vitruvius, 25 BC (Circa) Trans. 1826).

One can argue that an important “objective” for any classroom is “delight”. As Barrett et al argue:

“A classroom in a primary school is for children, and arguably should be designed to make attending school an interesting and pleasurable experience.”
(Barrett et al., 2015)

Thus “delight” has been included as an “objective” within the “Objectives System” for this analysis.

The following parts of this chapter are structured around this framework and conclude with a discussion of the value of the NSW Demountable Classroom to the communities the buildings serve. This discussion identifies the benefits, challenges and opportunities for this building type.

1.3 The Objectives system: The need for the Demountable Classroom

The description of the need for, and purpose of, the Demountable Classroom system in NSW has remained constant over the five decades that they have existed. In his pamphlet describing the changes and advances in the design of NSW schools between 1962 and 1972 Underwood (1972, p.11) explains that the new “Divisible Mobile Classroom” was designed by the Department for Public Works in 1965:

“[to provide]

- *virtually instant accommodation*
- *temporary facilities in special areas*
- *augmentation of existing schools*
- *a convenient means of adding to and later subtracting from existing schools.”*

Today the NSW Department for Education statement on Demountable Classrooms (NSW Government, 2014) explains that the purpose of the Demountable is to:

- provide accommodation for peak enrolments
- meet accommodation needs in schools from increased enrolments
- meet emergency needs as a result of fires or natural disasters
- meet needs arising from capital works or maintenance projects in schools.

The interviewees tell a similar story. Over the 35 years of their collective experience, they explain that the need

for and purpose of the NSW Demountable Classroom has been and remains the provision of emergency accommodation and accommodating fluctuating school populations.

Government Education Policy’s effects on the demand for classrooms

Government policy has been facilitated by the availability and utility of the Demountable Classroom system. Over the last 50 years a succession of policy decisions have increased the number of classrooms needed in schools. In 1961 the Wyndham report was published and became the Education Act of 1962. The act increased the school leaving age by one year to 16 years old and expanded the number of subjects to be taught to create a broad liberal education for pupils of all abilities (Hughes, 2002). In 1979 the Government cited the continuing drive to reduce class sizes as a reason for increasing the use of Demountable Classroom buildings (Hansard NSW 14/08/1979). Between 2004 and 2007 the Government instigated a specific policy for reducing the size of classes in Kindergarten, year 1 and year 2 to 20, 22 and 24 pupils respectively. In 2012 the school leaving age was raised further to 17 years old increasing the compulsory years at secondary school from 4 to 5. Each of these policy changes significantly increased demand for classrooms in individual schools.

Pedagogy has also changed significantly since the Demountable School was introduced 50 years ago. It has moved from a “chalk and talk” approach, led by a teacher instructing pupils sitting in rows, towards a

student-led approach to learning that requires “break out” spaces for group work combined with more traditional class arrangements for instruction. The development of pedagogy has led to the need to create a diversity of teaching spaces to accommodate the new teaching methods (Dovey and Fisher, 2014).

Demographics

The initial driver for developing the rapidly deployable classroom was the rapid growth in the NSW population between 1945 and 1971/72 and the corresponding growth in school populations. Associated with the growing population was the risk and later the reality of changing demographics within suburbs as young families matured. Burkhardt (1980) explores this problem in his thesis “Planning for the provision of school facilities in new communities in New South Wales” in which he illustrates that peak enrolment of a school is likely to be substantially higher than the long term average. Burkhardt compared the changing school demographics in areas of public housing projects and private housing developments. His data shows that in private housing developments, with considerably more diverse types of household than public housing projects in the 1970’s, it may take 15 years for the population of a new school to reach its peak and more than 25 years for the school’s population to stabilise around the long term average (Figure 1.3).

When the rate of overall population growth in NSW moderated after about 1980, the challenges raised by changing demographics in the State and specifically

Figure 8.2 A COMPARISON OF THE ENROLMENT PROFILES OF TYPICAL HOUSING COMMISSION AND PRIVATE DEVELOPMENTS

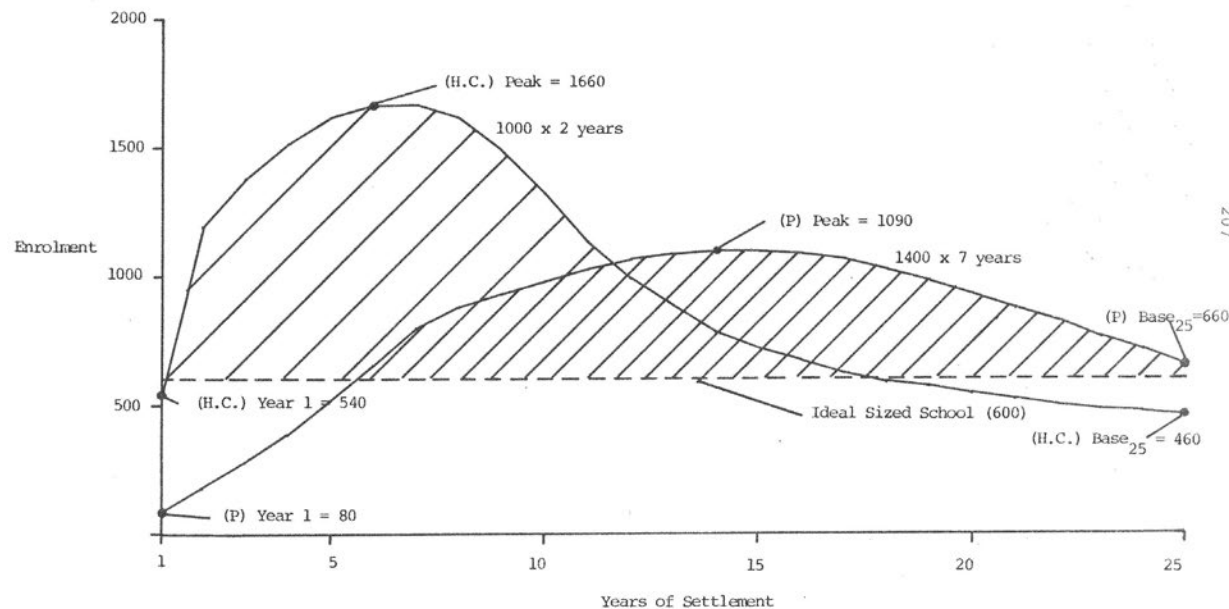


Figure 1.3: School population fluctuation

Graph from Burkhardt (1980) illustrating school population changes over time.
(H.C. – Housing Commission; P – Private housing estates)

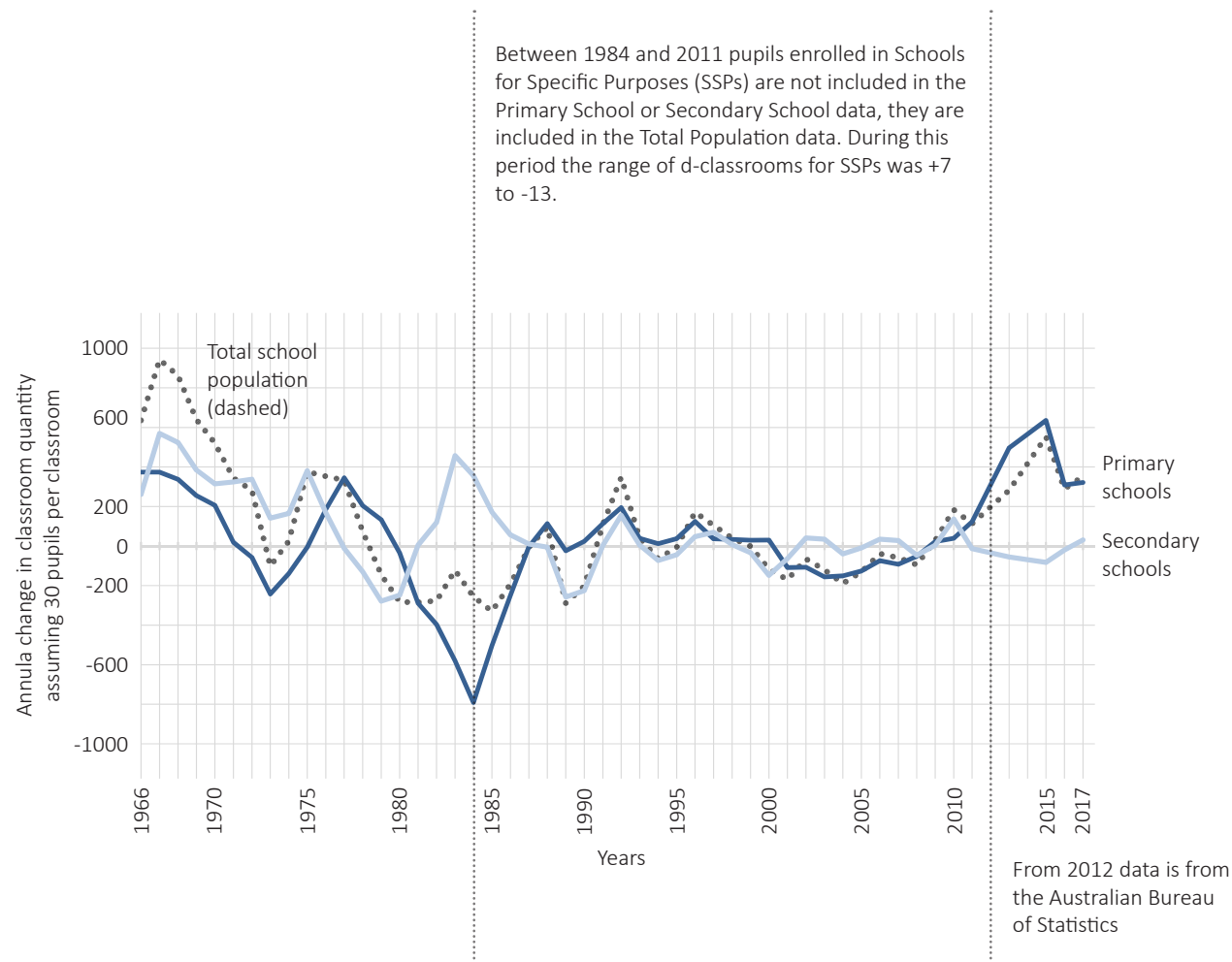


Figure 1.4: Change in the number of classrooms needed in NSW Schools over time

Graph illustrating the annual change in the number of classrooms required for the school population assuming 30 students per classroom. Data is sourced from the NSW Government 2011 Statistical Bulletin: Schools and students in New South Wales, Table 7 - School population statistics from 1965 - 2011 (NSW Department of Education and Community, 2012) and the Australian Bureau of Statistics (Australian Bureau of Statistics, 2018).

in suburbs continued: Figure 1.4 illustrates how the primary, secondary and total population of pupils in NSW Government schools has fluctuated between 1965 and 2017. In order to make the graph directly relevant to the use of Demountable Classrooms the graph uses changes in 'Classroom Units' from year to year, assuming one classroom is 30 students. The NSW Department of Education estimates that the school population will rise by a further 21% by 2031 (NSW Department for Education, 2017).

The problem of the changing scale of demand for schools in different suburbs has been raised regularly in the NSW Parliament. Examples of solutions to the problem include the development of complete Demountable Schools in Bateau Bay, Lake Macquarie in 1977 (Hansard NSW 24/03/1977), Baulkham Hills in 1979. In 1983 the construction of the Eraring power station in Morriston led to a sudden increase in the local school population and the use of Demountables (Hansard NSW 01/12/1984). More recently entire schools have been created from Demountables in Chatswood and in Ultimo, in Sydney's CBD (Interview E, 2014, NSW Department for Education, 2016, Architecture AU, 2018).

Population fluctuation and changing local demographics also leads to schools closing. This is illustrated by a debate in parliament in 1989 about the closure of public schools in Mosman where the local school was no longer sustained by the changing demographic of the local population. According to the debate 197 schools had already been closed across NSW between 1976 and 1988 (Hansard NSW 11/04/1989).

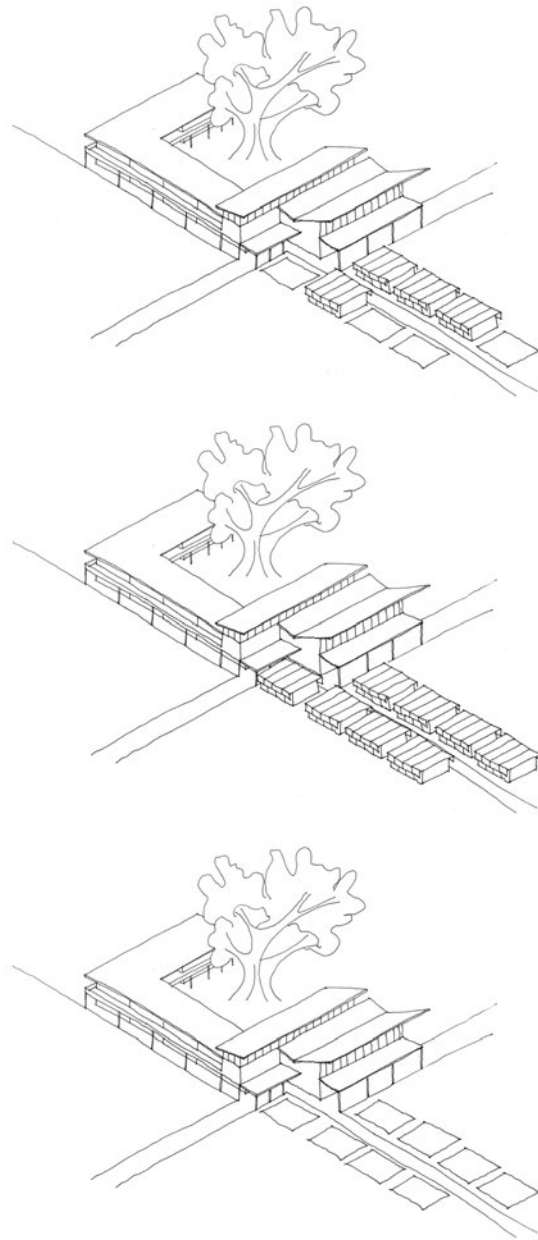


Figure 1.5: Core plus system

The core plus system illustrated in three stages that allow a school to expand and then contract over time using the NSW Demountable Classroom system.

(Drawings by author)

Core plus Schools

In the 1970's, 80's and 90's the NSW government had a policy of developing "core plus" schools where about 60 or 70% of the school was built as permanent facilities and 30% of classrooms were Demountable (Underwood, 1972, Interview B, 2014, Gan and Newton, 2012a). The concept allows teaching capacity in these schools to be adjusted rapidly to accommodate changing demand (Figure 1.5).

Emergency needs

There are many examples of Demountable Classrooms providing the NSW Government with school accommodation following arson, accident or natural disaster. The NSW Government maintains an entire Demountable School in reserve for use in emergency situations such as these (Interview D, 2014).

Delight

Notably absent from the objectives identified by the NSW department for Education (NSW Government, 2014) and others is any reference to 'good design', inspiration or 'delight'. What Fisher (2003) describes as, *"the 'actuality', or phenomenological experience, of the interaction between learning and the physical environment"*.

The OECD defined delight as:

“[the] essential and elusive quality of delight that lifts the spirit and affirms to both students and staff that there is more to education than simply acquiring the skills and knowledge to survive in an increasingly competitive world.” (OECD, 2001, p. vii)

The impact of the design of schools and school classrooms on pupil and teacher performance is a complex area of research (Barrett and Barrett, 2010). Tanner (2000) and others (RIBA, 2016, Barrett et al., 2015, Fisher, 2003) argue that the holistic experience of the built environment influences behaviour, which in turn effects learning outcomes, staff retention, efficiency and performance. Anecdotal evidence of this was provided in the Future Proofing Schools project investigating relocatable classrooms across Australia (Gan and Newton, 2012b). The Royal Institute of British Architects recent report “Better Spaces for Learning” (RIBA, 2016) used a variety of methodologies including a poll of 501 teachers from across the UK to ascertain the influence of the design of schools on their own and their pupils' performance. It reported an increase in staff productivity in “well designed schools”, that 9 out of 10 teachers believe school design is important, and that 1 in 5 teachers have considered resigning because of the poor condition of school buildings. Studies that use empirical evidence to demonstrate a connection between the physical environment and learning outcomes necessarily objectify 'good design' and so inevitably risk losing “the essential and elusive quality” that creates delight. Never-the-less their research is

informative. Tanner (2000) found a positive correlation between, “a positive overall impression” and higher test scores in 44 elementary schools in Georgia, USA. In a study of 153 primary school classrooms in the UK Barrett et al (2015) were able to quantify the impact of the physical environment of the classroom on student performance. They found that a combination of seven parameters (light, temperature, air quality, ownership, flexibility, complexity and colour) accounted for 16% of the variance in pupils' learning progress, about 50% of which is connected to factors associated with Indoor Environmental Quality (IEQ).

1.4 Building system: The Building fabric and construction of the NSW Demountable Classroom

NSW Demountable Classrooms consist of 4 or 5 units approximately 8.8m (L) x 2.4m (W) x 3.3m (H). One of the primary objectives of the design of the Demountable Classroom system was to provide a rapidly deployable and easily transportable classroom building (Underwood, 1972). This leads to a number of key design decisions based on

- Maximum dimensions permissible for road transport without an escort
- Maximum transportable weight and deployment weight
- Deployment method
- The need for a robust modular construction system

This means that the classrooms had to be robust and relatively light leading to the use of lightweight framed construction.

Deployment Method

The original proposal for deploying Mk. I classrooms was to use jacks (Underwood, 1972). This strategy has been superseded by the use of cranes (figures 1.6 & 1.7). Mk 1 classrooms were designed without lifting points so chain slings are used under the roof overhangs. Mk. II classrooms were designed with lifting points attached to the top of the vertical steel posts. Recently a policy of modifying the

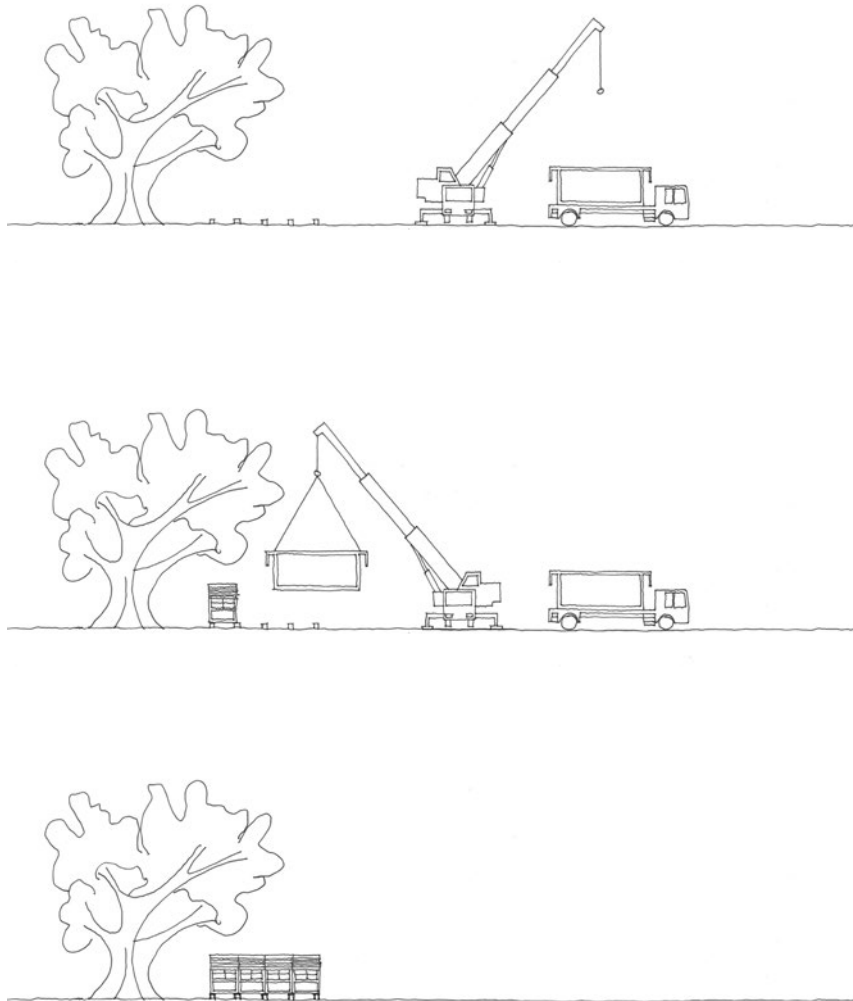


Figure 1.6: Deployment of a Demountable Classroom
(Drawings by author)



Figure 1.6: Deployment of a Mk I Demountable Classroom module
(Photographs by author)

Mk I classrooms to add lifting points has been implemented. These are additional steel flanges welded to the existing frame during substantial refurbishment exercises.

Modular construction

The Demountable Classroom system was conceived as a modular system at the macro and micro level. At the macro level classrooms, libraries and office buildings can be delivered to any site in NSW to create an entire school or augment existing schools. The classrooms themselves are made from four units and the walls in each unit are made from a variety of wall modules designed to accommodate the various functions the system is intended to accommodate (Figures 1.8 & 1.9). The Mk II panels were designed to facilitate the rapid interchange of panels and the adaption of buildings. In practice wall panels are rarely changed, typically only during substantial refurbishment work.

The ambition to create a system of interchangeable building modules was thwarted through perhaps the most mundane of processes: The classroom modules are fixed together by bolted connections through steel plate flanges on the outside of the classrooms. For expediency and ease of installation on the initial site these were drilled and bolted on-site during the first deployment of a unit (Interview C, 2014)/Observation), a very practical approach by the installation team that ensured that the holes on each adjacent classroom unit lined up. Unfortunately this has resulted in a situation where only the modules placed together during the

first deployment have holes that line through so each classroom unit can only ever be erected in its original configuration!

Building fabric

The NSW Demountable Classrooms are stored and refurbished at Cessnock and Golburn jails. The maintenance programmes at Cessnock and Golburn jails (Corrective Services Industries) strip the old classrooms back to the primary frame and rebuild them. A number of visits were arranged to undertake a detailed physical survey of classrooms in various stages of repair ranging from the primary frame to nearly complete. Because the work is undertaken by prisoners in a secure yard where cameras are not permitted the survey was recorded using sketches, physical measurements and notes.

The physical survey of both the MK 1 and MK 2 classrooms in combination with reference to the original drawings (NSW Government Architects Office, 1983, NSW Government Architects Office, 2001, NSW Government Architects Office, 1976 (circa)) show limited insulation, well below the current statutory regulations, and considerable thermal bridging through the primary and secondary steel frames. The primary frame of the Mk. I and Mk. II classrooms is a substantial steel frame described by interviewees as “bomb proof” (Interview A, 2014) (Figure 1.8).

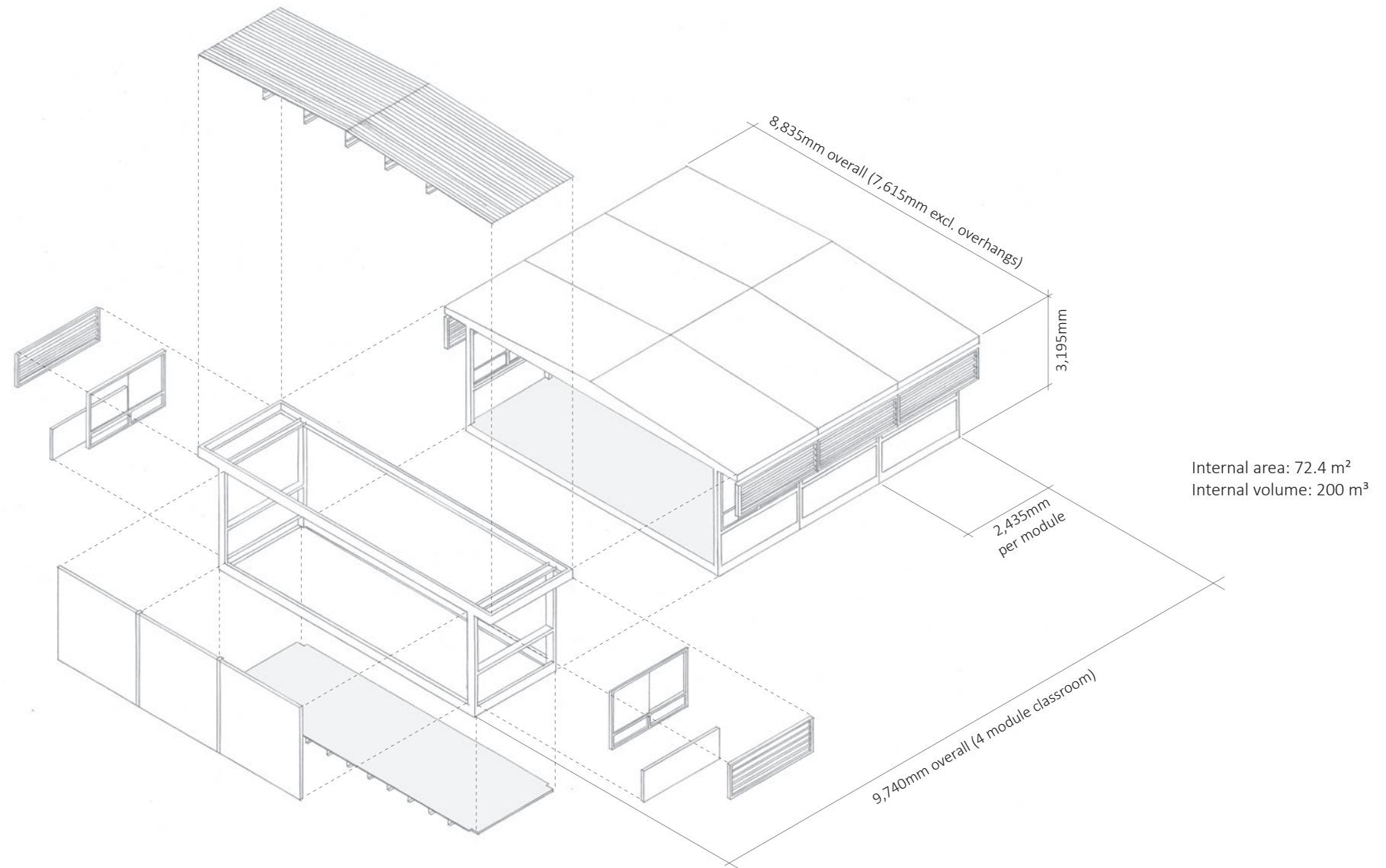


Figure 1.8: Mk I Demountable Classroom (exploded isometric)

*Mk I Demountable Classroom exploded isometric drawing illustrating the underlying modularity of the system.
(Drawings by author)*

1.5 Environmental System:

Internal Environmental quality and the passive and mechanical control systems

The Environmental System as a whole and the many sub-systems that it encompasses govern the physical comfort of the people who use the classrooms. Expressed more formally the Environmental System governs the Indoor Environmental Quality (IEQ) of the NSW Demountable Classrooms. IEQ is the combined effect of the following four factors on the experience of people who use the classrooms (Mendell and Heath, 2005, Soccio, 2014):

- Light
- Acoustics
- Air quality (Indoor Air Quality, IAQ)
- Thermal comfort

These four factors are mediated by the physical fabric of the classroom buildings and the passive and mechanical systems, for example shading and air conditioning, that are employed to control and change the IEQ in the classroom. Together the IEQ and the physical systems constitute the Environmental System.

The Physical fabric: passive and mechanical control systems

Internal comfort does not appear to have been a priority in the original design brief. The lightweight poorly insulated building fabric is unsuitable for creating an “acceptable” internal thermal environment, particularly in the more extreme climates away from the NSW coast. Buildings that are constructed using lightweight construction systems closely follow, or exceed, the external diurnal temperature profile (Pearlmutter and Meir, 1995, Cardinale et al., 2010, Sugo, 2009).

The external fabric of the NSW Demountable Classroom is constructed from a steel frame with numerous thermal bridges and very little insulation (refer to Chapter 2 and Soccio 2014 Case Study 4). Pearlmutter and Mier (1995) studied the thermal performance of lightweight housing in the arid Negev desert, Israel, using simulation and monitoring. The construction of these simple houses is similar to the NSW Demountable Classroom. Pearlmutter and Mier found that the internal temperature of the lightweight houses ‘exceed external temperatures in the afternoon’. They also observed that the lightweight structure

"....reacts to [thermal] stimuli in an extremely sensitive manner, changing temperature at the slightest input of energy."

Pearlmutter and Mier (1995) and Cardinale et al's (2010) research suggests that lightweight construction may not be the most appropriate fabric system for the climates of NSW.

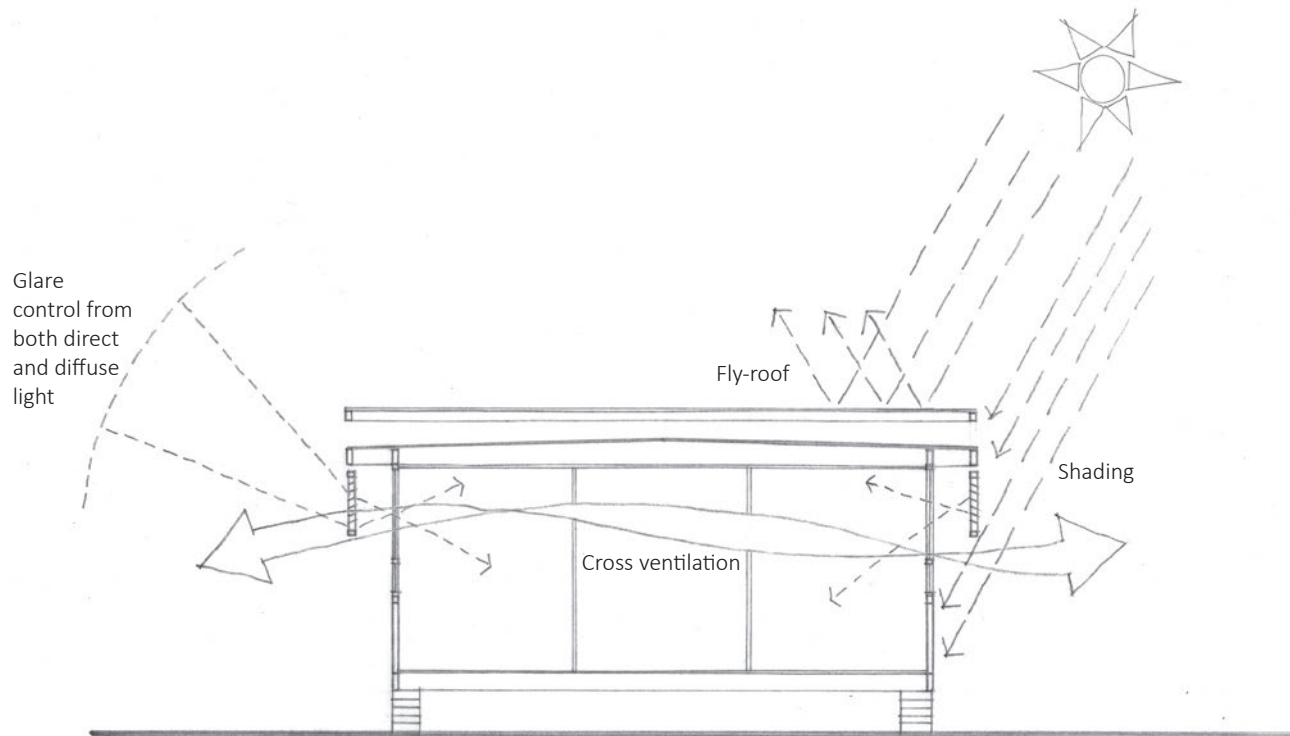


Figure 1.10: Passive environmental control strategies employed in the Mk 1 NSW Demountable Classroom
(Diagram by the author)

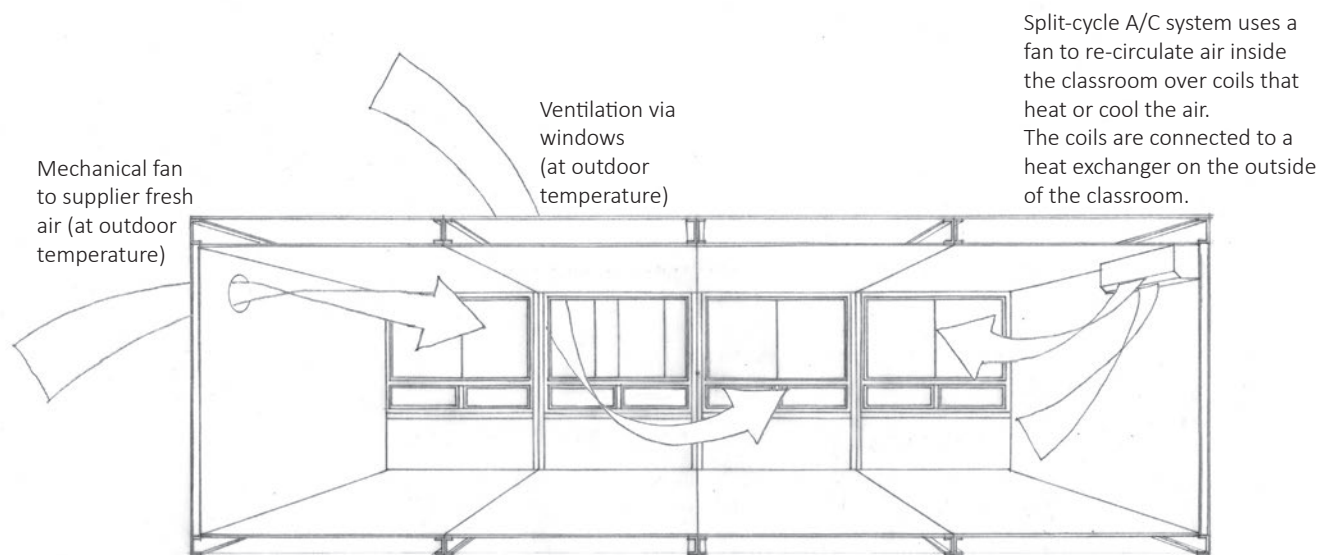


Figure 1.11: Mechanical environmental control systems in the Mk 1 NSW Demountable Classroom
(Diagram by the author)

Originally three passive strategies were employed to try and maintain comfort inside the classroom: (Figure 1.10)

- Shading the windows to reduce solar gain and reduce internal glare.
- Cross ventilation through opposing opening windows.
- The use of fly roofs in particularly hot climates.

In 2003 active environmental control using AC split-cycle systems was introduced to all NSW Demountables (Hansard NSW 8/09/2003) and has superseded the fly roof. The current specification of the AC systems is two 6.5kW split cycle systems per classroom (13 kW in total*). The split cycle system cools or heats and recirculates the air that is already inside the classroom. The split cycle systems do not provide ventilation because they do not supply any fresh air from outside. Fresh air from outside for ventilation must be provided either by opening windows or via the mechanical fan, both of which supply unfiltered air directly into the classroom at the current external air temperature (Figure 1.11).

IEQ in classrooms: A complex system

The four factors that constitute IEQ in classrooms are interrelated and interactive (Heschong, 2003, Higgins et al., 2005, Soccio, 2014). For instance, increased natural light may be beneficial but may also increase solar gain, reducing thermal comfort. Increased natural ventilation

** This is the rated capacity of the A/C system to move thermal energy in or out of the space as defined by AS/NZS 3823.*

may help mitigate the increased solar gain. Provided the outdoor air is clean increased ventilation may improve indoor air quality but also reduce the acoustic quality of the space by introducing external noise that makes it more difficult to understand the teacher. There is extensive literature exploring how these various factors influence student learning both in combination and individually. Mendell and Heath (2005) argue that poor IEQ in classrooms impairs learning either by increasing absenteeism, and so reducing the opportunities to learn; or by impairing performance in the classroom as a consequence of discomfort or other physical and cognitive impacts. Others argue that learning may also be impaired by a reduction in the motivation of students and teachers as a consequence of poor IEQ in classrooms (Higgins et al., 2005, RIBA, 2016, Blackmore, 2011, Chan, 2009, Bowen et al., 2008).

Chan (2009) concludes that it is the quality of the environment, i.e. the classroom, rather than whether or not it is a permanent or a portable classroom that is important. Importantly he also highlights a finding by Heise and Bottoms (1990) in which teachers expressed the view that it is their ability to teach rather than the physical environment that is the most important factor in enabling students to succeed. Chan used a synthesis approach to analyze 7 studies into the impact of portable classrooms on learning across 5 states in the USA.

Soccio (2014) has undertaken the only post occupancy evaluation of portable, prefabricated and relocatable

classrooms in Australia. Soccio concluded that IEQ in classrooms, and the opportunity to improve the IEQ in classrooms, is a consequence of three broad categories of factors:

- The construction of the classrooms, i.e. the physical fabric and systems.
- The design of the classrooms, including where they are placed within the school. For instance how close they are to a busy road, building site or other classrooms.
- Occupant behaviour, including how they choose to operate the building, or whether or not they know how to operate the building. A point reiterated by Cleveland et al (2015): 'The issue was not educating teachers about how to press the button, but when to press [the button].' (p.72)

Many of the investigations into the relationship between the Environmental System and learning, or elements of the Environmental System and learning, acknowledge the difficulty in disentangling cause and effect in such a complex physical and social system (Blackmore, 2011, Chan, 2009, Bowen et al., 2008, Heschong, 2003, Cleveland et al., 2015, Berry, 2002). All of these studies, and others (Mendell and Heath, 2005, Daisey et al., 2003, Higgins et al., 2005, Vinson et al., 2002) conclude that poor IEQ in classrooms and the fabric and systems that create poor IEQ contribute to less effective teaching and learning.

IEQ in classrooms: Individual factors

There are a broad range of studies and literature reviews from around the world exploring the influence of the four individual factors of IEQ on the performance of students and teachers in classrooms as well as their effect in various combinations. Higgins et al (2005) and Soccio (2014) both provide detailed reviews of existing research literature concentrating on IEQ. (Blackmore, 2011) uses an extensive literature review to explore the connection between learning spaces and learning outcomes based around a temporal framework that follows the design, construction, occupation and use of spaces. Daisey et al (2003) reviews the literature relating to Indoor Air Quality (IAQ) while Mendell and Heath (2005) reviews the literature relating to IAQ and thermal comfort in schools. De Dear et al (2015) include a literature review exploring the impact of thermal discomfort on learning.

All of the studies listed above consider IEQ factors and their relationship to learning outcomes in classrooms generally rather than in Demountable or portable classrooms specifically. With the notable exception of Soccio's study, there are no detailed studies of IEQ in Demountable Classrooms in NSW or more generally across Australia (Soccio, 2014, Blackmore, 2011). Soccio studied 8 prefabricated classrooms and 2 permanent classrooms located in 5 climates across Australia, including one NSW Demountable Classroom in South West NSW (Case Study 4). There are numerous anecdotal reports about IEQ and thermal comfort in NSW Demountable Classrooms in Parliament (Hansard

NSW), in the press, and Professor Vinson's report (Vinson et al., 2002). There are also anecdotal reports from similar buildings across Australia, for instance Fuller and Luther (2003) or the Future Proofing Schools reports which Soccio helped to write (Future Proofing Schools ARC Linkage Project, 2011, Future Proofing Schools ARC Linkage Project, 2012).

There have been a number of detailed studies in the USA exploring different aspects of IEQ in portable, relocatable or prefabricated classrooms (Chan, 2009, Jenkins et al., 2003exec, Whitmore CA et al., 2003, Shendell, 2003, Shendell et al., 2004b, Apte et al., 2002). These studies report both objective data and the subjective perception of users. Whitmore et al (2003) conducted a comprehensive study surveying a large range of IEQ factors in portable and permanent classrooms with complete results from 67 schools across California.

The detailed design of the form and fabric of these classrooms is not always reported and the climate in which the classrooms are located may be very different from the climates found in Australia and more specifically in NSW. What is interesting is that the IEQ problems being reported are similar to those reported in Australian studies.

Table 1.1 sets out a comparison between the issues identified in the studies from the USA and the Australian studies. The following section provides a brief review of literature relating to each of the four factors of IEQ.

	California study	Australian studies
Light		Glare and solar gain are problems
		NSW Demountable classroom had high daylight levels.
Acoustics	Portable classrooms had worse acoustic performance than traditional classrooms with 50% exceeding the outdoor noise nuisance standards (55 dBA).	Excessive noise levels that exceed recommendations are a problem.
	Noise levels inside all classrooms failed the international standard of 35 dBA.	
	50% of noise level measurements exceeded 55dBA	Poor Acoustic performance
	68% of air-conditioning units are turned off because of excessive noise.	Teachers turn off A/C units due to excessive noise.
Air quality	CO2 levels exceed 1000ppm 40% of the time in traditional and portable classrooms suggesting poor ventilation in all Californian classrooms.	Poor or inadequate indoor air quality: Mean CO2 levels > 1000ppm in 2/7 classrooms in summer and 3/7 classrooms in winter with an additional classroom borderline during summer and winter.
	17% more schools complained about poor IEQ in portable classrooms than traditional classrooms	NSW Demountable Classroom mean CO2 level is >1000ppm for more than 25% of occupied hours in summer and winter.
Thermal performance	Portable classrooms were colder than traditional classrooms. The survey was carried out during the winter.	Poor thermal comfort seasonally and diurnally (i.e. cold in the morning during cooler seasons and hot in the middle of the day during warmer seasons).
	Complaints about temperature were similar in portable and traditional classrooms (15.8% vs. 17.2% of schools)	High internal radiant (or globe) temperatures.

Table 1.1: IEQ observations from existing studies of relocatable classrooms

Key observations by Whitmore et al 2003 in California and Australian studies (Fuller and Luther, 2003, Future Proofing Schools ARC Linkage Project, 2011, Soccio, 2014).

Light

The evidence for the positive impact of natural light on student learning outcomes is not conclusive (Soccio, 2014, Higgins et al., 2005). The Heschong Mahone Group (Heschong, 2003) undertook an extensive study exploring the impact of daylight on learning in a variety of classrooms, including some relocatable classrooms. Initially they concluded that there was a simple positive association between daylight and student performance. Further analysis and data collection led them to conclude that the relationship is more complicated and integrated: Heschong found that the benefits of windows include natural light and interesting views, counter to the narrative that views are a distraction. Anecdotal comments by Soccio in Case Study 4 also support this finding (Soccio, 2014). Heschong found that windows and natural light can also cause excessive solar gain, causing thermal discomfort, and glare, causing visual discomfort, both of which hinder teaching and learning, findings supported by Soccio and the Future Proofing Schools project.

Acoustics

The intelligibility of speech, i.e. instructions and information being shared verbally in the classroom is very important. Younger student's language skills are not as developed as those of older children or adults and so younger students have greater difficulty in separating speech from background noise (Nelson, 2003).

Poor acoustic performance may be due to factors associated with the fabric of the classroom, mechanical

systems within the classroom or factors outside the classroom. For instance multiple hard surfaces, including window glass, may cause excessive reverberation. Mechanical systems, for instance air-conditioning systems, are reported to generate high levels of background noise that interferes with teaching to the extent that they are turned off (Fuller and Luther, 2003, Whitmore et al., 2003, Soccio, 2014). Noise from outside the classroom may result from building sites, major roads, playing fields or aircraft noise.

Whitmore et al (2003) found that the acoustic performance of portable and traditional classrooms was, statistically, the same. All classrooms had noise levels >35dBA and noise levels were >55dBA on more than 50% of measurements. 55dBA is the outdoor noise nuisance level in many Californian cities.

Soccio (2014) found background noise to be a problem in 7 out of the 10 classrooms surveyed in summer and 4 out of 10 classrooms in winter. Interviews with teachers suggest a large proportion of this noise is from the air-conditioning system.

Indoor Air Quality

Literature relating the quality of the indoor environment to student performance regularly cites ventilation rates as a problem in classrooms. There is strong evidence that low ventilation rates in classrooms significantly reduce pupils' attention and vigilance, and negatively affect memory and concentration (Bakó-Biró et al., 2012, De Giuli et al., 2012, Clements-Croome et al., 2008, Berry, 2002). In 2005 Mendell and Heath

published a detailed and critical review of research into the influence of indoor air quality and indoor thermal comfort on the performance of students in classrooms (Mendell and Heath, 2005). They concluded that the weight of evidence suggests, and in some cases strongly suggests, that lower student performance can be linked to poor air quality and thermal conditions.

Laboratory studies by Kajtar et al (2006) and Fisk et al (2013) demonstrate a correlation between higher CO₂ concentrations (>1000ppm) and lower cognitive performance. Bako Biro et al (2012) conducted a field study in 16 classrooms across 8 schools in the UK and concluded that there is 'strong evidence that low ventilation rates in classrooms significantly reduce pupils' attention and vigilance, and negatively affect memory and concentration.' Bako Biro et al recommend that CO₂ levels should not be above 1000ppm, corroborating a similar study by Coley et al (2007) and a recommendation by Daisey (2003) following a wide ranging literature review.

Soccio (2014) reports that the mean CO₂ concentrations in the 8 prefabricated classrooms she studied exceeded 1000ppm in 3 out of 7 (no data for case study 8) in the summer and winter with case study 7 reported with a mean of 997ppm in winter. The single NSW Demountable Classroom that was studied had mean CO₂ levels >25% above the recommended level of 1000ppm in summer and winter when the air conditioning was operating but 33% below this level when the classroom was naturally ventilated in spring and autumn.

Indoor CO₂ concentrations are used as a proxy for ventilation rates and Indoor Air Quality (IAQ) (Daisey et al., 2003). Shendell et al (2004a) used CO₂ concentration as a proxy for ventilation rates in 434 classrooms and showed a correlation between higher CO₂ concentrations and lower attendance rates. Other research into poor IAQ in classrooms measures indoor pollutants and demonstrates a connection between poor IAQ and increased incidence of poor health (Daisey et al., 2003, Mendell and Heath, 2005).

CO₂ levels in classrooms are often reported as either mean values or values based on spot checks (Shendell et al., 2004a, Soccio, 2014, Whitmore CA et al., 2003, De Giuli et al., 2012). The concentration of CO₂ inside classrooms varies over time as a consequence of ventilation rates, occupancy level and activity level (Figure 1.12) (Luther and Horan, 2014, Luther, 2012) . This is significant since the mean values may conceal very large variations in CO₂ levels during the day indicating significantly higher and lower CO₂ concentrations at different times (Bakó-Biró et al., 2012, Whitmore CA et al., 2003, Luther, 2012, Luther and Horan, 2014). Whitmore et al used continuous sampling in 136 classrooms (92 portable and 44 permanent) in California. The difference in CO₂ levels between classroom types were not significant but the variation in CO₂ concentrations within classrooms was significant: The mean CO₂ level was 1070ppm, CO₂ levels exceeded 1000ppm 42.8% of the school hours and exceeded 2000ppm 9.8% of the school hours.

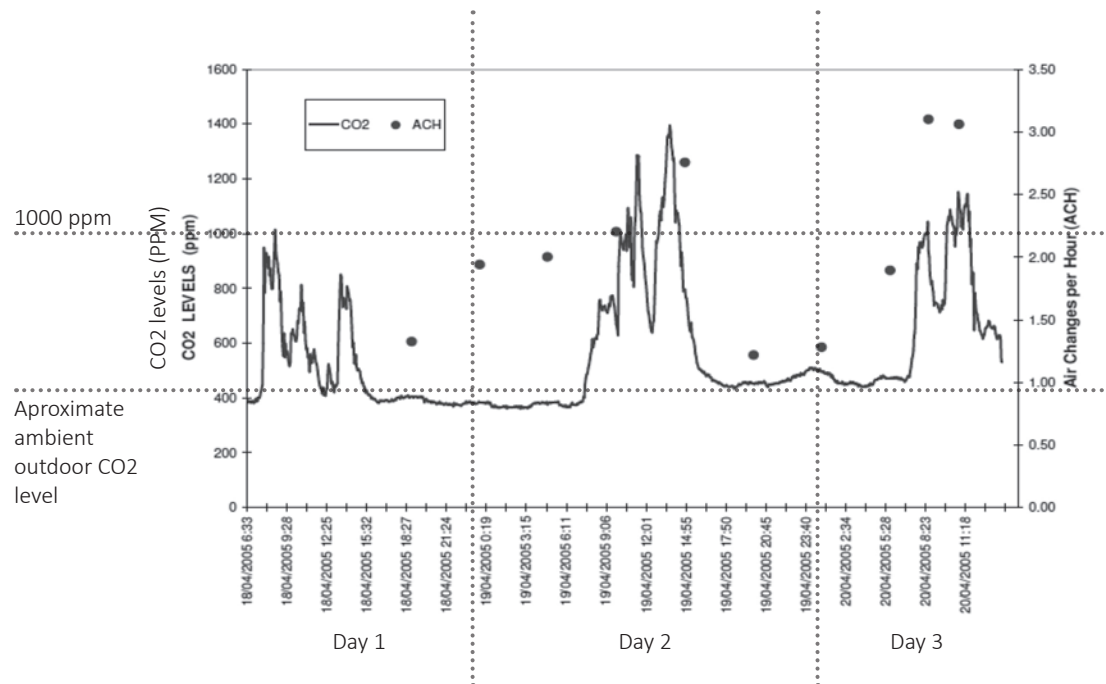


Figure 1.12: Variation of CO₂ levels in a classroom

Variation of CO₂ concentrations in a Chemistry Lab over three days in a school in Melbourne.

Graph from Luther (2012) 'Review of Measurements in Schools to Improve IEQ' with additional annotation by the Author.

CO₂ levels in the 16 UK classrooms monitored by Bako Biro et al (2012) show a very wide range of CO₂ concentrations. In 3 out of 16 classrooms CO₂ concentrations sometimes exceeded the range of the instruments (5000ppm). Mean CO₂ concentrations range from 644ppm (outdoor level 424ppm) and 2833ppm (outdoor level not recorded). The Standard Deviation (measurement of the spread or variation of data relative to the Mean) ranges from 23% to 70% of the Mean illustrating the wide variation of CO₂ concentrations, and associated ventilation rates, inside individual classrooms during the school day and between different classrooms.

All studies conclude that adequate ventilation rates in school classrooms are essential for maintaining appropriate indoor air quality (IAQ). Bako Biro et al (2012) and Daisey (2003) recommend a minimum outdoor ventilation rate of 8l/s per person* following earlier ASHRAE standards (ASHRAE 62, 2001). The current ASHRAE standard 62 (2016) recommends slightly different ventilation rates depending on the age of the children:

- For children <5 years old: 8.6 l/s.person
- For children aged 5 – 8 years old: 7.4 l/s.person
- For children aged >8 years old: 6.7 l/s.person

***WHAT DOES 8l/s MEAN IN A CLASSROOM?**

The volume of the Mk 1 NSW Demountable classroom is 200m³. With an occupancy of 31 people (30 students and 1 teacher) and a ventilation rate of 8l/s.person the ventilation rate per hour is 892,800l/hour or 892.8m³.

Therefore a ventilation rate of 8l/s mean an Air Change Rate (ACH) is about 4.46 ACH in a Mk 1 NSW Demountable Classroom

Thermal comfort

Mendell and Heath (2005) reviewed 11 papers that looked at the association between thermal conditions and performance or attendance in schools. Of those

- 3 found no statistically significant or noteworthy relationship.
- 5 found statistically or noteworthy outcomes that indicate decreasing thermal comfort caused a decrease in performance or attendance.
- 2 papers found conflicting results indicating both positive and negative outcomes from reduced thermal comfort.

Our perception of comfort

International standards for defining comfort are based around a steady state or heat balance model (ISO_7730, 2005, ASHRAE 55, 2013). The Adaptive Comfort Model, derived from field data, understands our perception of thermal comfort as a dynamic experience that is related to the recent or seasonal outdoor temperature (Humphreys, 1978, de Dear and Brager, 1998). In 'Thermal delight in Architecture' Heschong (1979) argues that our interaction with the thermal environment is a considerably more complex and dynamic social, cultural and physiological thermal experience than our current empirical models and standards allow for (ref. Chapter 5).

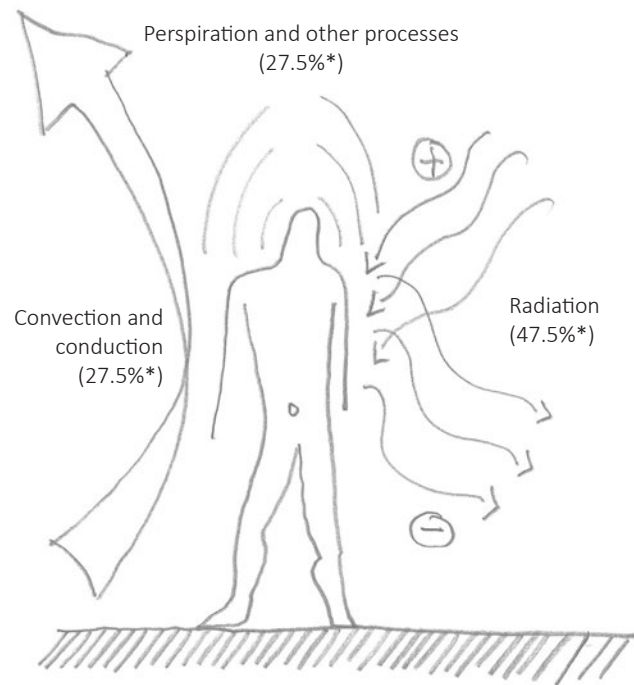


Figure 1.13: How we perceive comfort

An illustration of the perception of thermal comfort through the primary mechanisms of heat transfer (by the author after Moe (Moe, 2010) with thanks to Le Corbusier)

*The quantities are by Moe 2010

In essence people's perception of comfort is derived from four factors:

Radiation: Radiant temperature

The radiant temperature of the surrounding surfaces. This is the reason standing in the sun feels pleasant or warm even if the air is cold.

Conduction: Air temperature

The temperature of the air around us.

Convection and evaporation

The cooling effect of air movement, particularly when this is augmented with evaporation through sweating.

Experience and expectation

Our previous thermal experience and current expectations. This is the basis of the adaptive comfort model. Simply stated we acclimatise to particular seasons through our recent thermal experiences and those experiences set our expectation of what is cool, comfortable or too warm.

The first three of these factors deal with the physical exchange of thermal energy through the three primary modes of heat transfer (radiation, conduction and convection) (Figure 1.13) (Szokolay, 2008) (p.16). The fourth factor is temporal and more subjective (Humphreys, 1978). The combination of air temperature and radiant temperature has been shown to dominate our perception of comfort and are used to define the "Operative Temperature" which is taken to be the mean of the two (de Dear et al., 2014). The "comfort zone"

is defined using the operative temperature based on recent mean daily temperatures.

Thermal preferences and academic performance

Studies in climates ranging from the cool temperate UK to the sub tropics of Taiwan have shown that there is a preference among students and staff for “comfortably cool” conditions (Auliciems, 1969, Auliciems, 1972a, Zhang et al., 2007, Hwang et al., 2009, De Giuli et al., 2012).

De Dear et al (2015) undertook a thermal comfort survey in mechanically cooled and naturally ventilated school classrooms in nine schools located in mild and warm temperate, subtropical and arid climates in Australia. The study explored the thermal preferences of children in all classrooms without distinguishing between air-conditioned, mixed mode or naturally ventilated classrooms. The study found that children preferred a lower neutral temperature (neither hot nor cold) than that predicted for adults under the same conditions. The study also found that children demonstrated ‘considerable adaptability to indoor temperature variations’. The authors suggest that ‘more diverse thermal exposures in classrooms could possible account for greater degrees of thermal adaptability.’(SIC); and that ‘students in locations exposed to wider weather variations [show] greater thermal adaptability than those in more equable weather districts.’. An observation also made by Pepler (1972).

More detailed studies relating the temperature in classrooms and student academic performance have

also shown a correlation between “comfortably cool” conditions and higher levels of student performance (Auliciems, 1972b, Wargocki and Wyon, 2007, Pilcher et al., 2002). Wargoki and Wyon (2007) undertook an experiment using a pair of classrooms in a school in Denmark during the late summer. The experiment was performed twice over two successive years using a ‘cross-over’ design where the air temperature was reduced in one of the classrooms for a week and then the situation was reversed. They conclude that reducing the temperature in the classrooms improved the performance of two language based and two numerical tests. The improvements were mainly in terms of speed rather than errors. The children’s thermal sensations were reported as neutral rather than warm in the cooled classroom. An earlier study (Schaer and Shaffran, 1973) reported similar findings.

Thermal comfort in NSW Demountable Classrooms

Professor Vinson’s report makes clear the problems that his team found with IEQ in NSW Demountable Classrooms and, specifically, their thermal performance, and the impact this has on the ability of teachers and students to concentrate and learn (p.88) (Vinson et al., 2002). Page 28 of the report includes an account of children being hosed down to keep them cool. Comments in Parliament, the written press and on the radio, suggest that many people regard the NSW Demountable Classroom, and relocatable classrooms generally as uncomfortable places to learn or to teach.

There have been no detailed studies of thermal comfort in NSW Demountable Classrooms (Soccio, 2014, de Dear et al., 2015) but Soccio and the Future Proofing Schools project (Future Proofing Schools ARC Linkage Project, 2012, Cleveland et al., 2015) did undertake some thermal analysis of portable and prefabricated classrooms across Australia. The project collected air temperature and relative humidity data in 8 classrooms across 5 climate types (Tropical/Subtropical/Grassland/Arid/Temperate). The project also collected 'spot samples' of the radiant floor temperature (floor surface temperature) and thermal images of the inside and outside of the classroom buildings. Unfortunately the internal air temperature data tends to be reported as an average for the season (summer or winter) and so disguises the variation in temperature during the day. An issue highlighted by Soccio in a discussion about the internal air temperatures in Case Study 7 (Western Australia, Arid climate) where the mean ambient temperature was reported to be 27°C but occasionally reached 46°C, and was more than 28°C for 36% of occupied hours. The absence of corresponding data for the mean radiant temperature (globe temperature) makes understanding comfort conditions in the case study classrooms difficult. It should be recognized that collecting accurate air temperature and radiant temperature data in classrooms is difficult because the equipment must normally be fixed to the inside of an external wall near the ceiling so that it is out of the reach of children (Soccio, 2014, de Dear et al., 2015).

The study does provide some very useful anecdotal evidence from interviews with teachers and pupils and images taken with a thermal camera inside the classrooms, including Case Study 4 which is a NSW Demountable Classroom located in South West NSW.

Thermal images are, like spot samples, simply an instance in time, however they do indicate that the internal radiant temperature can be high, in particular the radiant temperature of the ceiling.

The notes associated with the thermal images of Case Studies 1 and 2 (Tropical climate, Northern Territory, p. 171) indicate that internal wall temperatures were between 26 and 28°C and ceiling temperatures >27°C. Case Study 3 (Subtropical climate, Queensland, p.179) shows ceiling temperatures ranging from 33°C to 39°C at a thermal bridge caused by a structural element at the connection between modules. Thermal images of Case Study 4 (Grassland climate, New South Wales, p. 202) suggest that the ceiling temperature is warmer than the walls in winter (the temperature scale is not shown). In summer the ceiling temperature is between 30 and 32°C with parts reaching 35°C.

The interviews with pupils and teachers reinforce the narrative that the internal thermal comfort conditions are often not comfortable despite the use of air-conditioning systems to control the air temperature:

"Because of the high summertime temperatures and low wintertime temperatures, I am forever adjusting the classroom to make sure the kids are comfortable." (Teacher, Case Study 4, p. 201)

In Case Study 5, located in temperate Victoria, the Classroom is described by students as feeling 'hot' in summer and 'cold' in winter. The teacher explains that

'The classroom feels especially cold in winter. I often feel cold right up until recess. I am glad to get out and have hot cuppa.[In summer] 'It is like a little hot box in here on some days'' Teacher Case Study 5 (p.204)

Summary

Higgins et al (2005) and Soccio (2014) both provide extensive reviews of existing literature relating IEQ and its various components to the performance of students and teachers in the classroom.

Research literature continues to support Mendel and Heath's conclusion that factors contributing to poor Indoor Environmental Quality (IEQ) including thermal discomfort, low ventilation rates and high CO₂ levels have a detrimental influence on the academic performance of students. All aspects of IEQ, lighting, acoustics, air quality and thermal comfort, are important. This thesis is primarily concerned with the thermal performance of the building fabric and the influence this has on the thermal comfort of those who use the NSW Demountable Classrooms. The NSW Demountable Classroom appears to have high levels of natural light, controlling the light and preventing the glare is achieved by external fixed shading and internal adjustable blinds. Acoustics is an important consideration but beyond the scope of this thesis. Acoustics is also often a site specific issue (e.g. a busy road or a playing field). Ventilation

levels in classrooms, including the NSW Demountable Classroom, are a problem internationally. The problem is simply that not enough fresh air is supplied to the classroom. This can be rectified by increasing the ventilation rates to 8 l/s.person (4 air changes per hour, ACH). Increased ventilation may cause other thermal comfort or acoustic problems. Thermal comfort in the NSW Demountable Classroom and portable or prefabricated classrooms generally appears to remain a significant issue despite the widespread use of air conditioning to cool or heat air inside the classrooms. The cooling or heating of the air inside the classrooms fails to address the impact of the radiant temperature of the internal surfaces (walls, ceiling and floor) on the occupants perception of comfort.

1.6 Resources system: Environmental and economic costs

Buildings have a local and global environmental cost as well as an economic cost. The environmental cost of buildings is made up of three parts:

- i. The impact of the building on the local environment, for instance the disruption or destruction of ecosystems on the land where the building is built.
- ii. The environmental impact of the CO₂, other greenhouse gasses and pollution associated with the extraction and production of the materials used to construct the building and later its demolition and disposal. This is normally called the “embodied energy” or “embodied CO₂-equivalent”.
- iii. The environmental impact of using the building. In the case of the Demountable Classroom that is the energy consumption of the classroom and the associated CO₂-e emissions. In Australia 95.7% of energy comes from carbon based sources (coal, oil and gas) (BREE, 2013). The only power source used in the Demountable Classroom is electricity and in NSW 1kWh of electricity produces 1.05 kg.CO₂-equivalent (Department for climate change, 2013)

Local environmental impact

At a local level the simple pad foundations mean that there is a minimal disruption to the local flora and that when the building is removed the site quickly returns to its natural state. The rapid installation and removal also benefits the school and local community by obviating the need for a construction site.

The embodied energy

Overall lightweight construction is generally relatively low in embodied energy compared to heavier weight construction. Within the fabric of the Demountable Classroom the substantial primary steel frame and steel sub-framing are the parts with the highest embodied energy/CO₂-e.

The robust construction and the ability to relocate the classrooms means that the resources embodied in the classrooms benefit multiple communities and reduces the under-utilisation of and associated redundancy in the state’s education infrastructure creating economic and environmental benefits.

Energy in use

Data on the energy consumption of NSW Demountable Classrooms has not been found. Anecdotal evidence suggests that the cost of running air-conditioning systems is a significant problem for schools:

*“Jim Cooper said air-conditioning was expensive.....
The one outstanding issue for schools is rising utility*

costs” (Jim Cooper, President of the Primary Principals Association; Telegraph 21/09/2011)

“Heating and cooling costs are very expensive with portables because it is all electric” Victorian principal quoted in Gan and Newton (2012a)

Observations of the construction of the building fabric, anecdotal evidence of poor thermal performance, limited research literature from Australia and abroad about similar buildings and the 13 kW air-conditioning systems fitted to each classroom suggest electricity consumption for air-conditioning and the associated CO₂-e emissions are likely to be substantial.

Economic cost

The NSW government owns around 6000 Demountable Classrooms. Assuming a conservative construction cost of about \$1,750/sq.m* the equivalent permanent classroom would cost about \$140,000 to construct (total). So the 6,000 Demountables (NSW Government, 2014) the government owns represent considerable value on the basis of a replacement cost of \$840 million.

There is also a social-economic cost to consider: These classroom buildings are refurbished by prisoners at Cessnock and Golburn Jails under a contract between the NSW Department for Education and NSW Corrective Services Industries. The refurbishment programme provides prisoners with employment in jail, an opportunity to learn new skills and demonstrable work experience that helps them find work or enrol in an apprenticeship following their release. This program creates a remarkable and significant additional socially progressive dimension to the NSW Demountable Classroom that has social and economic benefits for the prisoners, prisons, Department for Education and the community.

**Costs based on Rawlinsons 2016 cost for permanent classrooms including A/C of \$1,750/m² (p.73).*

Sq.m rates range from \$1,435/m² and \$1,815m² excl. A/C.

A/C is costed as an additional \$11 - \$11.50/m².

Regional loadings as multiples of the metropolitan Sydney costs quoted range from 1.01 in Newcastle, 1.05 in Coffs Harbour, 1.08 in Canberra to 1.26 in Broken Hill and up to 1.35 in Wilcannia.

In this exercise metropolitan Sydney costs have been used for all estimates.

(Rawlinsons, 2016)

The internal floor area of the classrooms is 74 m², the roof area, including overhangs and shading devices, is 86 m².

1.7 Activity System: Societies’ changing expectations of pedagogy and comfort

Community’s expectations of how and in what conditions their children are educated have changed over the 50 years the NSW Demountable Classroom has existed. Society’s understanding of developments in pedagogy and our understanding of the significance of comfort is informed by experience, debate in the media, significant reports from government and universities, and political debate within and with governments. This discussion has led to a reduction in class sizes and a move towards child-led learning.

Changing pedagogy and space planning

In the 21st century the community expects the process of education to be interactive and engaging. This new approach to the process of educating children places new demands on the spaces used for educating children. One interviewee explained that “a 21st century classroom is unrecognisable compared to a 20th century classroom” (Interview E, 2014). Pedagogy is transforming from a 'talk and chalk' approach where rows of children passively absorb instruction into an interactive, exploratory and constructive experience that is expected to be engaging (Dovey and Fisher, 2014, Cleveland et al., 2015). The widespread adoption of this 'new' pedagogy may be relatively recent, however the philosophical ideas that underpin the pedagogy have been developed and discussed throughout the

Typologies of learning spaces	Description	Annotation
CLASSROOM	A traditional closed learning space of about 40-60 sq metres for 20-30 students. If learning spaces are fully 'closeable' to this size with flexible walls then they are classified as classrooms.	Indoor Spaces
COMMONS	A learning space of greater than about 40 sq metres that cannot be fully closed into a 25 student classrooms (or smaller) and is not the major access route to any other commons or classroom, hence protected from major through traffic.	
STREETSPACE	An open learning space over about 3 metres width (allowing activity + circulation) that cannot be closed into classrooms and is exposed to major through traffic as the primary access space to other learning spaces.	In-between Space
MEETING AREA	A small learning area of less than 40 square metres accommodating groups of 5 to 20. While such spaces may house seminars, the key criterion is that they cannot house a traditional class size.	Indoor Spaces
FIXED FUNCTION	Any learning space fitted for specialized use such as 'Arts', 'Science', 'IT', 'Computers', 'Wet Area', 'Music', 'Drama', 'Resources'.	
OUTDOOR LEARNING	Any outdoor area defined on the plan as an integral part of the learning cluster, generally labelled 'outdoor learning', 'outdoor room' or 'learning court'. Simple access to the outdoors does not qualify.	Outdoor Space

Table 1.2: A typology of learning spaces
(Dovey and Fisher, 2014, p.48 Table 2)

twentieth century (Dovey and Fisher, 2014). This new approach places new demands on classroom spaces and there is a perception that the Demountable Classroom is unable to provide the flexible spaces that are required (Interview E, 2014, Gan and Newton, 2012)

Dovey and Fisher (2014) identify 6 types of learning spaces (Table 1.2). based on an analysis of this emerging pedagogy (Table 1.3). They then show how these learning spaces can be arranged into 5 different plan typologies that enable different levels of mutability (Table 1.4), which, in turn, enables and facilitates flexibility. Their paper emphasises that

- classrooms and learning space is constructed physically and socially, and that
- flexibility is enabled by physical changes, 'Convertible Space', and
- by the way space is used or inhabited, 'Fluid Space'.

'Convertibility' is the ability to change the size and volume of spaces using sliding or folding walls and moving furniture. This may not be possible during a teaching session and may require agreement or assistance from people beyond those using the space.

'Fluidity', or 'Fluid Space' is space that can be used in different ways or a collection of spaces that enable users to move between different kinds of space and activity seamlessly.

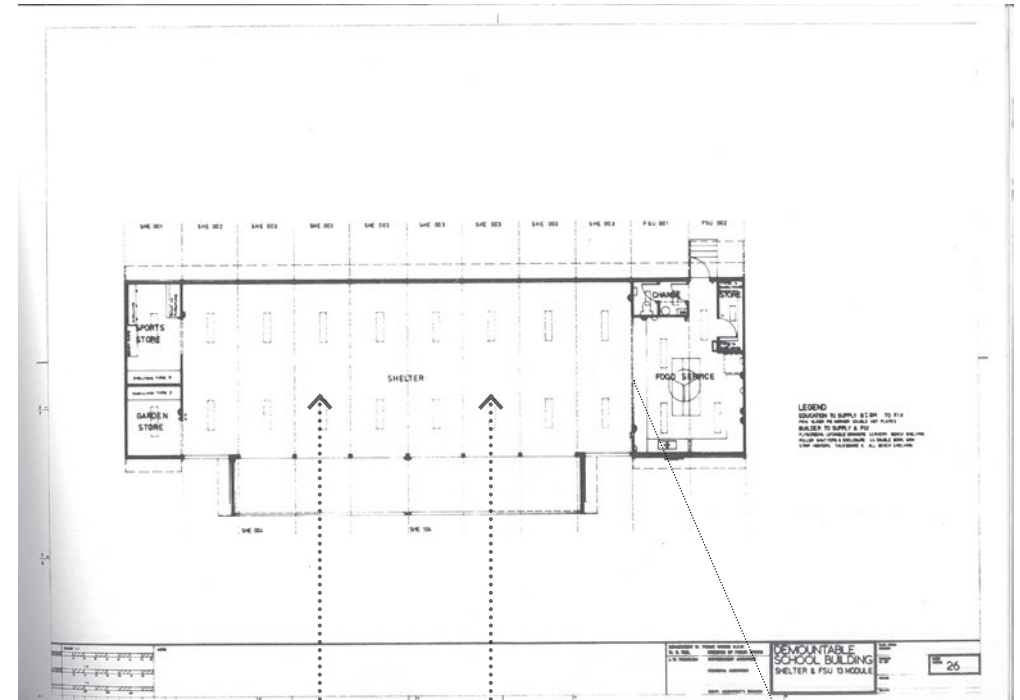
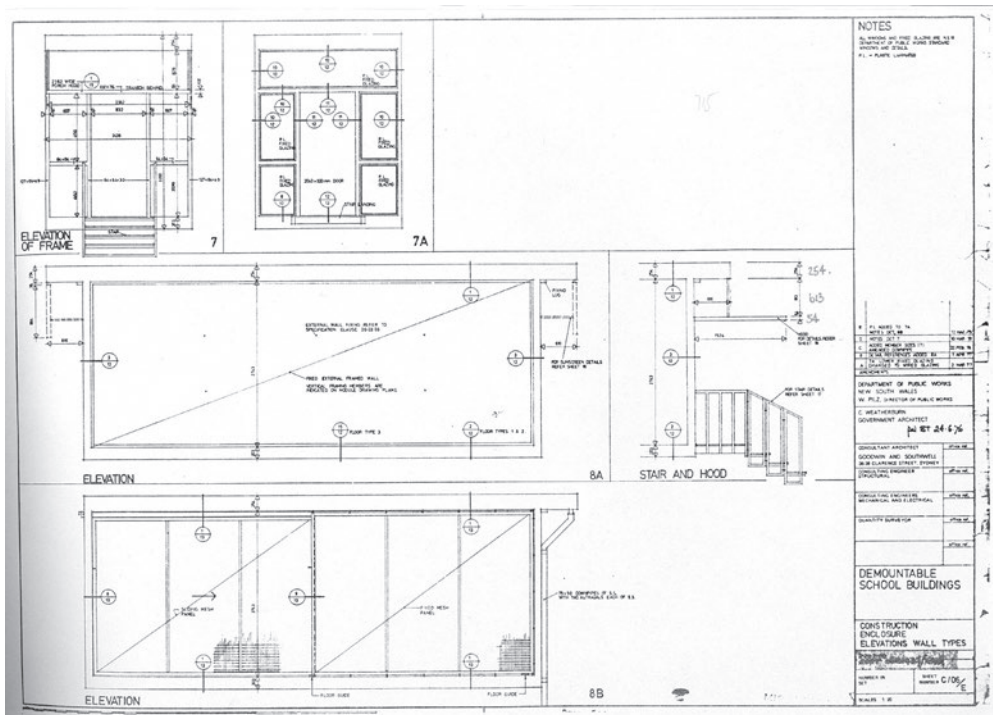
These two different ideas are not mutually exclusive but overlapping. A space, or group of spaces, may well enable both fluid and convertible flexibility. Dovey and Fisher describe these plans as 'Complex Adaptive

Typologies of student centred pedagogies	Description
PRESENTATION 25-150 students of information.	Students or teachers present to a largely passive group. Group size may vary from one class cohort to a full form or year. Such activities facilitate efficient communication
LARGE INTERACTIVE 25-75 students peer learning and team teaching.	Activities that move seamlessly from large to small group and back; often organized in sub-groups of 4-6 that can be subdivided again into 2s or 3s. Facilitates peer-to-peer learning and team teaching.
MEDIUM INTERACTIVE 10-25 students	Activities with a similar flow of movement to the above, but with a smaller group size and generally one teacher.
CREATIVE INTERACTIVE 10-25 students	Interactive activities but with an emphasis on hands-on learning in addition to pens and keyboards, plus access to a range of resources that may include art materials, wet areas, laboratory or outdoors.
SMALL INTERACTIVE 2-5 students	The 'breakout' model of problem-based and peer-to-peer learning with small autonomous groups that can disperse and take responsibility for their learning.
REFLECTION 1 student	Singular activities that include reading, writing or hands-on research to meet learning objectives.

Table 1.3: A typology of student-centred pedagogies
(Dovey and Fisher, 2014, p.47 Table 1)

Type	Space planning typologies or 'Cluster Types'		Description
A	Traditional + Corridor Clusters of traditional classrooms on a corridor	Traditionals	Group 1: Traditionals Two arrangements of traditional classrooms with the important distinction of 'B' having 'Streetspace' (an open leaning area combined with circulation)
B	Traditional + Streetspace Clusters of traditional classrooms around a 'Streetspace'		
C	Convertible classrooms: Traditional classrooms with sliding walls between them allowing two or more classrooms to be joined together.	Convertibles	Group 2: Convertibles The important distinction between C and D is that in C the classroom spaces remain separate from the Streetspace. In 'D' the Streetspace and classrooms can become a single space.
D	Convertible Streetspace Clusters of traditional classrooms with sliding or folding walls can be joined together and to the Streetspace		
E	Dedicated Commons The commons is protected and can not be converted or partitioned to form cellular classrooms. It is open plan, fluid.		Group 3: Dedicated Commons

Table 1.4: Five space planning typologies: 'Cluster types'
(Dovey and Fisher, 2014, from Figures 2-6)



Module designed to open to the outside

Moving partition

Figure 1.15: Original examples of NSW Demountable Classrooms' internal and external flexible all systems
 Examples of sliding wall panels (Left) and a plan typology that includes walls opening to the outside and internal moving partitions.
 (Plans from NSW Government Architects Office (1976 (circa)))



Figure 1.14: Example of an internal folding wall

*A folding screen in a derelict Mk 1 NSW Demountable Classroom block waiting for refurbishment at New England Trading, Newcastle, NSW.
(Photograph by the author)*

Assemblages'. They describe the traditional classroom as a fixed 'territory' and these new spaces as 'de-territorialised'. Both these descriptions highlight the complex social and physical mutability of these new ways of understanding and using teaching space.

The two NSW Demountable Classroom systems (Mk 1 and Mk 2) were designed to be adaptable. A study of the original plans and detail drawings shows that they included such 'modern' adaptations as sliding and folding internal partitions (Figure 1.14) and external walls that open up to the outside (Figure 1.15). The classroom modules were designed to be arranged in multiple configurations enabling the creation of spaces of different sizes, or a variety of spaces between classroom modules.

Dovey and Fisher (2014) define 4 types of indoor space plus 'Streetspace' and 'Outdoor Learning' (Table 1.2), each of which the NSW Demountable Classroom system provides. The internal spaces range from small meeting spaces, to traditional or flexible classroom spaces, to large spaces termed 'Commons'. The 'Streetspace' can be formed by arranging the classroom modules to create spaces between them as has been done in both the new 'Demountable' school in Ultimo, Sydney (Architecture AU, 2018), and the 'Bush campus' in Chatswood, Sydney (Bush Campus) (Figure 1.16).

The 5 conceptual planning typologies or assemblages range from the traditional classroom, through various forms of adaptability, to an open plan 'Commons' (Table 1.2). Dovey and Fisher (2014) identify 3 groups within



**Figure 1.16: NSW Demountable Classrooms
creating corridor spaces**

(Top)

Plan illustrating Mk 1 modules arranged to form a
corridor space

(Plans from NSW Government Architects Office
1976 (circa))

(Bottom)

A Corridor space or 'Streetpace' created by
arranging Mk 1 classroom modules at the Bush
Campus, Chatswood, Sydney.

(Photograph by Chatswood Public School)



these typologies and some important distinctions within the groups about how they relate to the 'Streetspace':

Type A and B are based around the traditional classroom. The important difference is the size of the space between the classrooms and whether or not it is simply circulation space (A) or becomes 'Streetspace' (B).

Types C and D are called 'the Convertibles' and are based around systems that enable walls to be added or removed. The important distinction is whether the conversion is between classrooms (C) or between classrooms and the 'Streetspace' (D) to create a single fluid space. The final type (E) is a single large open plan space or 'Commons'.

Figures 1.17 and 1.18 illustrate how the Mk. 1 and Mk. 2 NSW Demountable Classroom systems can create spaces that enable traditional (A & B), convertible (C & D) and 'Commons' (E) type plans. The manner in which the modules are arranged around a 'Streetspace' or corridor will distinguish plan types A and B, or C and D. The creation of wall modules that enable the classrooms to open to each other or the 'Streetspace' is evident in the plan and original drawings (Figures 1.14 to 1.18). Figures 1.19 and 1.20 show how the space typologies (Table 1.2) and planning relationships (Table 1.4) identified by Dovey and Fisher based on contemporary pedagogy can be mapped onto original plans.

These buildings were designed to be modular at several levels from the volumetric classroom module to individual façade modules. They were designed to adapt and be adapted to the changing needs and expectations of the people who use them. It appears that the opportunity for adaption are not being fully utilised.

Figure 1.17: Analysis of plan typologies for the Mk 1 NSW Demountable Classroom

A diagrammatic analysis of potential NSW Demountable Classroom plan types based on the three basic spatial typologies proposed by Dovey and Fisher (2015) (see table XXX):

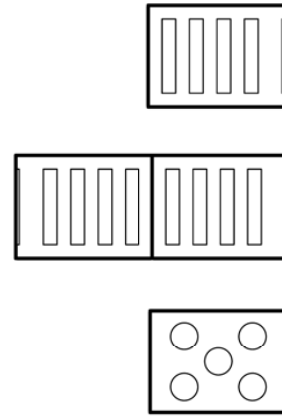
Types A & B - 'The Traditionals' arranged along a corridor or a 'Streetspace'.

Types C&D - 'The Convertibles' arranged along a 'Streetspace' or adjacent to a 'Commons'.

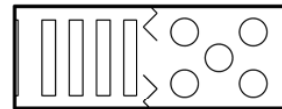
Type E - 'The Commons'

Based on the work of Dovey and Fisher (2014) and Cleveland et al (2015). Plans from NSW Government Architects Office (1976 (circa)) (Diagrams by author)

A&B
Traditional classroom
Presentation & group working



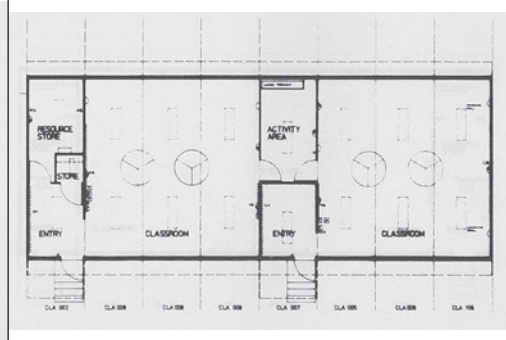
C&D
Convertible classroom



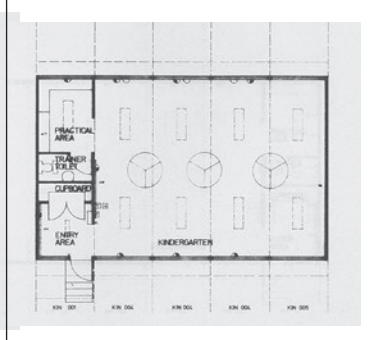
E
Open classroom / Dedicated Commons



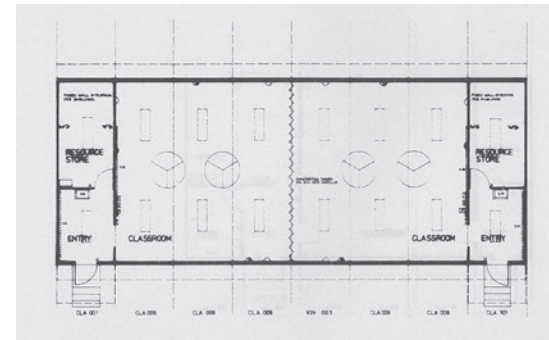
4 module classroom



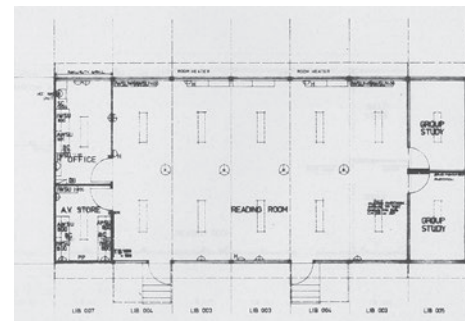
8 module double classroom



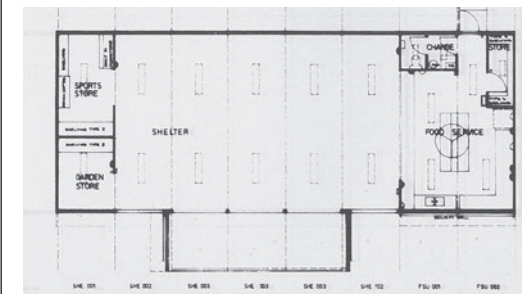
Single kindergarten (5 modules)



Double primary type classroom with a moving partition (8 module)



7 module Library



Shelter and Canteen (9 modules)

Figure 1.18: Analysis of plan typologies for the Mk 2 NSW Demountable Classroom

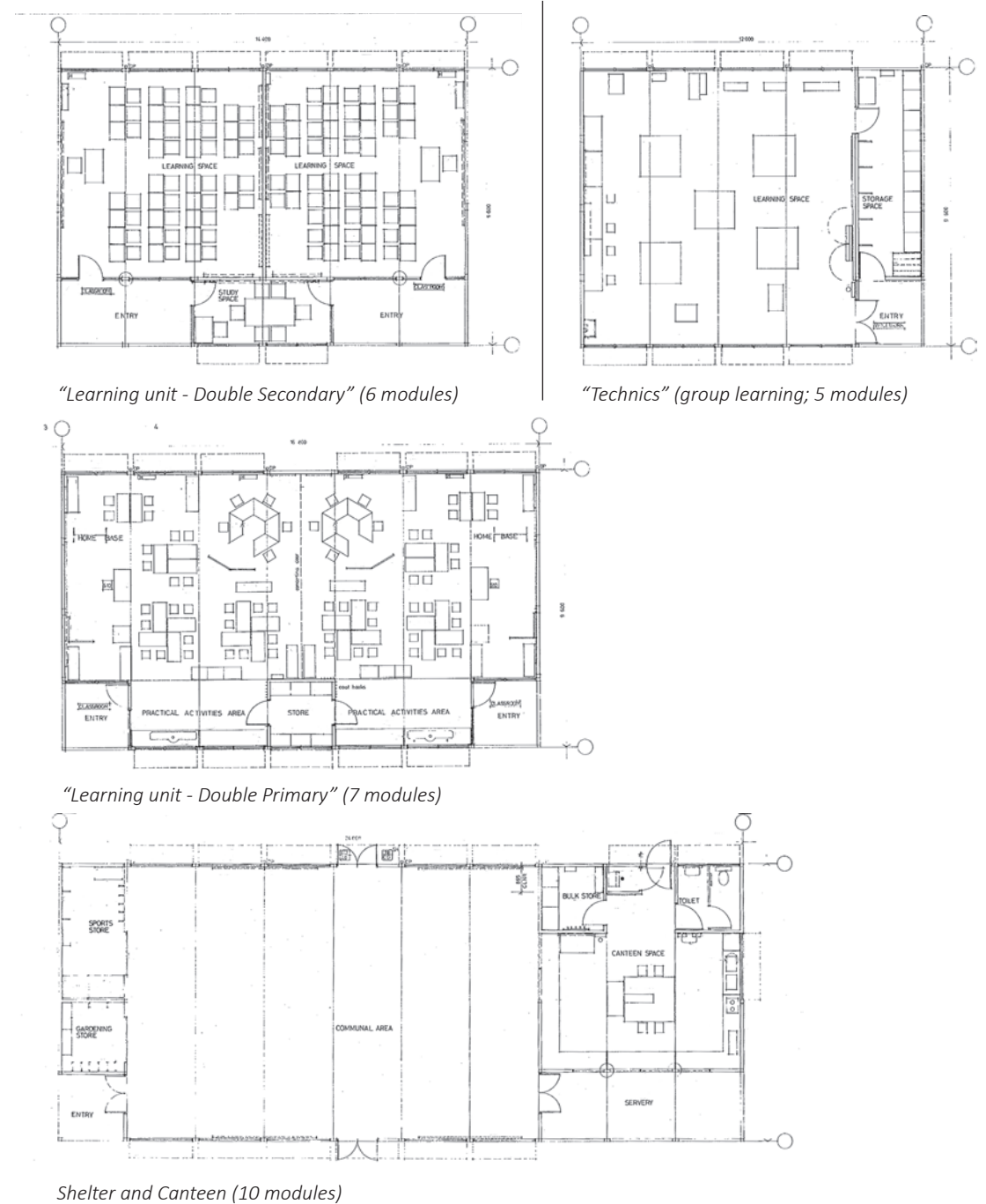
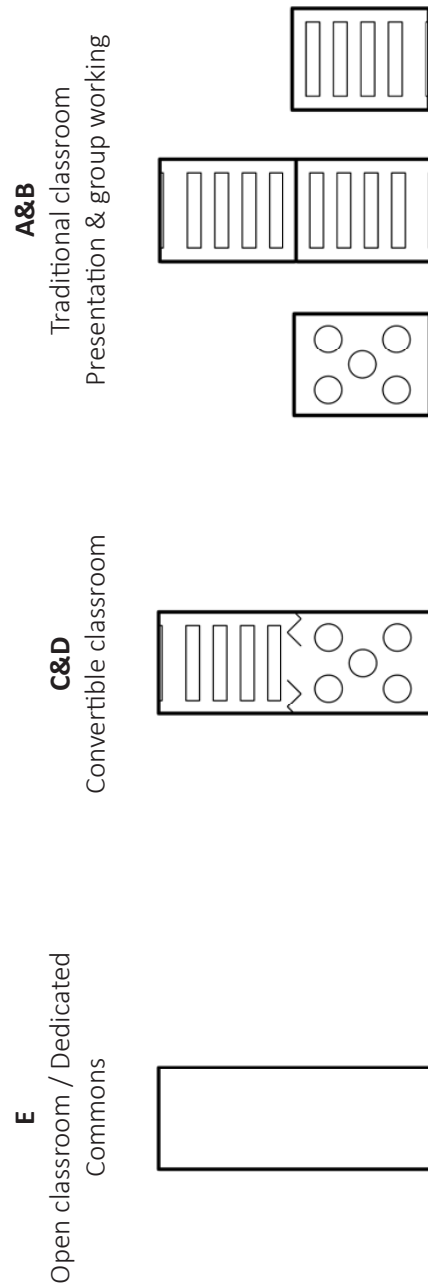
A diagrammatic analysis of potential NSW Demountable Classroom plan types based on the three basic spatial typologies proposed by Dovey and Fisher (2015) (see table XXX):

Types A & B - 'The Traditionals' arranged along a corridor or a 'Streetspace'.

Types C&D - 'The Convertibles' arranged along a 'Streetspace' or adjacent to a 'Commons'.

Type E - 'The Commons'

Based on the work of Dovey and Fisher (2014) and Cleveland et al (2015). Plans from NSW Government Architects Office (1976 (circa)) (Diagrams by author)



- Classroom
- Commons
- Street
- Meeting



**Figure 1.19: Modules as an 'Adaptive Assemblage':
Space typologies and planning relationships**

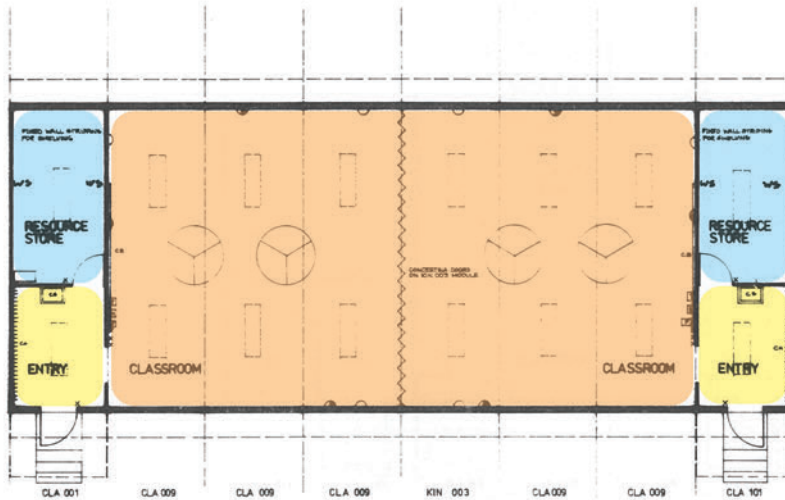
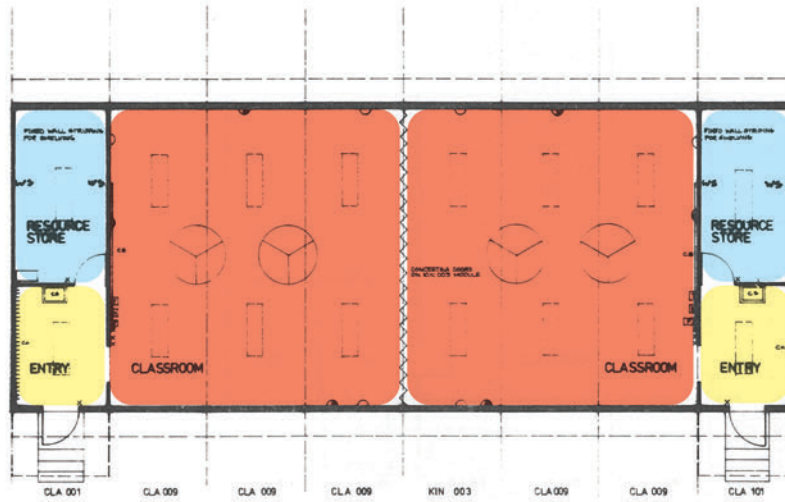
Mk 2 NSW Demountable Classroom

Plan for a secondary school library using 14 modules to create multiple space typologies and configurations: An 'Adaptive Assemblage'.

The plan has been colour-coded to reflect the space typologies and relationships described by Dovey and Fisher (2012)

Plans from NSW Government Architects Office (1983)

- Classroom
- Commons
- Street
- Meeting
- Fixed space



Configuration A becomes Configuration B



Figure 1.20: Modules as an 'Adaptive Assemblage': Changing space typologies and planning relationships

Mk 1 NSW Demountable Classrooms

Two original plans for arranging Mk 1 modules to create multiple space typologies and configurations:

An 'Adaptive Assemblage'.

The plans have been colour-coded to reflect the space typologies and relationships described by Dovey and Fisher (2012)

Plans from NSW Government Architects Office (1976 (circa))

(Diagrams by author)

Changing thermal expectations

Thermal expectations have also changed. A number of interviewees suggested that the provision of air-conditioning in classrooms is expected rather than considered to be the exception (Interviews B, C) as air-conditioning use in homes and other places has increased, a finding also observed in research by de Dear et al (2014). In the 17 years between 1994 and 2011 the use of mechanical cooling systems in Australian households changed from being the exception, 32% (Australian Bureau of Statistics, 2010) to common, 73% (Australian Bureau of Statistics, 2011).

The issue of temperature in Demountable Classrooms was first raised in the NSW Parliament in 1980 by an MP praising the facilities at the Bateau Bay Demountable Primary School but observing that “heat in the classrooms in the summer causes problems” (Hansard NSW 24/11/1980). In 1984 an Adjournment Debate was held in parliament concentrating on the possibility that poor indoor environmental quality (IEQ) could disadvantage the children and teachers who are trying to learn and teach in those spaces (Hansard NSW 02/05/1984). Later the same year the MP for Hawksbury suggested that:

“The higher range of temperatures creates conditions in which primary and infant school children cannot continue to learn and receive the benefit of their schooling.” (Hansard NSW 02/05/1984).

In 2002 Vinson highlighted the issue of temperatures in Demountable Classrooms in his report on the provision of public education in NSW (Vinson et al., 2002). In 2003 the Government announced that all Demountables would be fitted with air-conditioning (Hansard NSW 08/09/2003). The work of Soccio (2014) and reports in the media suggest that expectations of comfort in NSW Demountable Classrooms and other Demountable Classrooms across Australia are not being met despite the presence of air-conditioning.

1.8 Value: The concept of obsolescence

In the BPRU model “Value” is assessed by comparing, or evaluating, how well the various systems are meeting the “Objectives” and how much that costs in terms of the “Resources System”. Pinder and Wilkinson (2000a) describe buildings as “utilities rather than “assets” and, following Burton (1933), that their usefulness, or value, changes over time as the expectations and needs of society change. They suggest that the needs and expectations of building users, communities and society adapt to new technologies and improvements in construction methods so a building that continues to meet the objectives it was originally designed to fulfil may become obsolete because the objectives are no longer aligned to the expectations of the communities it was designed to serve: “Occupant expectations are the essential characteristic of obsolescence” (Pinder and Wilkinson, 2000a).

Following Burton (1933), Pinder and Wilkinson (2000b) argue that there are two classes of causation for obsolescence:

- Locational (extrinsic) causes
(e.g. changing demographics, population movement or density and changing climate)
- Building performance (intrinsic) causes
(e.g. The thermal performance of the building no longer meets the users expectations, changing pedagogy and changing technology in the classroom)

Factors are contributors to either class of obsolescence. Hyde et al (2012) have identified three types of factor based on the work of Pinder and Wilkinson:

- Economic factors
- Social factors
- Environmental factors

Building Performance and Building Obsolescence measure the same things and explain them in opposite ways: Building Performance is an essentially positive approach asking, “How well does this building perform?” Building Obsolescence measures the gap between the actual performance and the expectations of the users, ideally to understand and mitigate the shortfall in Building Performance.

Perception of quality: dawning obsolescence

When the first Demountables were introduced they were regarded as a high quality modern building innovation. The design won a Certificate of Merit in the Prince Philip Awards for Australian Design in 1968. In 1976 the then Minister for Education countered concern about Demountables calling them “excellent accommodation” (Hansard NSW 11/11/1976) and later “of first-class quality.” (Hansard NSW 01/12/1976)

In 1984 an Adjournment Debate was held in parliament suggesting that poor indoor environmental quality could disadvantage the children and teachers (Hansard NSW 02/05/1984).

In the 2002 report “Inquiry into the provision of public education In NSW” (Vinson et al., 2002) an entire

chapter is dedicated to the significance of the built environment on the quality of education and academic achievement in schools and an entire section to Demountable Classrooms. The report explains that:

“the quality of school buildings and their surrounds can also be a potent symbol of the regard (or otherwise) in which public education is believed to be held by governments and the community” (p.84)

In the section dedicated to the Demountable Classroom the report notes that:

“Demountables have been the subject of incessant criticism throughout the Inquiry.[in] the absence of air conditioning they are too hot; their insubstantial character detracts from the appearance and confirmed identity of a school.” (p.89)

Using Pinder and Wilkinson’s categorisation of obsolescence the relocatable classroom was specifically designed to avoid the locational, extrinsic causes of obsolescence by being relocatable, possibly with the exception of tight inner city sites (Interview E). The second-class, intrinsic building performance causes, have been shown to be a fundamental problem for the building typology. These intrinsic challenges are associated with the fabric of the building (the thermal performance) and the social utility of the building, that is the usefulness of the space for contemporary pedagogy and the esteem in which the buildings are held.

Over 50 years the Demountable Classroom has moved from being perceived as a design innovation to “a pejorative” (interview B). They are widely perceived as providing second class teaching accommodation, a view exemplified by the NSW Parliament 2003 motion calling for the House to acknowledge *“that the learning environment of a permanent classroom in regional New South Wales is a better learning environment than a Demountable Classroom.”* (Hansard NSW 8/09/2003).

The community’s changing perception of what is an acceptable teaching environment has changed in terms of both our understanding and knowledge of the importance of the teaching environment and the community’s expectations. The classrooms are derided for many reasons including their appearance, their perceived inability to adapt to contemporary pedagogy and their thermal performance. The difficulty of using the classrooms on tight urban school campuses is a fourth possible cause of obsolescence or at least the perception of obsolescence.

However, the social utility of these versatile buildings, deployable and operational across the state within days, is demonstrated in part by the fact that they have lasted for 50 years and continue to provide an economically and socially sustainable solution to the NSW government and the communities the government serves.

The classroom buildings are clearly useful and offer excellent value in terms of the cost and flexibility of the accommodation. However, it is argued that it is the community’s changing perception of what is an

acceptable thermal environment and our increasing knowledge of the importance of internal environmental quality (IEQ) on the efficacy of teaching and learning (Mendell and Heath, 2005) that are the primary reasons the Demountable Classrooms are regarded by the communities they serve as sub-standard, second rate or obsolete.

1.9 Opportunities for adaption: A high performance building typology

The concept of obsolescence is implicit in the BPRU framework of Operative Systems and Evaluation Systems. The work of Pinder and Wilkinson makes this explicit and highlights opportunities for positive change within the meta-system framework to improve the operation of the building in response to changing social expectations, the Evaluation Systems.

The concept of the industrially produced “Demountable” or prefabricated building has fascinated architects for many years. Kieran and Timberlake (2004) and Richard (2006) have argued that the industrially produced relocatable building systems provide a more economic construction method and a solution to obsolescence through relocation and adaption. Modular construction means that it can become relatively simple to modify the building to meet the changing expectations and needs of people and technology and location (Smith et al., 2011). This industrialised approach to construction offers opportunities for reduced waste and increased recycling of components and materials, associated with a reduction in cost and increase in quality (Kieran and Timberlake, 2004). More recent work on sustainable retrofitting (Hyde et al., 2012) highlights the opportunities for improving the performance of buildings by replacing elements of the building, for instance the cladding and glazing systems, that have become obsolete with new high performance

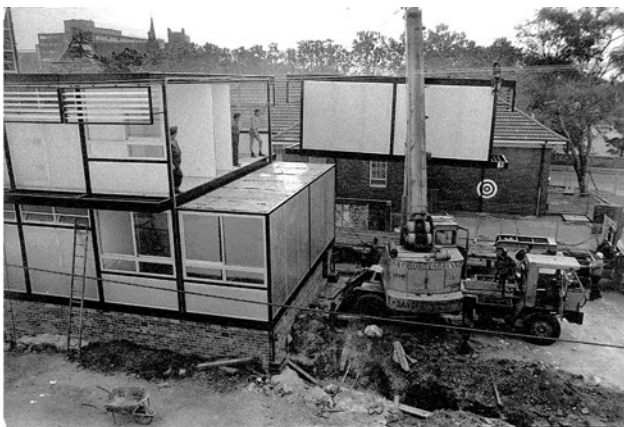


Figure 1.21: Two storey Mk 1 NSW Demountable classrooms

Mk 1 NSW Demountable classroom modules being assembled to create a two storey building circa 1970 (based on the car), exact date and location unknown.

(Photos: delivered anonymously to the NSW Department of Education)

elements. For the majority of buildings this process is disruptive.

What is perhaps unique about the NSW Demountable is that it has been specifically designed to adapt in the manner proposed by Hyde, Kieran and Timberlake and Smith through re-location, the addition, subtraction or replacement of volumetric classroom modules, or the replacement and upgrading of individual components. To date the NSW Demountable program classroom has utilised the opportunity to relocate, re-use and refurbish but appears to have largely ignored the opportunity for adaption. Classroom units in need of refurbishment are removed and replaced on their site while the unit requiring refurbishment is modified in an industrial setting elsewhere, currently by the NSW Corrective Services industries at Golburn and Cessnock Jails, and at New England Trading near Newcastle, NSW. The limited adaptive opportunities that have taken place include the addition of air conditioning from 2003, the addition of lifting points and an improved roof and gutter system.

A review of the original drawings (Figures 1.14 to 1.20) shows that the classroom system was designed to be flexible, including the movable internal partitions and walls that open to create inside/outside teaching spaces. The substantial steel frame enables stacking classrooms on tight urban sites. A new connection system has been developed to stack classrooms three high/ This was thought to be an innovation until some photographs from the 1970's were discovered (Figure 1.21).

but may well be capable of supporting stacking classrooms with the addition of an appropriate connection system.

The challenge of improving the thermal performance of these classrooms is significant. It has been shown that lightweight building envelopes tend to exacerbate rather than moderate diurnal temperature ranges in warm and hot climates. Pearlmutter and Mier's (1995) empirical measurement of the thermal performance of lightweight houses in two climates in Israel illustrates this. Cardinale et al (2010) illustrated the same point with a campervan in southern Italy. Cardinale et al also showed that there are strategies, or combinations of strategic interventions and additions to the building fabric, that can improve the thermal performance of these very lightweight and poorly insulated buildings. Work by the SEED collaborative (2015, Nelson, 2014) demonstrates that new relocatable classrooms can be designed as high performance buildings creating considerable pedagogical opportunity in the process of design, construction and use.

Adaption appears to have been at the heart of the conception of these buildings. The "bomb proof" primary steel frame offers a framework onto which adaptive strategies appropriate for the needs of contemporary communities can be applied.

1.10 Conclusion: Focus on improving thermal performance

The Demountable Classroom system was originally designed in 1965 and now, 50 years later, these same buildings are still widely used to achieve the original objectives. They are, however, regarded by many as obsolete. What is remarkable is that while examples of relocatable buildings existed in 1965, most notably from the second world war and its aftermath (Underwood, 1972), the implementation of an industrially produced and adaptable solution integrated into the provision of school infrastructure was radical and remains radical today. This chapter has shown that the NSW Demountable Classroom system provides NSW (and other) communities with an economically and socially efficient building system for the state's schools that remains radical.

The problems identified with the NSW Demountable Classroom are complex and contain elements of social perception, social value, pedagogy, politics and economics. One of the most significant problems is the thermal performance of these buildings and the thermal discomfort their poor performance causes those who use them.

This chapter has shown that the idea of adaption was a core concept for the design for these buildings. As a consequence this chapter suggests that new adaptive strategies can be developed to improve the thermal performance of these Demountable Classroom buildings

and the comfort of those who use them. Doing so has the potential to create a high performance building typology that may then act as an example for all building design.

Thus the research question emerges:

How can these buildings be transformed to improve their thermal performance and the thermal comfort of those who use them?

The objective of this research project is to develop socially, economically and environmentally viable proposals that will improve the thermal performance and indoor environmental quality of these classroom buildings.

Quantitative Analysis: A thermal simulation to test the anecdotal evidence

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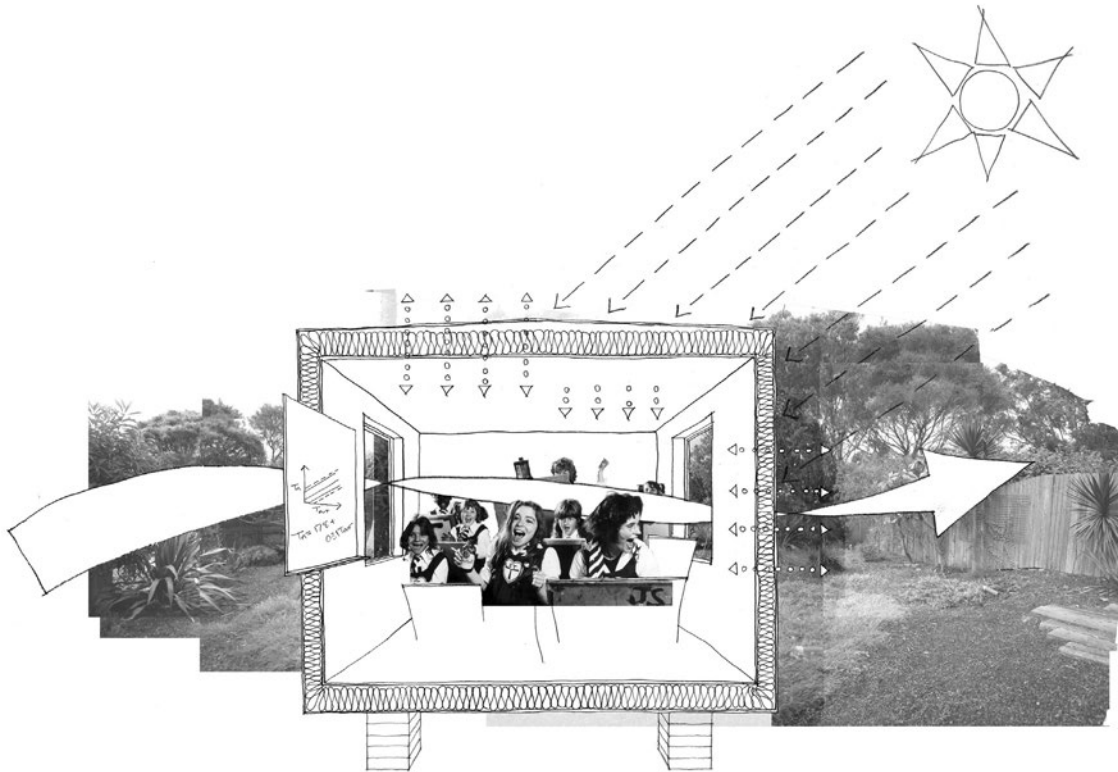


Figure 2.1: Comfort in a demountable
A collage
(Image by author)

2.1 Introduction:

The previous chapter explored the purpose, performance and perception of the NSW Demountable Classroom over the last 50 years based on documentary evidence and interviews. The chapter concluded that the need the classrooms were originally designed to fulfil remains today and that the NSW Demountable Classroom system continues to meet those original objectives, providing communities across the state with an economically efficient and socially sustainable system for dealing with the fluctuation in local school populations.

The chapter also found that these communities regard the NSW Demountable Classroom buildings as “second rate” or obsolete. The anecdotal evidence suggests that this is because of their appearance and, as this thesis argues, more significantly, their thermal performance. There are numerous reports of people citing overheating in these classrooms as a particular problem (See Part 1.8, Vinson et al., 2002, Hansard NSW).

This chapter explores the thermal performance of the existing Mk. I Demountable Classroom quantitatively using a computer simulation model. The quantitative simulation model will allow us to understand how thermal energy moves in and out of the classroom buildings during the day and night and so identify major problems. The model will also provide us with a more objective measure of the scale of the problem of thermal discomfort and energy consumption and the

consequential challenge in different climates across the state.

The first part of this chapter explores the various simulation strategies that can be used to evaluate the thermal performance of the Demountable Classroom building in different climates. The second part of the chapter explains how the selected computer simulation model is constructed, based on detailed survey information from existing classroom buildings undergoing refurbishment. The final parts of the chapter set out the results and the discussion of those results.

2.2 Quantitative modelling strategies

Depending on their objectives, different researchers use different strategies for modelling the environmental performance of buildings and to evaluate the effect of various interventions on the overall performance of buildings. The choice of model is dependent on both the purpose of the model and the information available to construct the model (ASHRAE, 2009, Fumo, 2014).

The literature contains a range reviews of approaches to modelling that differentiate between strategies in different ways, or to larger or finer degrees of differentiation (Pedersen, 2007, Crawley et al., 2008, ASHRAE, 2009, Foucuier et al., 2013, Fumo, 2014, Harish and Kumar, 2016). For the purposes of this thesis the various methodological approaches to modelling are separated into four categories ranging from a fundamentally empirical approach, to a data driven 'Black Box' approach based on statistical analysis, to a calibrated simulation model (Grey Box), to the use of validated digital simulation models (White Box). These categories will be discussed in the following order:

- a. Empirical measurement using physical test buildings
- b. Data driven Black Box models
- c. Computer simulation models (White Box)
- d. Computer simulation models calibrated using empirical data (Grey Box)

2.2.a Empirical measurement of physical models (test buildings):

The environmental performance of a physical building on a specific site can be measured using a variety of thermal and environmental sensors (temperature, thermal flux, air movement and air tightness etc.) at the same time as the local weather data is collected. This approach uses real buildings, scale models or parts of buildings to undertake comparative evaluation of the performance of different construction strategies in real time during real weather conditions.

Examples of this method include

- Givoni's exploration of the influence of the quantity of thermal mass, ventilation strategy and shading on the thermal performance of two small buildings in California (Givoni, 1998).
- La Roche and Milne's exploration of ventilation strategies, thermal mass and direct gain using two specially constructed test cells in Los Angeles, California (La Roche and Milne, 2004).
- Four test buildings constructed at Newcastle University, Australia, to investigate the thermal performance of brick construction in Australia (Sugo, 2004, Sugo, 2009).

2.2.b Data driven Black Box models

This approach requires empirical data for input and output variables. For instance, weather data and occupancy data as input or independent variables, and energy consumption and internal air temperature as output or dependent variables. The system uses statistical analysis to construct a mathematical model or description of the building that connects the statistical inputs (independent variables) with the output (dependent) variables (Pedersen, 2007, ASHRAE, 2009, Fouquier et al., 2013, Fumo, 2014). The term 'Black Box' is used because it is not necessary to understand, or model, the physical or social processes that determine how or why the input variables influence the output variables. It is a purely statistical methodology in which real world processes are hidden (Fumo, 2014). The method can provide accurate predictions within the parameters the available data dictates. So in the very simple example above where only weather, occupancy, energy consumption and indoor temperature data are known, the model could make predictions based on variations of these four variables, but not about any other variables because the model knows nothing about them. This approach includes multiple linear regression analysis, artificial neural networks, including Bayesian networks, and conditional demand analysis.

2.2.c Computer simulation model (White Box)

A computer simulation model uses an established software package to create a carefully constructed digital model of the building. The model is deterministic and based on "sound engineering principles" and the laws of thermodynamics (ASHRAE, 2009). ASHRAE (2009) describes this approach as a "Forward" or "Classical" approach that is intended to predict the behaviour of a building based on a physical description of that building, its environment and the way it is used (Hopfe, 2009). These models are called 'White Box' models because the processes within the model are defined by the people who create the model and the software package that underpins the model (ASHRAE, 2009, Fouquier et al., 2013, Fumo, 2014).

The software packages themselves have been developed and updated over many years (Crawley et al., 2008). The underlying accuracy of the model is confirmed using a validation process that checks the underlying algorithms and coding in the software against empirical data and other simulation model frameworks following protocols set out by ASHRAE Standard 140 and International Energy Agency (IEA) standards (Judkoff and Neymark, 1995, ASHRAE Standard 140, 2017, IBPSA, 2018).

While no model of any type can be described as completely valid (ASHRAE Standard 140, 2017), because all models are a simplification of reality, Fumo (2014) argues that

“although a model developed using accredited software is not a calibrated model; its results are assumed to be accurate enough to be considered valid.”

Particularly when compared to a reference model.

This approach has been adopted by a number of researchers to explore the impact of variations to the building fabric on internal temperatures, comfort and energy use in the context of improving construction systems in Australia (Gregory et al., 2008, Bambrook, 2011, Slee et al., 2014, Smith et al., 2012), the resilience of construction systems and homes to heat waves (Hatvani-Kovacs, 2017, Saman et al., 2013), and the resilience of construction systems to climate change (Brotas and Nicol, 2017, Hacker et al., 2008, Holmes and Hacker, 2007) (refer to Table 2.2 for a summary of these reports).

Others argue that, while building simulation models are reasonably accurate, it is a mistake to ignore the uncertainty that is implicit in a model. They argue that by explicitly identifying and expressing this uncertainty the model becomes more robust and more useful (Hopfe, 2009, Hopfe and Hensen, 2011, Junghans and Bae, 2016).

2.2.d Computer simulation calibrated using empirical data (Grey Box)

Computer simulation models can be calibrated using empirical data from the building the model is representing. The purpose of this methodological approach is to combine the strengths of ‘Forward’ computer simulation modelling with the strengths of the statistical approach so that the predictions from the computer simulation model reproduce, as closely as possible, the known (empirical) output variables for a set of known input variables (ASHRAE, 2009, Foucquier et al., 2013, Fumo, 2014).

The method relies on having appropriate empirical input and output data. The value and accuracy of the approach is dependent on the accuracy and quality of the data available for the process (ASHRAE, 2009, Fumo, 2014). The calibration process itself increases in complexity as the quantity of the data used increases. Whether that is the result of increasing the number of variables that are under consideration or increasing the time period over which the calibration is taking place (Sun and Reddy, 2006, ASHRAE, 2009, Fumo, 2014, Mustafaraj et al., 2014). Sun and Reddy (2006) and Mustafaraj et al (2014) argue that the significant challenge of calibration is that the problem (the model) is underdetermined, i.e. there are many more parameters to adjust than monitored variables. This leads to the potential for multiple solutions to the problem. The calibration process can also be dependent on the person undertaking the calibration (ASHRAE, 2009). In a study of an Irish office building Raftery et al (2011a) argue that the calibration

process used by the majority of researchers is based on personal judgment and is therefore subjective, prone to “fudging” and not evidence based. Sun and Reddy (2006) concur explaining that

“This “fudging” process often results in the manipulation of a large number of variables, which may significantly decrease the credibility of the entire simulation”.

Raftery et al (2011b) propose an iterative, systematic evidence based calibration process. They argue that this creates a more accurate digital model containing only verified information about the building and that the process creates an auditable decision trail.

Following Sun and Reddy (2006) Mustafaraj et al (2014) proposes a two stage approach: The first stage uses ‘as built’ information, that includes detailed plans, specifications and detailed envelope construction information, on-site inspections (a survey) and ‘typical’ schedules for occupants and systems to construct a computer simulation model of the building. The second stage uses a sensitivity analysis to identify the most influential parameters before conducting an iterative process, similar to an optimisation process, that adjusts the most influential variables to reduce the difference between the simulated and measured data.

Accuracy	The method should be sufficiently accurate to allow correct choices.
Sensitivity	The method should be sensitive to the design options being considered.
Versatility	The method should allow analysis of all options under consideration.
Speed and cost (resources)	The total time (gathering data, preparing input, calculations, and analysis of output) to make an analysis should be appropriate to the potential benefits gained.
Reproducibility	The method should not allow so many vaguely defined choices that different analysts would get completely different results
Ease of use	This affects both the economics of analysis (speed) and the reproducibility of results.

Figure 2.1: A summary of the criteria for choosing a modelling methodology
A summary of the criteria for choosing a modelling methodology identified by the ASHRAE Handbook (ASHRAE, 2009) p19.3

2.2.2 Discussion: Choosing a modelling methodology

The ASHRAE Handbook (ASHRAE, 2009) explains that

“The most important step in selecting an energy analysis method is matching method capabilities with project requirements.” (p.19.3)

And goes on to identify six criteria to be considered when selecting a modelling method (Table 2.1). The handbook also highlights the need for appropriate support to solve problems.

The following discussion of the four modelling strategies outlined above will be based on these criteria.

Each of the four approaches presents advantages and disadvantages. The detailed study of physical buildings has the significant advantage of being 'real' and so allows the researcher to document the outcome of the complex interactions of people, buildings and the environment.

However the three significant disadvantages demonstrated by the three studies cited above (Givoni, 1998, La Roche and Milne, 2004, Gregory et al., 2008, Sugo, 2004) are,

- The requirement to wait at least twelve months to collect data representative of all seasons.
- The limitation on directly comparable data imposed by the number of identical buildings available on a site to monitor simultaneously, i.e. under identical weather conditions.

- The difficulty in making modifications to the building fabric and the time needed to understand the impact of the modifications.

The second (Black Box) and fourth (Grey Box) approaches make use of empirical data to enhance the accuracy of the model. The second approach, the Black Box statistical model, overcomes the time constraint on understanding the impact of modifications by creating a statistical model that can predict the impact based on existing data. The limitation is that the number of variables that can be adjusted and predicted is directly proportional to the quantity and variety of empirical data collected to construct the model. For example understanding the impact of changing the U-value would require data from a number of classrooms with different U-values.

The fourth approach (the Grey Box calibrated building simulation model) overcomes the problems associated with the pure empirical (physical) model and the statistical Black Box model by using the empirical data to create a digital building energy simulation model that is calibrated (adjusted) to represent or reproduce known output variables for known input variables. This model can be used to carry out any number of parametric variations over any period of time for which a relevant weather file is available.

Creating a calibrated simulation model presents a number of challenges:

- i. The time required to undertake a robust calibration process. This is discussed at length by Raftery et al (2011b) in their proposal for an evidence based methodology. They highlight the tendency for researchers to follow an “ad-hoc” tuning process, rather than a formal, systematic and evidence based methodology, and the limitations this places on the quality of the model.
- ii. The time required to collect a useful body of empirical data in different conditions and the time needed to calibrate the model mean that this approach may not be appropriate for all studies.
- iii. As the model is modified to test variations in construction, use or climate it is, strictly speaking, no longer “calibrated”. The more substantial the variations or modifications made to the model the further it is from the original calibrated model.

The third approach offers a rapid simulation methodology at the cost of the loss of calibration against a set of empirical data. This may be viewed as a significant limitation since it means that the methodology, and therefore the value of the research, relies almost entirely on the quality of the software tool chosen and the quality of the construction of the digital model.

The choice of approach depends on many factors, in particular the purpose of the study, the ability to access or collect relevant empirical data and the time and resources available for the study. Fumo (2014) observes that

“The accuracy of an approach depends on the information that is available for the purpose of the approach Therefore, for the question of what approach is better, the answer depends on what type of the information is available and in what magnitude”

Purpose

The purpose of the study is to understand how variation or modification to the building envelope can improve the thermal performance of the NSW Demountable Classroom and the thermal comfort of those who use them.

Access to relevant empirical data

Accessing relevant and useful (good quality) empirical data proved impossible. Senior Professors within the Faculty of Architecture and people within the NSW Department of Education recommended against trying to collect empirical data in classrooms. Attempts to access data from existing studies (Cleveland and Soccio, 2013, Soccio, 2014, de Dear et al., 2015) were also unsuccessful because the agreements that enabled the data to be collected meant that it cannot be shared (Cleveland, 2018). ‘As built’ data has been obtained through the

NSW Department of Education, NSW Government Architects Office and surveys of existing classrooms undergoing refurbishment.

Time, cost and resources

Time and resources available to undertake this study are necessarily limited by the fact that it is a PhD undertaken by a single person and not part of a larger research program.

Of the four methodological approaches outlined above the second approach, Black Box statistical model, is not appropriate because

- It is not sensitive to all the possible design options under consideration
- It is not sufficiently versatile for the purposes of the project
- It requires resources that are not available

The remaining three methodological approaches are empirical physical testing, Grey Box calibrated simulation models or White Box validated simulation models. These three approaches offer three levels of reliability and flexibility in inverse relationship to the speed and ease of implementation. The first approach is impractical because

- It lacks the versatility necessary for the project
- It would significantly exceed the resources available in terms of time, cost and complexity (ease of use).

Some argue that the Grey Box calibrated simulation model methodology is essential for investigating the problems this research project seeks to explore:

“Building simulation tools have been used for testing retrofit alternatives worldwide. But results provided by software would not be worth if the base case was not correctly calibrated, i.e., the virtual model of the building under analysis must represent faithfully the thermal and energy behaviour of that building.”
(Westphal and Lamberts, 2005)

Unfortunately, the relevant empirical data required to enable this approach is not available. In addition, for reasons outlined above, the number of variations and modifications anticipated for the model in terms of both location (climate) and fabric, may mean that the reliability of the majority of the resulting models is comparable to the White Box ‘Forward’ computer simulation models rather than a calibrated simulation model (Mustafaraj et al., 2014).

The final methodological option, the White Box ‘Forward’ building simulation methodology is

- Sensitive to the design options being considered
- Versatile, allowing multiple options to be considered
- The resources required to construct the model in terms of information and time are available
- The model can be reproduced by others
- There is a considerable amount of support available to ensure the model can be constructed and used effectively.

The accuracy of White Box models is dependent on the validation process (ASHRAE, 2009, ASHRAE Standard 140, 2017, Fumo, 2014, Crawley et al., 2008, Crawley

et al., 2001). Fumo (2014) argues that the results from White Box models of specific buildings

“[that have] not been calibrated with measured data, their results are considered to be validated through the verification status of the tool/method used”,

the ‘tool’ being ASHRAE Standard 140 or the IEA BESTEST method (IBPSA, 2018). Fumo concludes that

“although a model developed using accredited software is not a calibrated model; its results are assumed to be accurate enough to be considered valid”.

All models are a simplification of reality, imperfect and contain uncertainty. The purpose of the validation process and then a calibration process is to reduce the uncertainty. Junghans and Bae (Junghans and Bae, 2016), (Hopfe, 2009) and Hopfe and Hensen (2011) propose using a sensitivity or uncertainty analysis to define the uncertainty within the model rather than trying to remove the uncertainty.

The White Box ‘Forward’ simulation methodology is widely used to understand how variations to building fabric and mechanical systems effect the thermal performance of the building and the consequential thermal comfort of those who use the building. See Table 2.2 for a summary of examples.

For this project the White Box ‘Forward’ simulation methodology will be used, combined with an analysis to identify the range of uncertainty in the model.

Research projects that used a White Box 'Forward' simulation methodology

Brotas and Nicol (Brotas and Nicol, 2017)

Brotas and Nicol use EnergyPlus to model the performance of a 'typical' London apartment in 6 different European climates under 3 different climate change scenarios (2020, 2050 & 2080). The model is based on minimum values in the relevant UK Building Regulations rather than being calibrated to an existing apartment. The occupation pattern and internal gains are also assumed and based on agreed standards. The study explores how two different modification scenarios can reduce predicted discomfort. The study shows how different strategies can improve predicted comfort in different climates. The study reveals some problems with assumptions embedded in the CIBSE TM52 overheating standard that may have undesirable consequences.

Hatvani Kovacs (Hatvani-Kovacs, 2017)

In her PhD thesis exploring the resilience of Australian housing to heatwaves Hatvani-Kovacs uses the AccuRate computer simulation engine to model of a single storey, detached, three bedroom home to simulate the performance of the house in mixed mode and naturally ventilated mode. The AccuRate simulation engine has been developed by the CIRSO and validated using the BESTEST protocol (AccuRate_Sustainability, 2012, Delsante, 2004). The study simulated 8 construction variations ranging from traditional double brick and uninsulated brick veneer to 8 star rated heavyweight and lightweight construction systems. The results indicated that Star Rating system does not indicate that the building is resistant to heat stress. A high star rating is also not necessarily indicative of low average (over a year) or peak cooling loads.

Saman et al (Saman et al., 2013)

Saman et al wrote a comprehensive report, titled 'A Framework for Adaptation of Australian Households to Heat Waves', exploring the resilience of housing and the population to heat waves. Part 4 of the report uses a series of simulations to understand the impact of retrofitting strategies and modified designs (re-design) of 5 Case Study houses on comfort and energy use during a heatwave. The report uses the AccuRate simulation engine used (AccuRate_Sustainability, 2012) to model five 'Base Case' houses are theoretical rather than based on a detailed analysis or calibration with existing houses. The fabric specifications and internal loads (occupancy etc.) are based on current building regulations and statutory rating protocols. The report considers Internal temperature, gross energy consumption during the heatwave and peak energy demand as the measurable variables and shows that some simple retrofitting strategies can reduce all of these measures and so improve the performance of these houses and their resilience to heat waves. Re-designing the houses by re-orientating them, changing the plan form, fabric and including a 'cool retreat' has a more significant impact on performance and resilience to heat waves.

Continued....

Table 2.2: Summary of research projects that use a White Box 'Forward' simulation methodology

Smith et al (Smith et al., 2012) and Gentle et al (Gentle et al., 2011)

The team led by Smith and Gentle use Energy Plus to model a very simple square building with internal dimensions of 10 x 10m x 2.4m high in the Sydney climate. The building has no doors, windows or internal loads. The building is air conditioned with set point temperatures set at 20oC and 25oC. The study uses a Representative Mean Year (.RMY) climate file. The study explores the impact of varying three parameters: Solar reflectance (R-sol), air change rate and the U-value of the roof. The study concludes that

- Cooling energy is sensitive to solar reflectance (R-sol) and sensitivity increases as Ventilation rate increases.
- Cooling energy is not sensitive to R/U-value, particularly at high levels of solar reflectance.
- Heating energy is not sensitive to solar reflectance but is sensitive to air change rates.
- Heating Energy is sensitive to the U-value of the building fabric.

Bambrook (Bambrook, 2011)

In her PhD thesis Bambrook used a building energy simulation program (IDA Indoor Climate and Energy 4.0) coupled with an optimisation program (GenOpt 2.0) to explore how a house that meets the local building code requirements can be improved and optimised to minimise the annual energy consumption. The house was modelled as a single space 20 x 10m in plan with a flat roof. The long side of the house faces north. The house is located near Sydney Airport (based on the weather file Longitude and Latitude). 5 parameters were chosen for optimisation: The wall and ceiling insulation value, the quantity of internal thermal mass, the window specification and the mechanical ventilation system. The PhD thesis concludes that relatively simple modifications to the building envelope and ventilation system can significantly improve the thermal performance of a house in the coastal climate of Sydney.

Hacker et al (Hacker et al., 2008)

Hacker et al report a study by ARUP that used the building energy simulation software Energy 2 developed by ARUP to model a simple two storey two bedroom house in South East England. Four versions of the house were modelled ranging from a lightweight timber framed version to a heavyweight concrete version. The lifetime CO2 emissions of these four versions were compared over a 100 year time horizon in which the climate data was adjusted every 20 years (2001 – 2020, 2021-2040 etc.) to reflect climate-change under a medium-high emissions scenario UKCIP02 (Belcher et al., 2005).

The model was not calibrated to any specific house. The values for the various defined (input) variables were clearly defined based on current best practice.

The study concludes that heavier weight construction will have lower lifetime CO2 emissions in scenarios that last longer than 21 – 25 years. Where the ventilation and cooling strategy employs a mixed mode approach rather than a fully air-conditioned approach the overall CO2 emissions are lower and the difference between the lightweight and heavyweight scenarios is smaller.

Continued....

Table 2 (continued): Summary of research projects that use a White Box 'Forward' simulation methodology

Holmes and Hacker (Holmes and Hacker, 2007)

Holmes and Hacker report on a project by ARUP, supported by the UK Department for Trade and Industry and with the collaboration of CIBSE and the Building Research Establishment (BRE). In this project four case study buildings in the UK (one school and three offices) are modelled using the Energy2 building energy simulation engine developed by ARUP. The buildings are real buildings but simplified for the purposes of the model. The models were not calibrated to data from the real buildings.

The purpose of the project was to demonstrate how the principals of low energy design, in particular the principals of natural ventilation, thermal storage (thermal mass) and mixed mode operation can create comfortable internal environments now and in the future under a medium-high emissions scenario (UKCIP02) (Belcher et al., 2005) in 2020, 2050 and 2080. The paper uses the adaptive comfort model to evaluate predict thermal comfort in the buildings in the different scenarios. The project includes testing modifications to both the fabric of the building by increasing thermal mass and external shading, and to the operation of the building by changing the ventilation strategies.

The paper concludes that using shading, thermal mass and well-designed ventilation strategy combined with a mixed mode cooling system can create comfortable, low energy buildings that are resilient in future climate change scenarios.

2.2.3 Choosing a simulation engine

The IBPSA website lists 56 'whole building' simulation engines listed as complying with BESTEST that have been updated since 2010 (IBPSA, 2018). The literature contains multiple reviews of simulation engines, including Crawley (2008), who considers 20 of the 'major' programs. Energy Plus (US Department of Energy, 2014) and ESP-r are two of the most commonly used and versatile simulation programs. Both programs are open source and free, although it can be challenging to use the direct interface for the simulation engine. There are two graphic interfaces available for Energy Plus: Open Studio (www.openstudio.net) and Design Builder (designbuilder.com.au). Open Studio is a free open source interface based on Google Sketchup. There is an on-line support community to provide assistance. DesignBuilder is not free but, after some experimentation with both Open Studio and Design Builder, offers a more detailed interface. The significant advantage Design Builder has over Open Studio or ESP-r is that there is local expertise available to the researcher to support using the software.

For this project Design Builder has been chosen as the modelling interface. After the model was constructed it was reviewed by Team Catalyst (teamcatalyst.com.au) who supply Design Builder (Design Builder Ltd.) in Australia and provide technical support and training for Design Builder across Australia.

2.3 The simulation model

A computer simulation model consists of three parts (Fumo, 2014, Hopfe, 2009):

- i. A description of the climate in which the building exists (part of the Environmental System)
- ii. A description of the physical fabric and geometry of the building (Building System).
- iii. A description of how the building is used including its energy systems (Activity System).

These three parts and how they are defined are described below. “All building models are simplifications of reality” (ASHRAE Standard 140, 2017) and so contain assumptions. The following section sets out the basis for those assumptions and, where possible, why particular choices have been made.

Overall the model uses ‘as-built’ information from original drawings, specifications and surveys (see part 1.2 & 2.3.2) to construct a detailed simulation model in line with the ‘first level’ of calibration described by Mustafaraj et al (2014) and other reviews and examples of simulation methodologies, for example Fumo (2014) and Holmes and Hacker (2007).

The objective is to create a model that is as accurate as possible given the information available. The model will be used to understand the thermal performance of the NSW Demountable Classroom and, as a consequence,

the thermal comfort of those who use the classrooms, in a variety of climates across NSW and in the largest range of weather conditions possible given the constraints of a 365 day modelling period. i.e. The simulation will include all 365 days of the year for each climate.

An index to where to find summaries of the information used for the simulations is provided in Table 2.3.

Index to summaries of information used in the simulation model

i. A description of the climate	Figures 2.2 – 2.7 summarise the climate information Figure 2.8- 2.12 provide site information including for each climate.
ii. A description of the physical fabric and geometry of the building	Figure 1.8 provides the overall dimensions and construction system. Figures 2.13 - 2.16 provide detailed construction information. Figure 2.17 lists the U-values of the different elements within the base model.
iii. A description of how the building is used including its energy systems	Tables 2.8, 2.10 & 2.12 summarise the information used in the model settings to describe how the building is used, including occupancy and other internal heat loads, ventilation, heating and cooling.
iv. Uncertainty analysis	Part 2.5

Table 2.3: Index to summaries of information used in the simulation model

2.3.1 A description of the climate in which the buildings exist (part of the Environmental System)

The first part of the computer simulation model is a description of the climate in which the classroom is modelled.

The state of NSW has the most diverse range of climates of any state in Australia ranging from cool temperate in the south, to hot and dry (desert) in the west, to hot and humid (sub tropical) in the north. It was decided to simulate the performance of the Demountable Classroom and proposed Solution Sets in five representative climates across the state (Figure 2.2).

In consultation with the Trevor Lee (Exemplary Energy) who specialises in developing climate data files for Australia, the five climates that have been chosen are:

- Hot and Dry (desert): Broken Hill
- Cool temperate: Canberra
- Warm temperate (inland): Richmond
- Warm temperate (coastal): Williamstown (Newcastle)
- Hot and Humid (sub-tropical): Coffs Harbour

The five climates are described below using data from the Bureau of Meteorology (BOM, 2014) with accompanying commentary explaining how and why the particular climate and location were chosen.

(Temperatures shown in brackets are the mean 10th and 90th percentile minimum and maximum temperatures respectively)

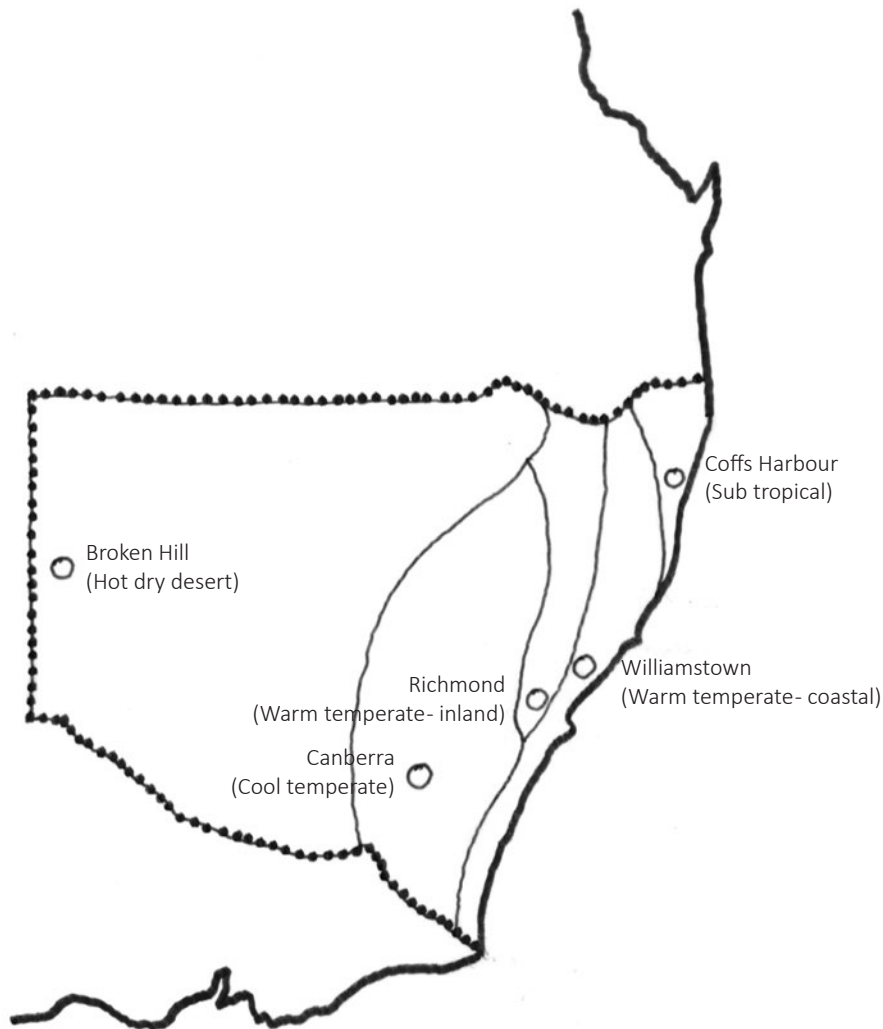


Figure 2.2: NSW Climates approximate categorisation
(Drawing by author)

Legend: Climate data

- 90th percentile max. daily temperature
- Mean max. daily temperature
- Mean min. daily temperature
- 90th percentile min. daily temperature
- Mean diurnal temp. range
- · - Mean daily solar exposure (MJ/m²)

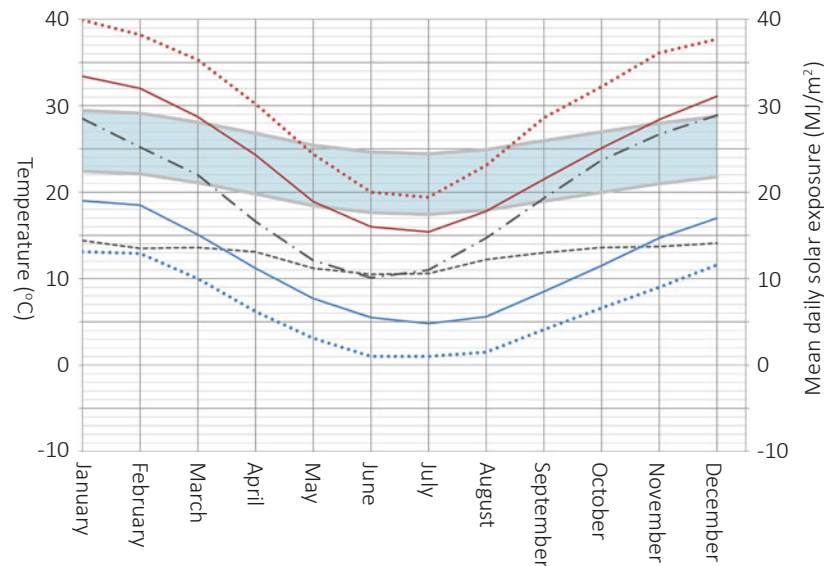


Figure 2.3: Broken Hill

Climate data for Broken Hill.

Monthly mean values based on the BOM climate data record (BOM, 2014)

For the computer simulation a “climate file” is used that is intended to represent a “typical” year including particularly cold and hot periods that one would expect rather than simply using daily or monthly mean temperatures. The climate files for the computer simulation provides hourly data. The climate files used in the simulation model were developed by Exemplary Energy Partners (Exemplary Energy, 2014) from data collected by the Australian Bureau of Meteorology and satellite data calculating solar radiation.

Hot and Dry (desert):Broken Hill

Daily Temperature ranges:

Winter: 5 to 16 (1 to 20) °C (July)

Summer: 19 – 33 (13 to 40) °C (January)

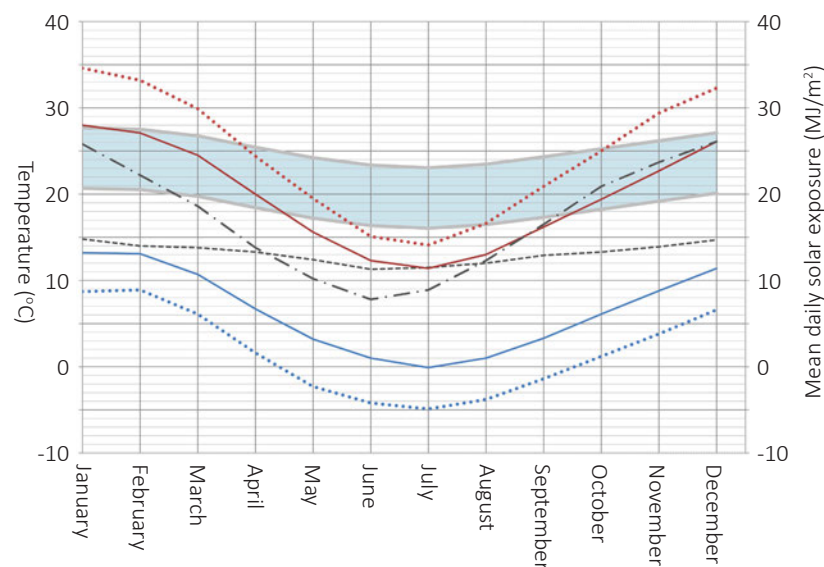
(Figure 2.3)

Broken hill is in the far west of the state approximately 1000 km from the NSW coast. The climate represents the more extreme climates of NSW. Although the population in parts of the state with this kind of extreme climate is low it is useful to understand how the building, and the proposed Solution Sets, perform in this more extreme situation. The climate of Broken Hill is similar to large parts of the west of the state, including Wagga Wagga.

Broken Hill has a hot dry desert climate (Koppen Classification) (BOM, 2016). The climate has very hot arid summers and cool winters. Average summer temperatures reach 33.4°C (January) with 10% of the maximum temperatures above 37.7°C in December and 39.9°C in January (hottest summer months). In the

Legend: Climate data

- 90th percentile max. daily temperature
- Mean max. daily temperature
- Mean min. daily temperature
- 90th percentile min. daily temperature
- Mean diurnal temp. range
- · - Mean daily solar exposure (MJ/m²)

**Figure 2.4: Canberra**

Climate data for Canberra.

Monthly mean values based on the BOM climate data record (BOM, 2014)

coldest months, June and July, the average maximum temperature is 20.0°C and 19.4°C respectively. 10% of nights are below -1°C in both months. The average rainfall is 200mm per year. There are cooling summer winds from the south and cold winter winds from the west. The environmental quality is dry and dusty.

Cool temperate: Canberra

Daily Temperature ranges:

Winter: 0 to 11 (-5 to 14) °C (July)

Summer: 13 to 28 (9 to 35) °C (January)

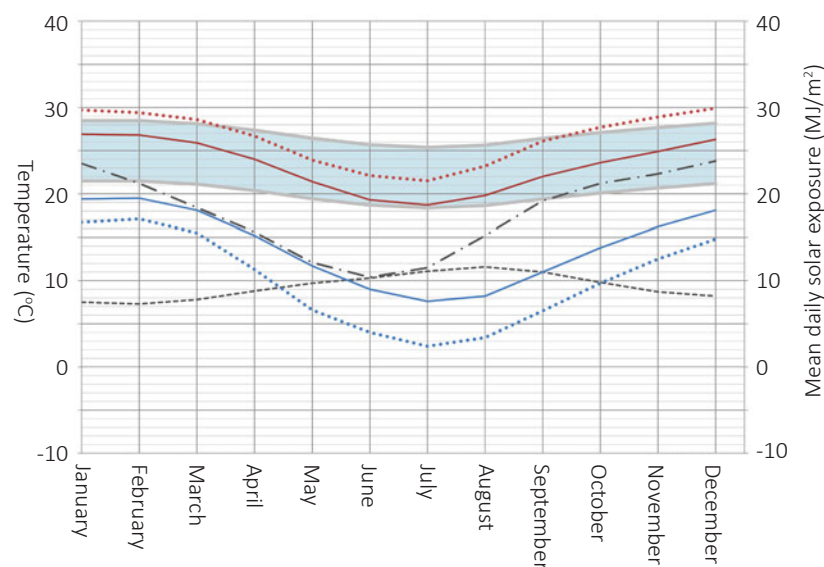
(Figure 2.4)

Between 50 and 100km from the coast of NSW a ridge of primarily sandstone plateaus runs from the south to the north of the state. Canberra sits within this region and has a continental cool temperate climate with warm to hot summers and cool to cold winters and distinct seasons. The climate is representative of this central ridge between the coastal climates and the more extreme climates inland as well as the climate in much of the southern part of the state. More generally it represents many of the extremes experienced across the state from cool to cold conditions in the winter, hot dry days in the summer and large diurnal ranges.

Canberra has a cool temperate climate (Koppen Classification) (BOM, 2016). The climate has warm to hot days in summer and cool winters. Average summer temperatures reach 28°C (January) with 10% of the maximum temperatures above 32°C in December and 35°C in January (hottest summer months). In the coldest months, June and July, the average maximum

Legend: Climate data

- 90th percentile max. daily temperature
- Mean max. daily temperature
- Mean min. daily temperature
- 90th percentile min. daily temperature
- Mean diurnal temp. range
- · - Mean daily solar exposure (MJ/m²)

**Figure 2.5: Richmond**

Climate data for Richmond.

Monthly mean values based on the BOM climate data record (BOM, 2014)

temperature is 15.1°C and 14.1°C respectively. 10% of nights are below -4.2 °C and -4.9°C respectively. The average rainfall is 616mm per year.

Warm temperate (inland): Richmond

Daily Temperature ranges:

Winter: 4 to 18 (-1 to 21) °C (July)

Summer: 18 to 30 (14 to 37) °C (January)

(Figure 2.5)

Richmond is on the inland edge of the coastal planes where they meet the edge of the sandstone ridge running up the eastern side of NSW. Richmond is 50km from the ocean. The fluctuations in the patterns of the warm temperate climate of NSW rapidly become more extreme as one moves away from the modifying influence of the ocean. This creates warmer summer and colder winter temperatures as well as larger diurnal variations in temperature. A significant proportion of the population and new construction are within this Western part of greater Sydney.

Richmond has a warm temperate climate (Koppen Classification) (BOM, 2016). The climate has warm to hot days in summer and cool winters. Average summer temperatures reach 30°C (January) with 10% of the maximum temperatures above 35.4°C in December and 37.4°C in January (hottest summer months). In the coldest months, June and July, the average maximum temperature is 17.9°C and 17.6°C respectively. 10% of nights are below 0°C and -1°C respectively. The average rainfall is 716mm per year.

Legend: Climate data

- 90th percentile max. daily temperature
- Mean max. daily temperature
- Mean min. daily temperature
- 90th percentile min. daily temperature
- Mean diurnal temp. range
- · - Mean daily solar exposure (MJ/m²)

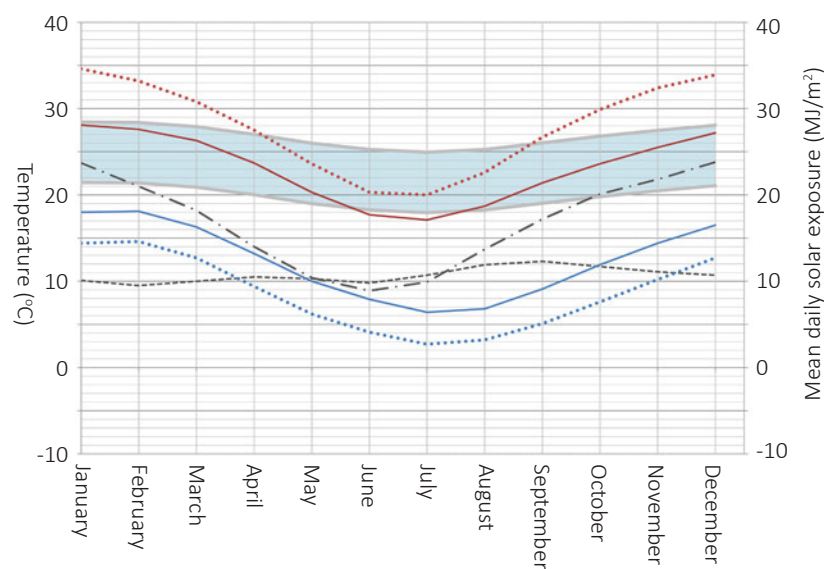


Figure 2.6: Williamstown

Climate data for Williamstown.

Monthly mean values based on the BOM climate data record (BOM, 2014)

Warm temperate (coastal): Williamstown (Newcastle)

Daily Temperature ranges:

Winter: 6 to 17 (3 to 20)°C (July)

Summer: 18 to 28 (14 to 35) °C (January)

(Figure 2.6)

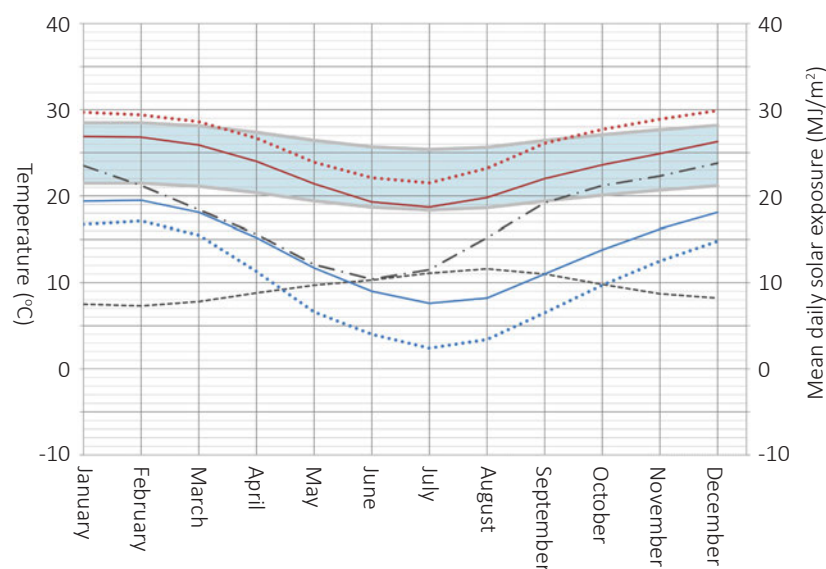
The climate is similar to Sydney the major population centre. The climate data from Williamstown RAAF base is more consistent with the majority of the suburbs in Newcastle and coastal Sydney than the data from the Sydney CBD (Observatory Hill) or Sydney Airport. Observatory hill is affected by the heat island of the CBD and the wind data is collected on the harbour (Fort Denison). The airport is in an exposed location on the coast and therefore likely to be windier, cooler and sometimes hotter than less exposed locations on the coast.

The majority of the population of NSW is concentrated along the coast and, particularly, around Sydney and Newcastle. The climate is heavily influenced by the ocean which moderates extremes of temperature in summer and winter. In summer cooling sea breezes, sometimes strong sea breezes, build up from mid or late morning and through the afternoon from the north east. In winter there is often less wind with cool or cold southerly winds and occasionally westerly winds being most noticeable.

Williamstown has a warm temperate climate moderated by the proximity of the ocean (Koppen Classification) (BOM, 2016). The climate has warm days in summer and cooler winters. Average summer

Legend: Climate data

- 90th percentile max. daily temperature
- Mean max. daily temperature
- Mean min. daily temperature
- 90th percentile min. daily temperature
- Mean diurnal temp. range
- · - Mean daily solar exposure (MJ/m²)

**Figure 2.7: Coffs Harbour**

Climate data for Coffs Harbour.

Monthly mean values based on the BOM climate data record (BOM, 2014)

temperatures reach 28.1°C (January) with 10% of the maximum temperatures above 33.9°C in December and 34.6°C in January (hottest summer months). In the coldest months, June and July, the average maximum temperature is 17.7°C and 17.1°C respectively. 10% of nights are below 4.1°C and 2.7°C respectively (3.2 °C in August). The average rainfall is 1121mm per year.

Hot and Humid (sub-tropical): Coffs Harbour

Daily Temperature ranges:

Winter: 8 to 19 (3 – 22))°C (July)

Summer: 20 to 27 (17 to 30) °C (January)

(Figure 2.7)

Coffs Harbour is known for its pleasant moderate climate that is rarely too hot or too cold. Situated on the north coast of the state it benefits from the warmth that comes from being closer to the equator and the moderating influence of the ocean.

Coffs Harbour has a warm humid sub-tropical climate (Koppen Classification) (BOM, 2016). The climate has warm days in summer and mild winters. Average summer temperatures reach 26.9°C (January) with 10% of the maximum temperatures above 29.9°C in December and 29.7°C in January (hottest summer months). In the coldest months, June and July, the average maximum temperature is 19.3°C and 18.7°C respectively. 10% of nights are below 4°C and 2.4°C respectively (3.4 °C in August). The average rainfall is 1701mm per year.

Site Selection

It was decided to model real sites rather than create an idealised scenario. Creating real sites has the advantage of grounding the project in the real world, introduces some of the quirks that are lost in idealised scenarios and avoids the problem of connecting the 'ideal site' with 'reality' and all the questions and variations that that alternative approach creates.

The individual sites were selected based on the following criteria:

- Proximity to the chosen weather data centre (e.g. Broken Hill airport)
- An existing Demountable Classroom on the site
- Ideally the classroom will be on its own or on the northern end of a row so that it is exposed to the largest possible amount of solar radiation (i.e. it is in the least advantageous position).

Sites were found by following the following three stages:

- i. Locating the weather station from which the weather file data for the simulation was collected on Google Maps.
- ii. Using the search facility to find “School” or “public school” nearby
- iii. A visual search on the Google and Bing aerial views to locate Mk I Demountable Classrooms on the school campus.

Site dimensions and relative positions were estimated from the aerial view (printed) using the google scale and known classroom dimensions to create an approximate plan. Other site information was collected from Street view and estimates were made of eave heights and probable roof pitches.

Site plans are illustrated in Figures 2.8- 2.12.

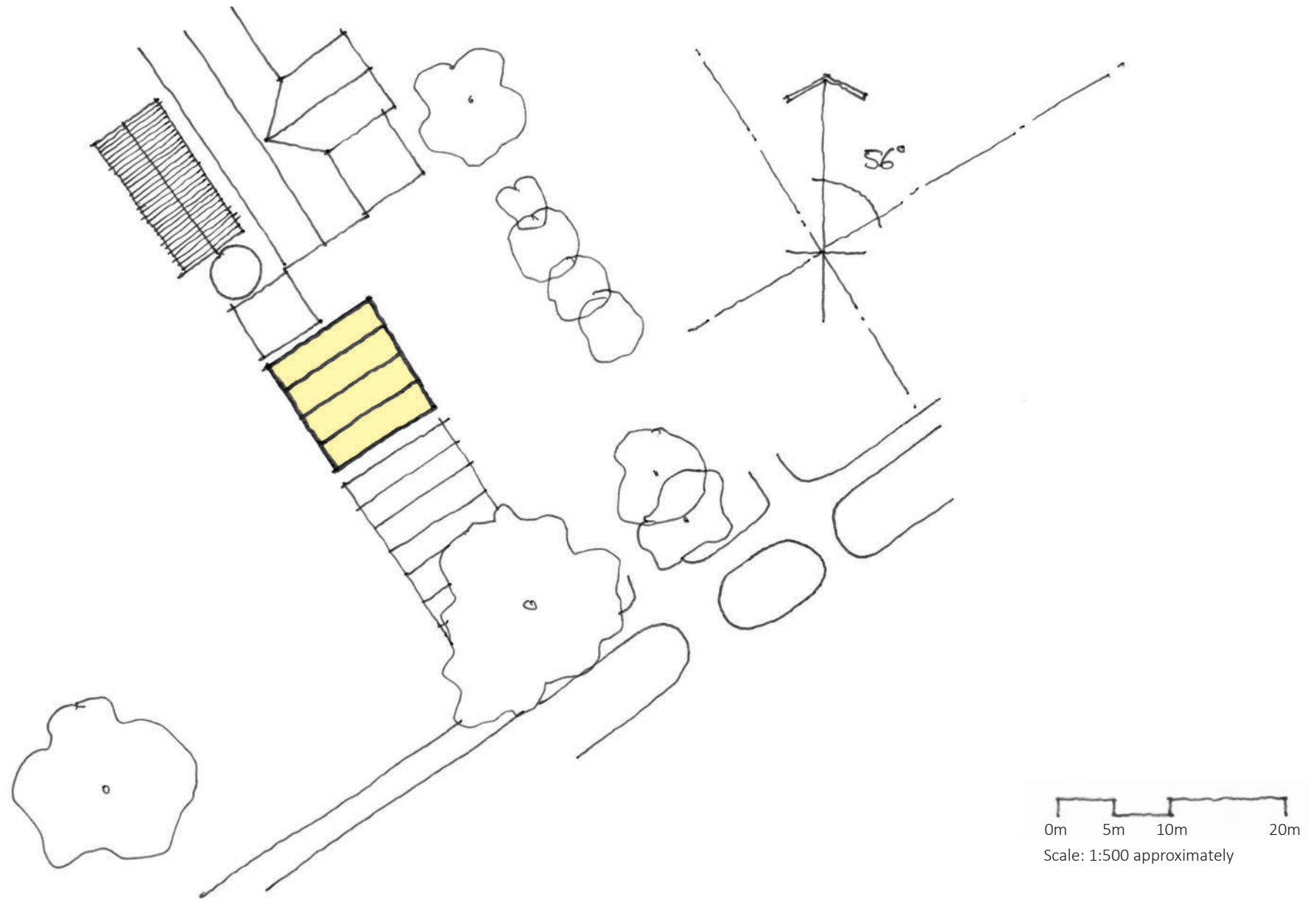


Figure 2.8: Broken Hill site plan
School of the Air, Lane Street, Broken Hill
Modelled classroom highlighted in yellow
(Drawing by author)

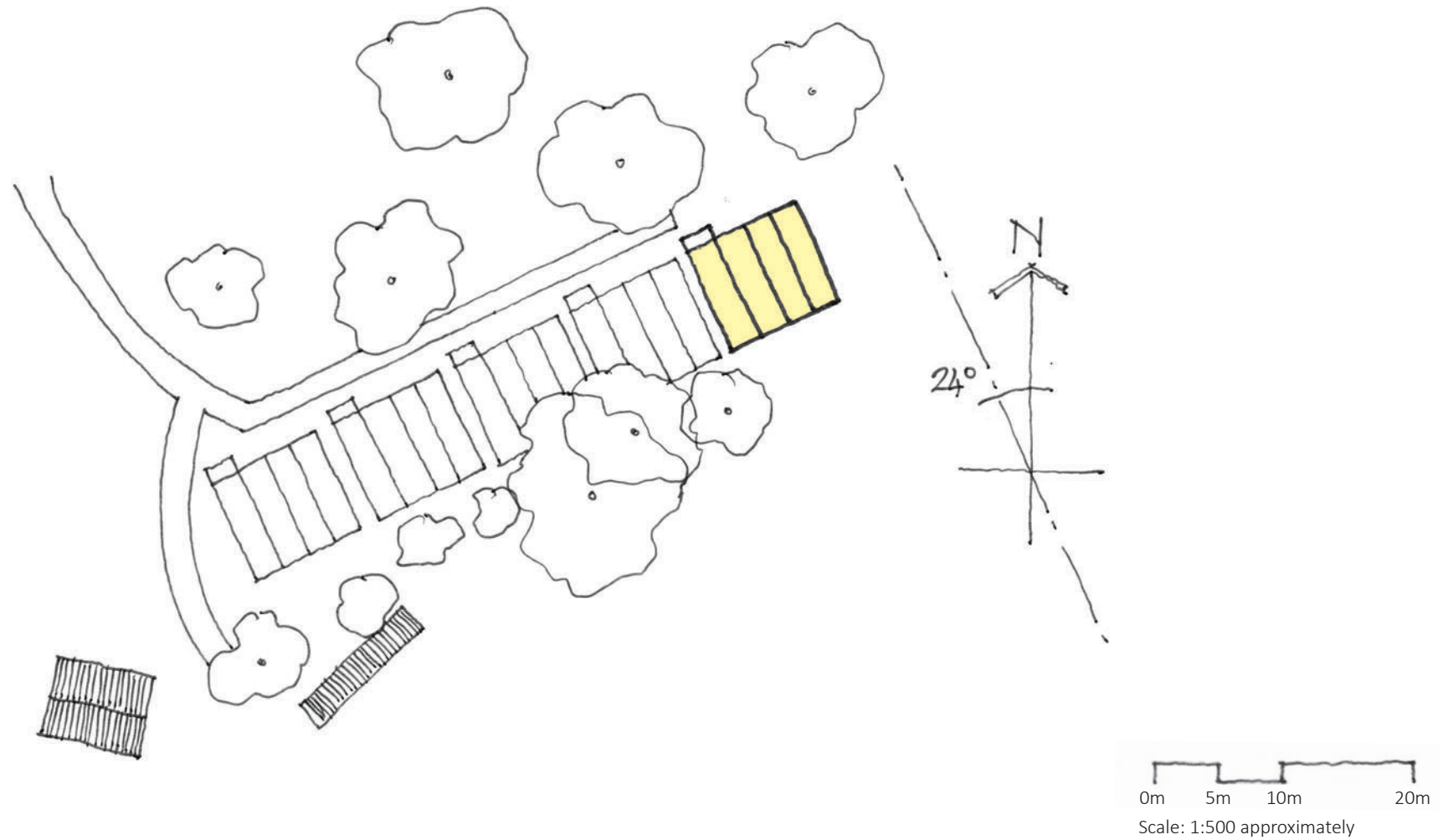


Figure 2.9: Canberra site plan
Queanbeyan West Public School, Queanbeyan
Modelled classroom highlighted in yellow
(Drawing by author)

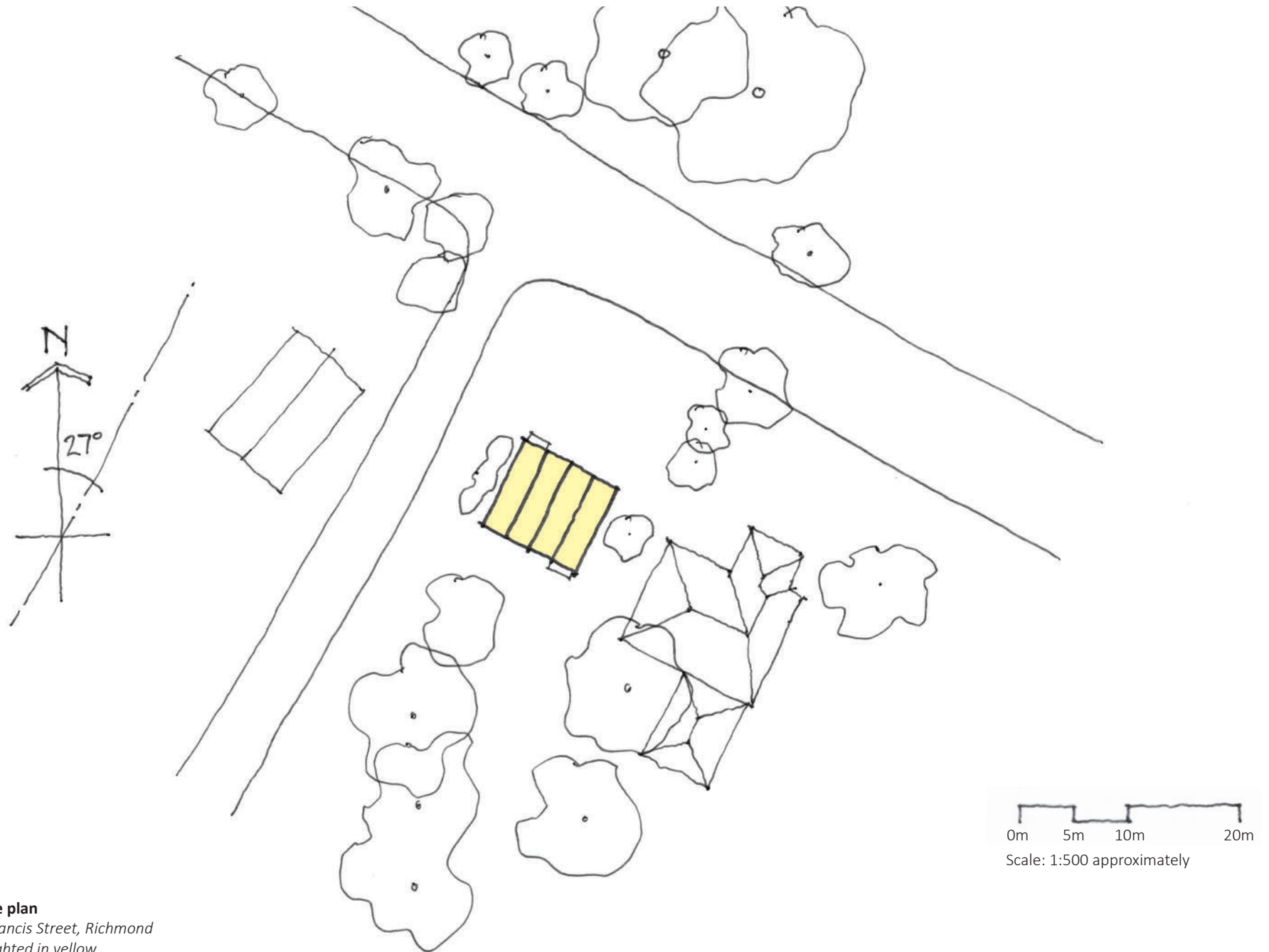


Figure 2.10: Richmond site plan
 Richmond Public School, Francis Street, Richmond
 Modelled classroom highlighted in yellow
 (Drawing by author)

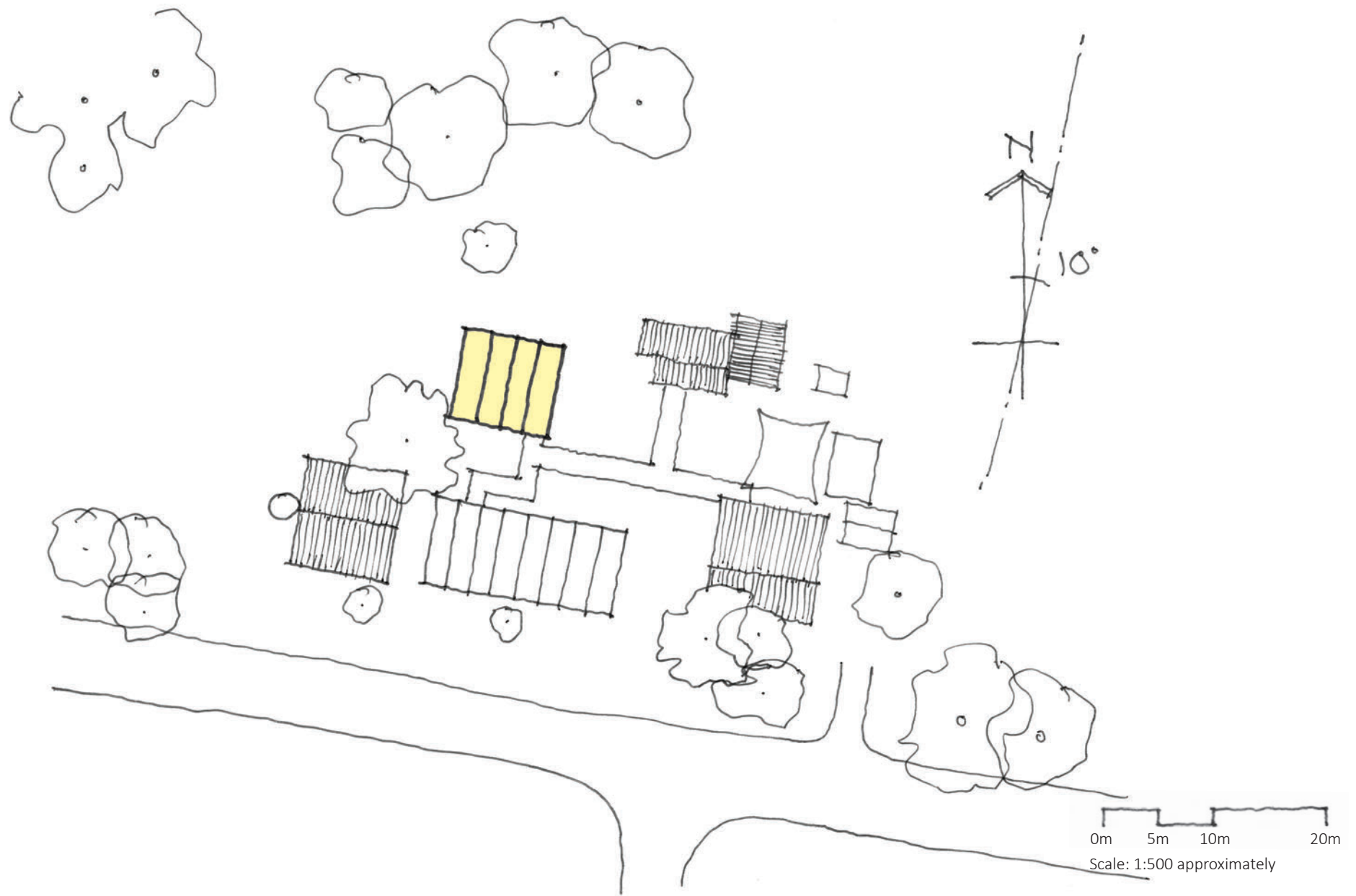


Figure 2.11: Williamstown site plan
Fern Bay Public School, Vardon Road, Fern Bay
Modelled classroom highlighted in yellow
(Drawing by author)

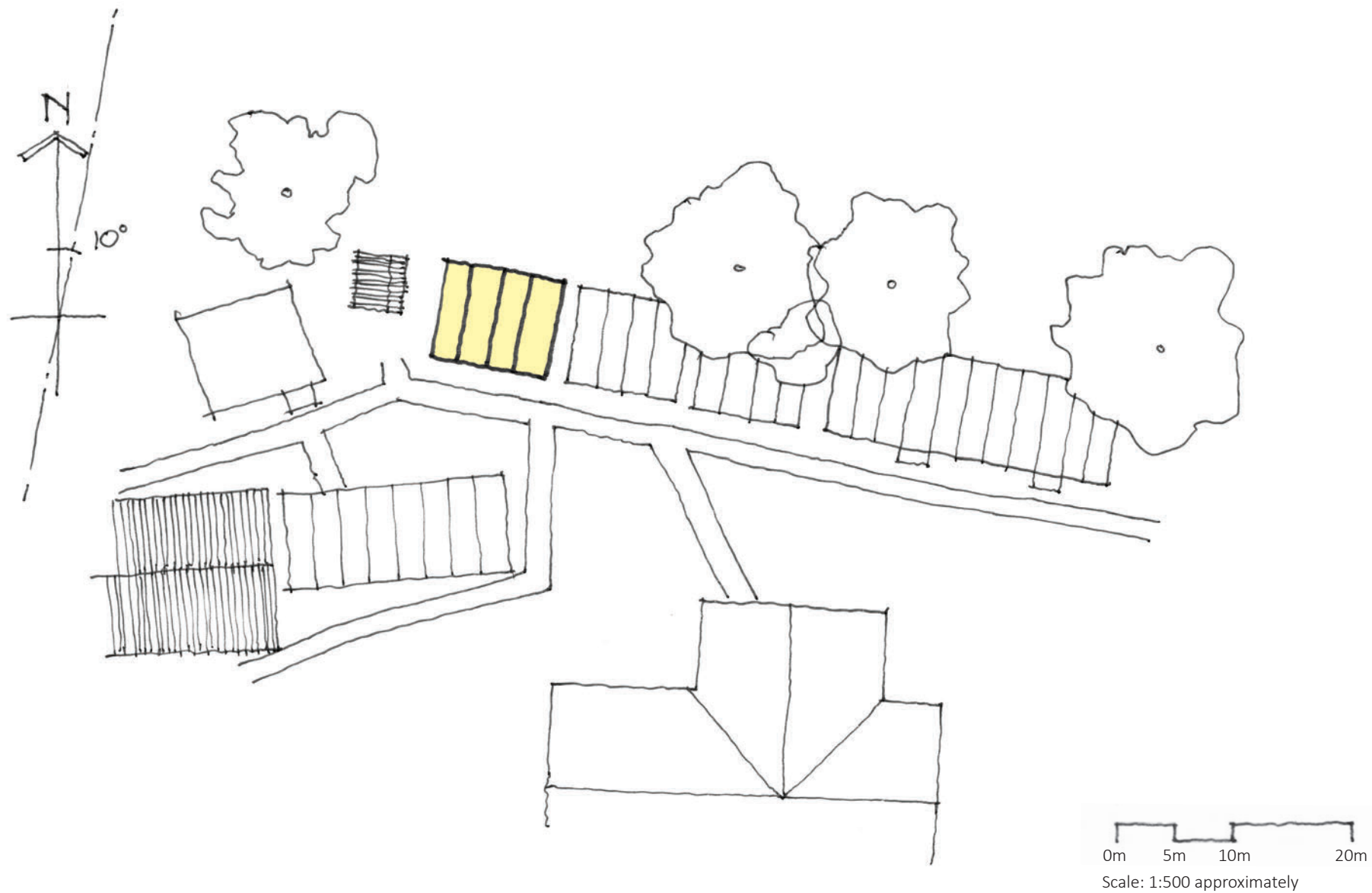


Figure 2.12: Coffs Harbour site plan
 Boambee Public School, Lindsay Road, Boambee
 Modelled classroom highlighted in yellow
 (Drawing by author)

2.3.2 The physical fabric and geometry of the building (building system)

Detailed information about the physical fabric of the classroom buildings was collected from three sources:

- i. A detailed survey of the existing buildings undergoing refurbishment
- ii. Original and current construction drawings and specifications
- iii. Manufacturers product information and other databases of generic material properties.

A detailed survey

A number of visits to Cessnock Jail were arranged where the NSW Demountable Classrooms are stored and refurbished. Refurbishment is undertaken by prisoners in a secure yard where cameras are not permitted. This meant that the detailed physical survey of the buildings undergoing refurbishment were recorded using sketches, physical measurements and notes. Surveys of a number of mk. 1 Demountable Classroom building units in various stages of repair ranging from the primary frame to nearly complete were undertaken. Detailed notes of the products used in the construction were also made and detailed specification information obtained from the manufacturers.

Original and current construction drawings and specifications

The NSW Government Architects Office provided a copy of the original drawings for both the Mark 1 (circa 1965) and Mark 2 (circa 1975) classrooms (NSW Government Architects Office, 1983, NSW Government Architects Office, 1965 - 1970 (circa)). The drawings include the original specifications as annotations. More recent drawings of typical details were also supplied (NSW Government Architects Office, 2001) and a copy of the current (2014) refurbishment specification was obtained.

Detailed physical properties of materials

The detailed physical properties of materials were collated from manufacturer's product information and other sources of information providing detailed generic properties of materials such as Keller and Rutz (2010) and the Design Builder database (Design Builder Ltd).

The fabric of the Demountable Classroom includes a considerable number of thermal bridges and complex sections (Figures 2.13 - 2.16).

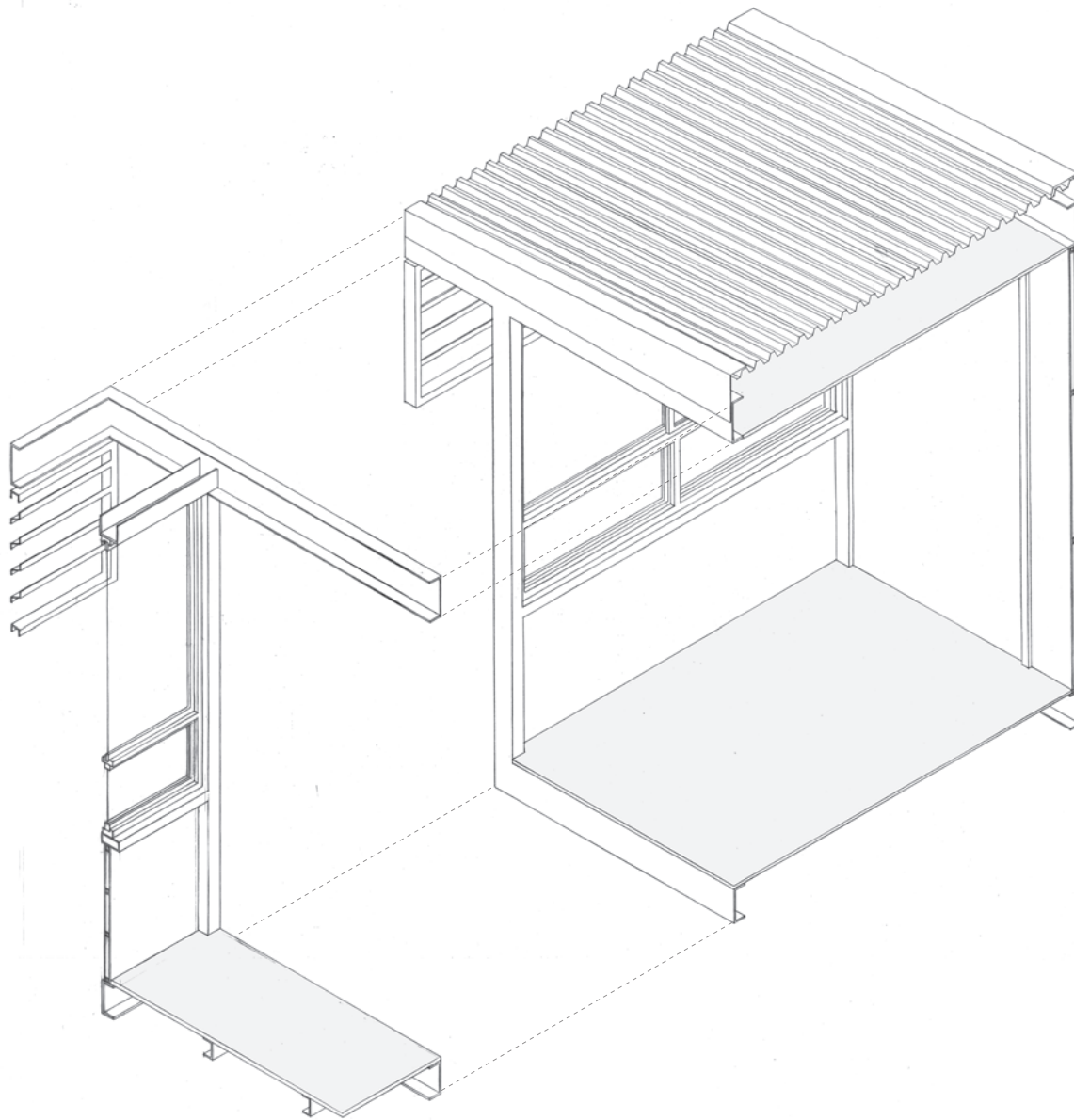


Figure 2.13: Exploded isometric of the existing classroom modules

*Exploded and cutaway isometric drawing of a Mk. 1 NSW demountable classroom illustrating the construction of the existing classroom modules
(Drawing by author)*

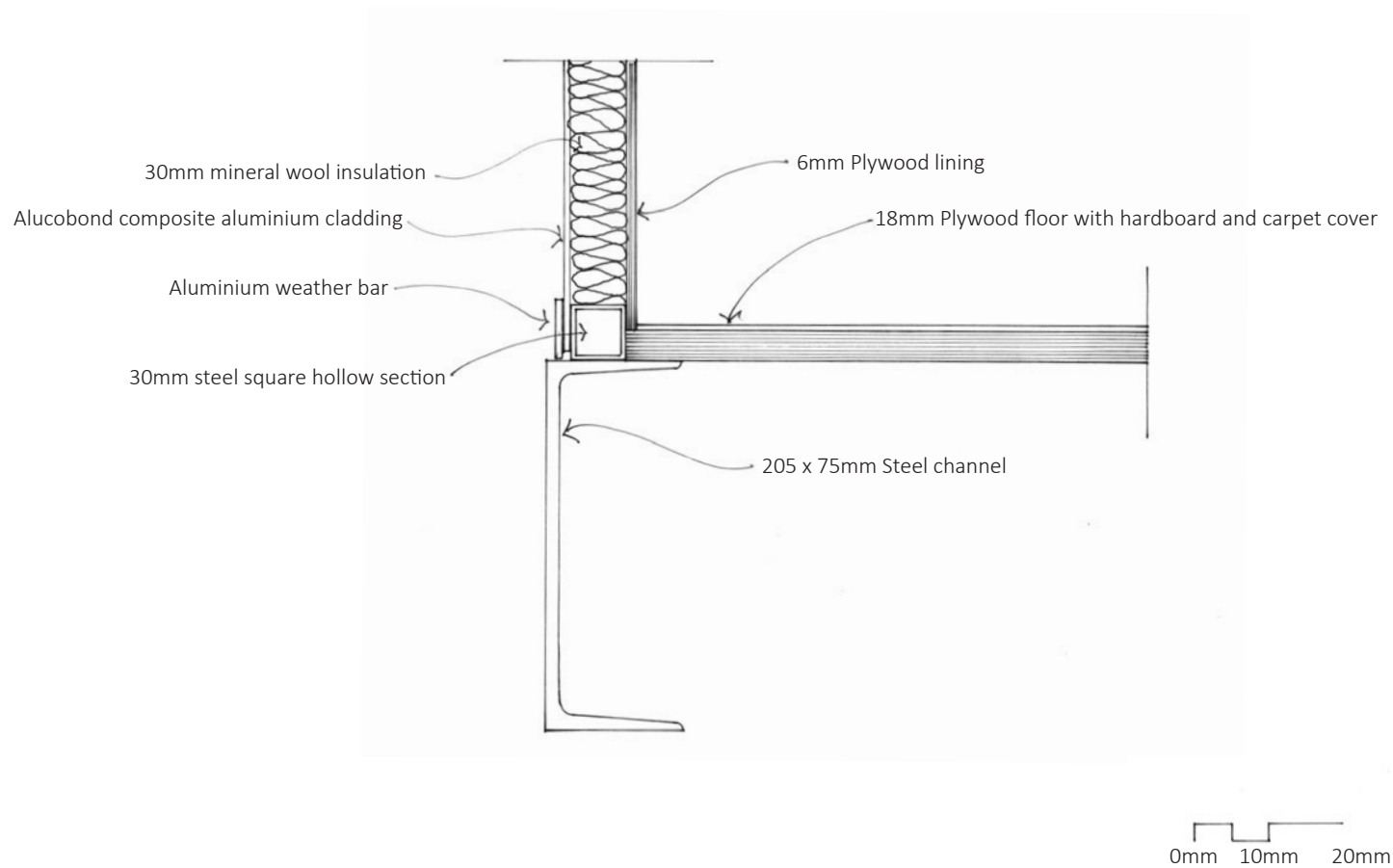


Figure 2.14: Floor detail

*Cross section of the floor and wall panel junction
(Drawing by author)*

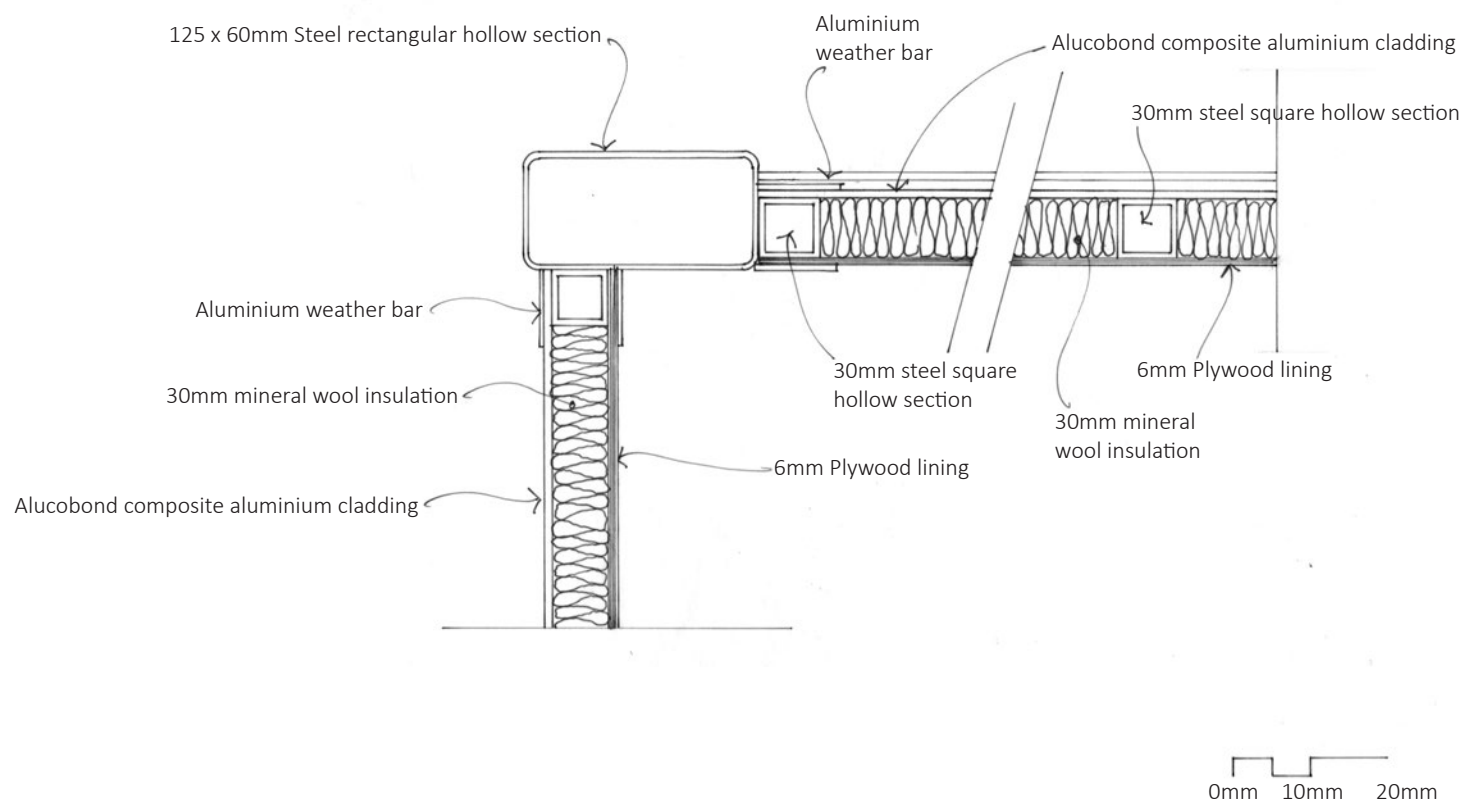


Figure 2.15: Wall detail

*Plan section detail of the corner of a classroom module
(Drawing by author)*

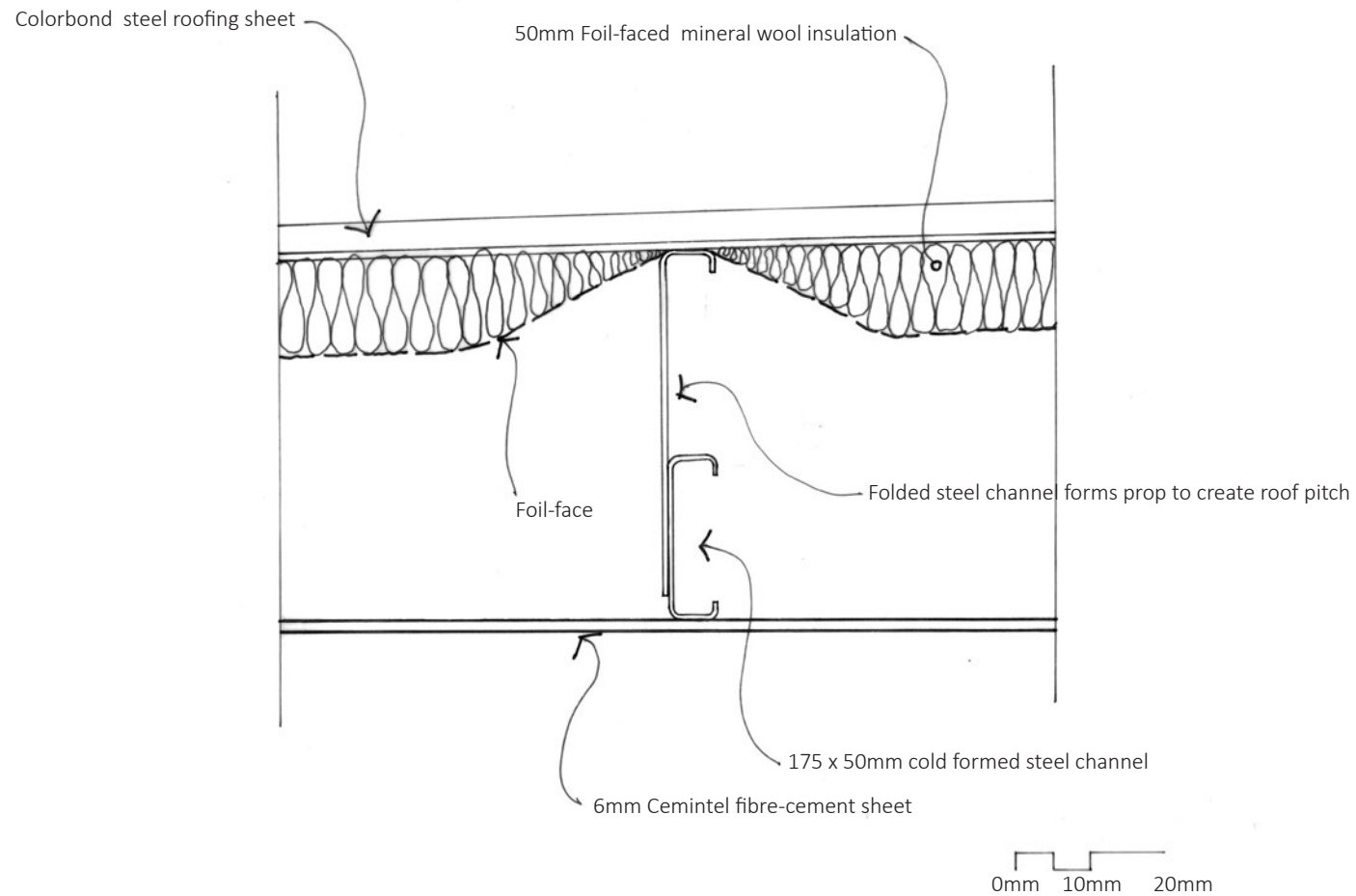


Figure 2.16: Roof detail
 Section detail of the roof construction
 (Drawing by author)

In order to account for this complexity in the creation of the thermal simulation model in Design Builder a two step process was adopted:

1. The first stage modelled individual elements or panels to provide an overall U-value
2. The second stage used these overall U-values to create a building model in Design Builder which is not able to model the complex thermal bridges.

Stage 1: Two dimensional thermal model of individual elements (physical fabric)

The existing fabric of the building was modelled and subsequent proposed 'solutions' or modifications to the fabric were modelled.

The overall construction of the classrooms is relatively simple but individual parts of the building contain complex thermal bridges formed by steel sections used in the primary and secondary structural frames and the composite construction of various elements, e.g. the wall panels. To understand the overall U-value of these different elements they were modelled using Therm 7 (THERM 7.3, 2015). Therm 7 is free software developed by the Laurence Berkeley Laboratory in California for analysing two-dimensional heat transfer through building products with complex or non-uniform sections.

Stage 2: The overall geometry

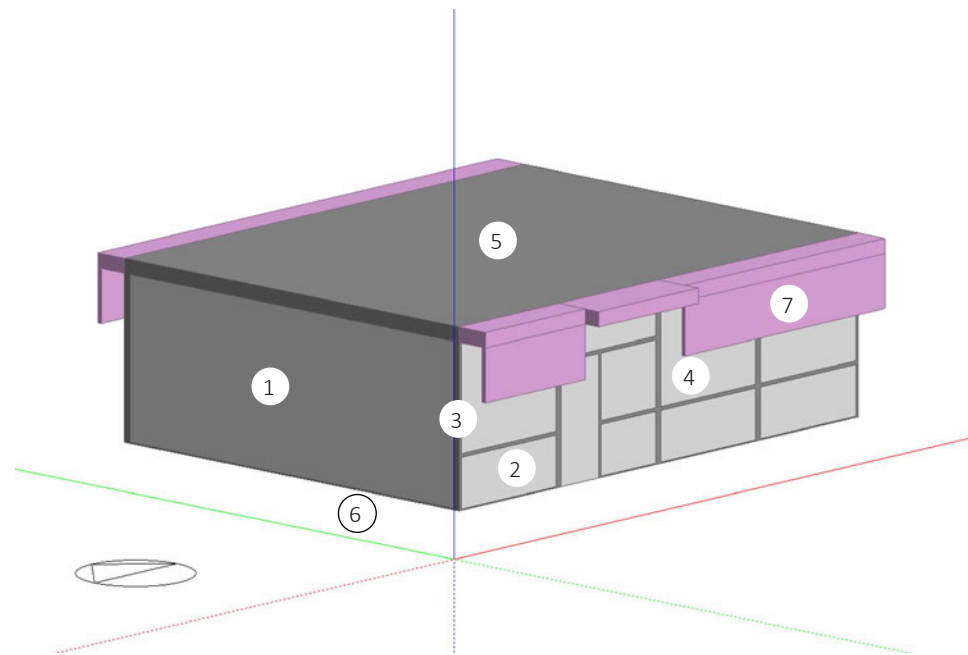
The overall geometry of a four bay classroom was modelled in Design Builder 4.7 (Design Builder Ltd).. The

dimensions for this model were taken from the detailed physical survey with supporting information from the original drawings.

Design Builder is a computer programme that provides a detailed interface with the digital building performance simulation engine Energy Plus developed over many years by the United States Department of Energy (US Department of Energy, 2014).

The model was constructed as a primary steel frame with in-fill panels defined as a “sub-surface” in the software. The detailed construction of these panels was included in the model with the exception of the secondary structural frame (i.e. internal studs or joists). The overall U-values for the different elements were adjusted to reflect the calculations from stage 1.

The building model (stage 2) can be seen in Figure 2.17. The U-values of the existing construction elements calculated in stage 1 are listed in the table included in Figure 2.17.



No.	Description	U-Value (calculated)
1.	End wall,	1.036 W/m ² .K
2	Infill panel	1.43 W/m ² .K
3	Primary steel frame (125mm / 60 mm)	3.39 W/m ² .K / 4.35 W/m ² .K
4	Window	5.58 W/m ² .K
5	Roof	1.25 W/m ² .K
6	Floor	2.11 W/m ² .K
7	Shading device	

Figure 2.17: Design Builder model

*Design Builder simulation model including a key to the simulated surfaces and their U-values
(Drawing from Design Builder model by author)*

2.3.3 A description of how the building is used (activity system).

The third part of a simulation model is the description of how the building is used. All models are an approximation to reality. This is particularly clear when we consider how the building is used by the occupants (Ahn et al., 2017): Understanding how individual teachers and classes inhabit their classrooms and how Utility Managers manage the classroom facilities they are responsible for is a key aspect of research by Soccio (2014) and the Future Proofing Schools Project (2012). Therefore all descriptions of how a building is used must be a generalisation and approximation to how buildings, in this case the NSW Demountable Classroom, are and will be used by particular teachers, classes and schools.

In the Design Builder computer simulation model the description of how the building is used and occupied is covered by the “Activity” and “HVAC’ templates. An explanation of these settings is tabulated in Table 2.8.

The ‘activity’ template describes the internal thermal loads of the classroom. This is a combination of ancillary loads, e.g. lighting, and the thermal energy input from people. The thermal energy input loads from people are a function of

Occupancy (the number of people)

X

Metabolic output per person (heat production per person)

The HVAC template describes how the classroom is heated, cooled and ventilated in order to maintain comfort.

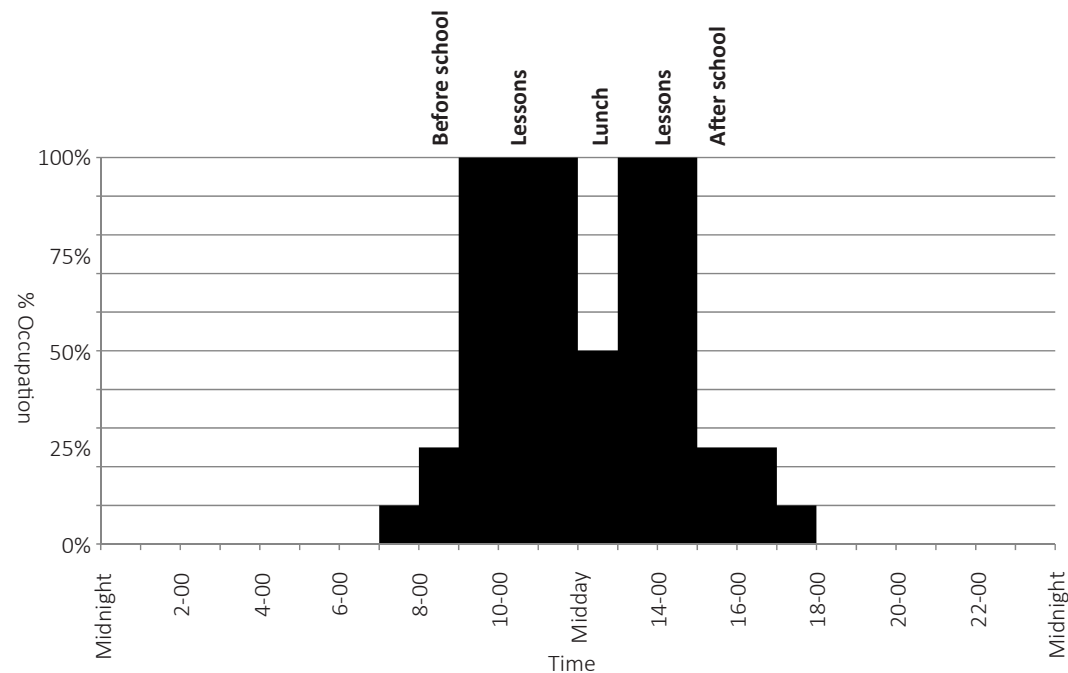


Figure 2.18: Occupancy schedule

Occupancy schedule illustrated as a bar graph based on a variety of sources

Occupancy

The objective of the model is to understand the thermal performance of the NSW Demountable classroom in different weather conditions in different climates. The purpose is not to predict how the classroom performs in a ‘typical’ school year. In order to maximise the available results (data points) the classroom occupation was set to all 365 days in the year so that every weather condition included in the weather file is modelled.

The daily occupancy schedule (Figure 2.18) was based on schedules from the National Construction Code (NCC, formally the BCA) (ABCB, 2016), the UK National Calculation Methodology (UK NCM, 2017) that is included with Design Builder, and a brief survey of timetables in schools. The NSW Department of Education says that actual school hours are from 9am – 3pm with some variation between schools (SMH Anna Patty, 2010). A review of school timetables and the NSW Department of Education website confirmed this indicating breaks in the morning and for lunch (between 45 minutes and 1 hour). There are a number of discrepancies between the NCC Schedule, the NCM Schedule and common practice in schools:

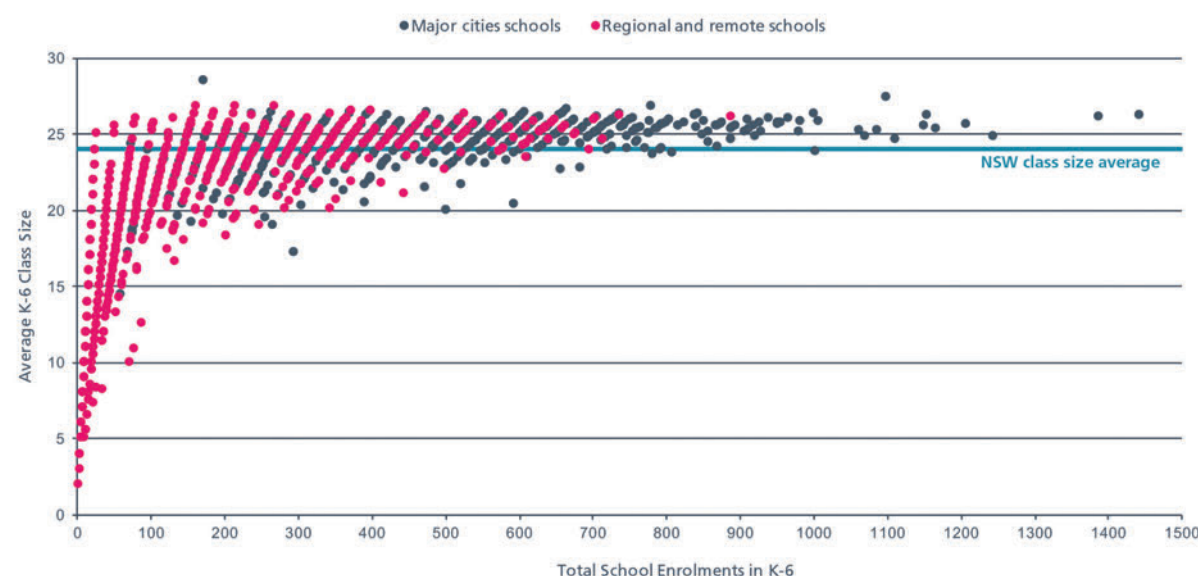
- Both the NCC and NCM schedules assume reduced occupancy for 2 hours over lunch. In schools the lunch break varies between 45minutes and 1 hour.
- The NCC schedule assumes 75% occupancy for the hour before school starts (8am – 9am) and 90% Occupancy during school. Statistics from the NSW Department of Education show that mean attendance at all schools between 2006 and 2017

was 92.3% and attendance at primary schools higher at 94.1% (NSW Department of Education, 2018).

- The NCM schedule assumes 75% attendance for the first hour of school (9am – 10am) and then 100% attendance during class times.
- The NCC schedule shows 70% occupancy for the hour after school finishes (3pm – 4pm), then 50%, 20% and 5% with occupation continuing until midnight.

For the purposes of this analysis the schedule (Figure 2.18) used assumes 100% attendance during classes in order to illustrate the conditions in a fully occupied classroom. The Schedule includes a 1 hour lunch break and some occupation before and after school, for example a teacher preparing classes, meetings and after school care.

The NCC suggests an occupancy rate of 2 sq.m per person which indicates 36 people in these classrooms (internal floor area of 72.1 sq.m). The Department for Education publishes class size statistics for years K to 6 (Primary and Junior school) (Table 2.4 and Figures 2.19).



Note:

- Total school enrolments represent the total number of K-6 students for each school as reported in the class size audit.
- Major Cities and Regional and Remote classifications are based on the Australian Statistical Geography Standard (ASGS).

Figure 2.19: Average class size in NSW

Average class size by remoteness and school enrolments, 2017: NSW government schools (figure 1 from NSW Department for Education, 2018)

School year	Government objective	Actual (2017)
K	20 (average)	19.1 (average)
1	22 (average)	21.3 (average)
2	24 (average)	22.5 (average)
3 - 6	30 (maximum)	26.2 (average)
7- 10	30 (maximum)	No data

Table 2.4: NSW Class sizes by year

(NSW Department for Education, 2017 & 2018)

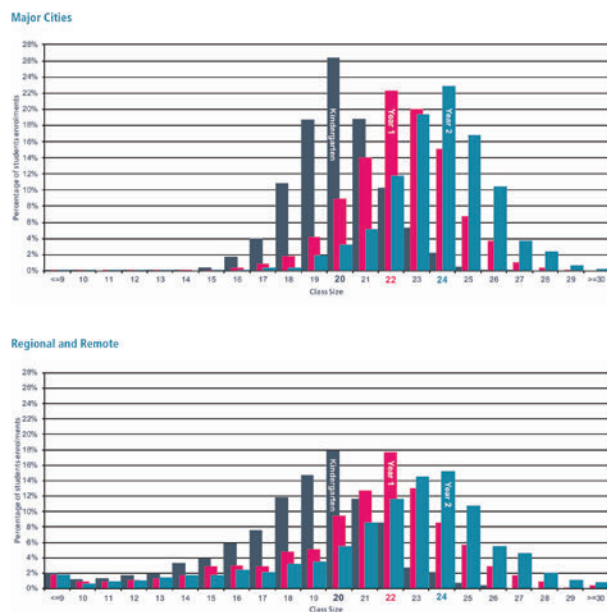


Figure 2.20: Distribution of class sizes in urban (top) and regional (bottom) NSW for years K, 1 & 2

Planned class sizes:

Year K - 20

Year 1 - 22

Year 2 - 24

(figure 6 from NSW Department for Education, 2018)

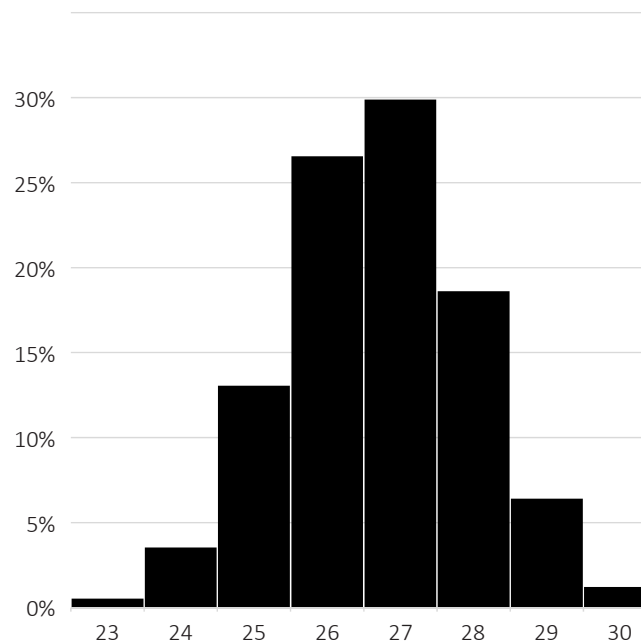


Figure 2.21: Estimated distribution of class sizes NSW schools for years 3-6 (junior school)

Based on a normal distribution and class size statistics from NSW Department for Education (2017 & 2018).

Mean: 26.2

Standard deviation: 1.3 (3 standard deviations = 4)

In 2017 the average (mean) class size in years K, 1 and 2 were 19.1, 21.3 and 22.5 respectively. The average class size for years 3 – 6 was 26.2. The NSW government aims to have class sizes containing no more than 30 students in years 3 – 10 (NSW Department for Education and NSW Teachers Federation, 2016). Figure 2.19 illustrates the average class size in each NSW primary school in NSW for 2017. The data is separated by size of school and whether it is a regional or urban school.

The graphs accompanying this data (Figures 2.20) illustrate that variation in class size in years K, 1 and 2 approximate to a normal distribution. The variation in class size for years 3 – 6 (primary school) and years 7 – 10, and 11 & 12 (secondary school) were not published. Using the information available and assuming a normal distribution and that a maximum class size of 30 is 3 standard deviations from the mean of 26.2 a class size distribution for years 3 – 6 has been created (Figure 2.21) (Note: the mean plus and minus 3 standard deviations includes 99.7% of all class sizes.) This suggests that with the Mean of 26.2 the most common class size (the Mode) is 27 pupils.

For the purpose of this analysis occupation will be set at 27 plus the teacher.

Metabolic output

In the standards metabolic output is calculated by multiplying together the following:

Metabolic factor (MET), which describes the level of metabolic activity relative to a person seated at rest (CIBSE Guide A, 2015).

The metabolic output of a person seated at rest (1 MET) defined as Watts per m². of body surface area. For an average adult this is taken to be 58.2 W/m² (CIBSE Guide A, 2015).

The surface area of the person. For an adult this is taken to be 1.8m² (CIBSE Guide A, 2015), but, obviously, varies for children.

In Design Builder the activity level is defined as Watts per Person and is dependent on the activity. The metabolic rate is then defined separately as a factor of the activity level (W/person) to account for the different size of people. The factors are defined between 0 and 1.0 with children proposed as 0.75, women 0.85 and men 1.0.

MET factor

The National Construction Code (ASCB, 2016) refers to CIBSE Guide A (2015) for the metabolic rate of children in a classroom. CIBSE Guide A proposes a rate of 1.3 MET for “customary [UK] summer temperatures” of 21 – 25 °C; and a rate of 1.4 MET for “customary [UK] winter temperatures”, 19 – 21 °C. De Dear et al (2015) report a study in 9 Australian schools in 5 climates. The study collected 2850 survey responses which included

recording an activity value of either ‘sitting’ or ‘active’ and assigning a MET value of 1.2 or 3.0 respectively based on ASHRAE 55 (2013). They report a mean MET value from all students of 1.51.

Haddad et al (2014, Haddad, 2016) have undertaken a study to establish a more accurate basis for assigning MET values to children based on a detailed literature review and survey data obtained from 58 primary school classrooms in Iran. The survey was undertaken during warm and cool seasons. Haddad et al conclude that a MET value of 1.3 and resting metabolic rate of 58.15 W/m² is the most robust estimate of children’s metabolic rate in classrooms.

For the purpose of this analysis the MET value will be set at 1.3.

Body surface area

CIBSE Guide A (2015) takes the average adult body surface area to be 1.8 m². The ASHRAE Book of fundamentals Chapter 9 (2013) assigns the same value to the average adult male. The body surface area of children, quite obviously, has a wide range. Haddad et al (2013) and Haddad (2016) reports a variety of values based on a literature review. These are tabulated together with the default value from Design Builder (Table 2.5).

For the purposes of this thesis a child's body surface area will be taken to be 70% that of an adults, 1.26m².

Reference	Body surface area	% relative to average adult (1.8m²)
(Havenith, 2007) 9 – 10 year olds	1.23 m ² Range 1.12 – 1.34 m ²	68% Range 62%- 74%
(Havenith, 2007) 10 – 11 year olds	1.29 m ² Range 1.17 – 1.41 m ²	72% Range 65%- 78%
(Mors et al., 2011) 9 – 11 year olds	1.14m ²	63%
(Haddad et al., 2013)	1.14m ² (adult size 1.73m ²)	66% (accounting for adult size)
Design Builder	1.35m ²	75%

Table 2.5: Estimated body surface area for children

Based on the work of Haddad et al (2013), Haddad (2016) and the default values in Design Builder

Ventilation rate

The NSW Demountable Classroom operates as a mixed mode building. When the building is naturally ventilated the air change rate is defined by the local weather. When the building is operating in heating or cooling mode ventilation is supplied by a mechanical fan directly from outside at the outside air temperature (refer to Section 1.5).

The significance of the ventilation rate to the quality of the internal environment in the classroom and the impact that has on people in the classroom is discussed in Chapter 1 (Section 1.5). There are a range of minimum ventilation rates recommended by international standards ranging from 6.7 L/s.person for people older than 8 years (ASHRAE 62, 2016) to 10 L/s.person (CIBSE Guide A, 2015). For this project a minimum ventilation rate of 8 L/s.person will be used following the recommendations of Bako Biro et al (2012), Daisey et al (2003) and the earlier ASHRAE 62 standard (2001). This will ensure that the results of the study are predicated on an adequate ventilation rate.

The modular construction of the classrooms means that there are multiple opportunities for uncontrolled air infiltration. The joints between the modules are sealed with a rubber gasket however it is not known how effective this is. The air leakage rate of the model will be set at 'Poor' on a scale of 'Very Poor', 'Poor', 'Medium', 'Good' and 'Excellent'. The actual rate of leakage is calculated by the model each hour.

Heating and cooling strategy: Thermostat settings

The NSW Demountable Classroom operates as a very simple mixed mode system. Heating is provided when it is “too cold” and cooling is provided when it is “too hot” by two split-cycle air-conditioning units. The units use fan coils inside the classroom to heat or cool the air that is recirculated inside the classroom. Ventilation of the classroom is controlled by opening and closing the windows or through a mechanical fan that draws air into the space directly from outside (Figure 1.11). Defining “too cold” or “too hot” is ultimately a subjective decision and normally a decision controlled by the teacher in charge of the classroom.

For a simulation model it is necessary to determine these temperatures based on a standard set of principles or evidence of common practice.

The NSW government “Education Facility Standards and Guidelines” (EFSG) sets out various criteria for temperature control and ventilation in a classroom (NSW Department for Education, 2014a). Design Guide DG 02 sets out an overall principle of preferring a naturally ventilated solution. The provision of air conditioning in a classroom space is governed by the mean maximum outdoor temperature during January (NSW Department for Education, 2014b). For new construction air conditioning is only provided where the mean maximum temperature is above 33°C. For Demountable Classrooms this is reduced to 27°C although in reality all Demountable Classrooms are

fitted with split cycle air-conditioning units (Interview C, 2014; Hansard 08/09/2003, Survey observations) .

For fully air-conditioned spaces where the air is heated or cooled before being delivered to the space Design Guide DG 55 makes no distinction between the various climates that exist across the state. Temperatures in a space are specified as 21°C +/- 1°C in winter and 24°C +/- 1°C in summer. There is no specification for naturally ventilated spaces or spaces operated in mixed mode with split cycle air-conditioning fan coil units within the NSW EFSG design guidance.

Current international standards (ASHRAE 55, 2013, ISO_7730, 2005) define buildings as either naturally ventilated (free running) or air-conditioned (active heating and cooling) and apply two different comfort standards (Nicol and Humphreys, 2002, Brager and Baker, 2009, Deuble and de Dear, 2012, Luo et al., 2015, Barbadilla-Martín et al., 2017). The adaptive comfort model is applicable to the naturally ventilated buildings and the considerably more restrictive and prescriptive steady state model is applicable to the buildings with active heating and cooling. In the standards mixed mode buildings, like the NSW Demountable Classroom, are included in the second category because they employ active heating and cooling systems as part of an overall strategy for creating, or controlling, thermal comfort.

A number of research projects have suggested that the steady state PMV model is not appropriate for mixed mode buildings and that the adaptive model, or a version of the adaptive model, is more appropriate

(Nicol and Humphreys, 2002, Humphreys and Nicol, 2002, McCartney and Fergus Nicol, 2002, Luo et al., 2015, Manu et al, 2016, Barbadilla-Martín et al., 2017). They demonstrate that the thermal environment, and occupants response to the thermal environment, in mixed mode buildings is dynamic rather than static and that an adaptive approach is more appropriate. The adaptive comfort model is predicated on a dynamic thermal environment and a corresponding dynamic, or active, response to that environment by people.

The adaptive comfort model and mixed mode buildings

The adaptive comfort model is based on the principle that “people have a natural tendency to adapt to changing conditions in their environment” and that their perception of comfort and ability to achieve thermal comfort is governed by a complex series of systems including culture, climate, social factors and the building or other environment that they are occupying (Nicol and Humphreys, 2002). The adaptive principle observes that if a change occurs people will act to restore their comfort taking advantage of 'adaptive opportunities' such as opening or closing a window, adjusting their clothing or turning on or off a cooling or heating system such as the split cycle air-conditioning units in the classrooms (Nicol and Humphreys, 2002, Baker and Standeven, 1997). A variety of field studies and meta-analyses have shown that the overarching predictor of comfort is the recent thermal experiences of people governed by the mean outdoor temperature (Humphreys, 1978, de Dear and Brager, 1998, Nicol et al., 1999, Nicol and Humphreys,

2010). Based on these analyses equations are derived, the most common being the ASHRAE Standard 55 equation (Equation A):

$$T_n = 0.31T_{rm-out} + 17.8 \quad \textbf{(Equation A)}$$

T_n is the “neutral temperature” (neither too hot nor too cold) as defined by the Adaptive Comfort Model defined by ASHRAE 55 (2013). “ T_{rm-out} ” is the weighted running mean outdoor air temperature over the previous 7 – 30 days, calculated with a decay factor of between 0.6 and 0.9.

The comfort band for 80% acceptability is $T_n \pm 3.5^\circ\text{C}$.

Nicol and Humphreys (2002) argue that because people’s perception of comfort is based in their experience of recent weather conditions (T_{rm-out})

“It seems unlikely that people using a building should modify their responses to it on the basis of their expectations of its services”.

They go on to argue that for buildings that are actively heated or cooled

“The idea of an ‘adaptive algorithm’ to define a variable indoor temperature in terms of the running mean of the outdoor temperature is attractive”.

Manu et al (2016) have proposed an adaptive comfort model for all types of building (air conditioned, mixed mode and naturally ventilated) in India: The Indian Model of Adaptive Comfort (IMAC). It is notable that in this model the acceptability bands associated with the mixed mode buildings are 3.6°C ($\pm 1.8^\circ\text{C}$) wider than

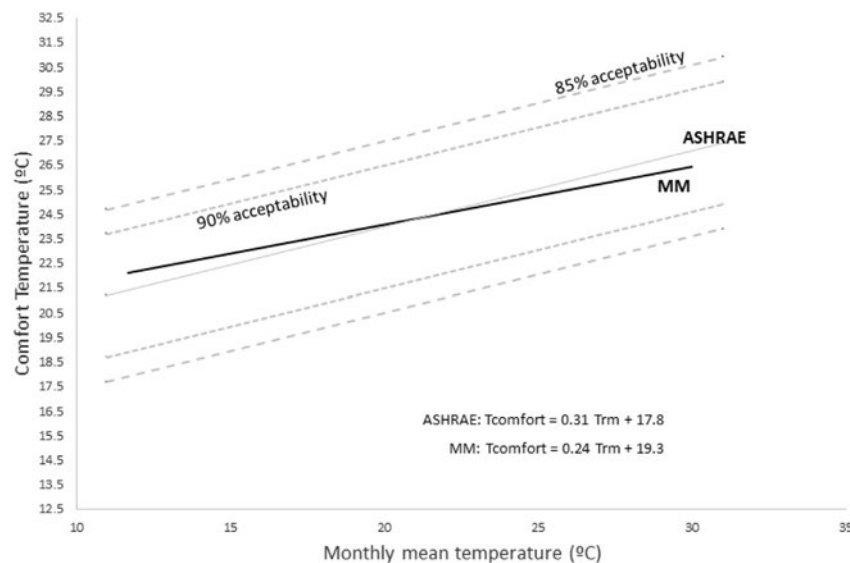


Figure 2.22: Comparison of a new Adaptive Comfort model for Mixed mode buildings with the ASHRAE 55 model

A comparison of the Adaptive Comfort model developed for Mixed Mode (MM) office buildings in Seville, Spain, with the ASHRAE 55 Adaptive Comfort model illustrating the close correlation. (figure 11 from Barbadilla-Martin et al., 2017)

for naturally ventilated buildings, however the slope of the graph (rate of change of the comfort zone relative to Trm-out) is about half that of naturally ventilated buildings.

In another study in Seville, Spain, Barbadilla-Martin et al (2017) developed an adaptive thermal comfort model for mixed mode office buildings based on 4,243 questionnaires from a 12 month study. They compared their result to the results from other studies and existing adaptive comfort standards and showed a close correlation with the existing ASHRAE 55 standard (Figure 2.22).

Controlling the thermostat: Using an adaptive strategy to determine heating and cooling set points

The control of the thermostat settings is ultimately a personal choice and, in the case of a classroom, normally the executive choice of the teacher in charge of the classroom. The EFSG guidelines state that control of the air conditioning system should be by an “authorised person” and that users should be “discouraged” from changing the settings.

In Australia the National House Energy Rating Scheme (NatHERS, 2012) has been developed by the ABCB (Williamson et al, 2007) to govern the thermal performance and energy efficiency of housing in Australia. The NatHERS protocol assumes that houses operate in a mixed mode similar to that used in NSW Demountable Classrooms. The NatHERS protocol understands the use of air conditioning systems as an adaptive measure (Nicol and Humphreys, 1973, Nicol

and Humphreys, 2002) together with opening and closing windows and the adjustment of clothing. The NatHERS software uses the adaptive comfort model to define the cooling set point temperatures based on local conditions in January (Chen, 2016a, NatHERS, 2012). The EFSG guidelines DG55 (NSW Department for Education, 2014) uses the mean maximum air temperature in January to define when air conditioning should be available in classrooms. Users and occupants of both domestic dwellings and the Demountable Classroom are likely to move between inside and outside fairly regularly. In the case of the classroom this happens between lessons, during breaks and before and after school. The frequency of these movements will depend on the school and the year group.

There is some debate about children's preferred temperature, with some suggesting that children have a preference for slightly cooler temperatures than adults (de Dear et al., 2015), while others have found that children have the same preferences as adults (Teli et al., 2015). One of the problems with this area of research is the small sample sizes compared to the sample sets derived from adults in office environments from which the adaptive comfort model was developed (de Dear and Brager, 1998, Nicol and Humphreys, 2010). All are agreed that children are as adaptable, or more adaptable, than adults and that like adults their tolerance of a range of conditions increases with exposure to different conditions.

For this analysis the heating and cooling set points have been defined using the protocols that underpin the NatHERS protocols for the following reasons:

- It is a statutory Australian standard that uses the adaptive comfort model to define set point temperatures in mixed mode buildings.
- It is based on the expectations of adults and adults control the use of mechanical heating and cooling in classrooms.

Establishing the thermostat settings for this project

The next part of this chapter discusses the results from the initial computer simulations of the five sites modelled for this project. The initial results are discussed here because they lead to a more detailed investigation and re-definition of the thermostat settings used in the final simulations.

The explanation for choosing the particular climates and individual sites has been set out in the previous parts of the chapter. The evaluation criteria used to define comfort are set out later in the chapter, part 2.4.

The statutory NatHERS thermostat settings were adopted for the first round of modelling. The results from this modelling revealed a particularly high level of overheating discomfort and relatively low energy consumption in Broken Hill compared to the other climates, and an annual energy consumption in Richmond 26% higher than the mean annual energy consumption of the other four climates (range of 22% higher than Williamstown to 31% higher than Coffs Harbour) (Figures 2.23 & 2.24). These unexpected

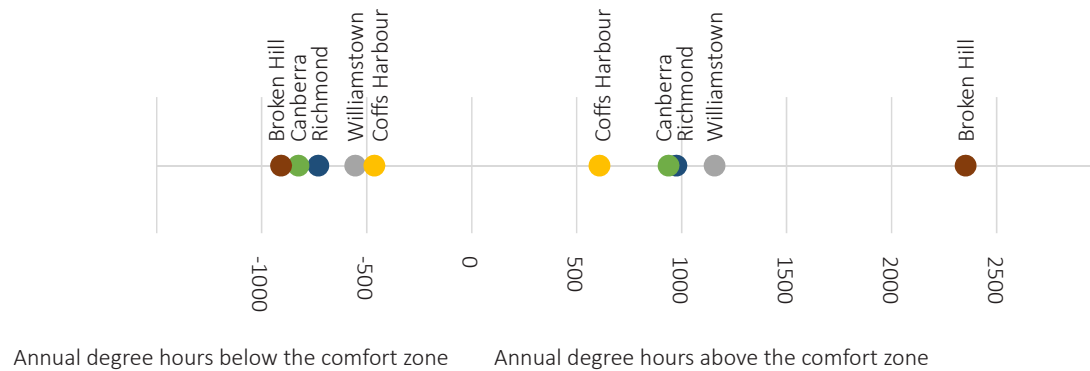


Figure 2.23: Annual degree hours above and below the comfort zone

Annual degree hours above (+) and below (-) the comfort zone defined using the adaptive comfort model

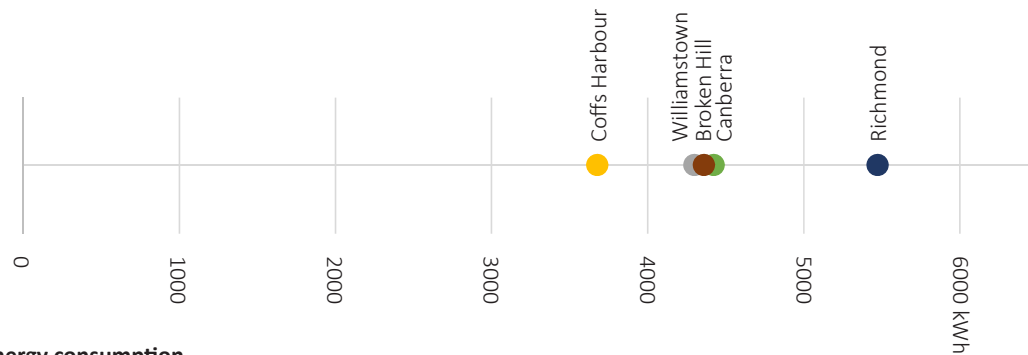


Figure 2.24: Annual energy consumption

Annual energy consumption for heating and cooling (kWh)

results prompted a further evaluation of the model, weather files and other settings that concluded by comparing the thermostat settings set out in the NatHERS Accreditation Software Protocol (NatHERS, 2012) and the thermostat settings that are generated if the method described by Chen (2016a) is used based on

- The mean monthly outside air temperature derived from the Bureau of Meteorology climate data record (BOM, 2014); and
- The mean monthly neutral temperature calculated from the daily neutral temperature derived from the weather data in the climate file used in the simulation (Exemplary Energy, 2014). The daily neutral temperature is based on a weighted running mean outside temperature following the methodology set out in section 2.4.

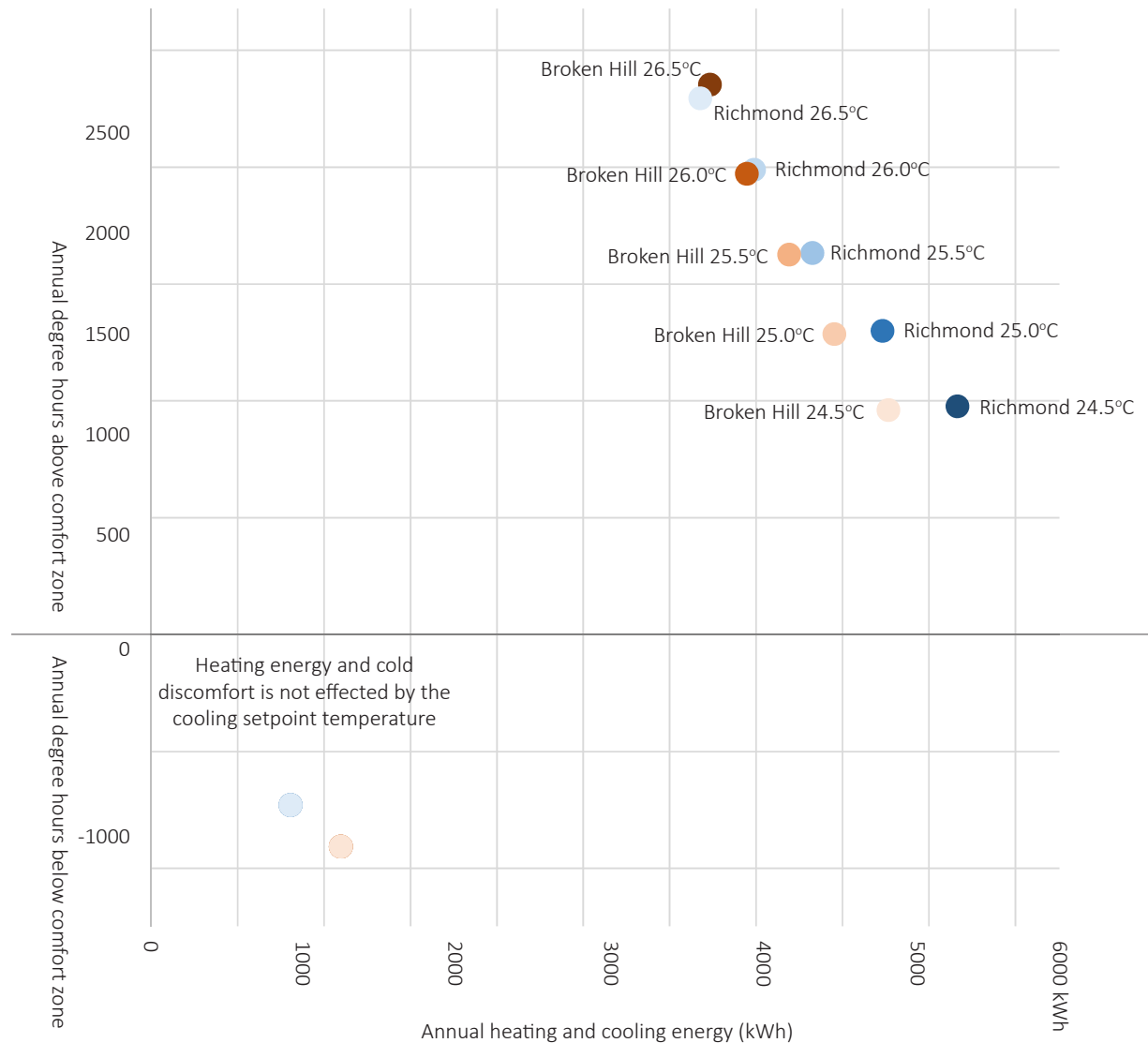
	Broken Hill	Canberra	Richmond	Williamstown	Coffs Harbour	
	26.5	24	24.5	25	25	NatHERS official standard
	25.9	24.2	25.2	24.9	25	<i>Tn calculated from BOM data for January</i>
Dec.	25.2	23.5	24.9	24.4	24.3	Monthly mean Tn calculated from the daily Tn which is based on a weighted daily mean temperature using the climate file weather data (see below). NatHERS standard says it takes the neutral temperature from January assuming January is the hottest month - sometimes February is hotter
Jan.	25.9	24.1	24.9	25.1	25.0	
Feb	25.3	23.9	25.1	25.1	25.2	
						<i>*The highest Tn are shown in bold</i>

Table 2.6: Neutral temperatures calculated using the Adaptive Comfort Method

Neutral temperatures calculated using the Adaptive Comfort Method based on data from NatHERS, Bureau of Meteorology (BOM) and the climate file used in the computer simulation model.

The results of this exercise are tabulated in Table 2.6 and show that in three of the five climates Tn defined by NatHERS is within 0.1 or 0.2°C of Tn calculated from data from other sources. For two of the climates, Broken Hill and Richmond, the discrepancy between the NatHERS setting and the other two sources increases to between 0.6 and 0.7°C. This is a small temperature difference but has a significant impact on both the predicted energy consumption of the building and predicted comfort in the building.

Figure 2.25 illustrates a sensitivity analysis using the climates of Broken Hill and Richmond. The cooling set point temperature was changed in 0.5°C increments. In Richmond the predicted annual cooling energy consumption increases by approximately 500kWh for every 0.5°C reduction in the cooling set point. In Broken Hill predicted energy consumption changes by approximately 300 kWh for every 0.5°C change in cooling set point temperature. Discomfort due to overheating increases as the cooling set point temperature increases.



Based on the information available it is unclear why the discrepancy between the cooling set point temperatures established from the three sources occurs in only two out of the five climates. Private correspondence with Chen (Chen, 2016b) established that the NatHERS thermostat settings are derived from the weather data in the statutory NatHERS “typical mean year” climate file (.TMY file) prepared by the CIRSO and not the longer term average derived from the BOM data set (BOM, 2014).

Figure 2.25: Sensitivity analysis for Broken Hill and Richmond

Annual heating and cooling energy (kWh) on the horizontal (x) axis plotted against total hours above and below the comfort zone plotted on the vertical (y) axis. The graph illustrates the sensitivity of both the number of uncomfortable hours and the quantity of energy used to maintain comfort to the cooling set point temperature.

NatHERS set point temperatures are the dark dots: Broken Hill 26.5°C, Richmond 24.5°C

Defining thermostat settings for this project

For the purposes of this project we will adopt the principle of the NatHERS protocol, which is a national standard, and use the prescribed adaptive comfort equation (Equation A) to calculate the cooling set point temperature based on the mean temperature during January. The mean temperature in January will be derived from the Bureau of Meteorology data base (BOM, 2014). The heating set point temperature will be set at 20°C. The set point temperatures are set out in Table 2.7. This approach ensures that the set point temperatures in each of the five climates is derived from the same method and data. This strategy assumes that the heating and cooling set point temperatures in the split-cycle air-conditioners in the classrooms cannot be adjusted by the teacher other than to turn them on or off which they will do when either the air temperature inside the classroom or outside the classroom moves beyond one or other of the set point temperatures.

It is clearly possible to argue that the heating and cooling set point temperatures for each classroom should follow local conditions throughout the year and be derived from local data either on a monthly basis or on a daily basis using a weighted running mean formula in a similar manner to that proposed by McCartney and Nicol (McCartney and Fergus Nicol, 2002). This approach will be considered later in this thesis (see Chapter 5, section 6.0).

	Broken Hill	Canberra	Richmond	Williamstown	Coffs Harbour	
	25.9	24.2	25.2	24.9	25	<i>Cooling set point temperature calculated from BOM data for January</i>
	20.0	20.0	20.0	20.0	20.0	<i>Heating set point temperature</i>

Table 2.7: Cooling set point temperatures for the thermal simulations

Occupancy	The following occupancy schedule is used:								
	Midnight- 7.00	7.00 - 8.00	8.00 - 9.00	9.00 - midday	Midday - 13.00	13.00 - 15.00	15.00 - 17.00	17.00 - 18.00	18.00 - Midnight
	0%	10%	25%	100%	50%	100%	25%	10%	0%
	Closed	Preparation	Arrival and preparation	Classes	Lunch	Classes	After school activity	Final administration	Closed
	24 hour occupancy schedule. Occupancy: 27 pupils + 1 teacher								
Metabolic output	Metabolic rate (MET) is set at 1.3 based on Haddad et al (2014) and Haddad (2016). Body size is 70% of an average adult. (Note: In Design Builder Metabolic output is defined as Watts/person, the person is an average adult man. The metabolic output is then adjusted by a factor (0 - 1.0) reflecting the body size of the occupants relative to an average adult man (factor 1.0).)								
Clothing	Summer clothing is 0.4 CLO (Light clothing) Winter clothing is 0.8 CLO (Warm clothing) Note that the adaptive comfort standard used in this study does not use the clothing level to calculate comfort levels and assumes clothing will be adjusted to maintain comfort.								
Heating, cooling and ventilation strategy	Mixed Mode The classrooms operate in a mixed mode strategy with two split cycle 6.5 kW air conditioning units heating or cooling the air in the classroom when natural ventilation is not capable of maintaining a comfortable temperature. The "Cooling set-points", i.e. the temperature at which mechanical cooling begins and natural ventilation stops are fixed based on the adaptive comfort model and the BOM weather data record at 20°C following the NatHERS protocol (NatHERS, 2012). Natural ventilation occurs between the heating (low) and cooling (high) set points. For a more detailed discussion of these settings see 'The adaptive comfort model and mixed mode buildings' in Section 2.2.3 above.								
	Continued....								

Table 2.8: Summary of Activity and HVAC settings for the model

Summary of Activity and HVAC settings listing the fixed parameters in the "Activity" and "HVAC" settings in the design builder model

Thermostat settings		Broken Hill	Canberra	Richmond	Williams-town	Coffs Harbour	
	Cooling set point	25.9 °C	24.2 °C	25.2 °C	24.9 °C	25.0 °C	
	Heating set point	20°C	20°C	20°C	20°C	20°C	
HVAC sizing and simulation	In the computer simulation the model calculates the size of the split cycle system using the 'Energy-Plus' method based on a steady state model for summer and winter plus a 'safety factor'. Fresh air is supplied through natural ventilation from the opposing windows and the door or through a mechanical fan. Both strategies deliver air into the classroom at the current external temperature. HVAC Coefficients of Performance(COP) Heating Coefficient of Performance (COP): 2.35 Cooling Coefficient of Performance (COP): 1.80						
Ventilation rates	Natural ventilation is calculated by the simulation model depending on the prevailing weather conditions. The free area of the windows when open was calculated to be 37.4%. The mechanical fan delivers ventilation at a rate of 8L/s.person.						
Air leakage	Air leakage was set at 'poor'. Air leakage is calculated by the model based on this setting and the prevailing weather.						
Energy supply	The buildings rely on electricity for all their energy requirements which is supplied from the NSW grid.						
Lighting, computers etc.	Lighting is set as 5W/sq.m with battens fixed to the ceiling. The lights are all on during occupied hours. Office equipment (computers etc.) was set at 4.7w/sq.m and is all on during occupied hours.						

Table 2.8 (continued): Summary of Activity and HVAC settings for the model

Summary of Activity and HVAC settings listing the fixed parameters in the “Activity” and “HVAC” settings in the design builder model

2.4 Evaluation criteria

The simulation model generates data on the energy flows through the building fabric, ventilation rates, the temperatures of the external and internal surfaces as well as the external ambient dry-bulb temperature (air temperature) and the internal dry bulb, radiant and operative temperatures and energy consumption at hourly intervals for a year. The information generated by the digital model can be used to provide three types of data:

- i. Thermal comfort
- ii. Energy flows and temperatures inside through and outside the building
- iii. Energy consumption of the building for heating and cooling.

Of these three types of data the first, thermal comfort, is the most important criteria since it is about the anticipated experience of people in the building. Thermal comfort, or dis-comfort, is predicted by applying the Adaptive Comfort Method to data generated by the simulation model. The second and third data sets, thermal energy flow and temperature, and energy consumption, are generated by the digital simulation model.

The second two criteria help us to understand the causes and the cost of the first. That is where, how and

possibly why thermal energy is flowing through the building and creating unacceptable temperatures. The buildings are equipped with split cycle air conditioning units to heat and cool the air inside the classrooms and so try and improve or control thermal comfort. The electrical energy they use has a direct financial cost to the school and a broader cost to the global environment due to the carbon dioxide emitted as a result of the electrical energy generation.

2.4.1 Thermal comfort

In order to assess the thermal performance in the simulation model, the adaptive comfort model has been chosen to predict comfort (ASHRAE, 2013).

The Demountable Classrooms operate in a mixed mode. Some may argue that the presence of the split cycle cooling system means that the adaptive model is not appropriate because the existing international standards tend towards a clear distinction between pure free running or naturally ventilated buildings and buildings with mechanical heating and cooling systems (Nicol and Humphreys, 2002, Luo et al., 2015). However, as has been discussed earlier in this chapter (Section 2.3) there is a growing body of research that argues that the adaptive model is applicable to mixed mode buildings (Humphreys and Nicol, 2002, Nicol and Humphreys, 2002, Deuble and de Dear, 2012, Luo et al., 2015, Manu et al., 2016, Barbadilla-Martín et al., 2017). Barbadilla-Martín et al (2017) have shown that an adaptive algorithm that has been developed in a climate with a wide range of outdoor temperatures (Seville, Spain)*

*Mean monthly temperatures for Seville, Spain:

Annual mean maximum outdoor air temperature:
16.0 °C (January) – 37°C (July), with days >40°C;

Annual mean minimum outdoor air temperature:
6.0°C (January) – 20.0 °C (July & August)

closely matches the ASHRAE 55 (2013) adaptive comfort model (Figure 2.22).

The adaptive comfort model has also been used to assess or predict comfort in mixed mode buildings: De Dear et al (2015) used the adaptive comfort method to assess comfort in a range of Australian classrooms that included naturally ventilated, air conditioned and evaporatively cooled classrooms. Whether the air conditioning system was a fully ducted system or a split cycle re-circulating system was not specified. Holmes and Hacker (2007) used the adaptive comfort model to predict thermal comfort in three UK buildings, including one school, under a variety of climate change scenarios as part of a CIBSE project.

For this project the adaptive comfort model has been chosen for the following reasons:

- The adaptive comfort method considers comfort in response to the local outdoor climate that the students and teacher experience frequently because they are entering and leaving the classroom for school breaks or to move to other classrooms.
- The ventilation to the classrooms is direct from the outside either through open windows or a mechanical fan in the wall. There is no air handling unit.
- the split cycle unit cools or heats the air in the classroom; it does not supply conditioned (fresh) air to the classroom (ref. Figures 1.10 & 1.11). Therefore the heating and cooling system may be considered as an adaptive strategy (Nicol and Humphreys, 1973,

Nicol and Humphreys, 2002).

- The classrooms were originally designed as free running buildings
- NSW government policy is that all classrooms should be naturally ventilated or operated using a mixed mode strategy.
- The addition of a split reverse cycle air-conditioning system provides mechanical cooling and heating when limits of the passive strategies are reached.

The adaptive comfort model predictive formula

The adaptive comfort model (ASHRAE, 2013) was adopted for the analysis and prediction of comfort in the classroom. In 2012 de Dear and Candido (de Dear and Candido, 2012) proposed an adaptive comfort model for naturally ventilated buildings across NSW following the daily weighted mean temperature approach proposed by Nicol and Humphreys (Nicol and Humphreys, 2010, Nicol and Humphreys, 1973). The equation used to calculate the mean outdoor temperature is a simplified exponentially weighted running mean (de Dear, 2006):

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

(Equation B)

Where

- T_{rm-od} is the exponentially weighted running mean of outdoor dry-bulb temperatures from the previous 7 days
- T_{od-1} is the mean outdoor temperature today -1 (yesterday),
- T_{od-2} is the mean outdoor temperature two days ago (the day before yesterday) etc.

The daily running mean temperature outdoors is then used to calculate the neutral temperature (T_n) and the upper and lower 80% acceptability thresholds based on ASHRAE adaptive comfort formula:

$$T_n = 0.31T_{rm-od} + 17.8$$

(Equation A)

Upper and lower acceptability thresholds are taken to be 3.5 degrees above and below the neutral temperature respectively. The adaptive comfort model predicts the

“operative temperature”. The operative temperature is taken as the mean of the dry-bulb air temperature and radiant temperature in a space and is considered to be the best measure of human comfort (CIBSE Guide A, 2015). People experience the temperature of their surroundings through the three methods of heat transfer: Radiation, convection and conduction. Radiation accounts for about half of our experience, and air temperature, through direct conduction, convection and other processes, accounts for the other half.

De Dear and Candido also proposed that heat wave events should be excluded from the calculation, however since this simulation uses a “typical” weather year it is assumed that there are no extremes that need to be excluded. The number of hours the temperature inside the classroom is within and outside the comfort zone during working hours (08.00 – 18.00) was then calculated and plotted for each of the five climates.

Thermal comfort analysis

The analysis uses:

- i. The number of working hours below, within and above the comfort zone in total and as a percentage.
- ii. The number of working “degree-hours” below, within and above the comfort zone.
- iii. The number of days each year that thermal discomfort is experienced.
- iv. The number of working hours the classroom is operating with natural ventilation (no mechanical heating or cooling).

A “degree-hour” is the number of degrees above the comfort zone multiplied by the amount of time (hours) that that occurs (examples in Table 2.9). For periods inside the comfort zone the number of hours has been multiplied by one.

The first measure (i) illustrates the proportion of time the classroom is comfortable and uncomfortable (too hot or too cold). The second measure (ii) indicates the magnitude of the discomfort. For instance, the temperature in a classroom may be above the comfort zone by 1°C for two weeks but the magnitude of the problem is small compared to a classroom that is above the comfort zone by 4°C for just a few days.

EXAMPLE 1

Classroom is above the comfort zone by 1°C for 5 hours a day for 5 days:

1°C x 5 hours x 5 days

= 25 degree-hours above comfort zone

EXAMPLE 2

Classroom is above the comfort zone by 4°C for 3 hours a day for 3 days:

4°C x 3 hours x 3 days

= 36 degree-hours above comfort zone

Table 2.9: Degree hour examples



Figure 2.26: Electricity transmission pylons

PHOTO: Olly Coffey - Flickr

2.4.2 Energy consumption and associated green house gas emissions

The Green Star Council target energy consumption for heating and cooling in classrooms is $26.8 \text{ kWh/m}^2\cdot\text{year}$ (GBCA, 2009). This benchmark is generalised across NSW rather than providing a climate specific target.

The computer simulation model predicts the amount of energy (kWh) used by the split cycle system for heating and cooling. This predicted kWh is used to assess whether or not the Solution Sets have increased or reduced the energy consumption, or efficiency, of the building. The simulated building is 72.1 m^2 so the GBCA target is 1932 kWh/year .

Carbon emissions

In Australia 95.7% of energy comes from carbon based sources (coal, oil and gas) (BREE, 2013). The only power source used in the Demountable Classroom is electricity and in NSW 1 kWh of electricity produces $1.05 \text{ kg.CO}_2\text{-equivalent}$ (Department for climate change, 2013). $\text{kWh} \times 1.05$ will be used to predict the quantity of $\text{CO}_2\text{-equivalent}$ emitted as a result of using electricity from the national electricity grid.

2.5 Uncertainty and sensitivity

Uncertainty and sensitivity describe two different things (Macdonald, 2002). Uncertainty describes the levels, or boundaries, of confidence around the results of the model. Sensitivity describes, or illustrates, how the modification of input parameters to the model changes the results generated by the model.

While many researchers argue that the results from a validated computer simulation model are “accurate enough to be considered valid” (Fumo, 2014) (refer to Table 2.2 for a summary of relevant research projects). Others argue that it is important and useful to understand, explicitly, the uncertainty within a model and the impact of this uncertainty on the model’s results (Chen et al., 2017, Junghans and Bae, 2016, Ding et al., 2015, Silva and Ghisi, 2014, Hopfe and Hensen, 2011, Hopfe, 2009, Macdonald, 2002).

All models are a simplification of reality (Judkoff and Neymark, 1999) and within each of the areas listed above simplification, generalization and necessary assumptions, however well founded, lead to some uncertainty. The sources of uncertainty within a computer simulation model can be described in terms of (Figure 2.27):

- Input parameter uncertainty, i.e. uncertainty around the precise value of input parameters, for example occupancy and metabolic activity.
- Software programming uncertainty, i.e. uncertainty within the algorithms and assumptions embedded within the software.

(de Wit and Augenbroe, 2002, Coakley et al., 2014, Judkoff and Neymark, 1999)

These two sources of uncertainty and their impact on the data generated by the model used in this thesis are discussed in the following two sections:

2.5.1 Input parameter uncertainty

The impact and quantification of the uncertainty created by the potential variation within the specification of the input parameters to the model has been discussed and quantified extensively in the literature (Judkoff and Neymark, 1999, Macdonald, 2002, de Wit and Augenbroe, 2002, Hopfe, 2009, Hopfe and Hensen, 2011, Coakley et al., 2014, Ding et al., 2015, Bae, 2016, Junghans and Bae, 2016, Chen et al., 2017, Ahn et al., 2017).

For this thesis the input parameter for the simulation model have been considered in three parts:

- Climate and location (part of the Environmental System)
- Physical fabric (Building System)
- How the building is used (Activity system)

Table 2.10 describes the areas of uncertainty within the input parameters used in the model. Levels of confidence, ranging from low, to moderate, to high, are assigned to each input parameter listed in the table based on the source of the information. The table identifies five input parameters with low or moderate levels of confidence. Of these Building Orientation and Thermostat Settings are explored separately.

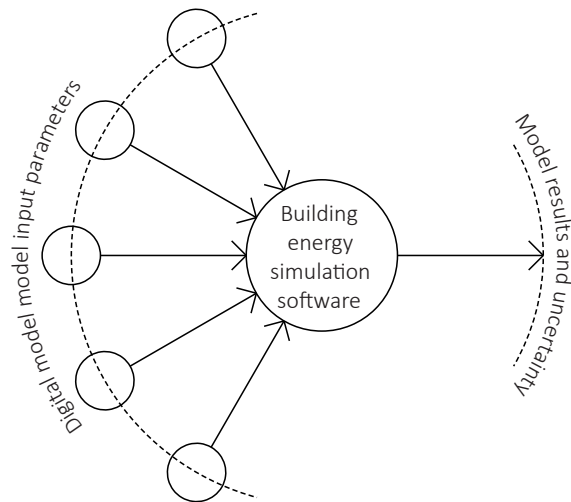


Figure 2.27: Diagrammatic description of the simulation model
A diagrammatic description of a digital building energy simulation model with input parameters, software and output or results

	Notes	Summary & ranges of confidence
Climate and location	Climate The climate data is certain to the extent that it is constructed from BOM data to represent a ‘Typical Mean Year’ (TMY) following appropriate standards and protocols. The weather in a particular place is different every year. The .TMY file designed to provide a weather and climate file that is broadly representative of the location.	High level of confidence The impact of climate on the performance of the building is demonstrated by repeating the simulations in the five climates representative of NSW.
	Location The locations are real locations situated close to the weather stations used to construct the TMY files. The details of the site have been constructed based on aerial images at a resolution of about 1:500.	High level of confidence
Physical fabric	Building fabric The physical properties of the building have been analysed to a high level (detailed survey and modelling of thermal bridges/complex construction). The thermal properties of the materials have been obtained from the manufacturers and cross referenced with standard databases.	High level of confidence The project explores and illustrates how a variety of configurations of building fabric effect the thermal performance of the classrooms.
	Building construction (infiltration) The level of infiltration is very uncertain – but likely to be high. In the model the level of infiltration is calculated hourly depending on weather conditions. The airtightness of the buildings is set on a five point scale between ‘Very Poor’ (1) and ‘Excellent’ (5). For these simulations it is set at ‘Poor’ (2).	Moderate – low level of confidence Range of confidence: ‘Poor’ (prob. 50%) ‘Very Poor’ (prob. 50%)
		Continued....

Table 2.10: Areas of uncertainty within the computer simulation model

	Notes	Summary & ranges of confidence														
	Building Geometry: overall dimensions) The overall dimensions of the classroom are based on original drawings and a physical survey.	High level of confidence														
	Building Geometry: Orientation Building orientation is based on site information. The impact of different orientations is uncertain.	Dependent on site														
How is the building used?	Occupancy The occupancy level defined in the model is based on statistics from the NSW Department of Education This data shows that the mean class size for years 3 – 6 is 26.2 plus the teacher. Extrapolating from this data (ref. table xxx) the most common class size is 27 plus a teacher. The maximum class size is 30 although, occasionally, classes may be larger than 30 pupils.	Moderate level of confidence. the simulation model uses the most common class size (27 plus a teacher). However there is, inevitably, variation in class sizes (data from Figure 2.21): <table><tr><td>Class size</td><td>Probability</td></tr><tr><td>25 + Teacher</td><td>13.1%</td></tr><tr><td>26 + Teacher</td><td>26.6%</td></tr><tr><td>27 + Teacher</td><td>29.9%</td></tr><tr><td>28 + Teacher</td><td>18.6%</td></tr><tr><td>29 + Teacher</td><td>6.4%</td></tr><tr><td>30 + Teacher</td><td>1.2%</td></tr></table>	Class size	Probability	25 + Teacher	13.1%	26 + Teacher	26.6%	27 + Teacher	29.9%	28 + Teacher	18.6%	29 + Teacher	6.4%	30 + Teacher	1.2%
Class size	Probability															
25 + Teacher	13.1%															
26 + Teacher	26.6%															
27 + Teacher	29.9%															
28 + Teacher	18.6%															
29 + Teacher	6.4%															
30 + Teacher	1.2%															
	Metabolic output The total metabolic output in the classroom is a product of the metabolic activity (MET) and the size of the people in the classroom (body surface area). The MET level has been set at 1.3MET based on the work of Haddad et al (1014) and Haddad (2016). Body surface area has been set at 70% of an adult based on various estimates in the literature (refer to Table 2.5).	Moderate level of confidence. Range of confidence for Metabolic Output: <table><tr><td>62% average adult</td><td>(prob. 33%)</td></tr><tr><td>70% average adult</td><td>(prob. 33%)</td></tr><tr><td>78% average adult</td><td>(prob. 33%)</td></tr></table>	62% average adult	(prob. 33%)	70% average adult	(prob. 33%)	78% average adult	(prob. 33%)								
62% average adult	(prob. 33%)															
70% average adult	(prob. 33%)															
78% average adult	(prob. 33%)															
	Thermostat set points Varying the thermostat setpoint temperature has a significant impact on the operative (T-op) inside the building and the energy consumption of the building.	Moderate – High level of confidence. The impact of thermostat settings is illustrated earlier in this chapter and explored again in chapter 5.														

Table 2.10 (continued): Areas of uncertainty within the computer simulation model

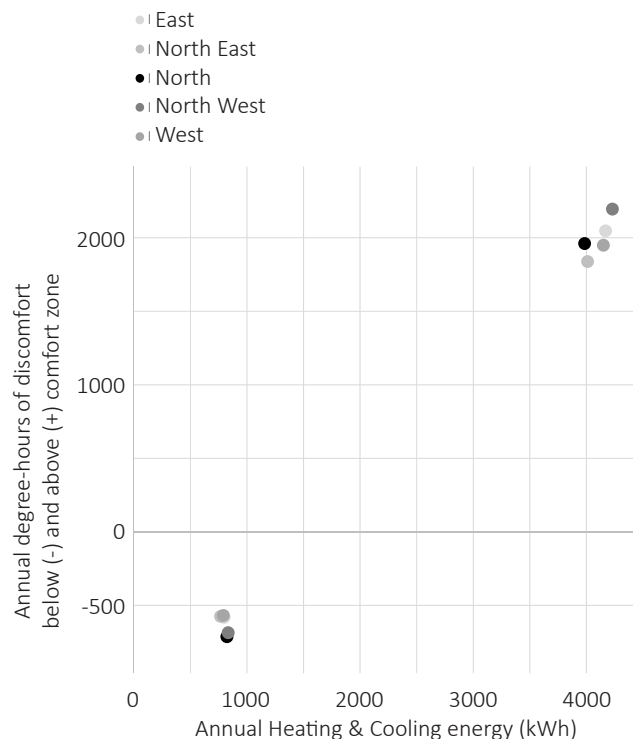


Figure 2.28: Analysis of building orientation on comfort and energy demand

*The affect of the orientation of the classroom on annual discomfort and annual heating and cooling energy demand
Climate: Richmond*

Building Orientation

Building orientation may affect the thermal performance of the Demountable Classroom building. Building orientation is determined by the particular site conditions and is not an error or uncertain variable within the model.

A series of simulations using the Base Case model (the existing NSW Demountable Classroom) have been carried out in the Richmond Climate (arguably the most extreme) in order to understand the impact of building orientation on thermal performance. In the simulations the classroom was orientated with the windows façade facing East, North East, North, North West and West. The thermal performance from each of these five orientations are illustrated in Figure 2.28. It appears that orientation has a modest impact on heating and cooling energy (6% and 9% range from minimum respectively) and a more significant impact on degree hours of discomfort with overheating discomfort ranging from 1,838 to 2,195 Degree-Hours or 19% of the minimum. The orientation that creates the most discomfort is North West.

Thermostat settings

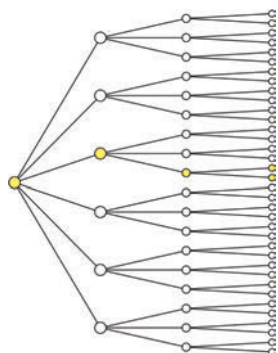
The impact of thermostat settings on the thermal performance of the classroom was explored earlier in this chapter and is significant. Thermostat settings are determined by the school or the teacher in the classroom. The basis for the thermostat settings used in the model are explained earlier in this chapter. The

impact of the thermostat settings and assumptions about comfort are explored in more detail in Chapter 5.

Probability tree

The impact of the three remaining input parameters with low or moderate levels of confidence are explored in an uncertainty analysis based on a probability tree (Gendebien et al., 2014, Zhang et al., 2007). The parameters are the number of pupils in the classroom (occupancy), the level of metabolic activity and the level of infiltration of outside air (air-tightness or air leakage). These are discussed in more detail earlier in this chapter. The probability tree provides a graphically clear and accessible interpretation and expression of how uncertainty can propagate though the model to create multiple possible outcomes (Barton et al., 2004). The levels within the tree are independent of each other (i.e. discrete). The probability assigned to the branches propagating from each node are taken from literature, or, where no probability or frequency data was found, assigned equal probabilities (Figure 2.29).

Each potential combination of input parameters defined within the tree is simulated and the results (annual cooling and heating energy demand, annual Degree-Hours outside the comfort zone) are tabulated with their associated probabilities. The probability of each outcome is calculated by multiplying the probabilities down the branches of the tree. The results of all the simulations are then collected in 'buckets' with a range approximately 1/5 of the total range of the data (maximum output minus minimum output). The results



Class size	Probability
25 + Teacher	13.1%
26 + Teacher	26.6%
27 + Teacher	29.9%
28 + Teacher	18.6%
29 + Teacher	6.4%
30 + Teacher	1.2%

Occupancy
Class size has been extrapolated from NSW Department of education data. Refer to Figure 2.21.

Metabolic output
Metabolic output is based on a MET value of 1.3 and a body surface areas of 62% (prob. 33%), 70% (prob. 33%) and 78% (prob. 33%) of an average adult (1.8m²) Refer to Table 2.5.

Infiltration
The rate of infiltration of outside air is set as 'Poor' (prob. 50%) and 'Very Poor' (prob. 50%) using the default templates in the Design Builder software.

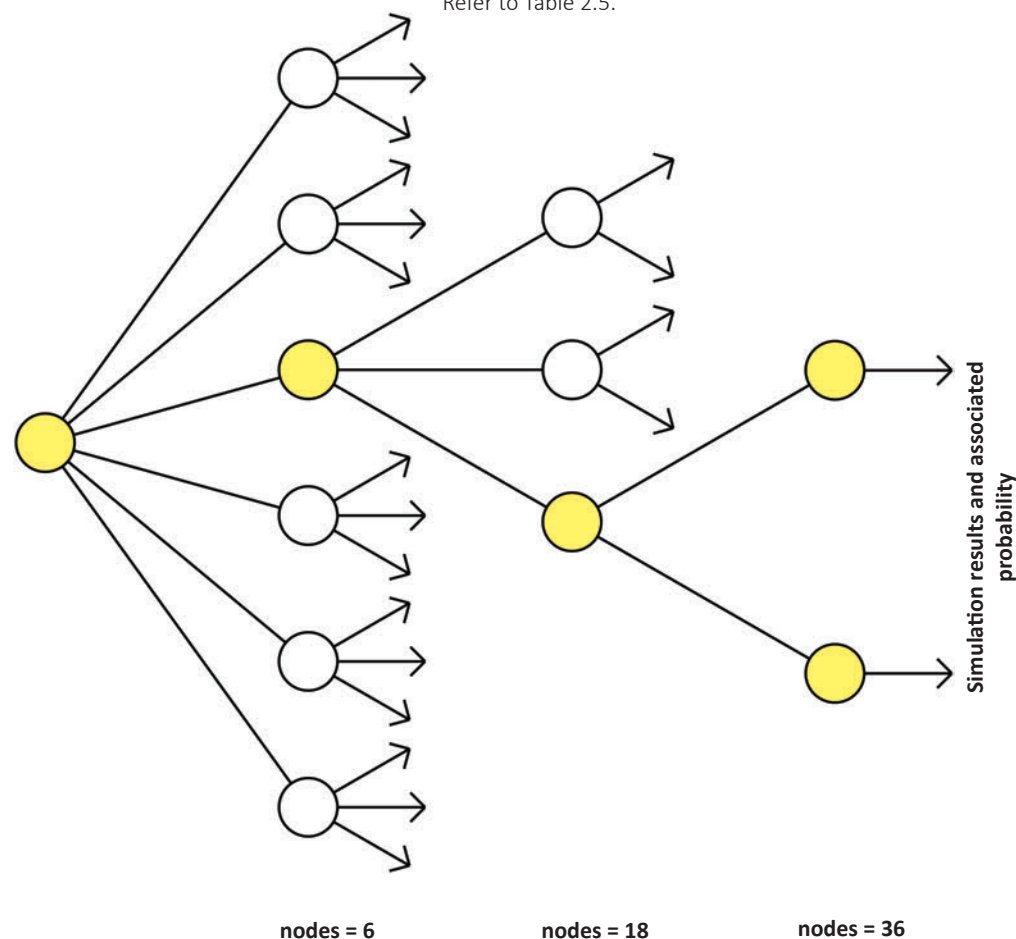


Figure 2.29: Probability tree (part)
The branches of the probability tree illustrated with parts of the tree not shown to enable the tree to be annotated.
The complete probability tree is illustrated in the top left corner.

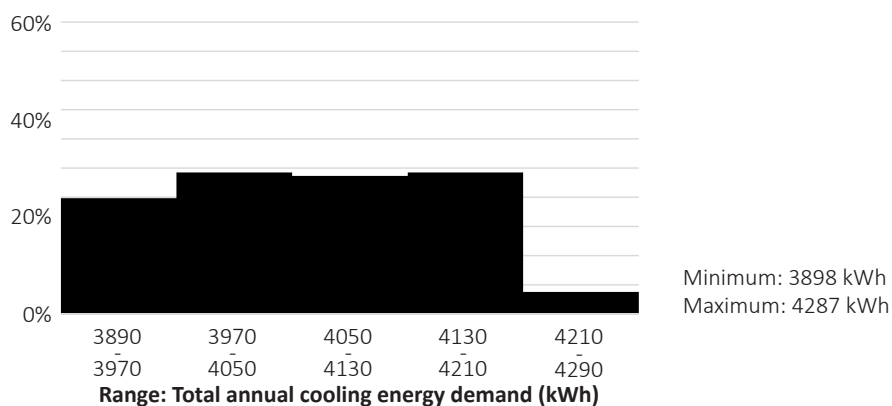
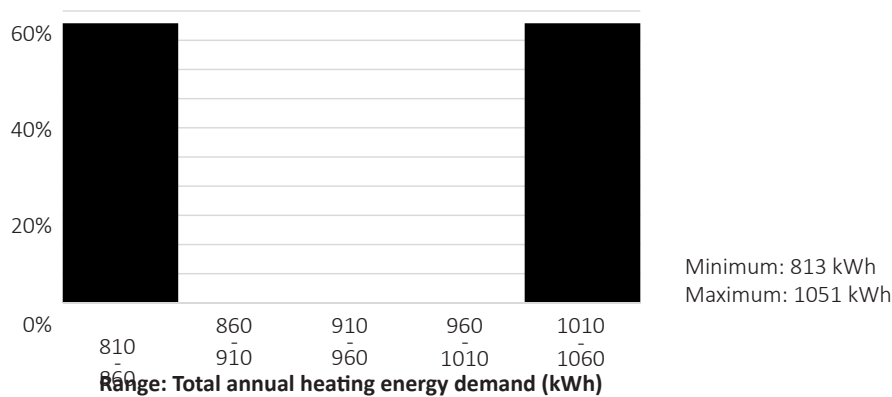
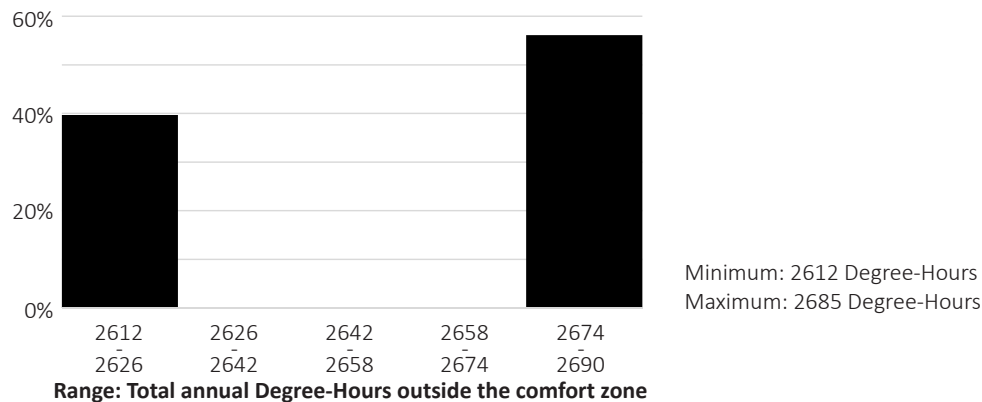


Figure 2.30: Probability distributions of results from uncertainty simulations

Bar charts illustrating the probability of obtaining a result within a particular range given the levels of uncertainty defined in the probability tree.
Climate: Richmond

of this exercise illustrate the total range of potential results from the model and their probability given the levels of uncertainty defined in the probability tree. These results are illustrated in Figure 2.30.

The distributions do not follow a normal distribution curve and the variation within the results is small, for instance the maximum number of degree-hours outside the comfort zone is just 4% more than the minimum number across all the simulations.

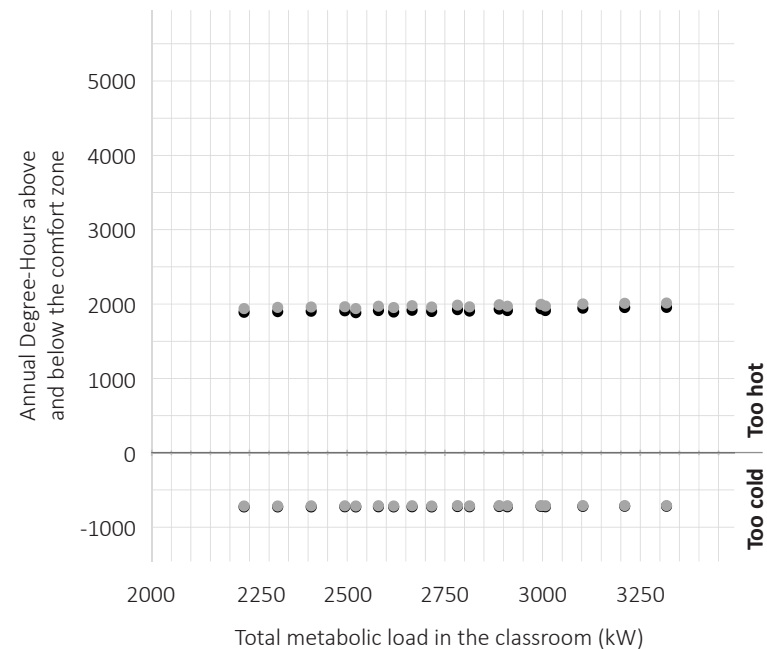
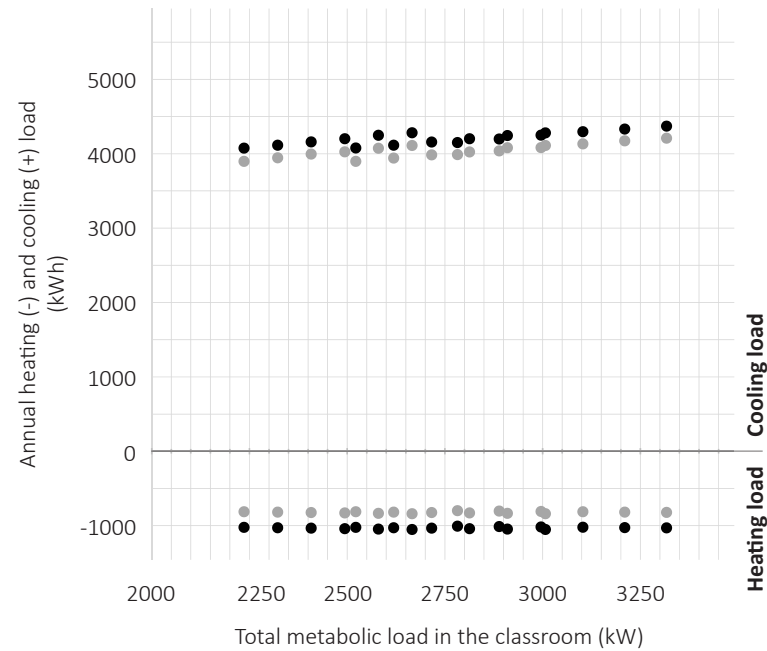


Figure 2.31: Simulation results indicating sensitivity to metabolic load and infiltration

Scatter plot of annual heating and cooling load (top) and degree-hours above and below the comfort zone (bottom) plotted against total metabolic load.

These results are prior to any uncertainty from the simulation software is considered.

NOTE: The degree-hours below the comfort zone for the classroom with 'very poor' airtightness are hidden behind the results for the classroom with 'poor' airtightness.

Climate: Richmond

A further sensitivity analysis has been undertaken using the simulation results: Figure 2.31 shows the annual heating and cooling energy demand and the annual degree-hours above and below the comfort zone plotted against the total metabolic energy input into the classroom. The results from simulations with 'Poor' and 'Very Poor' infiltration are also differentiated. The maximum metabolic energy input is 48% more than the minimum.

Overall the variation in discomfort and energy use is fairly small across all the simulations. The variation between the models with Poor and Very Poor infiltration is larger than the variation as a consequence of changing the total metabolic energy in the classrooms. The annual cooling energy has the largest variation increasing by 8% (Poor) and 7% (Very Poor) as a consequence of increasing metabolic energy level by 48%. Increasing the infiltration rate reduces the thermal performance of the classroom, particularly in terms of energy demand (which increases).

Modelling (software) uncertainty

The uncertainty that exists within the software, algorithms and the assumptions embedded in the computer simulation model is discussed but rarely quantified (Macdonald, 2002, de Wit and Augenbroe, 2002, Hopfe and Hensen, 2011, Coakley et al., 2014, Ding et al., 2015, Chen et al., 2017). Bae (2016) suggests that the information needed to quantify the uncertainty in the software is not available and so proposes an uncertainty probability range based on a normal distribution curve with the limits (3 standard deviations from the mean) set at +/- 20% of the mean. However this appears to be an arbitrary decision with no information to support the figure or the distribution.

In their reports on the development of the IEA BESTEST building simulation model validation protocol Judkoff and Neymark (1995, 1999) explain that discrepancies arise from particular simulation algorithms within the simulation program and so their impact on the output from the simulation program may be very specific, or occur under specific conditions, rather than as a broad distribution. Importantly Judkoff and Neymark (1995) explain that the performance ranges of the simulation models

“...do not represent the truth. They do represent the best state-of-the-art in whole building simulation prediction” (p.2-147).

The simulation software used in this project is Energy Plus version 8.6 through the Design Builder interface. The most recent validation report available on the

	Range of results from 11 Building Simulation Energy models evaluated in the ASHRAE Standard 140/ BESTEST process					Engy Plus results	
Results for Case 610: Lightweight building with shading.							
	Lowest	Highest	Mean	Range	Range as % of Lowest	Energy Plus result	Energy Plus % from Mean
Annual heating (kWh)	4335	5786	5098	1451	33.5%	4422	-13.3%
Annual cooling (kWh)	3915	6139	5144	2224	56.8%	4746	-7.7%
Results for Case 600: Lightweight building, no shading and free floating (no mechanical heating or cooling)							
	Lowest	Highest	Mean	Range	Range as % of Lowest	Energy Plus result	Energy Plus % from Mean
MAX Temp. (°C)	64.9	75.1	67.7	10.2	15.7%	65.3	-3.6%
MIN Temp. (°C)	-18.8	-15.6	-17.6	3.2	-17.0%	-17.4	-1.1%
MEAN annual T (°C)	24.2	27.4	25.3	3.2	13.2%	25.8	1.9%

Table 2.11: BESTEST results from the validation of Energy Plus 8.2

Energy and temperature results from the ASHRAE Standard 140/BESTEST validation process for Design Building version 8.2 for total annual heating and cooling energy for Case 610 48 m² lightweight building with shading, and for Case 600FF 48 m² lightweight building, free floating without shading. (Henninger and Witte, 2014)

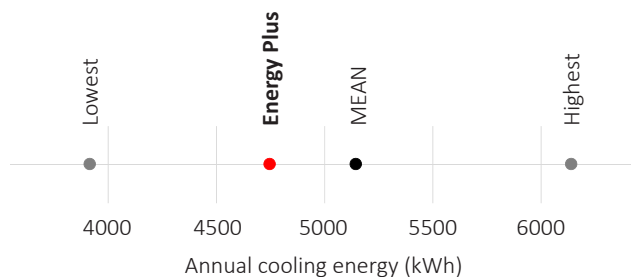
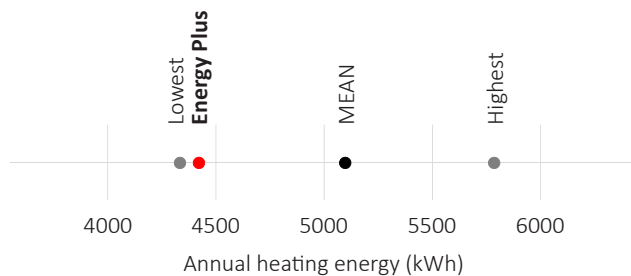
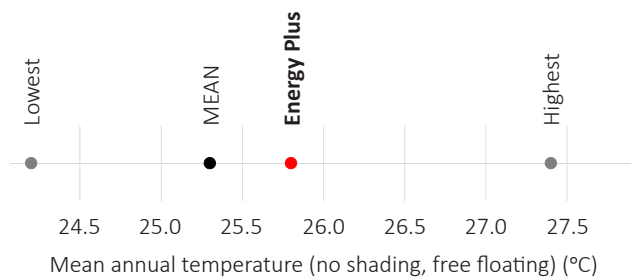


Figure 2.32: BESTEST results from the validation of Energy Plus 8.2

Energy and temperature results from the ASHRAE Standard 140/BESTEST validation process for Design Building version 8.2.

(Top) Mean annual temperature in Case 600FF lightweight free floating example.

(Middle) Total annual heating energy for Case 610 lightweight building with shading.

(Lower) Total annual cooling energy for Case 610 lightweight building with shading.

(Henninger and Witte, 2014)

Energy Plus website (www.energyplus.net/testing, accessed May 2018) is for Energy Plus 8.2 (Henninger and Witte, 2014). Within the validation report a comparative analysis (Judkoff and Neymark, 1999) of Energy Plus and 10 other comparable whole building energy simulation programs is undertaken using a simple building similar to the NSW Demountable Classroom. The building is a single space 8m long, 6m wide and 2.7m high, of lightweight construction with a flat roof and suspended timber floor. It has two large south (solar) facing windows. Case 600 has no shading and Case 610 has a 1m overhang on the south side.

The results from this analysis provide a useful indication of the performance of Energy Plus in relation to other building simulation programs. The results of the simulation comparison are illustrated in Figures 2.32 and Table 2.11. The figures for annual heating and cooling energy are from Case 610, with shading. The figures for annual temperatures are from Case 600FF, no shading and no heating or cooling (free floating).

Relative to the other simulation software programs Energy Plus

- Underestimates heating load, it produces a result close to the bottom of the range, 13.3% below the mean.
- Is in the mid-range of cooling load, 7.7% below the mean.
- Is in the mid-range, but above the mean, for predicting annual mean temperature. It should be noted that the mean value for the results from all the simulation programs is towards the lower part of the range and the range itself is only 3.2°C.

2.5.3 Summary

The uncertainty analysis illustrates that uncertainty within the simulation engine is more significant than uncertainty around the input parameters that have been identified as having low or moderate levels of confidence for a particular level. The total level of metabolic activity within the classroom appears to have a very small impact on overall thermal performance. The level of infiltration is more significant with increasing infiltration reducing the overall thermal performance of the classrooms.

All models contain some uncertainty. When describing the development of the ASHRAE standard for the validation of building simulation models (ASHRAE Standard 140, 2017) Judkoff and Neymark (1999) explain that

“There is no such thing as a completely validated building energy simulation computer program. All

building models are simplifications of reality. The philosophy is to generate a range of results from several programs that are generally accepted as representing the state of the art in whole-building energy simulation programs”

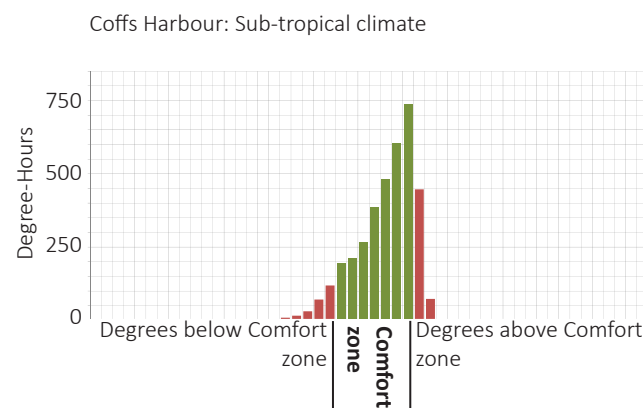
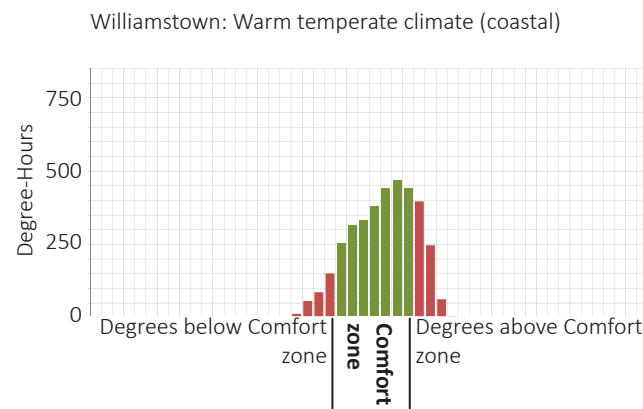
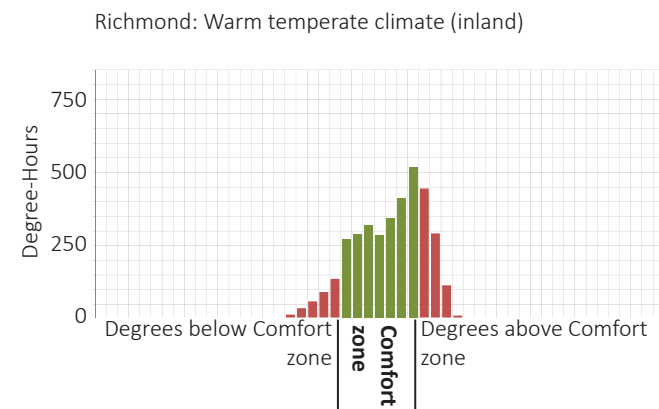
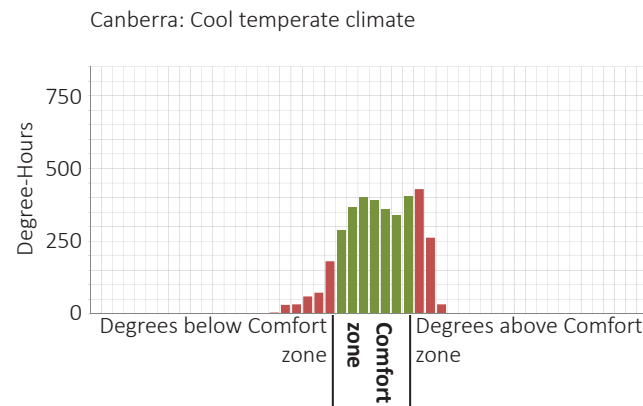
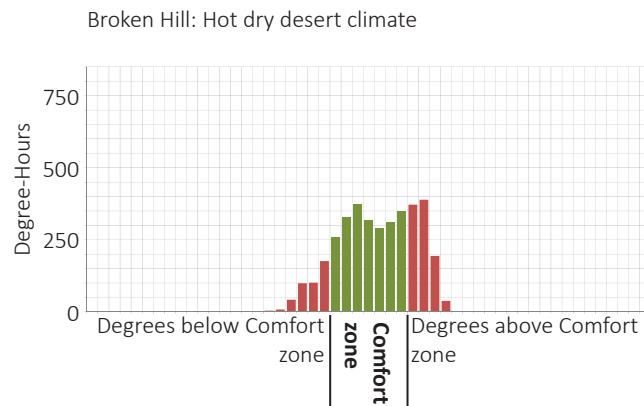
The simulation model is a tool. How it is used and how the results are interpreted must be done in the context of understanding the levels of confidence and uncertainty that surround the results. The purpose of the model needs to be considered as part of this context (ASHRAE, 2009, Fumo, 2014). In this project the model is not intended to predict an absolute ‘true’ value but rather enable the comparison between options by indicating, with a reasonable degree of confidence, the tendency of the performance for the classroom under different circumstances and configurations.

The Energy Plus model is stable and, while it may underestimate or overestimate specific values, there is a high level of confidence that it can illustrate the tendency of the changing thermal performance of the NSW Demountable Classrooms in response to proposed interventions to a reasonable and useful degree of accuracy.

The uncertainty generated in the results by the input parameters are easier to express quantitatively. In this project this uncertainty will be expressed by simulating a minimum, middle and maximum scenario based on the analysis of the probability tree (Table 2.12).

Minimum simulation scenario:	Occupation: Mean metabolic output per person: Infiltration rate:	25 pupils plus one teacher 86 W Poor
Middle & primary simulation scenario:	Occupation: Mean metabolic output per person: Infiltration rate:	27 pupils plus one teacher 97 W Poor
Maximum simulation scenario:	Occupation: Mean metabolic output per person: Infiltration rate:	30 pupils plus one teacher 107 W Very Poor

Table 2.12: Minimum, middle and maximum simulation scenarios
The main simulation scenario and the two extreme simulation scenarios used to indicate the range of confidence



Figures 2.33: The thermal performance of the existing classroom in five climates (SET 01)

Bar charts illustrating the number of degree-hours below, within and above the comfort zone (shown green) in one degree increments for the five different representative NSW climates.

UNITS: Bars are in one-degree increments

2.6 Results, analysis and discussion

In Chapter 1 the thermal performance of the NSW Demountable Classroom in climates across the state has been identified, anecdotally, as the principle reason for the poor reputation of these buildings. The quantitative evaluation methodology, set out above, has identified two primary criteria to evaluate the thermal performance:

- Thermal comfort
- Energy consumption.

The following analysis and discussion is in two parts:

The first focuses on an overall assessment of the thermal performance of the classrooms in all five climates over the whole year by considering the number of working hours below, within and above the comfort zone (Figure 2.33), and the predicted annual energy consumption of the classrooms.

The second part explores the performance of the classrooms using current understanding of the experience of thermal comfort as a starting point. The results and analysis explore the performance of the classroom over a single day in summer and winter in terms of both temperature and thermal flux. The days (24 hours) are taken as the mean performance in January (summer) and July (winter). The analysis uses the classroom in Williamstown as a representative example. The patterns observed in Williamstown are repeated in the other four climates with slightly increased or decreased magnitude.

Overall assessment

Overall the pattern of performance in terms of both comfort and energy consumption appears to be similar across all five simulated climates: The proportion of the working day the classrooms are predicted to be comfortable is, with the exception of Broken Hill (61%) and Richmond (67%), over 70%. The annual energy consumption of the classrooms ranges from 3677 kWh (Coffs Harbour) to 4418 kWh (Williamstown) and 4881 kWh (Richmond), or 20% and 33% more than the most efficient classroom, Coffs Harbour, which still uses double the GBCA target of 1932 kWh/year (GBCA, 2009).

Figure 2.34 illustrates this clustering of performance as a scatter graph plotting each classroom on a grid comparing annual energy consumption (Y axis) with the proportion (%) of working time the operative temperature in the classroom is within the comfort zone. Figures 2.33 and 2.35 illustrate the proportion of

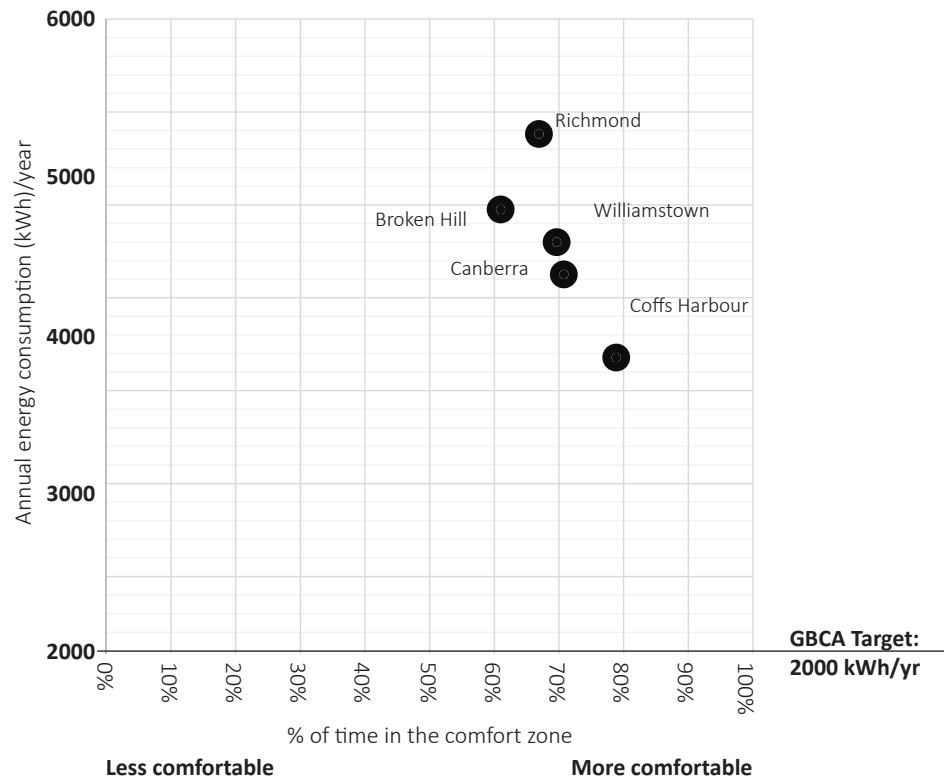


Figure 2.34: Scatter plot illustrating the annual energy consumption and time in the comfort zone

Scatter plot illustrating the annual energy consumption (Y axis) plotted against the proportion (%) of working time the operative temperature in the classroom is within the comfort zone.

The plot illustrates the relative performance of the existing classrooms in each of the five climates and, in particular, the relatively high level of discomfort in Broken hill and the relatively high energy consumption in Richmond.

The GBCA Green Star target energy consumption is less than 2000 kWh/year

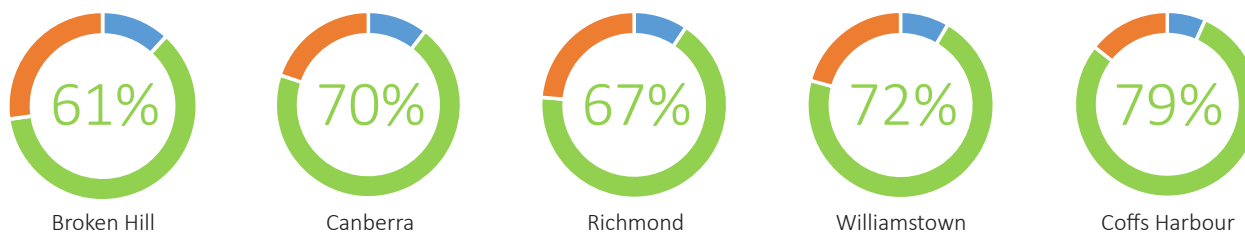


Figure 2.35: Percentage of time within the comfort zone
 Percentage of time within the comfort zone (green), above (red) and below (blue)



Figure 2.36: Annual number of degree-hours of discomfort
 Annual number of degree-hours of discomfort above (red) and below (blue) the comfort zone

the days below, in and above the comfort zone for each climate.

The analysis of the data confirms the anecdotal observation from Chapter 1 that being too warm in the classroom is the primary challenge in all climates: There are significantly more working hours (about 2 ½ times) above the comfort zone than below (Figures 2.33 - 2.36).

When the magnitude of the discomfort problem is calculated using the degree-hours formula this analysis is reinforced (Figure 2.36).

Energy consumption is also dominated by the cooling load (Figure 2.37) in all climates except Canberra where the cooling and heating loads are about equal (1917 kWh and 2382 kWh respectively).

In conclusion, when considering the overall thermal performance of the classrooms, the dominant issue is overheating and the reduction of the energy used to try and keep the building cool. The magnitude of the problem does not appear to vary substantially in the five different climates. Notable exceptions to this observation are the extent of overheating in Broken Hill (degree hours and time) and the heating demand in Canberra.

Improving thermal comfort in these classroom buildings is the primary objective of this project because it is the aspect of thermal performance that directly effects the experience of people using the building . Chapter 1 outlined how improving thermal comfort in the NSW Demountable Classroom could make a significant contribution to achieving better learning environments for children and teachers. Energy consumption is driven by the need to maintain comfort and therefore reducing energy consumption is directly related to thermal comfort. This means that it is necessary to understand thermal comfort and the causes of discomfort in the classrooms.



Figure 2.37: Annual energy demand and CO₂-e production

Annual heating (red) and cooling (blue) energy consumption in kWh.

Annual CO₂-e production as a consequence of generating the electricity using carbon based fuels.

A conversion factor of 1.05 kg CO₂-e.kWh is used, the BREE (2013) factors for grid electricity in NSW.

Analysis of thermal experience

These principles are useful to help understand the thermal experience in the Demountable Classrooms in all climates. A review of the mean temperatures inside each of the five simulated classrooms during the hottest month (January) highlights the following points:

- i. The mean Operative temperature is at the upper limit of what is considered to be comfortable (the comfort zone) indicating that it is above this level several days of the month.
- ii. The Air temperature is maintained in the middle of the comfort zone by the split cycle AC system.
- iii. The internal surface temperatures (floor, walls and, particularly the ceiling) which define the internal radiant temperature, are above the comfort zone.
- iv. The surface temperature of the ceiling is 10°C higher than the internal air temperature.
- v. The surface temperatures are also above, and in the case of the ceiling significantly above, the comfort zone (>5°C).

Figure 2.38 shows the predicted mean internal and external temperatures for the Williamstown classroom and illustrates the points made above. It is important to emphasise that these are mean temperatures for the month meaning that some daily temperatures will be

above this level. During January, the warmest month of the year*, the operative temperature in the classroom in Williamstown is within the comfort zone for the entirety of the working day only 10 out of 31 days.

During the coldest month of the year, July, significant differences between the wall, ceiling and air temperatures also occur, particularly in the morning when the internal wall and ceiling temperatures are up to 10°C below the air temperature. In the afternoon the internal ceiling temperature is above the comfort zone (Figure 2.38).

The asymmetry of the thermal environment within the classroom contributes to discomfort. ASHRAE explains that *“a person may feel thermally neutral as a whole but still feel uncomfortable if one or more parts of the body are too warm or too cold”* (ASHRAE, 2009). ASHRAE Standard 55 (ASHRAE, 2010) explains that “in general people are more sensitive to asymmetric radiation caused by a warm ceiling than that caused by hot and cold vertical surfaces”. ASHRAE 55 sets an upper threshold for the temperature difference between the ceiling and the floor of 5°C, the equivalent international standard ISO 7730 (ISO_7730, 2005) sets no boundary below which discomfort is not expected. During summer the asymmetry between the floor and ceiling of these classroom buildings is at the upper limit or above the threshold set by ASHRAE.

*All 365 days within the .TMY weather file are used in this analysis so that the performance of the NSW Demountable Classroom building is considered in the broadest range of conditions available within the simulation weather file.
Refer to part 2.3

Legend: Temperatures

- Outside air temperature
- - - External roof temperature
- Ceiling surface temperature
- - - Mean external wall temperature
- Mean internal wall temperature
- Internal air temperature
- Internal operative temperature

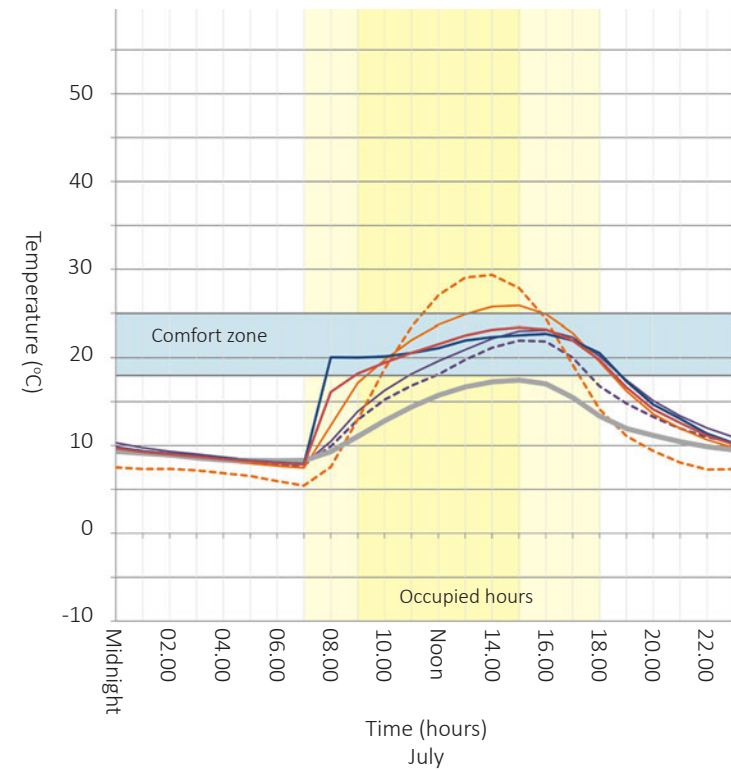
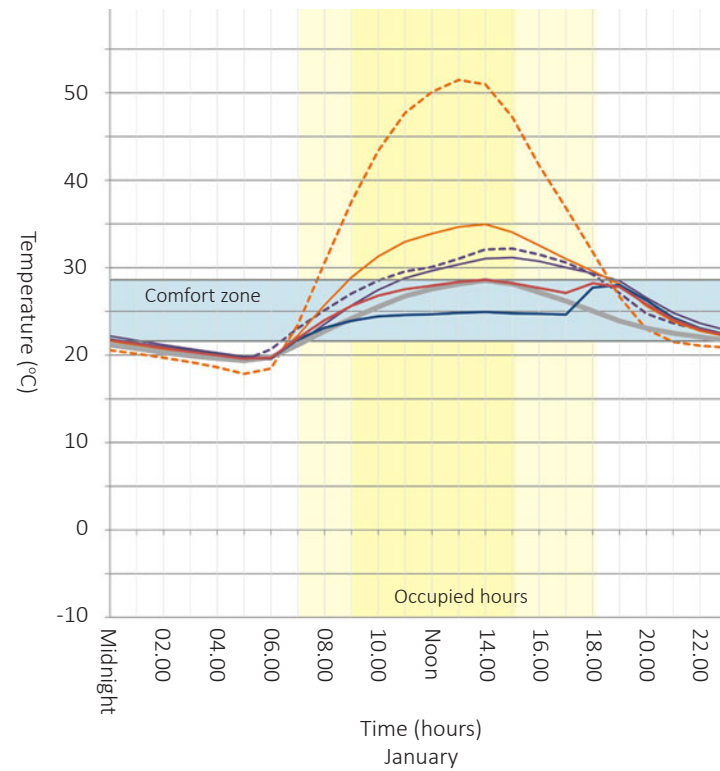


Figure 2.38: Mean hourly temperatures plot for Williamstown in January (left) and July (right).

ASHRAE 55 and ISO 7730 also consider floor temperature a potential cause of discomfort. Pupils, particularly primary school pupils, may spend a considerable amount of time sitting on the floor and so floor temperature is important (Campbell, 1991, Soccio, 2014, p.64). The floor in the Demountable Classrooms is a single sheet of plywood exposed below to the outside air. In Williamstown in summer (January) the mean floor temperature exceeds 30°C and in winter it is below 20°C for the first three hours of the working day (08.00 – 11-00). Both situations increase discomfort.

It is clear that the temperature in the classrooms both overall (operative temperature) and the temperature of individual surfaces are often at the limit of or exceeding what is generally regarded as acceptable.

Thermal Flux: thermal energy in the classroom space

The air conditioning system only controls the air temperature (Figure 1.11). This is illustrated by in the temperature graph for January (Figure 2.38), the dark blue line is air temperature. As explained above, the occupants' perception of thermal comfort is driven by a combination of air temperature and radiant temperature (combining to create the operative temperature). The temperature of the internal surfaces is driven by the thermal flux, which is the flow of thermal energy through the fabric of the building. The thermal flux is, in turn, driven by a combination of the temperature difference between the inside and outside of the building fabric and the conductivity of the fabric. The other significant factor in the overall thermal flux

of the space are the internal gains and losses, primarily the people in the space (gains) and the air conditioning (losses); and external gains or losses, primarily from the sun or to the sky.

Predicted thermal flux for January and July (summer and winter) in the Williamstown classroom are illustrated in Figure 2.39.

The thermal flux entering the space, that is the flow of thermal energy into the space, is dominated by the occupants who account for about 50% of the energy entering the space during summer and about 80% of the energy entering the space in winter, excluding heating.

Thermal flux leaving the classroom, losses, are through the floor and via ventilation during the summer. During the winter the losses through the floor are very significant and the losses due to ventilation also increase. Thermal losses also occur through the walls. Losses through the roof occur during the first half of the day.

Legend: Thermal flux

- Roof
- Opaque walls
- Windows
- Floor
- Ventilation
- Internal loads
- - - Air-conditioning
- dT inside-outside

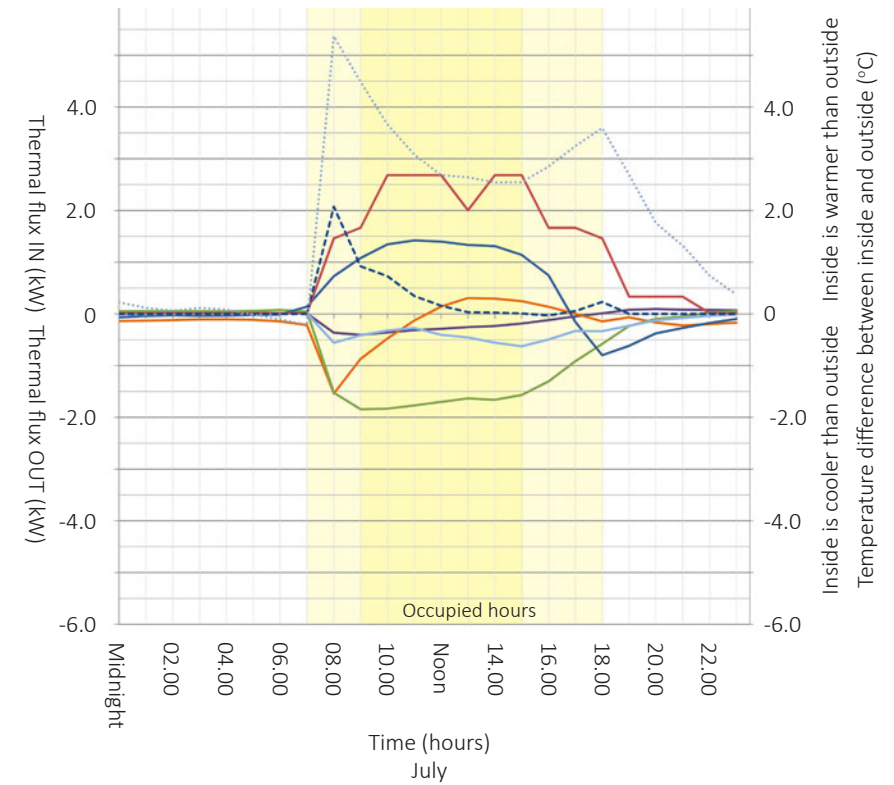
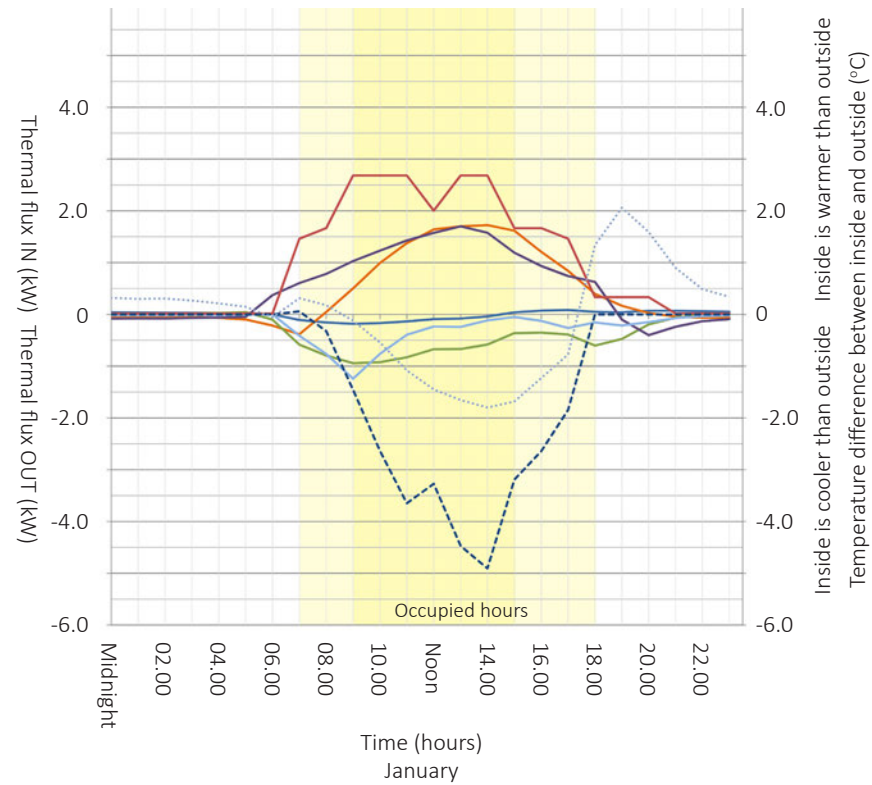


Figure 2.39: Mean hourly thermal flux in and out of the classroom in Williamstown in January (left) and July (right).

Thermal inputs: The whole system

It has been established that overheating is the dominant problem and this occurs in all months of the year in all climates. The analysis of the thermal flux (movement of thermal energy) has shown that internal gains (people) and conduction and radiation (windows) through the fabric of the building are the two significant inputs. The gains from the people (the pupils) in the classroom are fixed by the number of pupils in the class. The gains through the fabric of the building are driven by the external temperature of the building envelope which is significantly above the external air temperature. The temperature of the external envelope is largely a function of the solar radiation landing on it (Szokolay, 1987). The quantity of solar radiation landing on the roof of the classroom building is about 20 times the value of the internal gains in summer and about 10 times the internal gains in winter in all five climates.

Improving comfort and reducing energy consumption

The primary use of energy in these buildings is to attempt to control the thermal comfort of the building users. The air temperature in the buildings is maintained within the comfort zone, however the operative temperature, the best indicator of comfort, can only be partly controlled by the air conditioning system and is heavily influenced by the temperature of the external envelope of the building.

Energy consumption will only be reduced if thermal comfort is improved. Improving thermal comfort means that the building fabric must be improved so that it is able to deflect or resist the enormous thermal loads it is exposed to from the sun. Energy consumption in winter and cold thermal discomfort in winter is a smaller problem than overheating and cooling energy in summer (Figures 2.36 and 2.37). The floor temperature and the asymmetry between the floor temperature and ceiling temperature also contribute to discomfort in summer and winter.

2.7 Conclusion

A digital thermal simulation model of the NSW Mk I classroom was constructed based on detailed survey information and original drawings. The model was simulated in five climates from across NSW that were chosen to be representative of the diversity of climates across the state. Thermal comfort was assessed using the adaptive comfort model.

It has been shown that the anecdotal evidence suggesting that the NSW Demountable Classroom building suffers from an overheating problem is correct and that overheating is the dominant problem in all seasons and in all of the five climates the model was simulated in. The patterns of thermal performance and energy consumption were surprisingly similar in all five climates despite the wide variety of climate conditions.

More detailed analysis and reasoning has shown that the problems of thermal performance, particularly overheating and the associated energy consumption, must be addressed by improving the thermal performance of the building fabric and, in particular, helping it to resist or deflect the enormous thermal energy loads imposed on it by the sun. These loads lead to high internal radiant temperatures throughout the year and are a significant contribution to the thermal discomfort experienced by people who use the classrooms.

The challenge is significant because the current annual energy consumption of these buildings is slightly more than double the Green Building Council of Australia's target and the classrooms are only completely free of discomfort during working hours for, at most, just over 10% of days annually (Figure 2.40).

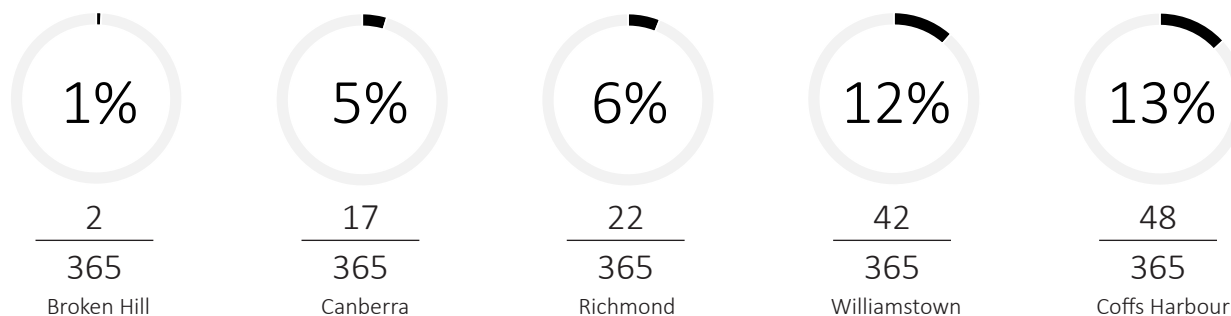


Figure 2.40: Number of days per year when ALL working hours (08.00 - 18.00) are within the comfort zone

Defining a strategic approach to implementing solutions to the problem of thermal performance

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3.2 Three strategies	148
3.3 Discussion	152
3.4 Conclusion.....	154



Figure 3.1: The movement of a Mk 1 Demountable Classroom during refurbishment in Cessnock.
(The Author)

3.1 Introduction

Chapter 1 explained that, despite continuing to fulfil a vital role within the infrastructure of education facilities in communities across the state, the NSW Demountable Classrooms are regarded as second rate or obsolete by the communities who use them. The chapter identified the poor thermal performance of the classrooms as the primary reason for this poor perception.

Chapter 2 used a detailed computer simulation model to confirm what the anecdotal evidence in Chapter 1 suggested. Chapter 2 concluded that the problems of thermal performance, and consequently the thermal comfort of the buildings users, need to be addressed by improving the thermal performance of the building fabric and, in particular, helping it to resist or deflect the enormous thermal energy loads imposed on it by the sun.

The objective of the investigation is focussed on the development of socially, economically and environmentally viable proposals that will improve the thermal performance of these classroom buildings and the thermal comfort of those who use them.

There are many potential technical solutions to the problem of thermal performance. In the real and pragmatic world in which these classrooms and school communities exist there are also numerous economic, social, political and environmental constraints that will inform how the technical solutions can be implemented. The implementation method and the choice of technical

solutions are interrelated. As with all design-research the process of investigating and answering these two questions was iterative and simultaneous: The answer to one question informing and re-framing the answer to the other.

It is not possible to reflect or capture this cyclical process in a linear discourse that relies on consecutive or successive argument. Therefore this chapter will discuss overall strategic approaches to implementing technical solutions, or Solution Sets. The following chapter will explore the range of technical solutions that are available.

This chapter concludes by identifying one approach to implementing the technical solutions as the basis for the discussion in the following chapters.

3.2 Three strategies

There are three possible strategic approaches to implementing technical solutions that will improve the thermal performance of the Demountable Classroom buildings:

1. Replacement of existing Demountable Classrooms with a new design
2. Off-site refurbishment of the existing Demountable Classrooms
3. On-site modification of the Demountable Classrooms



Figure 3.2: Construction of Refuge Gervasutti, Mont Blanc Massif, Italy
A high performance prefabricated structure assembled at 2,500m above sea level cantilevered off the edge of a cliff above a glacier. It is designed to create thermally acceptable conditions inside in an environment that experiences extremes of hot and cold.
 IMAGE: Open Buildings, LEAPfactory
 Copyright: Francesco Mattuzzi

Approach 1: Replacement – create a new design

The Demountable Classroom is 50 years old and clearly no longer fulfils the expectations of the communities they serve. One solution to this problem would be to simply replace all of the NSW Demountables with a new model. The new design would be able to benefit from the best aspects of the existing classrooms as well as the latest innovations, research and design expertise for prefabricated industrially produced relocatable buildings. This proposal creates opportunities for learning and the demonstration of pioneering design solutions (Figure 3.2).

However, this approach raises a number of economic and environmental challenges:

The 6000 classrooms owned by the NSW government represent a significant asset. They are generally in a reasonable or good state of repair and their replacement would represent a considerable financial cost and environmental cost in terms of embodied CO₂ and CO₂-equivalent.

Developing a new design and manufacturing 6000 classrooms would be a large economic imposition and take several years to achieve (See section 1.7 and 1.11).

Approach 2: Off-site refurbishment

An off-site refurbishment strategy would remove the classroom buildings to an industrial facility where they can be stripped back to the structural frame and a new, significantly improved thermal envelope constructed around the frame. In many respects this process is exactly what the classroom system was designed to facilitate with inter-changeable panels. In theory classrooms that are removed from a school could be simultaneously replaced with improved Demountable Classrooms.

Currently the Demountable Classrooms are refurbished at a rate of 3% per year (Interview C) in Golburn and Cessnock jails through a contract with the NSW Correctional Service Industries. This contract provides employment, training and rehabilitation to inmates, a scheme that adds an additional layer of social benefit and engagement to the building system. The opportunity to improve the thermal performance of the envelope during the refurbishment process has not been utilised to date.

The challenge the proposal creates is primarily a time constraint: If the refurbishment rate is maintained at 3% it would take 30 years to upgrade 6000 classrooms.

Increasing the rate of refurbishment creates two potential problems: The first is that a substantial increase in the number of classrooms being refurbished would reduce the number of classrooms that are available on school sites to teach in (because they are being refurbished off-site). The second is that it

is unlikely that NSW Corrective Services Industries (Cessnock and Golburn Jails) would be able to increase their refurbishment capacity by 5 – 10 times. This would lead to the need to introduce other private sector contractors and probable consequential increase in costs. Currently labour costs are relatively low because prisoner's labour is relatively low cost.

Material costs will vary depending on the novelty of the technologies employed to improve the performance. New and therefore less established technologies (e.g. Phase Change materials) tend to cost more than more conventional technologies.

The environmental cost in terms of embodied energy is likely to be low because the primary structure, the substantial steel frame, is retained, and much of the secondary steel framing could also be retained or recycled.

Approach 3: On site refurbishment

Rather than remove and replace the classrooms that are on school sites across the state this proposal suggests creating strategies that can be implemented while the classrooms remain in the schools. The strategies must necessarily be simple, or at least rapid, so that the work can be carried out during periods when the classrooms are not being used (weekends or holidays) or minimise disruption to school timetables.

The requirement for speed and simplicity suggests that the proposals are likely to be economic since construction cost is normally proportional to time and complexity.

On site refurbishment presents its own challenges as well as a number of opportunities for the use of climate specific adaptation, social engagement and the development of practical education experiences that can be integrated into the school curriculum:

Opportunities:

- On site refurbishment eliminates the costs of transport and cranes to remove and replace classrooms.
- On-site refurbishment creates the opportunity for site specific responses to climate.
- On-site refurbishment suggests that local contractors can be engaged to carry out the work. This may reduce labour costs and has the potential peripheral advantage of distributing the benefit of the financial investment to communities across the state.

- This proposal places the responsibility and authority to improve the thermal performance of the classrooms with those who will benefit most from the implementation of the strategies.
- The decentralisation of responsibility creates the opportunity to engender a sense of ownership and reinforce the significance of the school within the broader community.
- The proposal creates pedagogical opportunities: The SEED project (The SEED Collaborative, 2015) and the work of Peter Hubner (Blundell Jones, 2007) both demonstrate how school communities of all ages can become involved in and learn from the process of designing and implementing bio-climatic school buildings and that this learning process can continue long after construction is complete.

Constraints and challenges:

- Site specific strategies should not interfere with the ability to relocate the classroom building.
- The proposal creates the potential for a conflict of responsibility between those who own the classrooms, the state, and those who are responsible for implementing the improvements, the school.

3.3 Discussion

The objective of the project is to develop proposals that will improve the thermal performance of the NSW Demountable Classroom and the thermal comfort of those who use them. The proposals must be socially, economically and environmentally achievable. This statement of overall objectives defines a number of criteria that have been discussed previously and are summarised here (Table 3.1):

Objectives	Criteria
Thermal performance and internal environmental quality	Thermal comfort
Socially achievable	Speed of implementation Social engagement and opportunities for learning
Economically achievable	Low cost of implementation (financial cost)
Environmentally sustainable	Low embodied CO2-e (embodied energy) Low annual heating and cooling energy consumption

Table 3.1: A summary of the Social, economic and environmental objectives and assessment criteria

All three approaches create an opportunity to test and develop simple strategies for significantly improving the thermal performance of NSW Demountable Classroom buildings. This will lead to learning at an individual, community, state and international level if the results of these improvements are documented and shared. Successful solutions or sets of solutions can be incorporated into the existing Demountable refurbishment programme (Approach 2) and new designs for Demountable Classrooms (Approach 1) or on-site refurbishment (Approach 3).

When these three approaches are considered together:

- Approach 1 involves the complete replacement of the existing 6000 Demountable Classrooms. This is likely to take a considerable amount of time and be expensive both in terms of financial investment and embodied energy.
- Approach 2 presents two challenges: At the current rate of refurbishment it will take about 30 years to complete which is not a socially, politically or environmentally acceptable timeframe. A much faster refurbishment programme is likely to reduce the number of classrooms available for use in schools (because they are being refurbished) and may also increase the cost.
- Approach 3 makes simplicity and low cost the two primary constraints to ensure the proposed solutions

can be implemented on-site and coordinated at a local level. This approach seeks to maximise the speed of implementation and minimise the disruption to the schools use of the classrooms.

- The delegation of responsibility and authority to a local level means that those who benefit the most from the modifications are empowered to initiate the improvements in their schools.

Of the three approaches the third, on-site refurbishment, minimises the cost of refurbishment by making simplicity a key requirement and obviating the cost of cranes and transport. The requirement for speed minimises the disruption to the school. The proposed use of local trades persons creates local economic advantages and distributes the financial benefits of the investment across the state.

When the three approaches are considered together the third approach appears to achieve more of the objectives than the other two proposed implementation strategies (Figure 3.3).

3.4 Conclusion

This chapter considered three different approaches to implementing modifications to the NSW Demountable Classroom that would improve their thermal performance and consequently the thermal comfort of those who use them in a manner that is socially, economically and environmentally viable. The chapter has concluded that an approach that creates technical solutions that can be implemented while the classrooms are on-site achieves more of the objectives more efficiently than the other two approaches. This approach makes simplicity, speed and low cost its primary constraints.

This approach creates a number of challenges and opportunities in relation to defining responsibility for the work. The opportunity to delegate responsibility to a local level means that these who will benefit most from the modifications are empowered to initiate the improvements to their classrooms.

The next chapter will explore a range of technical solutions to the problems of thermal comfort and thermal performance in these classroom buildings and consider them in the context of creating simple and low-cost design solutions that can be implemented using a local, on-site approach. The criteria for this discussion are outlined at the beginning of the next chapter.

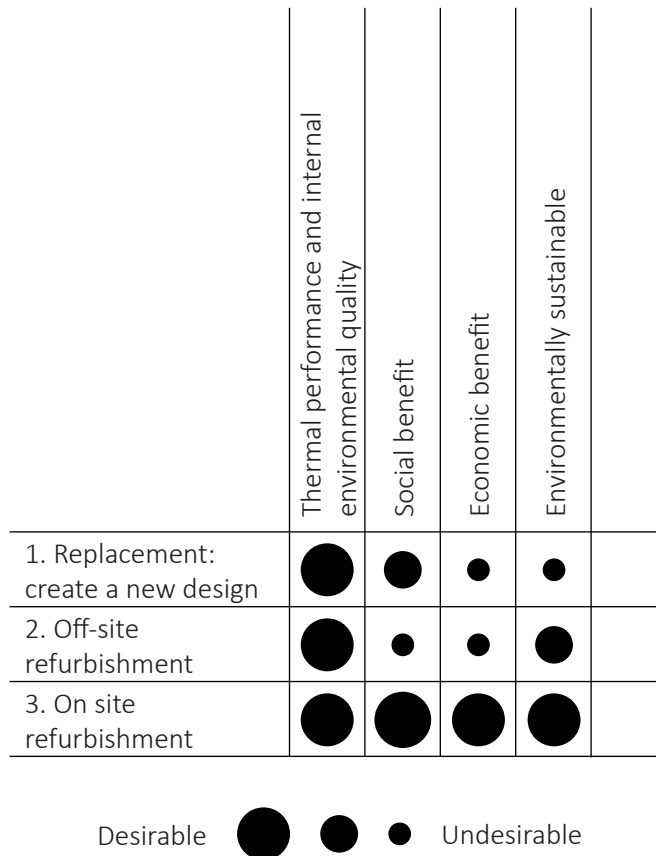


Figure 3.3: Graphic comparison of the three strategies against four criteria

Developing technical solutions to improve the thermal performance of the NSW Demountable Classroom



Figure 4.1: NSW Demountable Classrooms

*Mk. 1 Demountable Classrooms, Caringbah Public School, Caringbah
(Photograph by the author)*

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4.1 Introduction

Chapter 4 discusses various technical solutions and combinations of solutions, “Solution Sets” (Hyde et al., 2009), that maybe employed to improve the thermal performance of the NSW Demountable Classroom in the context of the social, economic and environmental sustainability issues discussed previously and the purpose and utility of these classroom buildings.

The first part of this chapter briefly restates the findings of the previous three chapters. The second part of the chapter sets out evaluation criteria for possible technical solutions based on the discussion, observations and findings of the previous chapters. The third part of the chapter describes potential technical solutions based on a detailed review of published research literature. The fourth part of the chapter compares the technical solutions discussed based on the evaluation criteria established at the beginning of the chapter. As an outcome of the comparison the chapter concludes by proposing a number of individual technical solutions and sets of solutions to improve the thermal performance of the NSW Demountable Classroom within the “simple and low cost” framework identified in the conclusion of Chapter 3.

Findings from previous chapters

Chapter 1 concluded by asking how these Demountable Classroom buildings can be transformed to improve their thermal performance and the thermal comfort for those who use them. Chapter 1 also concluded that

proposals to improve the thermal performance of these buildings and the thermal comfort of the building users must be socially, economically and environmentally achievable.

Chapter 2 identified the poor thermal performance of the building fabric and the enormous thermal loads imposed on the fabric by the sun as the two principle problems. Chapter 2 also provided a more detailed analysis that suggested that during summer the high surface temperatures of the walls, ceiling and sometimes the floor were the main contributors to the thermal discomfort. The high surface temperatures are often at the limit of or exceed what is considered to be comfortable. The high temperatures raise the Operative Temperature (the comfort temperature metric) and cause an asymmetrical thermal experience contributing to discomfort (ISO_7730, 2005, ASHRAE, 2010). The surface temperature and air temperature are often 10°C apart in all five of the simulated climates and the difference between the ceiling temperature and the floor temperature is more than 5°C in all of the simulated climates.

In winter a similar but opposite problem occurs during the morning: In all climates the internal surface temperatures are below what is considered to be comfortable for the first few hours of each day.

The energy consumed by these classrooms is used primarily to control comfort using split cycle air Conditioning units, for instance maintaining an air temperature of 25°C while all the internal surface

temperatures are in excess of 30°C. Energy consumption can only be reduced if the thermal performance of the building fabric and the thermal comfort of those who use the classrooms is improved.

Chapter 3 discussed a range of strategic approaches to the problem of thermal performance and concluded that an approach that ensures that the proposed technical solutions can be implemented on-site with minimum disruption to the schools achieves more of the objectives more efficiently and, in particular, achieves the established social, economic and environmental objectives.

The chapter concluded that in order to be successful the approach must make simplicity, speed and low cost the primary constraints when designing technical solutions. In addition to these objectives the ability to rapidly relocate and deploy the NSW Demountable Classroom must be maintained. Therefore any technical solution that can improve the thermal performance of the classrooms must also consider the following four criteria:

- Financial cost
- “Buildability” including speed of implementation
- Environmental cost
- The effect on the ability to relocate the classroom units

These Evaluation Criteria are discussed in more detail below.

4.2 Evaluation Criteria

The discussion of the criteria is qualitative. Such a complex problem with so many interrelated elements or “systems” does not lend itself to wholly numeric or quantitative analysis (Onyx, 2014). The descriptions of each of the four criteria conclude by defining what is considered desirable and undesirable in the context of this research project. The technical solutions will be scored against these definitions as low (undesirable), medium and high (desirable).

Financial cost

The financial cost of the proposed Solution Sets depends on,

- a. The cost of the materials, and
- b. The cost of the labour needed to install the materials.

The cost of the materials is dependent on availability and ubiquity of use. Materials that are ubiquitous in construction are commonly available across the state and are normally relatively affordable. Materials that are new, innovative or technically advanced are normally less readily available and therefore potentially relatively more expensive.

The cost of labour, that is the cost of the people who install the Solution Sets, is dependent on the amount of time needed to install the system and the skills needed to install the system. Innovative, unfamiliar or

technically advanced materials may require specialist installers or installers with high levels of skill, or different skills, who may not be available, or may be relatively expensive. Materials that are familiar will be readily available, relatively simple and quick to install and so reduce the overall cost.

Undesirable	Desirable
High overall cost	Low overall cost

‘Buildability’ and speed of implementation

Construction time and complexity are often correlated to cost. ‘Buildability’ is a term used within the construction industry to describe the ease with which a particular design or element can be constructed. The term encompasses at least four aspects of construction that are in many ways interrelated:

Availability of materials

The ease with which the materials needed to build the proposal can be obtained and delivered to the particular site. Common materials will be available locally. Specialised materials may need to be ordered in advance from NSW’s major city Sydney, (Australia’s largest city) or from overseas.

The skill level required

Consideration needs to be given to the skill level needed to carry out the work. For instance, is it something an inexperienced DIY enthusiast can do? Or does the

proposal require a skilled joiner or other highly qualified tradesperson? Are these skills likely to be widely available across the state or are their only a limited number of people with the necessary skills?

Speed of construction

An understanding of how much time the construction process will take is needed. For the retrofitting of the Demountable Classrooms speed has been identified as a key constraint. Solutions that can be installed quickly will allow classrooms to be retrofitted during weekends or school holidays and so minimise the disruption to school timetables. Speed of construction reduces the time and so the cost of labour which accounts for approximately 2/3rds of construction costs.*

Complexity of construction

Understanding how many different components need to be assembled and how many different skills are needed, and so need to be coordinated, in order to assemble them. The more complex the construction the more care, time and skill are needed to complete the task contributing to overall costs and increasing the challenge of achieving the overall objective. Simplicity of construction has been identified as a key constraint.

**Based on current small construction contracts and contract negotiations*

Summary

Together these four elements help define “Buildability”, i.e. the simplicity or complexity of the construction process, the ease and speed with which it can be achieved and therefore the cost and probability of sub-standard work.

Undesirable	Desirable
Complicated	Simple

Environmental impact

The environmental impact of the proposed Solution Sets includes:

- The embodied energy of the materials
- The opportunity to recycle the waste material during construction or later in the building’s life.
- Opportunities for re-using components
- The toxicity and bio-degradability of the materials when they are no longer needed (waste).

(Woolley et al., 2000)

Undesirable	Desirable
High environmental impact (High embodied energy and toxicity, low re-cycling and bio-degradability)	Low environmental impact (Low embodied energy and toxicity, low re-cycling and bio-degradability)

	Undesirable	Desirable
Financial cost	High overall cost	Low overall cost
“Buildability” and speed of implementation	Complicated	Simple
Environmental impact	High environmental cost (High embodied energy and toxicity, low re-cycling and bio-degradability)	Low environmental cost (Low embodied energy and toxicity, low re-cycling and bio-degradability)
The ability to rapidly relocate the classroom units	Creates a barrier to relocation and transportation	Does not change the ability of the classroom to be relocated and transported.

Table 4.1: Summary of evaluation criteria

The ability to rapidly relocate the classroom units

Chapter 1 explains that the NSW Demountable Classroom was designed to provide communities with a rapidly deployable and relocatable classroom system so that the Department for Education can create “virtually instant [teaching] accommodation” (Underwood, 1972). This is the essential characteristic and function of the NSW Demountable Classroom system and any technical solution to the problem of thermal comfort must not impede the rapid deployment and relocation of individual classroom buildings and units. The proposed technical solutions must also be designed in such a way that the solutions are either robust enough to cope with this process or, if necessary, they can be removed easily.

Undesirable	Desirable
Creates a barrier to relocation and transportation	Does not change the ability of the classroom to be relocated and transported.

4.3 A review of technical strategies available for improving the thermal performance of the building envelope

Put simply, the objective and purpose of the building envelope is to modify the local environment so that being inside the building is more comfortable than being outside the building (Vitruvius, 25 BC (Circa Trans. 1826).

When the principle is applied to the context of the NSW Demountable Classroom it means that the purpose of the building envelope of the classroom is to moderate the external environment in order to create an internal environment that, at best, enhances learning and, at worst, does not detract from learning. To achieve this, the building envelope needs to resist the passage of thermal energy through the fabric either from the inside to the outside or the outside to the inside. The direction of resistance may vary depending on the season, the day or the time of day and can be described as either

Defensive:	Resisting the passage of thermal energy from the outside to the inside
Retentive:	Resisting the passage of thermal energy from the inside to the outside

Many of the strategies employed to deal with these two situations are similar or the same, however the

magnitude of the heat load that must be resisted is significantly higher in the defensive situation than retentive situation. For instance, the data in Chapter 2 shows that in the summer (January) in Williamstown the mean maximum temperature difference between the outside roof surface and the inside ceiling surface is 17°C; and between the outside roof surface temperature and the internal air temperature the mean maximum difference is 27°C. In winter (July) the mean maximum temperature difference between the outside roof surface and inside ceiling surface is less than 5.5°C (-5.5°C to +1.4°C). The mean maximum temperature difference between the outside roof surface and inside air temperature is -12.5°C because the outside surface is so cold in the morning. This temperature difference reduces to -1.5°C by 10am and +7°C by 1pm (outside less inside).

The climates of New South Wales are diverse but a commonality is that they all have periods that are warm or hot with high levels of solar radiation. The analysis of the thermal performance of the existing Demountable Classroom in Chapter 2 identified external heat gains as the primary challenge to comfort inside the classroom. The primary purpose of the building envelope must, therefore, be to “defend” the space against the

infiltration of thermal energy. The following section will review strategies described in existing academic research literature that could be employed to create a “defensive” thermal envelope for the classrooms, organised under the following themes:

- Resistive insulation
- Reflective insulation
- Ventilated cavities
- Shading
- Vegetation
- High emittance paint (High-E)

The final strategy that is explored does not “defend” the building from external thermal gains but moderates the internal thermal environment:

- Internal thermal mass

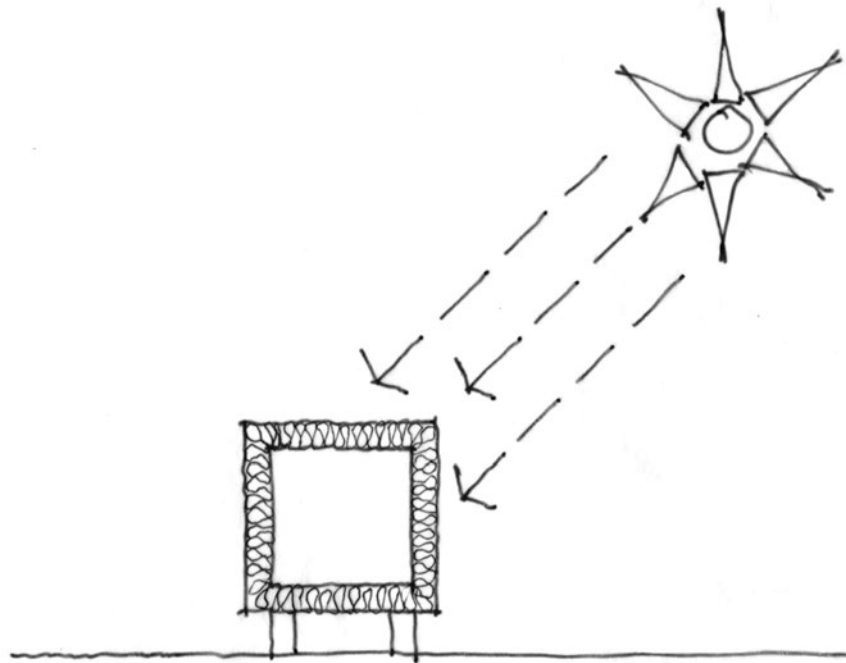


Figure 4.2: Resistive insulation
(Drawing by author)

Resistive insulation

The most common kind of insulation is bulk or “resistive” insulation (Figure 4.2). This insulation relies on the thermal resistance of the material to resist the conduction of thermal energy through the building envelope. There is a general belief articulated through legislation and by construction professionals that bulk insulation improves the thermal performance of buildings. However, within the literature there is a growing body of work that suggests the situation is rather more complicated than the adage “more is better” acknowledges:

“Insulation in general tends to be more effective (in terms of cost and environmental benefits) in heating-dominated buildings in colder climates. It is less effective in cooling-dominated buildings with large internal heat loads in warmer climates.” (Li et al., 2013)

In a small field study (8 houses) Taylor (Taylor et al., 2000) demonstrated that some insulation is considerably better than no insulation in the warm-hot summer climate of Pretoria, South Africa but that the quantity of insulation (50, 75 or 100mm) of mineral wool made little or no difference to summer comfort. Jaffal (Jaffal et al., 2012) demonstrates the same phenomenon when the insulation thickness in a conventional roof of a house in La Rochelle is varied from 0 to 300mm in a simulation model. The introduction of 50mm of an unspecified type of insulation reduces annual cooling demand from 7 kWh/m².year to 2.5 kWh/m².year but the introduction

of additional insulation does not reduce cooling energy demand further. Annual heating energy demand continues to fall as additional insulation is added but the reduction is smaller with each additional 50mm of insulation.

Giovanardi et al (Giovanardi et al., 2008) used simulation to show that wall insulation levels reduced heating load but, within a range of 150 – 280mm, had no significant effect on cooling loads. A study of Iranian construction in Tehran by Farhanieh and Sattari (Farhanieh and Sattari, 2006) calculated that as insulation levels increase both the cooling and heating loads are reduced following a law of diminishing returns.

Investigating the concept of the Zero Energy Building (ZEB) in the Mediterranean climate of southern Italy Evola et al (Evola et al., 2014) demonstrated that increasing insulation levels from 20 to 50 to 80mm marginally increased the cooling load. The increasing insulation levels had a more significant effect on reducing the heating load.

Masoso and Grobler (Masoso and Grobler, 2008) used a Design Builder model to simulate the thermal performance of a three storey brick office building in the hot dry climate of Botswana. They varied the insulation levels of the walls and the set point temperature of the cooling system. The results demonstrate that as the U-value of the walls increases there comes a point when the cooling load also starts to increase. The point at which this occurs depends on the set point temperature for the cooling system and the change becomes more

pronounced as the set point temperature is increased. Presumably this is also affected by climate although the influence of climate is not discussed in the paper.

All of these examples consider the effect of increased insulation values on medium to high thermal capacity (high mass) buildings. Unfortunately there does not appear to be extensive research literature exploring the efficacy of the use of bulk insulation or the appropriate quantities to resist the passage of thermal energy in lightweight buildings in warm or hot climates. Pearlmutter and Mier (Pearlmutter and Meir, 1995) observed that the internal surface temperature of lightweight houses in the Negev Highlands, Israel, fluctuates “with the slightest input of energy”. These buildings are a similar construction to the Demountable Classrooms but with significantly more (although still modest) levels of insulation. Budaiwi et al (Budaiwi et al., 2002) demonstrate that the conductivity of bulk insulation products increases by about 16% as the temperature of the insulation increases from about 10°C to 40°C. When combined with a wall or roof construction that includes a high mass (concrete) inner layer, the k value (conductivity) is shown to increase by between 4 and 17% depending on the orientation, colour of the outer surface and material temperature.

The modelling of the existing classrooms discussed in Chapter 2 found that in the lightweight construction of the NSW Demountable Classroom the temperature of the roof surface exceeds 50°C (mean maximum during January (Summer) in Canberra). The corresponding ceiling temperature is 35°C which is cooled by the

air-conditioned air (24°C). In Broken Hill the mean maximum roof temperature in summer exceeds 55°C and the mean ceiling temperature exceeds 35°C with the internal air temperature maintained at 26°C.

Summary

In summary the literature exploring the performance and behaviour of resistive thermal insulation in buildings in different climates appears to be limited. The literature that has been found suggests that the utility of resistive insulation is greater in cool, heating dominated, climates than in warmer, cooling dominated, climates (Li et al., 2013). The utility of the insulation has also been shown to follow a “law of diminishing returns” (Giovanardi et al., 2008) and increasing the quantity of insulation beyond a particular point may even become counterproductive (Masoso and Grobler, 2008).

Reflective insulation

The other common form of insulation is reflective foil or “radiant” barrier insulation. This kind of insulation relies on the material’s ability to reflect rather than absorb radiant energy. In practice reflective insulation and resistive insulation are often used in combination and a number of researchers have investigated this strategy. Medina (Medina, 2000) found that increasing the level of resistive insulation reduced the contribution of the radiant insulation to the overall reduction of heat flux through the building envelope to an air conditioned space. D’Orazio et al (D’Orazio et al., 2012) constructed a tiled roof with an R-value of 4.0 K.m²/W and found that the addition of reflective insulation had a small influence on the quantum of heat flux, a reduction of up to 0.5 W/m².K, but that the heat flux through the roof was fairly modest (2 W/m²) which was attributed to the high insulation levels. When the reduction in heat flux through the roof caused by the introduction of the reflective barrier is considered as a proportion of the total heat flux in the base case it is 17%, and so shown to be significant. D’Orazio et al’s experiment considered both air conditioned and un-conditioned spaces and found that the ceiling temperature was the same with or without air conditioning. D’Orazio et al concluded that *“reflective Insulation is less effective in buildings with high insulation levels”* although it appears that this observation is based on a comparison with results from others because D’Orazio et al do not vary the resistive insulation in their test.

Soubdhan et al (Soubdhan et al., 2005) conducted a useful experiment using four small test cells (1.2m x 1.2m x 0.5m high) in Guadeloupe in the West Indies. The test cells had lightweight walls and floor insulated with polystyrene. The roof construction was varied and the space below the white corrugated steel roof was ventilated in two of the constructions. The heat flux is calculated from temperature and other data rather than measured directly. The results suggest that resistive insulation can be an effective barrier to incoming thermal flux. The R-value of the two types of resistive insulation used are not reported but can be estimated at R1 (1 K.m²/W). The experiment concluded that a radiant barrier is also useful and that its performance when resisting incoming radiation is improved when it is combined with a ventilated cavity.

Summary

In summary it appears that reflective insulation may enhance the performance of a construction containing resistive insulation, particularly when combined with other strategies such as a ventilated cavity. Where other strategies are highly effective the contribution of reflective insulation becomes marginal in absolute terms.

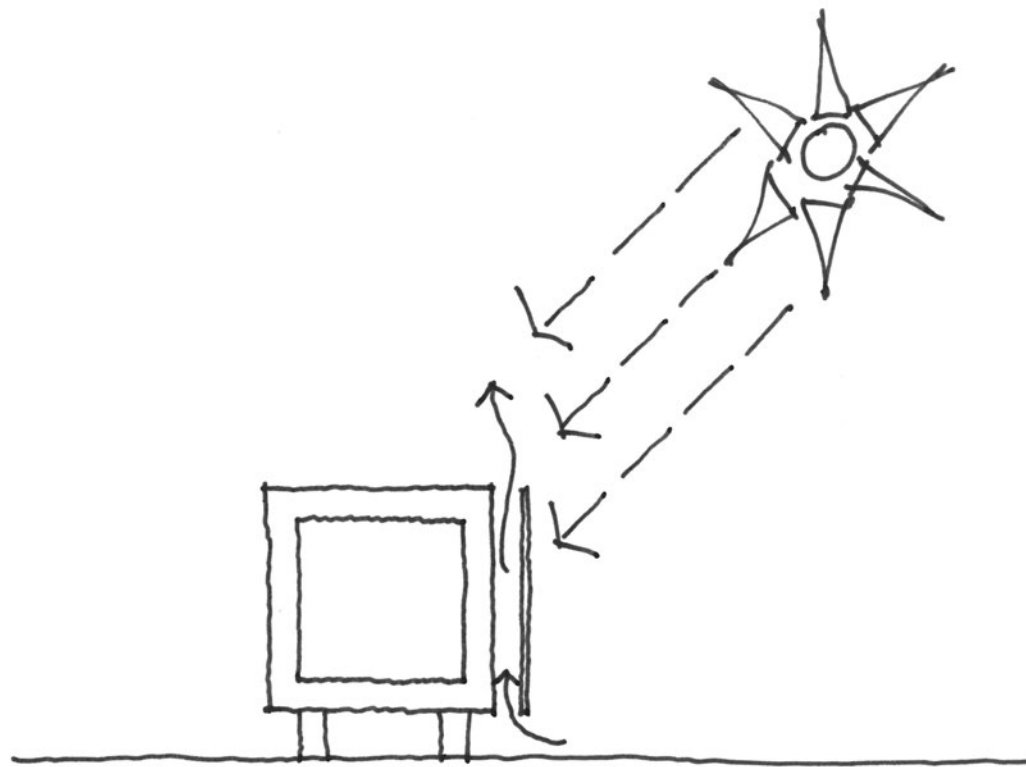


Figure 4.3: Ventilated cavities
(Drawing by author)

3.3 Ventilated roof and wall cavities

Various researchers have investigated how creating a ventilated cavity on the external face of the wall or roof can reduce the conduction of energy, that is thermal energy flux, from the outside of the building to the inside (Figure 4.3). The basic principle of this strategy is that the external skin of the building becomes hot, this causes air in the cavity immediately behind the external skin to warm up and so rise through the cavity (Figure 4.4). The cavity becomes a narrow chimney drawing air at the ambient external air temperature in at the base. The system uses the passage of air through the external cavity to dissipate a proportion of the radiant thermal energy from the sun before it is conducted through the building fabric. The building fabric is therefore resisting a temperature difference (ΔT) between the internal air temperature and the air temperature in the cavity (close to the external ambient temperature) rather than a combination of the external ambient air temperature and the solar radiant temperature, often called the sol-air temperature.

Chang et al (Chang et al., 2008) conducted laboratory tests on a small model of a prototype system they developed that combined the double skin, a reflective barrier (insulation) and a concrete slab (not dimensioned) as the inner layer; the outer skin was a corrugated steel sheet. They found that the location of the reflective barrier affected the performance of the cavity. When the roof pitch is 30° and the ventilated cavity is 50mm deep placing the reflective foil barrier on the bottom of the cavity halved the conduction

through the slab compared to when the barrier is on the underside of the outer skin. The pitch of the roof and depth of the cavity are also important. The effectiveness of the system increases as the pitch increases. Vertical cavities, i.e. a wall, are between two and four times more effective than horizontal cavities depending on the depth of the cavity. The depth of the cavity is marginally significant when the pitch of the cavity is more than 45° from horizontal but as the pitch tends towards the horizontal below 45° a greater depth becomes increasingly more effective at removing heat energy. At 30° a depth of 200mm is about 50% more efficient than a depth of 50mm and at 0° the 200mm cavity is almost twice as effective as the 50mm cavity.

D’Orazio (D’Orazio et al., 2012) also found that the introduction of a radiant barrier below the roof tiles increased the air speed within the cavity and also the temperature of the tiles and caused a proportionately significant but quantitatively small reduction in the thermal flux through the roof (see above). In an earlier experiment investigating the use of highly insulated roofs in the Mediterranean. D’Orazio (D’Orazio et al., 2010) found that in a lightweight well insulated test building the introduction of a ventilated cavity between the copper roof (including a 15mm OSB base) and the insulation (120mm EPS foam board) reduced the heat flux through the roof construction by around 50%.

Gagliano et al (Gagliano et al., 2012) conducted a similar experiment using fluid dynamic simulation software (CFD) to model a ventilated cavity in a tiled roof using fixed environmental conditions. They concluded that

placing the ventilated cavity immediately below the tiles was most effective and may reduce the overall heat flux through the roof structure by up to 50%.

In a series of thorough papers using computer modelling and calculation rather than physical experiments Ciampi et al (Ciampi et al., 2003, Ciampi et al., 2005) showed that for both walls and roofs ventilated cavities significantly reduce heat flux through the building fabric. The outer materials, location of the insulation and size of the ducts were varied. The internal and external temperature were assumed to be constant for the calculations.

Table 4.2 summarises the results for both roofs and facades.

	Façade (Ciampi et al., 2003)	Roof (Ciampi et al., 2005)
Reductions in thermal flux	Reductions in thermal flux through the facade of up to and possibly even above 40% can be achieved with a vented cavity in summer.	Savings of up to 35% can be achieved with a vented roof cavity and up to 15% with a micro-cavity In winter the cavity causes losses- this is when the internal T is lower than the outside T and the sol-air T of the roof surface.
Depth/height of the cavities	Saving (S%) increases as the depth of the duct increases. The correlation follows a law of diminishing returns until it is approx. nil at 0.3m (300mm). Air velocity increases as d increases up to about 0.15 or 0.20m before reducing slightly.	Savings increase as the height of the vent. cavity increases. This is most marked in the “micro-cavity” 0.02- 0.04m (20- 40mm); above 0.15m (150mm) the saving flatten or decline slightly. Laminar flow occurs up to a depth of about 0.04m (40mm). Depths larger than this generate turbulent flow.
Effect of solar radiation	The saving increases as solar radiation increases. the saving is a proportion (%) so flux into the space also increases as solar radiation increases.	Savings increase as Solar radiation increases
Relative position of the cavity and insulation layers	When the insulation is moved to the outer surface S increases up to a point (15%-20%) before falling rapidly	Insulation placed above the ventilation cavity reduces performance- although with copper there may be an optimum amount to place above the cavity (20%?).
Other significant observations	The location of the insulation and the nature of the external material influence the performance of the system. It appears that higher thermal mass and absorptivity increases the saving. 50mm asbestos cement (FC sheet) is nearly as good as 50mm brick. When the density of the inner surface of the cavity was varied between 600 kg/m ³ - 1200kg/m ³ - 2000kg/m ³ there was no significant variation in performance.	Tiled roof generates larger energy savings than a copper roof. Findings supported by D’Orazio et al (D’Orazio et al., 2010). Savings increase as the pitch increases

Table 4.2: Summary of the findings by Ciampi et al
(Ciampi et al., 2003, Ciampi et al., 2005)

Summary

In summary ventilated cavities in both the outer part of the wall and roof can significantly reduce the amount of thermal energy that travels through the building fabric (thermal flux). The depth of the cavity, pitch of the roof and external material all influence the effectiveness of this strategy. There appears to be a maximum useful depth above which no improvement in performance is seen. Providing an outer cladding material with some thermal capacity is beneficial, an observation supported by Parker and Sherwin (Parker and Sherwin, 1998). The strategy uses the solar energy landing on the skin of the building to remove that energy before it enters the building (Figure 4.4). In winter this may be counterproductive.

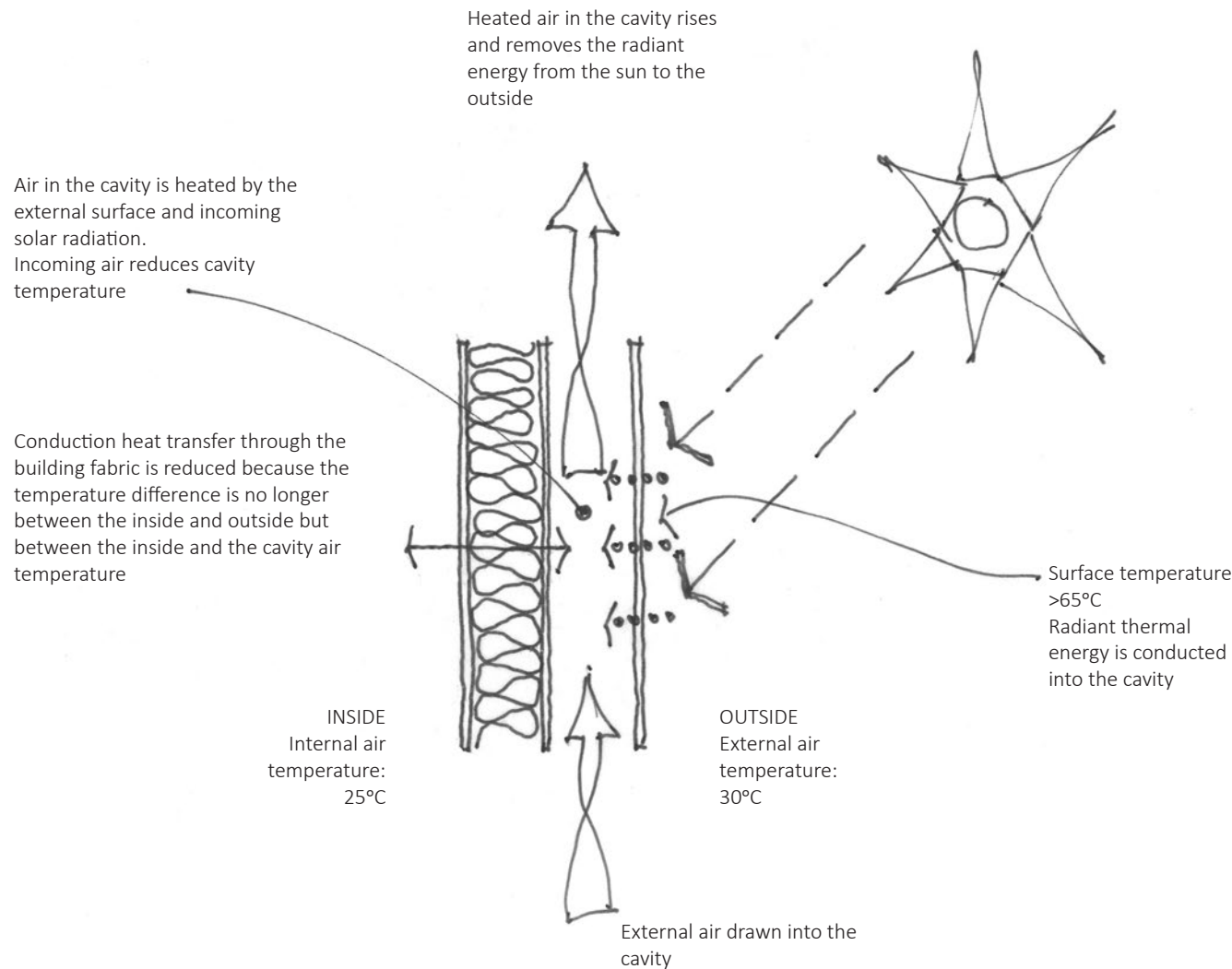


Figure 4.4: Ventilated facade system

*Diagrammatic representation of ventilated cavity strategies
(Drawing by author)*

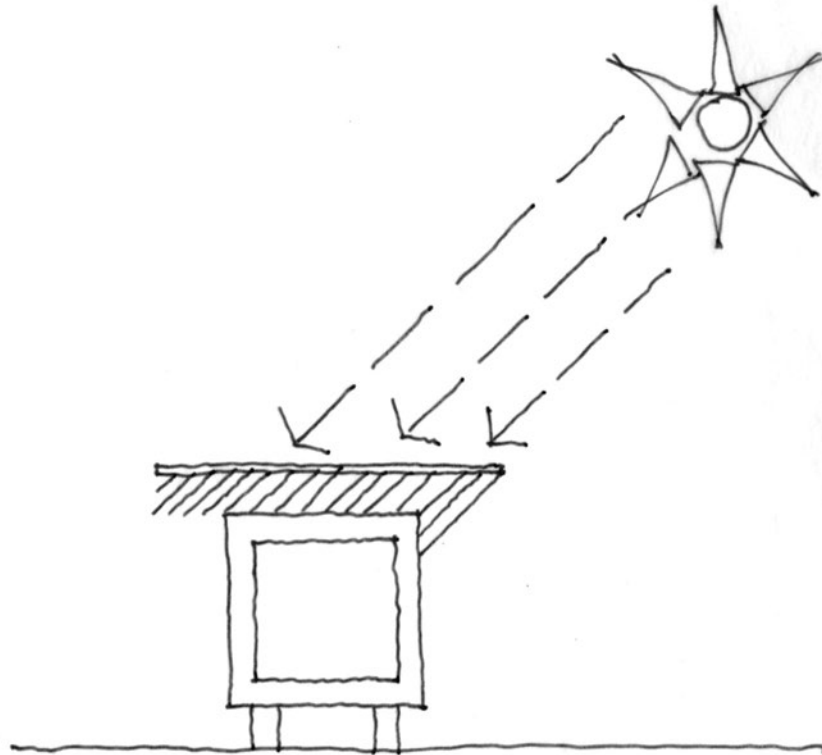


Figure 4.5: Fly-roof
(Drawing by author)

Whole building shading

Shading the whole building, or creating a “fly roof” (Figure 4.5) or second roof 300mm or more above the roof enclosing the internal space is a strategy that can be seen on lightweight static caravans in campsites across NSW (Figure 4.6) and southern Europe. It is also a strategy that was employed on NSW Demountable Classrooms before the introduction of Air Conditioning (Interview C, 2014). Despite the vernacular examples and precedents, for example Le Corbusier’s Pavilion d’Exposition in Zurich, Switzerland, empirical research on this area seems to be limited. See Meng (2006) for architect references – eg. Charles Correa and Ken Yeang.

Cardinale et al (Cardinale et al., 2010) used a validated simulation model of a mobile home in Bari, southern Italy, to explore the effectiveness of various ventilation, shading and thermal capacity strategies to improve the thermal performance of this lightweight space. The whole building shading strategy placed a second roof above the primary (original) roof with an unspecified space between the two. Of the five strategies tested the shading strategy was the most effective reducing the internal air temperature by about 7°C compared to the unshaded version. The introduction of forced ventilation of the internal space instead of natural ventilation had little or no additional impact on the internal temperature.

Many researchers exploring the benefits of vegetated (green) roofs identify the shading effect of the foliage as a major contributing factor to the improvements



Figure 4.6: Caravan with a fly-roof, Stroud, NSW
(Photograph by author)

in thermal performance (Kumar and Kaushik, 2005, Tabares-Velasco and Srebric, 2009, Jaffal et al., 2012). Akbari et al (Akbari et al., 1997b) found a cooling energy saving of about 30% in two houses in Sacramento, California where they shaded part of the walls of the two houses with trees. They also found that the presence of the trees significantly reduced the external wall temperature and local air speed.

Summary

The limited research suggests that shading the whole building envelope from solar radiation is a simple and effective strategy to significantly reduce heat flux entering the building and consequential overheating inside the building.

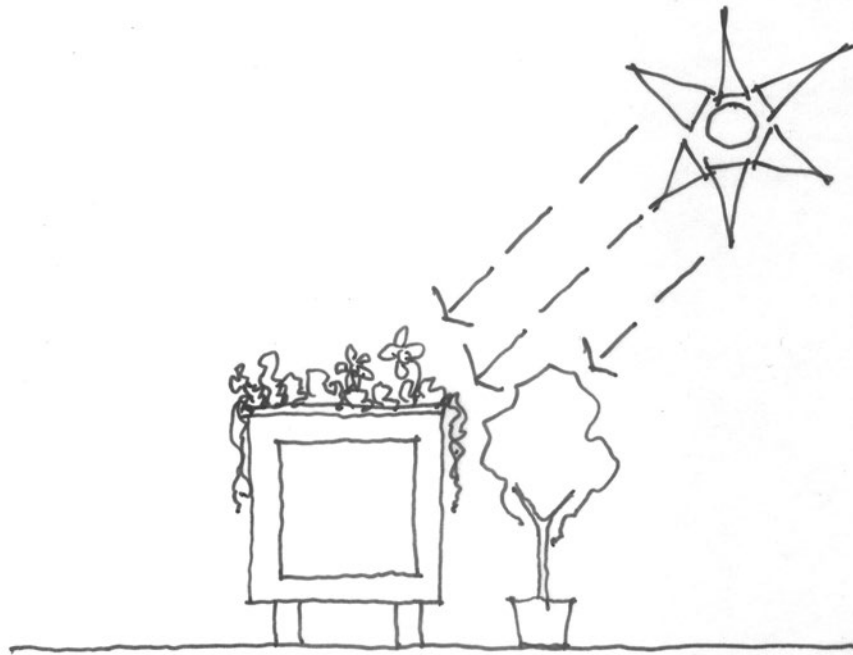


Figure 4.7: Vegetated envelopes and “green roofs”
(Drawing by author)

Vegetated envelopes

Vegetated building envelopes have been shown to significantly improve the thermal performance of building envelopes (Jaffal et al., 2012, Williams et al., 2010). The strategy involves planting being incorporated into the roof and, occasionally, the walls, and creates a number of environmental benefits beyond thermal performance including creating additional natural habitats, improving air quality and reducing noise levels (Jaffal et al., 2012) as well as, to a limited extent, reducing or slowing stormwater run-off (Jaffal et al., 2012, Williams et al., 2010).

Green roofs and walls enhance the thermal performance of the building and, in particular, the ability of the envelope to keep the building cool, by combining three effects (Jaffal et al., 2012, Tabares-Velasco and Srebric, 2009, Akbari et al., 1997b):

- i. Shading: The plant foliage shades the building envelope.
- ii. Evaporative cooling: The plants draw water up from the soil, the water evaporates from the plants' leaves causing the air immediately around the plant to cool (latent energy) and so the air temperature immediately adjacent to the building is reduced.
- iii. Thermal capacity: The thermal capacity (thermal mass) of the soil moderates the diurnal variation of the temperature of the building envelope surface and so the temperature of the whole envelope. The

soil is able to absorb thermal energy during the day without significantly changing temperature itself and release the thermal energy during the night.

Jaffal et al (Jaffal et al., 2012) created a computer simulation model of a family house with an irrigated extensive green roof planted with sedum. The house was simulated in three different European climates (Stockholm, La Rochelle and Athens) and demonstrates a significant reduction in cooling load compared to a “conventional roof” in La Rochelle (96% reduction) and Athens (52% reduction). There is no cooling load in Stockholm. Heating demand increases slightly in Athens, (7%), is unchanged in La Rochelle and reduced by 8% in Stockholm when compared to the same house with a conventional roof construction.

Tabares-Velasco and Srebric (Tabares-Velasco and Srebric, 2009) conducted laboratory experiments on a green roof sample with a soil depth of 90mm with and without plants. They demonstrated that the shading of the plants’ foliage, latent heat flux (evaporation of moisture) and moisture in the soil all play a role in reducing the overall heat flux through the roof. Overall heat flux through the roof is reduced by approximately 50% when plants are grown in the soil of the green roof construction. It was also found that in summer cooling conditions heat flux is minimised when the soil is wet despite the increased conductivity of the construction.

The management of green roofs and, in particular, the maintenance of appropriate levels of water in the soil is a particular challenge for this construction strategy in

Australia. Williams et al (Williams et al., 2010) discuss this in their comprehensive paper “Green roofs for a brown land”. “Green roofs” are normally separated into Intensive and Extensive strategies. Intensive roofs have soil depths greater than 200mm (>200mm) and can support larger and more complex range of plants. Extensive roofs have a soil depth of less than 200mm, often less than 150mm (<150mm) and support low growing succulents and stress resistant herbaceous plants with small root systems. They must be able to survive a broad range of temperatures and extended periods of drought. Native herbaceous perennials and desert annuals from South East Australia are strong candidates for colonising Australian extensive roofs (Williams et al., 2010). Since 2010 green roofs and walls have become fashionable with a number of high profile projects utilising them in Sydney (Central Park, Broadway and One Bligh Street), however these and other examples tend to be intensive and require considerable maintenance and irrigation.

An alternative strategy is demonstrated in a regularly cited paper by Akabri et al (Akbari et al., 1997b). Akabri et al used trees grown in pots to shade the walls of two houses in Sacramento, California and measured the effect on the demand for cooling energy. A computer simulation model was used to extrapolate the empirical data. They found that the shade yielded a reduction in seasonal cooling energy demand of 30% with peak demand reduction of about 27% and 42% for the two houses. They found that the presence of the trees

“dramatically reduced both the temperature of the exterior surfaces and the wind speed”.

Akabri et al used trees grown in pots to create a green canopy around the buildings. Ground spreading creepers, climbing or falling vines grown in pots or planters could create a similar effect. This strategy overcomes the challenges of

- i. retaining water in a shallow extensive soil bed
- ii. the weight of the soil on the roof because the planters can be supported locally or placed on the ground.

Summary

Green roofs and vegetated facades offer significant opportunities for helping keep buildings cool. The approach creates a number of peripheral environmental benefits including improved air quality, cooler air and the creation of natural habitats and increased biodiversity. The climates of NSW and the weight of the system present some particular challenges to this approach.

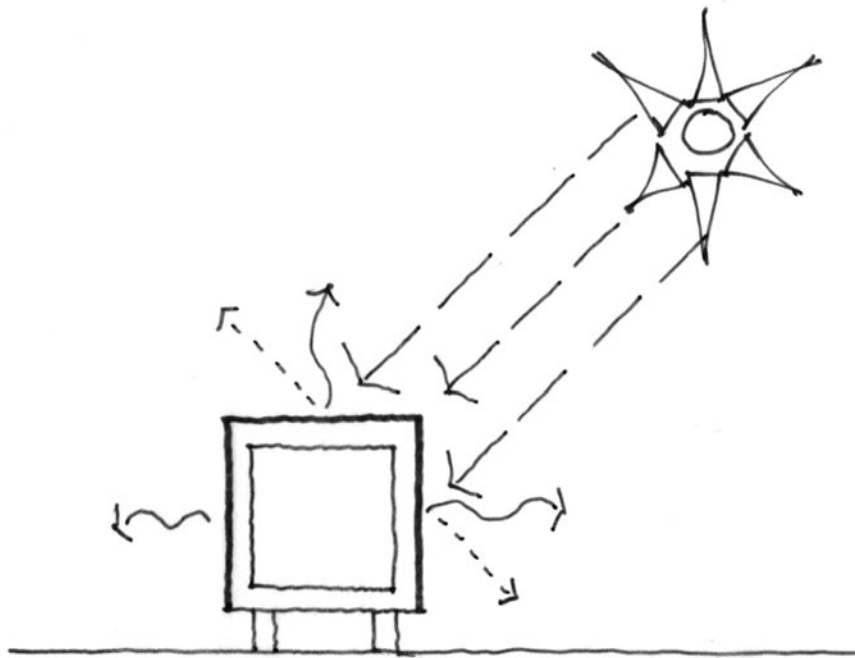


Figure 4.8: High-E coating
(Drawing by author)

High-E coatings

Surface coatings in the form of paint that reduces the quantity of solar radiation absorbed by the surface and increases the rate at which thermal energy is dissipated by the surface achieve many of the energy efficiencies of green roofs and whole building shading (Figure 4.8). These coatings achieve this without the additional weight and survival problems of green roofs or the additional structure of a secondary roof.

High albedo or solar-reflective and high emittance paints work by maximising the quantity of short wavelength radiation that they reflect and maximising the longwave radiation, heat energy, they emit (Bell et al., 2003). Electromagnetic radiation arriving from the sun is short wave radiation, the visible spectrum and above. On most surfaces 50% or more of this radiation is absorbed by the material. The temperature of the material, a reflection of the energy stored in the material, increases and the energy is re-radiated as longwave radiation which is heat. High albedo paints use carefully selected pigments to reflect the shortwave radiation and radiate the longwave radiation.

These paints have been improved over the last 20 years but the principle, and the opportunity for energy savings, have been observed regularly over that time.

In 1997 Akbari et al (1997a) reported on an experiment where the roofs of two lightweight timber framed classroom buildings in Sacramento, California where painted with high albedo paint. Using empirical results extrapolated using a computer model they

demonstrated that energy savings of 35% could be achieved by using the high albedo paint on the roof of the classroom.

Simpson and McPherson (1997) used a series of small test cells in Tuscon, Arizona to demonstrate that white metal roofs work better than silver metal roofs because white is much better at emitting (emittance) radiation than silver. The white roofs were 20 – 30°C cooler than the silver or dark roofs.

Parker and Sherwin (1998) used six test cell roofs to show that the albedo or reflectivity of the roof reduces the air temperature in the attic space. They also found that increasing the thermal capacity (thermal mass) of the roof surface and the ventilation rate in the attic space both reduced the temperature in the attic space.

An experiment using prefabricated 15m² telecoms buildings in California demonstrated the benefits of external thermal mass combined with a high-emittance coating (Akbari, 2003). The huts were constructed from 125mm thick precast concrete panels with 50 mm of insulation on the inside. They contain large quantities of electronic equipment creating a high internal heat load. It was found that coating the buildings in a high-albedo and high-emittance paint delayed and reduced the peak temperature of the outside surface of the building. The high-emittance paint encouraged night cooling of the external thermal mass, reducing the temperature of the mass in the early morning. This mass then took longer to heat up than on the unpainted huts with a consequential delay and reduction in peak temperature.

Bell et al (2003) used lab tests, simulations and site measurements to explore the thermal performance of roofs coated with high-albedo (85%) and high-emittance (95%) paint on the Sunshine Coast in southern Queensland, Australia. They suggest that energy savings of more than 50% are achievable for the supermarket buildings they used for field tests. They also found that on clear days the surface temperature of the insulated coated roof was cooler than the uninsulated coated roof. They suggest that this means the un-insulated roof is being heated from below and that the coating, even in the middle of the day, is causing significant radiant cooling to the sky.

Gentle et al (2011) explored the relationship between albedo, U-value and emittance. Smith et al (2012) explored the relationship between albedo, U-value and internal ventilation rates. Both showed that as the albedo of the roof increases the influence of the U-value of the roof on cooling energy demand decreases. Smith et al showed that cooling energy is also sensitive to internal ventilation rates and that as albedo increases the influence of ventilation rates reduces, the reduction in influence is more pronounced for higher rates of ventilation and higher U-values. Gentle et al corroborated Akbari (2003) observation that emittance value is important for night cooling strategies.

Smith et al (2012) found that heating energy is not sensitive to albedo but that it is sensitive to ventilation rates and the U-value of the building envelope.

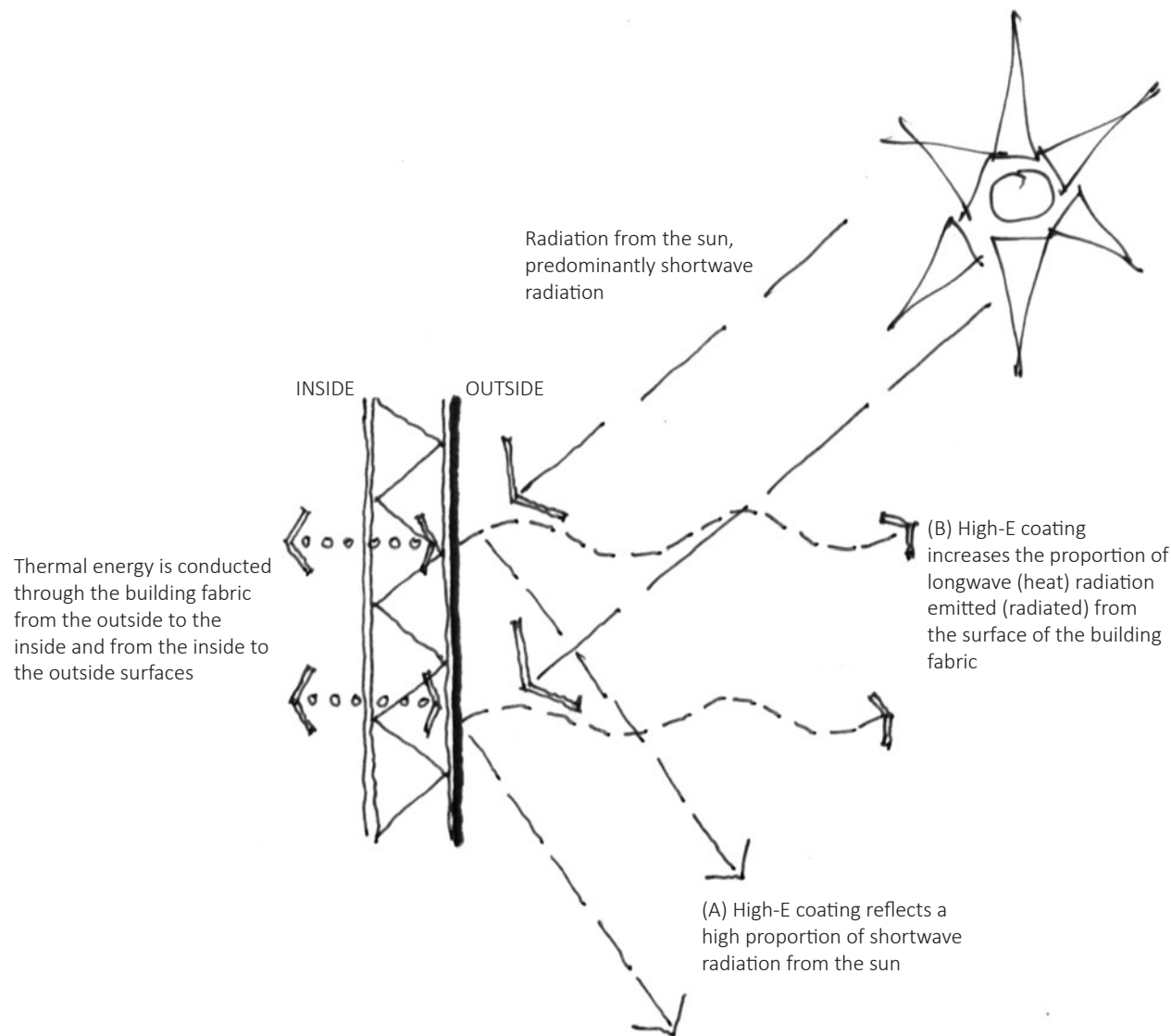


Figure 4.9: High-E coatings detail

Diagram illustrating radiant and conductive energy transfer through the building fabric coated with a High-E paint.

The High-E coating reduces the quantity of solar radiation absorbed by the surface (A) and increases the amount of thermal energy that is re-radiated from the surface (B).

(Drawing by author)

Finally in 2014 Miller et al (2014) measured the air temperature in and around some classrooms in Queensland. Miller et al found that in Townsville (north Queensland) high albedo and emittance paint on the roof significantly reduced the air temperature in the roof cavity on hot days ($>34^{\circ}\text{C}$) from 16°C above ambient air temperature to $2\text{--}3^{\circ}$ above ambient air temperature. They also showed, but did not discuss, that in naturally ventilated classrooms in Brisbane (South Queensland) the application of the paint to the roof causes a reduction in the internal air temperature, relative to a classroom without a modified roof, and that the difference is significantly increased when the ambient outside air temperature is above 24°C .

Summary

In summary, research shows that specially formulated paints that increase both the solar reflectance and emittance of surfaces can create significant reductions in annual cooling energy demand and costs, and reduce indoor air temperatures (Figure 4.9). Night cooling strategies, that may involve the use of external thermal mass, may reduce cooling energy demand further. The use of these coatings does not increase heating energy demand.

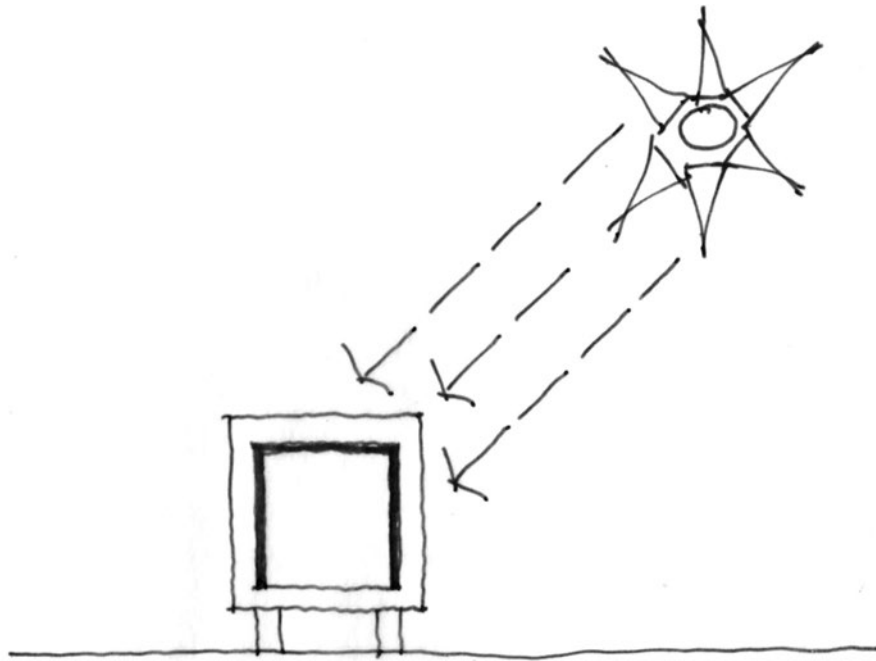


Figure 4.10: Thermal mass
(Drawing by author)

Internal thermal mass

The strategies described above attempt to prevent thermal energy entering the classroom space. They are “defensive”. The strategy discussed below uses the building fabric in the classroom space to improve the comfort in the space.

Thermal mass, traditionally bricks, stone or concrete, is used inside a space to absorb the thermal energy from the warm air in the space without significantly changing the temperature of the thermal mass material (Figure 4.10). This cools the ambient air temperature and because the surface temperature of the thermal mass is lower than the ambient air temperature; it also reduces the Operative Temperature. People in the space feel a cool sensation because they are radiating thermal energy to the surrounding surfaces. The thermal energy stored in the thermal mass is removed at night by allowing or forcing cooler night time air through the building.

Slee et al (2014a) have demonstrated that the effectiveness of adding additional thermal mass to a space reduces as more mass is added, following the law of diminishing returns (Figure 4.11). Significantly, this paper suggests that the reduction in the effect on internal air temperature of adding the additional thermal mass is quite rapid. So only a small amount of thermal mass is needed to have a significant effect on the diurnal temperature variation in a space and therefore on thermal comfort. The quantity of thermal mass that is useful in space depends on the local

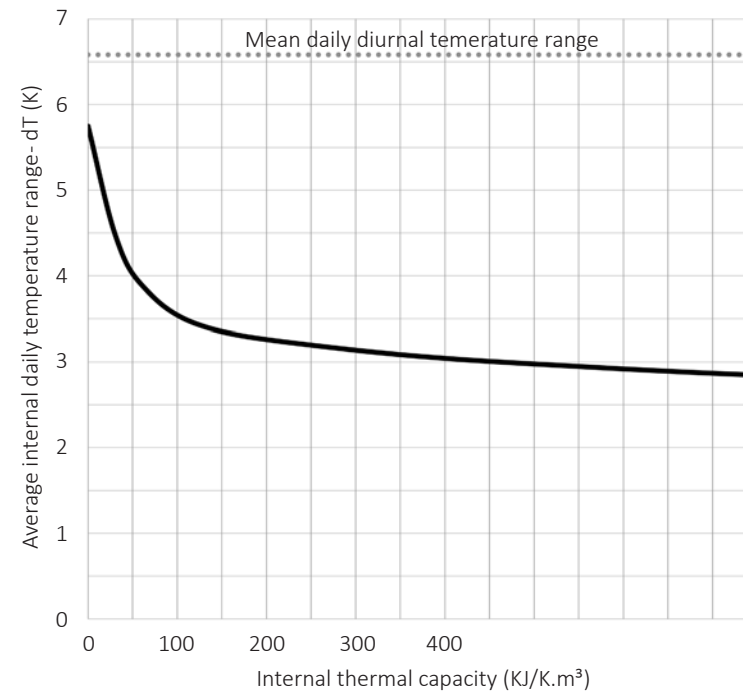


Figure 4.11: Diminishing influence of thermal mass

The influence of thermal capacity on the diurnal variation of the temperature in a test cell in the warm temperate coastal climate of Sydney, NSW (based on Slee et al (Slee et al., 2014a))

climate and the overall strategy (Slee et al., 2014b). The same paper shows that the distribution of mass in the space is also significant. Baggs and Mortensen (2006) argue that the important relationship is between the surface area of the mass in the space and the volume of the space. Baggs and Mortensen’s argument is shown to be supported by other literature in a review of “rules of thumb” by Slee and Hyde (2011). The temperature of the surfaces in the space play a significant role in the occupants perception of comfort (Moe, 2010) (See Chapter 2, Thermal Comfort).

The development of “lightweight” thermal mass in the form of Phase Change Materials (PCM) is a rapidly expanding area of research (Memon, 2014). Phase change materials can absorb much more thermal energy per unit of mass because they utilise the latent energy that is required to change a material from a solid to a liquid state. In a simulation study using phase change material plasterboard in an office building in Kew in the UK during August (late summer) Kendrick and Walliman (2007) concluded that peak temperatures can be reduced by 3-4 °C and that hours over 24 °C (the upper limit of the comfort band) can be reduced by 80%. They observed that the night cooling phase of the diurnal cycle is critical to the effectiveness of the strategy.

Kendrick and Walliman also observed that when the conductivity of the plasterboard containing the phase change material was too high the phase change material melted too early leading to higher temperatures in the afternoon. Cardinale et al (2010) made a similar observation in the simulation of a campervan in

southern Italy. They found that the conductivity of the board the phase change material is part of is critical. In their experiment this was a polyurethane insulating foam board. When the phase change material was a low proportion of the board, 22.8%, it did not significantly influence the temperature in the campervan (which was fully shaded). When the lining was modelled as 100% phase change material, a significant effect on the maximum and minimum temperature and diurnal range of the space was observed. Whether the problem was that the insulating foam prevented the 22.8% phase change material interacting with the space or whether there was simply not enough thermal capacity to influence the temperature in the space is not discussed. Kendrick and Williamson highlight this potential problem with phase change material in their simulation: Because the absorption of thermal energy only occurs when the phase change material is changing state if all the phase change material has changed state (melted) then the building returns to functioning as a lightweight structure and temperatures can rise rapidly. In an extensive literature review of research into phase change materials Memon (2014) observes that choice of phase change material, the quantity of material and the manner in which it is embedded in the building needs to be carefully considered in each case, reflecting the anticipated occupation patterns in the building and the particular climate. Memon finds that the majority of the research considers “pure PCM” rather than the micro-capsules that are common in systems intended for construction and that the thermal performance

guidelines provided by manufacturers may be over-optimistic.

Summary

Limited quantities of thermal mass, also referred to as thermal capacity, can make a significant contribution to reducing the diurnal temperature variation in a space and so improve comfort.

Traditional “thermal mass” materials that combine high thermal capacity, admittance (the rate of energy absorption) and conductivity continue to absorb thermal energy as the temperature of the thermal mass increases until the material temperature is above the material’s apparent surface temperature.

Phase change materials (PCM) must be ‘tuned’ to absorb thermal energy within a particular temperature band, the point at which the material changes phase (normally from solid to liquid) and have a specific thermal capacity. When all of the material has changed phase the PCM no longer influences the temperature within the space. In addition to the challenge of predicting the thermal capacity required in a space, the manner in which the PCM material is encapsulated and included in the space is critical to the performance of the PCM material and must be understood prior to specification.

4.4 Comparison of strategies

The previous section has set out the research behind a variety of strategies that may reduce the thermal discomfort and annual energy demand in the NSW Demountable Classrooms. This section sets out a comparison of those strategies based on the criteria set out in part 2 of this chapter (Financial cost/Buildability/Environmental impact/Relocation). Initially this is done in the form of a table (Table 4.3) where each strategy is assessed qualitatively against the four criteria set out in part 2 using a simple three-point scale: Low (undesirable), medium and high (desirable) signified by a small, medium or large circle.

	Financial cost	"Buildability"	Environmental cost	Relocation
Resistive insulation	●●●	●●●	●●●	●●●
Reflective insulation	●●●	●	●●●	●●●
Ventilated roof & wall cavities	●	●	●●●	●
Whole building shading	●	●●●	●●●	●●●
Vegetated envelopes	●	●	●●●	●
High-E coatings	●●●	●●●	●	●●●
<i>Internal thermal mass</i>				
Conventional thermal mass	●●●	●●●	●	●
Phase Change Materials	●	●	●●●	●●●

Table 4.3:

Comparison of strategies rated against four criteria rated Low (un-desirable), medium and high (desirable) signified by a small, medium or large circle. (Woolley et al, 2000)

High (Desirable) ●●● Low (Un-desirable) ●

Resistive insulation

Resistive insulation has been shown to be useful for avoiding overheating and retaining heat in cold weather in several studies (Li et al., 2013). It has been shown that the benefits of resistive insulation for preventing overheating rapidly diminish as more insulation is added. The current construction of the NSW Demountable Classroom is, effectively, uninsulated due to the significant number of thermal bridges and the minimal quantity of the insulation that is present. Additional insulation in the form of a foam board could easily be installed on the interior faces of the existing walls and ceiling. Insulation can also be added between the floor joists. Foam board is not expensive, easy to cut and can be glued in place. Foam boards do have an environmental cost since they are manufactured from oil based chemicals and are likely to be difficult to re-use or recycle. They also offer significant environmental benefits by improving the thermal performance of buildings.

The highest performing (lowest k-value) foam insulation board is PIR (Poly-isocyanurate) commonly used in refrigerated trucks and other applications needing maximum thermal resistance for minimum thickness of material. PIR board is available in a variety of thicknesses (15, 20, 30, 40 – 70mm CSR Xtratherm). It is not a robust material so in a classroom environment it will need to be covered by a layer of 6mm fibre-cement sheet to provide impact protection.

Reflective insulation

Reflective insulation scores well when assessed against the four criteria set out in part 2 of this chapter (table 3). However, the contribution of reflective insulation to the reduction in cooling load appears to diminish as other strategies, for instance resistive insulation, become more effective. Reflective insulation can contribute to the performance of ventilated cavities but they present their own challenges (see below). Given a variety of other strategies that offer the possibility of significant savings reflective insulation is not a strategy that appears to be suited to the current classroom retrofitting project.

Ventilated roof and wall cavities

Ventilated roof and wall cavities offer significant opportunities for reducing cooling load. Unfortunately the roofs of the NSW Demountable Classrooms have a very low pitch and the ventilated roof cavity system requires a moderate pitch to be effective. It is not feasible to change the pitch of the classroom roofs because

- i. Creating a roof with a moderate pitch will increase the height of the classroom and in turn create vertical clearance when transporting the classrooms, e.g. under bridges.
- ii. Changing the pitch of the roof is a significant construction exercise that does not fit with the need for simple, low skill and rapid construction strategies

identified for this project.

Creating a ventilated cavity on the external face of the walls may be more feasible but these would need to be extremely robust to deal with the process of relocation and also increases the overall dimensions of the classroom units which may then exceed the maximum dimensions for transport without an escort (overall maximum dimensions for a vehicle 12.5m long x 2.5m wide x 4.3m high (NSW Department for Transport roads and Maritime Services, 2015) This is a promising strategy for a new design but not suitable for the current retrofitting proposal.

Whole building shading

There is strong evidence of the effectiveness of whole building shading in vernacular construction, architectural precedent and limited research literature. A whole building shading system already exists for the NSW Demountable Classroom but is now rarely, if ever, used.

Alternatively, a canopy over the whole classroom is a fairly simple though possibly substantial construction project. The canopy can be completely independent of the classroom, designed to be easily dismantled, and offers the opportunity to create shaded outdoor space while the classroom is in place and after it has been removed.

Whole building shading offers an economic, low environmental impact and achievable strategy to alleviate overheating in Demountable Classrooms.

Vegetated envelopes

Vegetated envelopes offer multiple environmental benefits for the building users and more broadly. For the retrofitting of the NSW Demountable Classroom this strategy has limited utility for a number of reasons:

- i. The traditional extensive (shallow soil) and intensive (deep soil) roof systems place significant additional structural load on the roof structure. This means that the roof structure will need to be modified which is not practical given the constraints for this project.
- ii. The vegetation that is likely to be appropriate in one region of NSW is unlikely to be appropriate in several others. Limiting or increasing the complexity of relocation.
- iii. The proposal to use plants in pots (Akbari et al., 1997b) may mean that the two problems identified above are overcome but large trees in pots are expensive and difficult to move. Creeping or climbing plants take time to grow. They may also make relocation difficult.

For these reasons vegetated building envelopes are a strategy that will not be used in this project but will be noted as a potential additional strategy for innovative schools who anticipate having the time to plant, grow and later remove the plants.

High-E coatings

Paint systems designed to reflect a very large proportion of incoming solar radiation (short wave radiation) and emit or radiate large proportions of longwave radiation (heat) have been shown to be an extremely effective strategy for reducing cooling energy demand in a wide variety of low rise buildings including lightweight school buildings. This technology is “high tech” but simple to apply offering a relatively inexpensive and rapid solution to overheating that needs minimum building materials and has a low environmental impact (the paint is water based), although the environmental impact of the manufacturing process is not known. The strategy will not impede the relocation of the classrooms.

Internal thermal mass

The use of thermal mass (thermal capacity) to improve thermal comfort in buildings in warm and hot climates is often recommended (Hollo, 1986, Reardon, 2001). Materials that are commonly used to provide thermal mass are heavy which makes the approach unsuitable for a building that is designed to be transported and relocated.

Phase-change materials (PCM) offer an alternative relatively lightweight source of thermal capacity by utilising the latent energy needed to change a material from a solid to a liquid. Phase change material boards are expensive and not commonly available. The technology is also limited in the quantity of excess thermal energy that can be absorbed and must be “tuned” to a specific temperature. Phase change

material boards are therefore not suitable for the retrofitting strategy proposed for this project because the desired temperature for absorption varies with regional climate. The cost and availability of these boards are also constraints.

Slee et al (2014a) have shown that the quantity of thermal mass that is needed to make a significant difference to the thermal comfort of occupants may be quite small. Slee and Hyde (2011) and Baggs and Mortensen (2006) have also suggested that the relationship between the volume of the space to the surface area of the thermal mass is the most important relationship for determining the effectiveness of the thermal mass.

This means that a small amount of thermal mass, for instance fibre-cement sheet, distributed across all wall and ceiling surfaces offers a relatively lightweight strategy for implementing the use of thermal mass to moderate internal temperature fluctuations in Demountable Classrooms. Fibre-cement sheet has the advantage of traditional thermal mass because it continues to absorb thermal energy as the temperature rises. Fibre-Cement sheet is a very common and inexpensive building product. The environmental impact of cement based products is significant (Mahasenan et al., 2003, Hammond and Jones, 2008). This proposal suggests using relatively thin layers of fibre-cement sheet which would minimise but would not obviate the environmental cost.

4.5 Conclusion: Proposed Solution

Sets for testing

This chapter has explored a variety of potential strategies to improve the thermal performance of the NSW Demountable Classroom and so improve the comfort of those who use the classrooms and reduce the quantity of energy used to heat and cool the classrooms. The strategies were evaluated against the following four pragmatic criteria:

- Financial cost: low overall cost.
- 'Buildability': Simple to construct.
- Environmental cost: Low environmental cost.
- Relocation: Does not impede the relocation of the classroom units.

These criteria were designed to ensure that the proposals can be implemented based on the retrofitting approach identified in Chapter 3. The evaluation led to the selection of four strategies:

- Resistive insulation
- Whole building shading
- Internal thermal mass
- High-E coatings

These strategies will be evaluated both individually and in various combinations using a computer simulation model and are discussed in the next chapter, Chapter 5.

Evaluation of the Solution Sets

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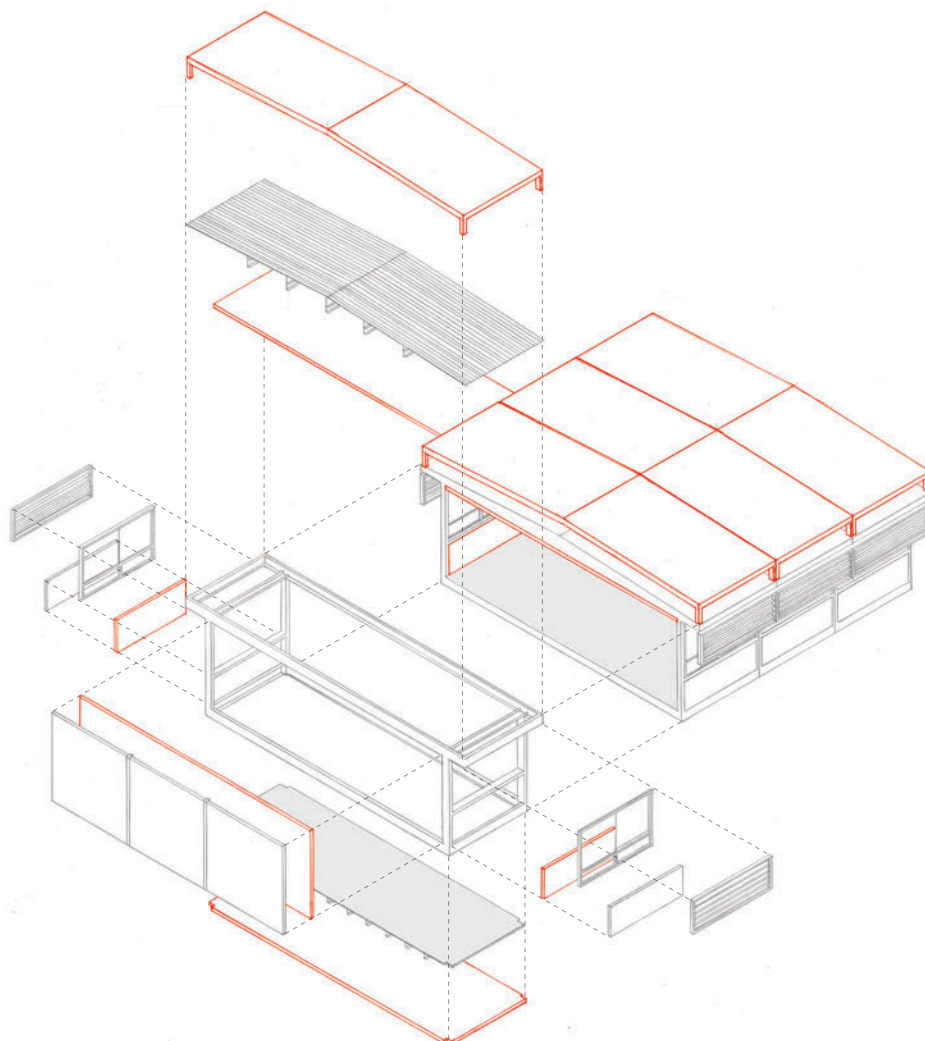


Figure 5.1: Exploded isometric drawing of the NSW Demountable Classroom and Solution Sets

Isometric drawing illustrating the modular classroom system with one module exploded to show the individual components and modifications (in red).

(Drawing by author)

Modifications to the building envelope			Codes for the Solution Set simulations		
Existing situation (base-case)			Set 01	The existing situation	
	Additional insulation			Set 02	An additional 40mm insulation
				Set 03	An additional 80mm insulation
		Additional thermal mass	Set 04	An additional 40mm insulation + 18mm F/C sheet	
			Set 05	An additional 40mm insulation + 36mm F/C sheet	
					Set 11
		Additional insulation			Set 12
			The variation with 80mm of insulation was not simulated		
	Additional thermal mass		Set 14	An additional 40mm insulation + 18mm F/C sheet + fly-roof	
			Set 15	An additional 40mm insulation + 36mm F/C sheet + fly-roof	
					Set 21
			The intermediate variations were not simulated		
	+ Insul.	+ T/ mass			
			Set 25	An additional 40mm insulation + 36mm F/C sheet + High-E coating	
	Modifications to the building envelope			Codes for the Solution Set simulations	

Table 5.1: Codes for the Solution Set simulations for each site.
Refer to table 2 for more details.

5.1 Introduction

This chapter uses the thermal simulation model and evaluation criteria set out in Chapter 2 to evaluate the effectiveness of the Solution Sets proposed in the conclusion of Chapter 4. In each case the three scenarios set out in table 2.12 (Chapter 2 section 2.5.3) are simulated. These scenarios illustrate a Minimum, Middle (and primary) and Maximum scenario. The Minimum scenario has the lowest class size, metabolic activity and air infiltration. The Middle and primary scenario has the most common class size (Figure 2.21), medium range of metabolic activity and the same infiltration rate as the Minimum scenario (Poor). The Maximum scenario has the largest class size (30), highest metabolic activity and highest infiltration rate (Very Poor).

The Solution Sets are intended to improve the thermal performance of the NSW Demountable Classroom and are described below. The chapter then sets out the evaluation criteria before describing the results of the simulations in two stages. First the results of the simulations are considered in terms of annual comfort and energy demand. Second, the model of the classroom in Richmond is used to explore the impact of the Solution Sets on the mean daily performance of the classroom in January, the hottest month, and July, the coldest month.

The results are followed by a discussion and review of the thermostat settings that have been used in the model. The simulation model is used to explore the effect of modifying these settings on the predicted

thermal comfort and predicted energy demand. The penultimate part of the chapter looks at the introduction of Photo Voltaic panels to generate carbon-free energy to operate the air-conditioning system. The final part of the chapter assesses the possible cost of implementing the Solution Sets in terms of time, money and additional weight.

The various Solution Sets can be separated into four groups that represent four overall strategies:

- Increased resistive insulation
- The introduction of thermal mass using fibre-cement sheet.
- Whole Building Shading
- High-e coatings

These strategies will be evaluated as a series of Solution Set combinations as set out in Tables 5.1 and 5.2 (the code SET... refers to the Solution Set number). They are described below and illustrated in Figures 5.1 to 5.5:

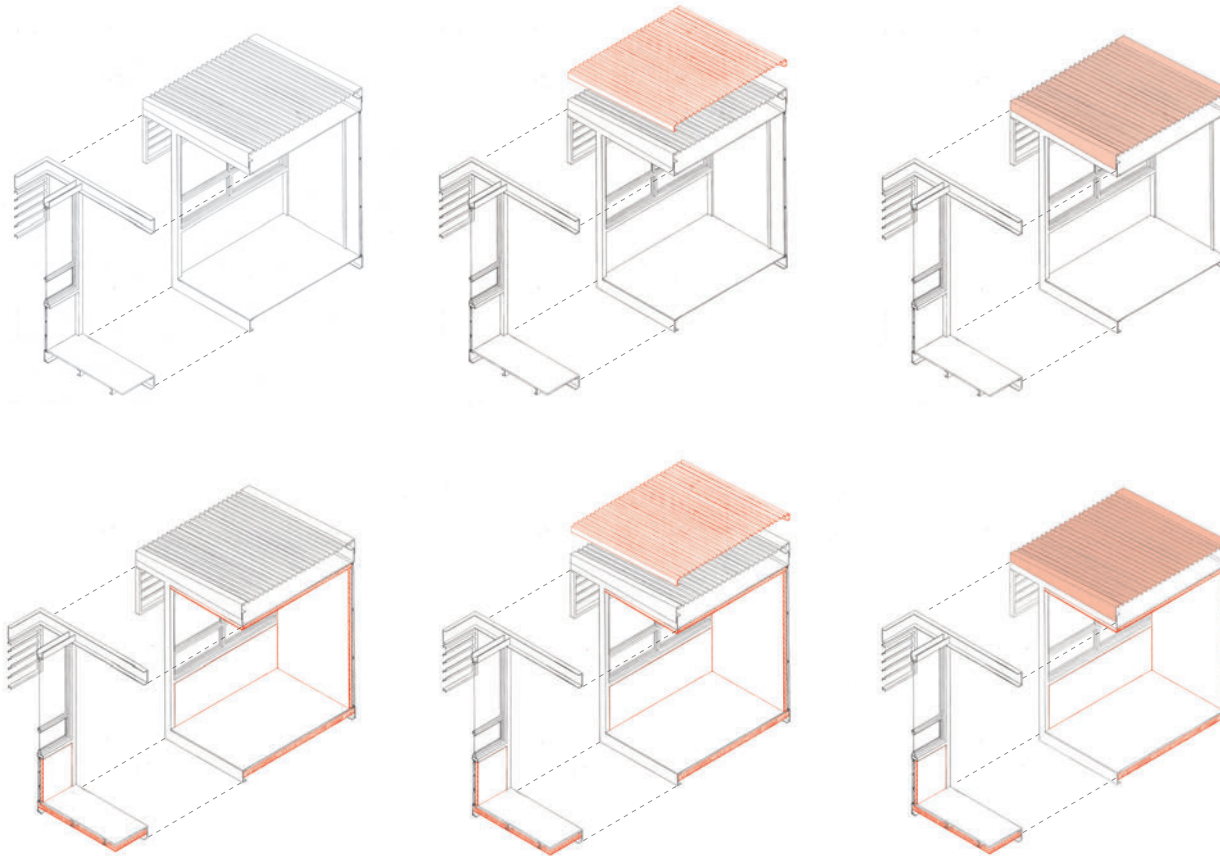


Figure 5.2: Solution Sets

Solution Sets illustrated as exploded cut-away isometric drawings illustrating with the additions shown in red.

TOP ROW: SET 01, Existing; SET 11, Fly roof; SET 21, High-E coating

BOTTOM ROW: SETs 02 - 05, Additional insulation and thermal mass; SETs 12, 14 & 15, Fly roof with additional insulation and thermal mass; SET 25, High-E coating with additional insulation and thermal mass

Refer to Table 2 for detailed specifications.

(Drawing by author)

Solution Set	Floor	U-value W/m ² .K	Walls (1) end walls; (2) Infill panels	U-value W/m ² .K	Roof	U-value W/m ² .K
SET 01 Base	Plywood floor	2.11	Steel framed panels	(1) 1.04 (2) 0.90	Foil-faced blanket	1.25
SET 02	R2.5 insulation between existing steel joists. Fibre-cement soffit to underside.	0.70	40mm PIR insulation board 6mm Fibre-cement sheet Fixed to inside on walls.	(1) 0.32 (2) 0.73	40mm PIR insulation board 6mm Fibre-cement sheet Fixed to existing ceiling.	0.42
SET 03	R2.5 insulation between existing steel joists. Fibre-cement soffit to underside.	0.70	80mm PIR insulation board 6mm Fibre-cement sheet Fixed to inside on walls.	(1) 0.20 (2) 0.42	80mm PIR insulation board 6mm Fibre-cement sheet Fixed to existing ceiling.	0.26
SET 04	R2.5 insulation between existing steel joists. Fibre-cement soffit to underside.	0.70	40mm PIR insulation board 18mm Fibre-cement sheet Fixed to inside on walls.	(1) 0.32 (2) 0.73	40mm PIR insulation board 18mm Fibre-cement sheet Fixed to existing ceiling.	0.42
SET 05	R2.5 insulation between existing steel joists. Fibre-cement soffit to underside.	0.70	40mm PIR insulation board 36mm Fibre-cement sheet Fixed to inside on walls.	(1) 0.31 (2) 0.72	40mm PIR insulation board 36mm Fibre-cement sheet Fixed to existing ceiling.	0.41
SET 10 series	As the above with a fly roof (i.e. SET 11 is the base building with a fly roof).					
SET 20 series	As the above with a High-E paint on the outside of all walls and roof.(i.e. SET 21 is the base building with a a High-E paint on the outside of all walls and roof.).					

Table 5.2: Specifications of the Solution Sets

(for key to end walls, infill panels and other components refer to Chapter 2, figure 20)

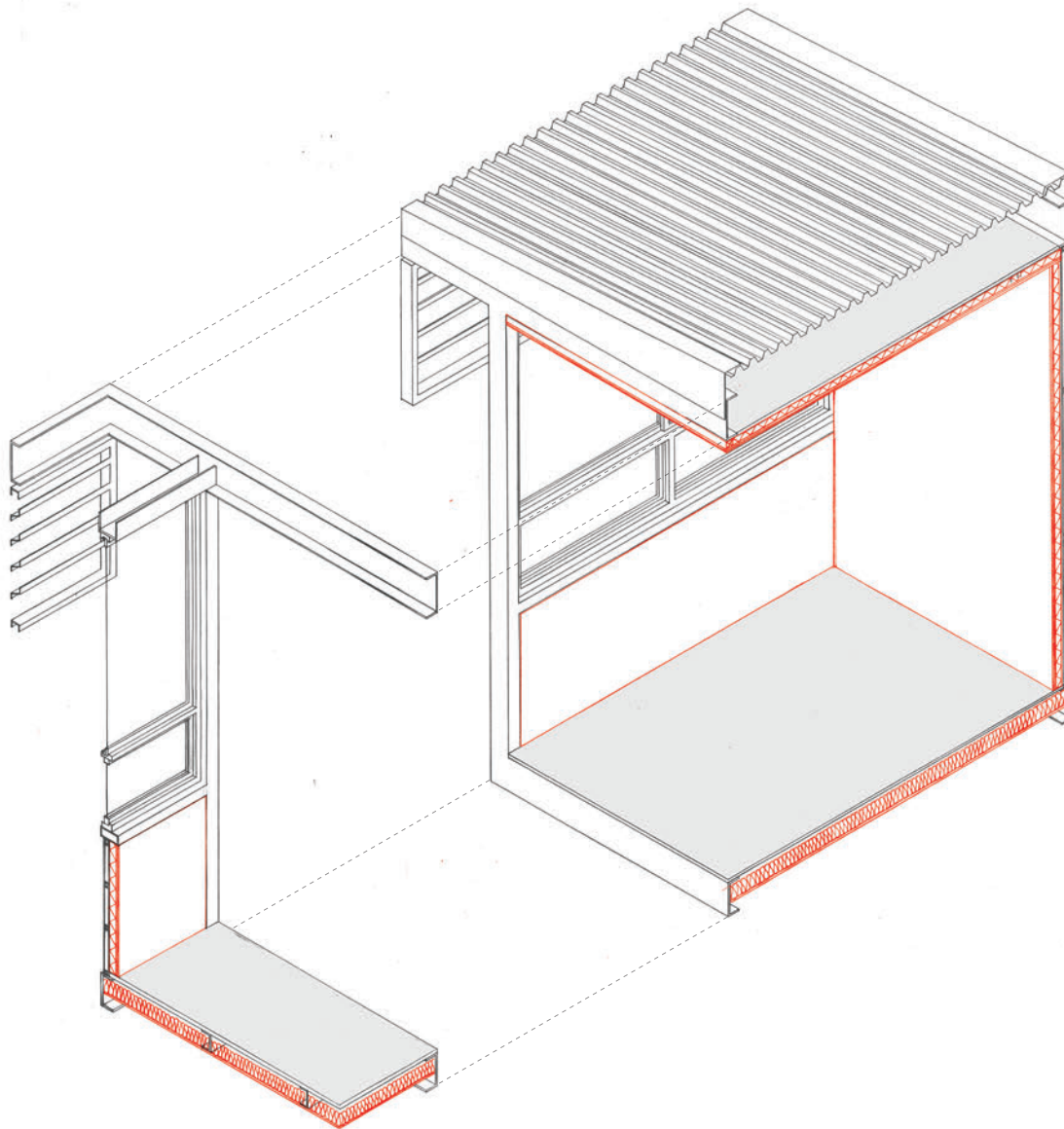


Figure 5.3: Solution Sets 02, 03, 04 and 05

Exploded cut-away isometric drawings illustrating the additions with the additions shown in red.

Solution Set: Additional of Insulation and thermal mass to the building envelope.

Refer to Table 2 for detailed specifications.

(Drawing by author)

Additional insulation

SET 02: Additional 40mm insulation

SET 03: Additional 80mm insulation

Insulation will be added to the floor, walls and ceiling. The insulation added to the floor will be R2.5 insulation batts enclosed by 6mm of fibre-cement sheet. The insulation added to the walls and ceiling will use one and then two layers of 40mm PIR insulation with a 6mm fibre-cement sheet cover (Figure 5.3).

The buildings are currently effectively un-insulated and so it is clear that some insulation will be useful. The first question is how much insulation will be useful?

Additional thermal mass

SET 04: Additional 40mm insulation and 18mm fibre-cement sheet

SET 05: Additional 40mm insulation and 36mm fibre-cement sheet

Based on the analysis in Chapter 4 thermal mass should, to some extent, be insulated from the external envelope so that its primary effect is on the internal thermal loads of the building. For this reason the use of thermal mass will be evaluated in combination with some insulation by increasing the thickness of the fibre-cement sheet lining from 6mm to 18mm and then 36mm (Figure 5.3).

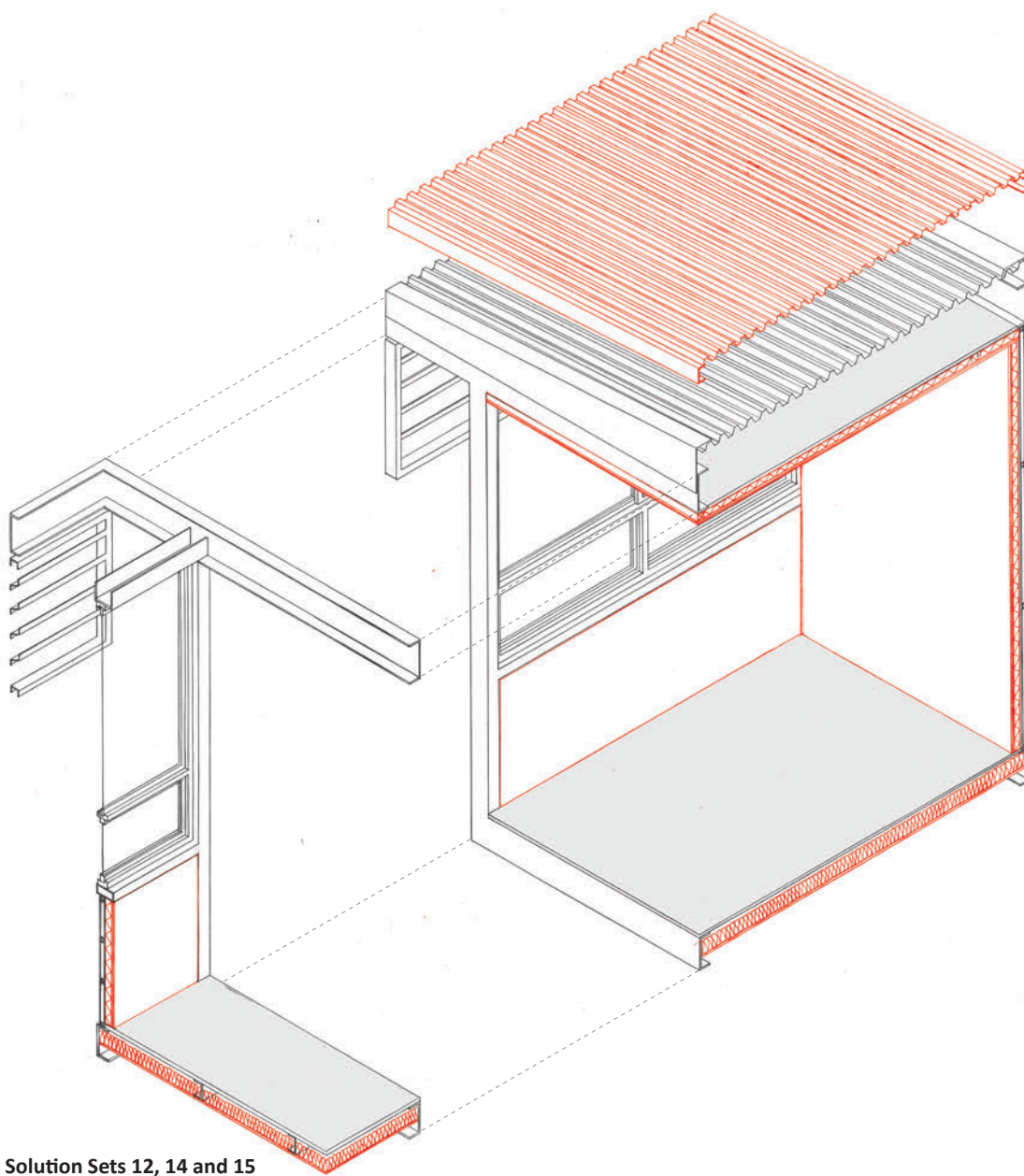


Figure 5.4: Solution Sets 12, 14 and 15

Exploded cut-away isometric drawings illustrating the additions with the additions shown in red.

Solution Set: Fly-roof with additional Insulation and thermal mass to the building envelope.

Refer to Table 2 for detailed specifications.

(Drawing by author)

Whole building shading

SET 11: Base case (existing) with a fly-roof

SET 12: Additional 40mm insulation (SET 02) with a fly-roof.

SET 14: Additional 40mm insulation and 18mm fibre-cement sheet (SET 04) with a fly-roof.

SET 15: Additional 40mm insulation and 36mm fibre-cement sheet (SET 05) with a fly-roof.

This is an existing but seldom used solution for the NSW Demountable Classroom typology and a solution that can be seen in vernacular low cost lightweight buildings across NSW such as static caravans. The solution will be simulated on its own (SET11) and in combination with the Solution Set combinations including insulation and thermal mass (SET 02- 05).

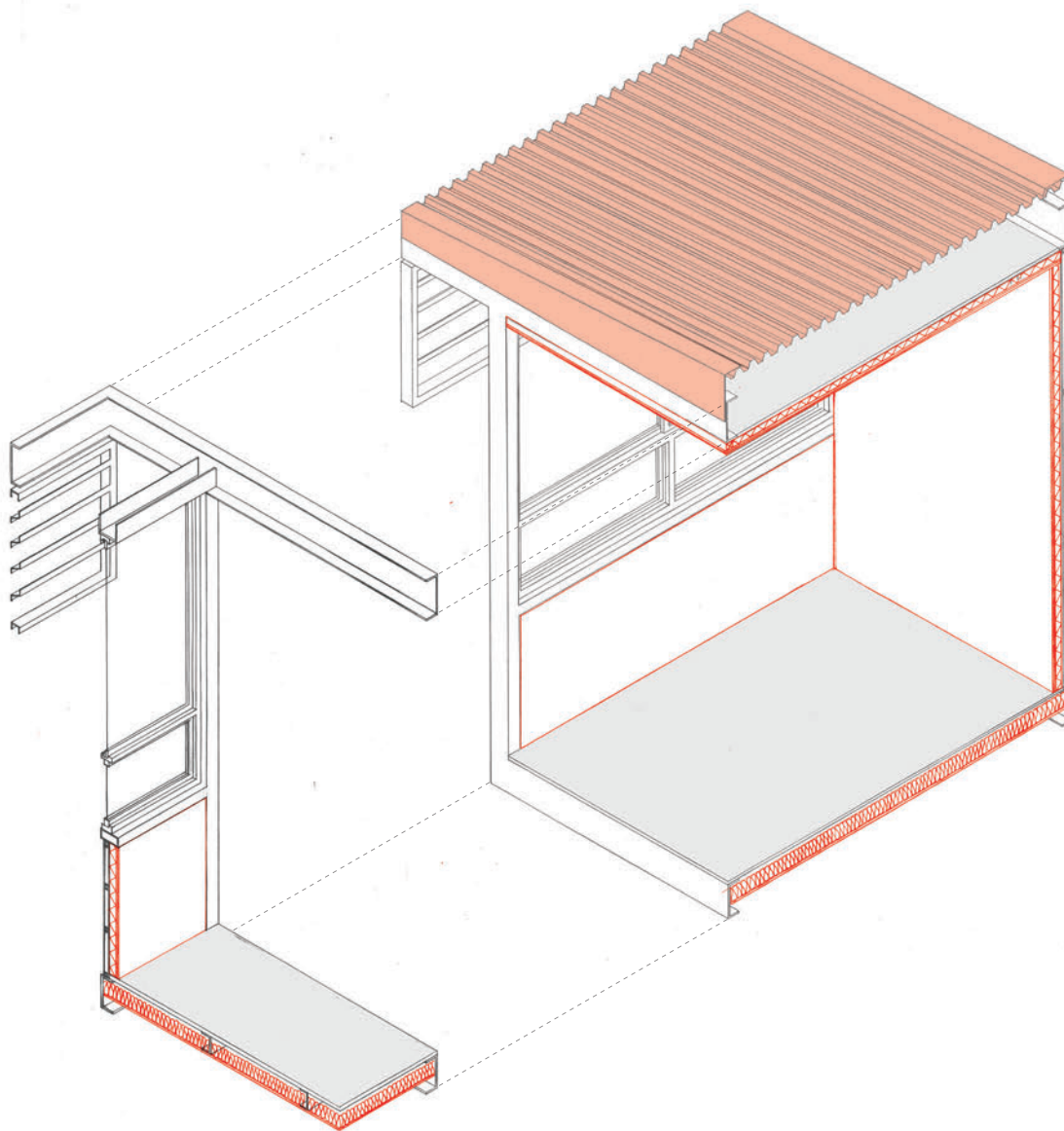


Figure 5.5: Solution Set 25

Exploded cut-away isometric drawings illustrating the additions with the additions shown in red.
 Solution Set: High-E coating with additional Insulation and thermal mass to the building envelope.
 Refer to Table 2 for detailed specifications.
 (Drawing by author)

High-E coatings

SET 21: Base case (existing) with a High-E coating to external opaque surfaces.

SET 25: Additional 40mm insulation and 36mm fibre-cement sheet (SET 05) with a High-E coating to external opaque surfaces.

The analysis in chapter 4 suggests that the impact of this strategy on the thermal performance of the Demountable Classroom will be very similar to that of whole building shading. This strategy will be simulated on its own and in combination with the most effective of the various Solution Set combinations including insulation and thermal mass, SET 05 (This is a cyclical research process reported as a linear narrative).

Evaluation criteria

The evaluation criteria are described in detail in Chapter 2. In brief they are:

- Predicted annual energy consumption (kWh) and associated CO₂-e emissions.
- Predicted thermal comfort.

Predicted annual energy consumption will be calculated by the simulation model and expressed in kWh. The Green Building Council of Australia (GBCA) energy target for classrooms in NSW is 26.8 kWh/m².year (GBCA, 2009), which equates to 1932 kWh/year for these classrooms. For the purposes of this analysis this has been rounded up to 2000 kWh/year.

The associated CO₂-equivalent emissions will be calculated by multiplying energy consumption by a conversion factor of 1.05kg.CO₂-e/kWh (BREE, 2013).

Thermal comfort will be predicted using the adaptive comfort model (ASHRAE, 2013, EN 15251, 2007) where the neutral temperature is predicted using a weighted running mean outside air temperature (de Dear and Candido, 2012). The magnitude of discomfort will be assessed by:

- Calculating the number of “degree-hours” outside the comfort zone (number of degrees above or below the comfort zone multiplied by the number of hours).
- The proportion of working hours above, within and or below the comfort zone.

5.2 Annual comfort and energy performance of the Solution Sets

The five sites that have been simulated are located in a broad range of climates ranging from the benign climate of Coffs Harbour to the extreme desert climate of Broken Hill. Despite this the response to the various interventions in all five climates follows very similar patterns.

The simulation results are illustrated graphically and provide an overview of the annual performance based on the predicted annual discomfort in degree-hours and the annual energy consumption in kWh (Figures 5.6 - 5.11). The Minimum and Maximum scenarios are indicated by pale lines. Where the Middle (and primary) scenario overlaps either of the other scenarios they are hidden behind the middle scenario. This graphic description is followed by a discussion of the annual performance of the classrooms in the different climates.

A more detailed analysis of the effect of the various Solution Sets on the thermal performance of the NSW Demountable Classroom and the consequential energy consumption of the classrooms and comfort of the occupants follows. The detailed discussion uses the simulation of the classroom in Richmond as the example and considers the performance in the hottest month, January, and the coldest month, July.

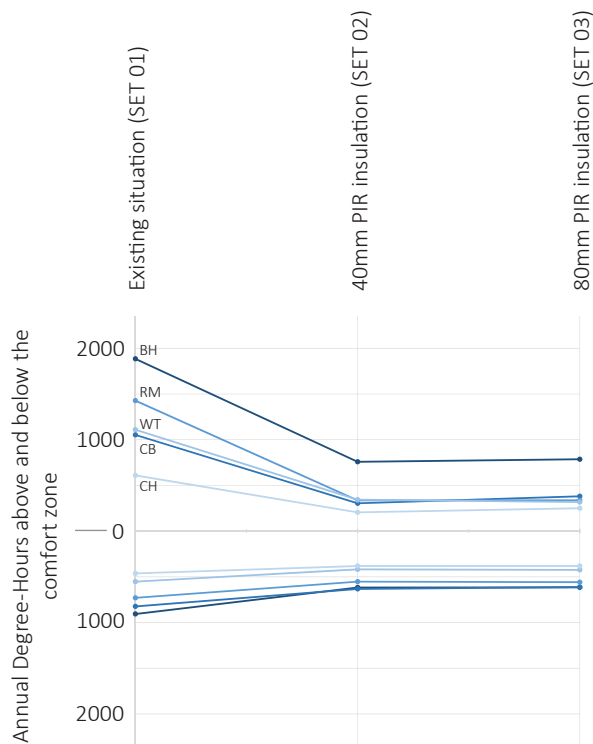


Figure 5.6a: Predicted annual thermal discomfort

The impact on comfort (degree-hours) of adding insulation to the external envelope of the classroom.

CLIMATE: All climates

(BH - Broken Hill; CB - Canberra; RM - Richmond;
WT - Williamstown; CH - Coffs Harbour)

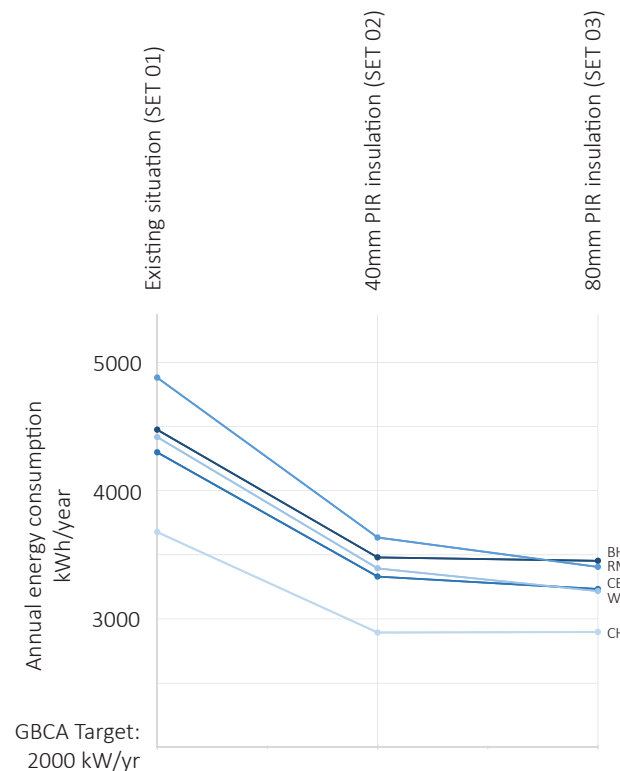


Figure 5.6a: Predicted annual energy consumption

The impact on annual energy consumption (kWh) of adding insulation to the external envelope of the classroom.

CLIMATE: All climates

(BH - Broken Hill; CB - Canberra; RM - Richmond;
WT - Williamstown; CH - Coffs Harbour)

5.2.1 Annual performance: Additional insulation (SET02 & SET03)

The U-value of the building envelope is increased by adding bulk insulation to the floor, walls and ceiling. The simulation results are shown in Figure 5.6. They indicate that in all climates insulating the floor and adding 40mm of insulation significantly reduces discomfort in the classroom, particularly the problem of overheating. There is also a significant reduction in annual energy consumption. Increasing the insulation on the walls and ceiling to 80mm makes no additional impact on reducing discomfort. The increased insulation does not reduce annual energy consumption in Broken Hill and Coffs Harbour. In Canberra, Richmond and Williamstown the increased insulation reduces annual energy consumption a further 2.8%, 6.3% and 5.2% respectively based from the Base Case SET 01. The results correspond to the “law of diminishing returns” observed by Giovanardi et al (2008) in their investigation of the influence of thermal insulation on the performance of a passive solar house in Italy and the observations of Li et al (2013) in their review of strategies for zero energy buildings.

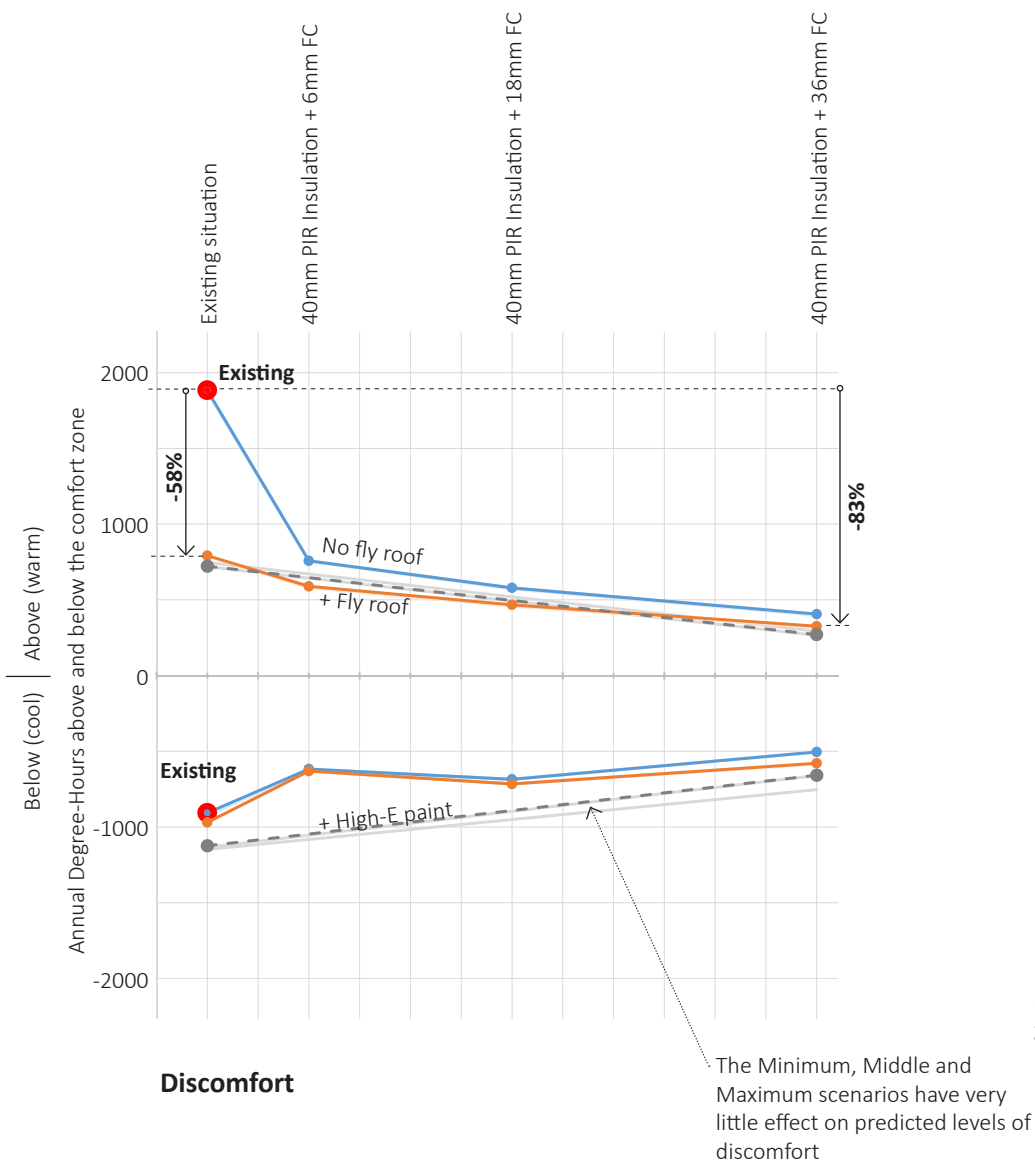


Figure 5.7a: Predicted annual thermal discomfort (degree-hours)

The impact on comfort (degree-hours) of adding insulation to the external envelope of the classroom.

CLIMATE Broken Hill

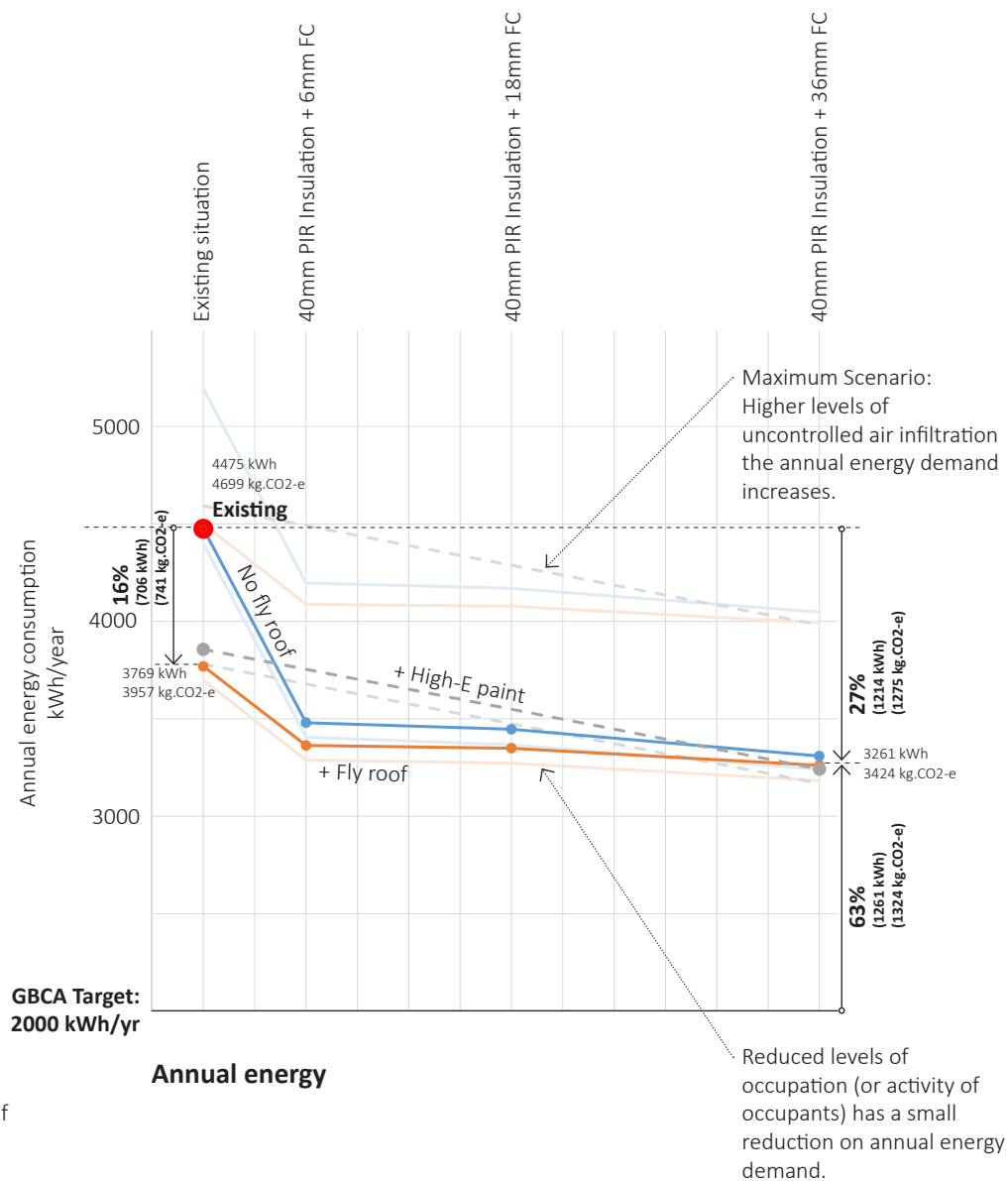


Figure 5.7b: Predicted annual energy consumption (kWh)

The impact on annual energy consumption (kWh) of adding insulation to the external envelope of the classroom.

CLIMATE: Broken Hill

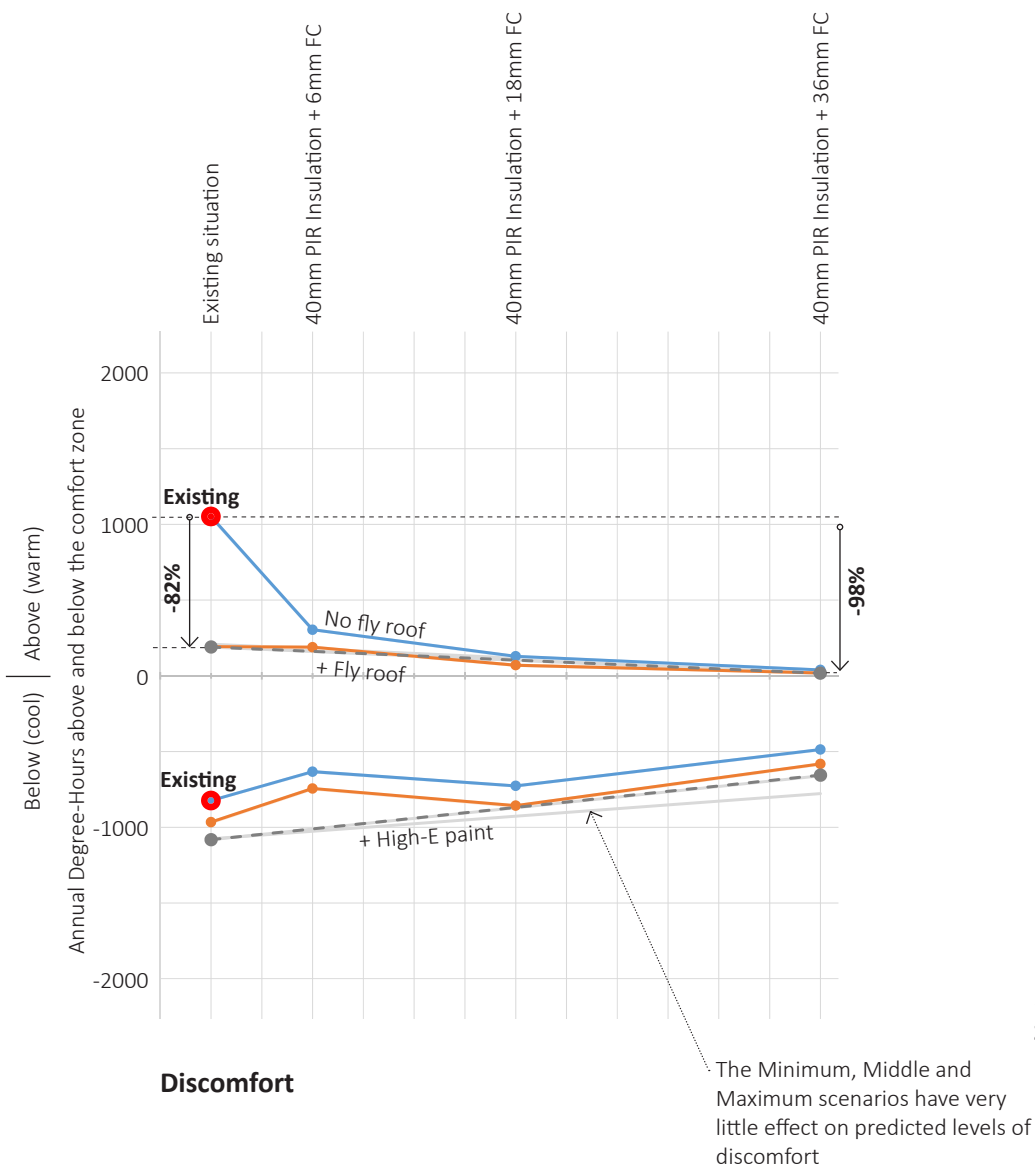


Figure 5.8a: Predicted annual thermal discomfort (degree-hours)

The impact on comfort (degree-hours) of adding insulation to the external envelope of the classroom.

CLIMATE: Canberra

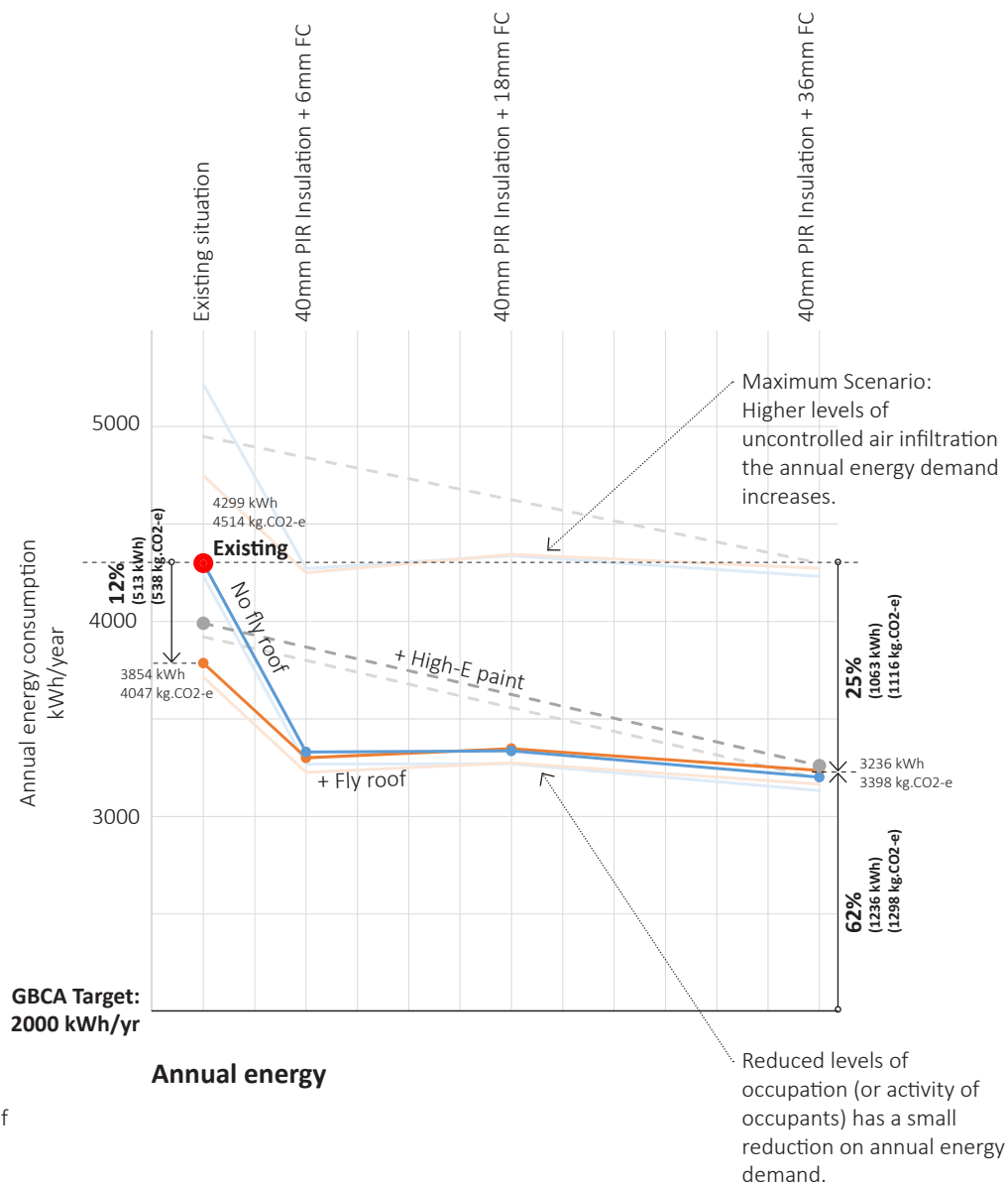


Figure 5.8b: Predicted annual energy consumption (kWh)

The impact on annual energy consumption (kWh) of adding insulation to the external envelope of the classroom.

CLIMATE: Canberra

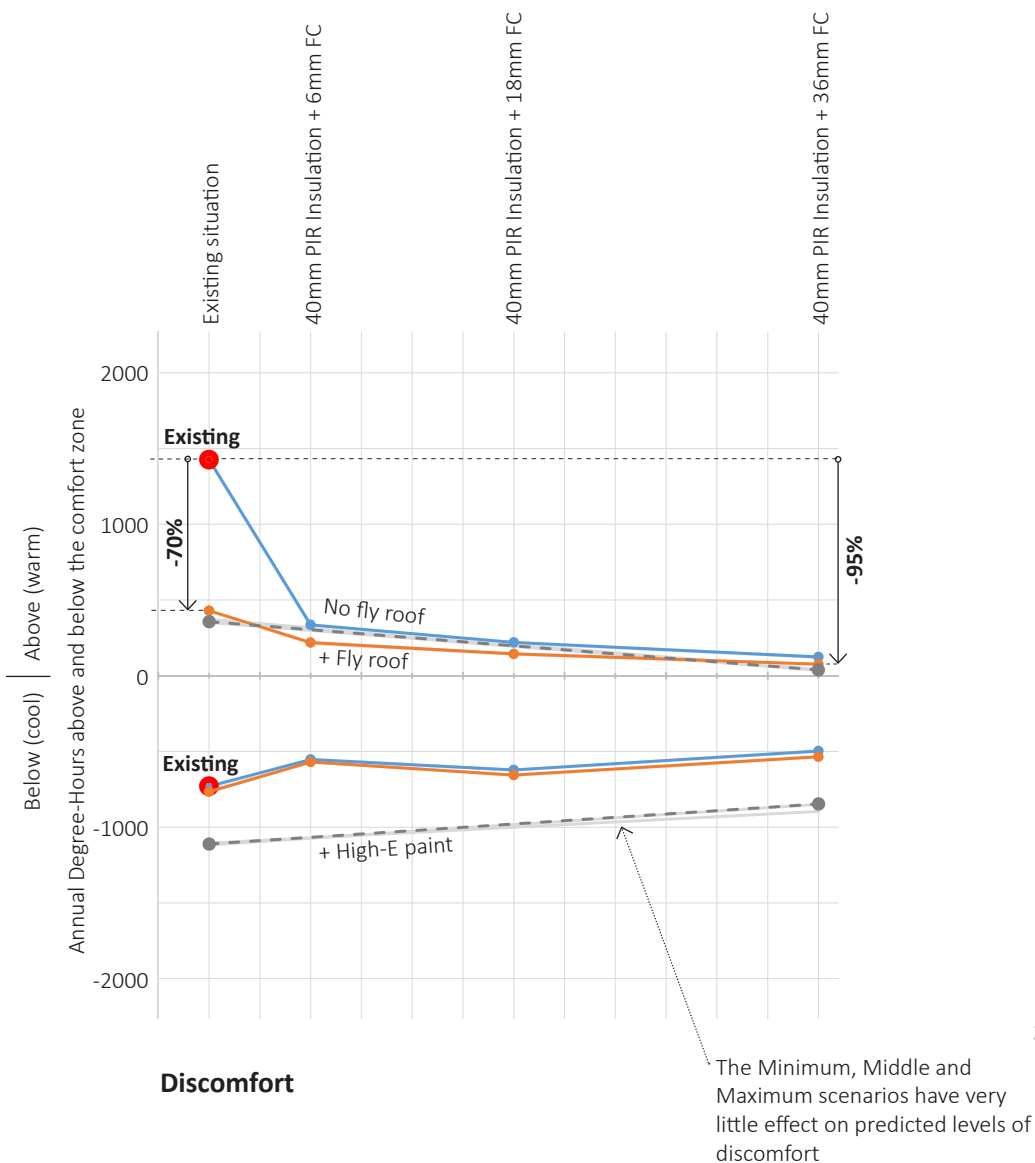


Figure 5.9a: Predicted annual thermal discomfort (degree-hours)

The impact on comfort (degree-hours) of adding insulation to the external envelope of the classroom.

CLIMATE: Richmond

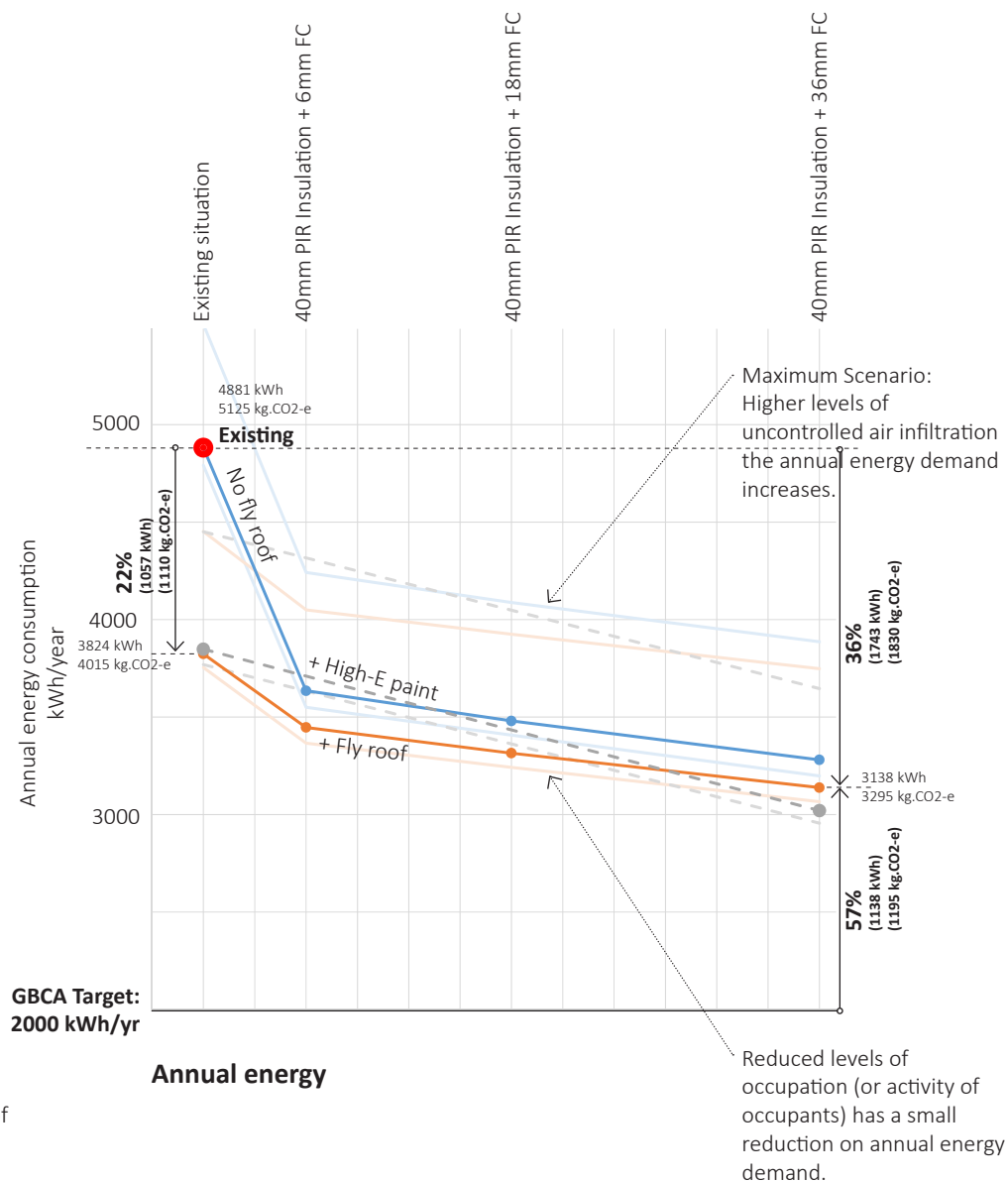


Figure 5.9b: Predicted annual energy consumption (kWh)

The impact on annual energy consumption (kWh) of adding insulation to the external envelope of the classroom.

CLIMATE: Richmond

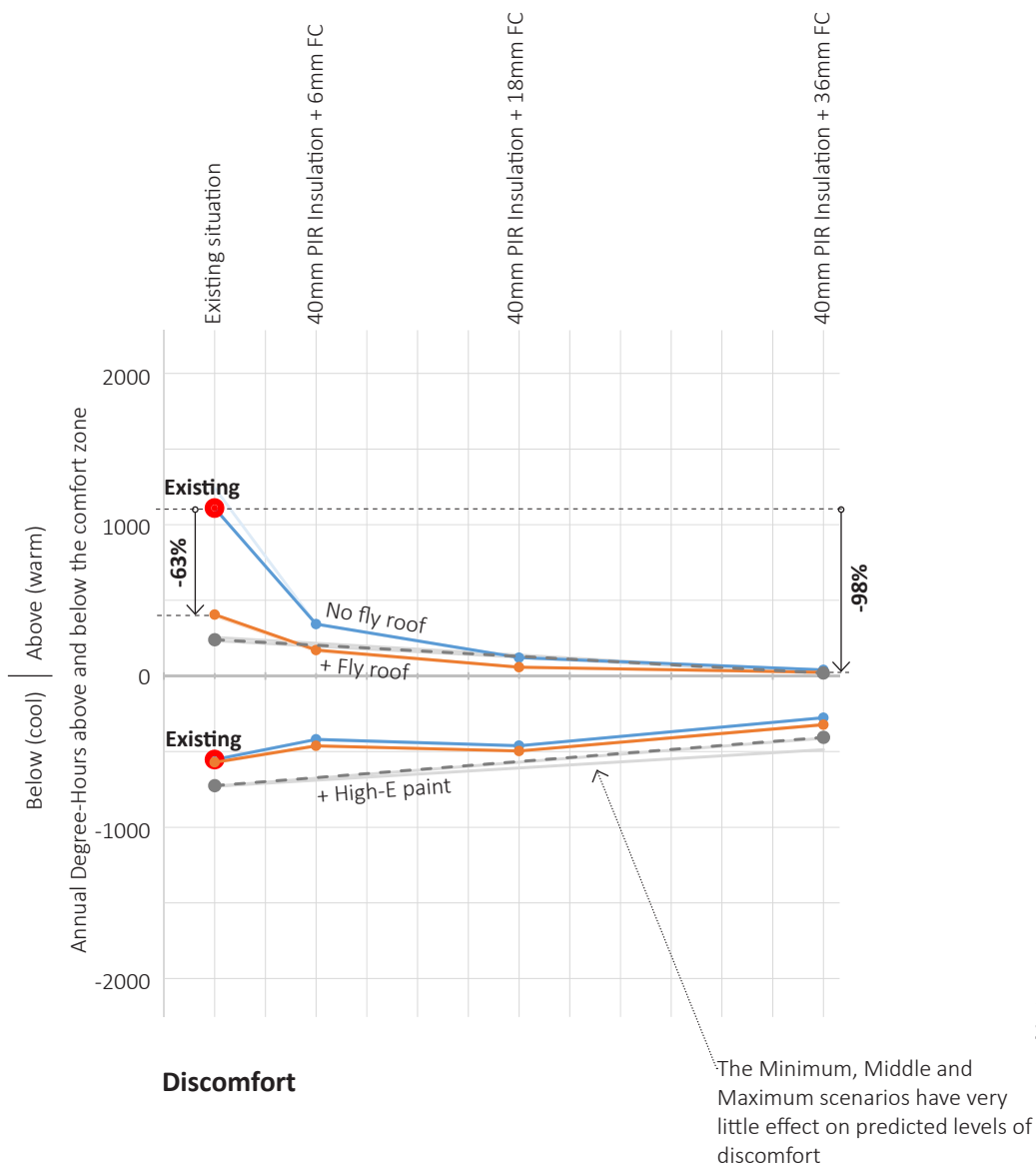


Figure 5.10a: Predicted annual thermal discomfort (degree-hours)

The impact on comfort (degree-hours) of adding insulation to the external envelope of the classroom.

CLIMATE: Williamstown

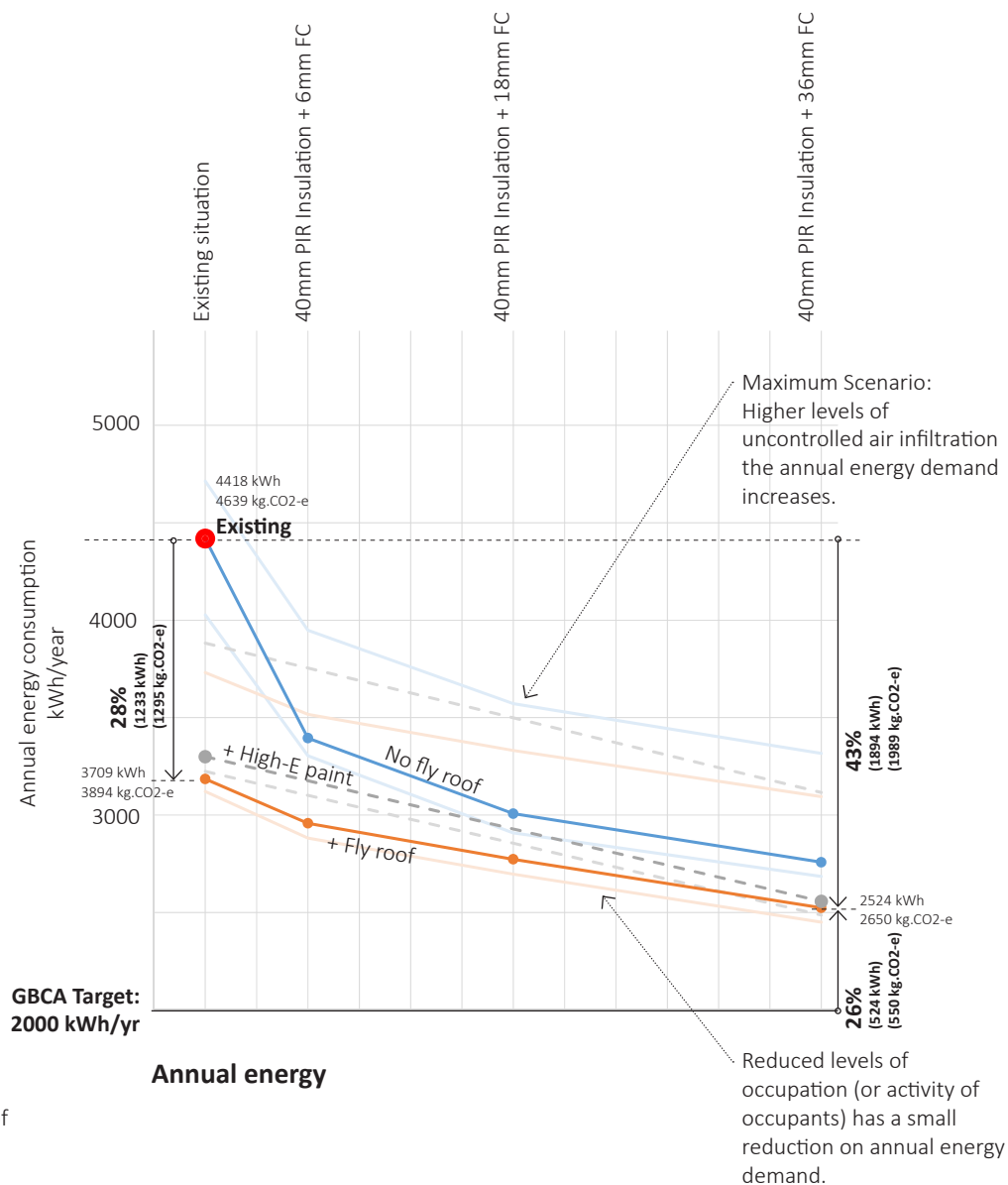


Figure 5.10b: Predicted annual energy consumption (kWh)

The impact on annual energy consumption (kWh) of adding insulation to the external envelope of the classroom.

CLIMATE: Williamstown

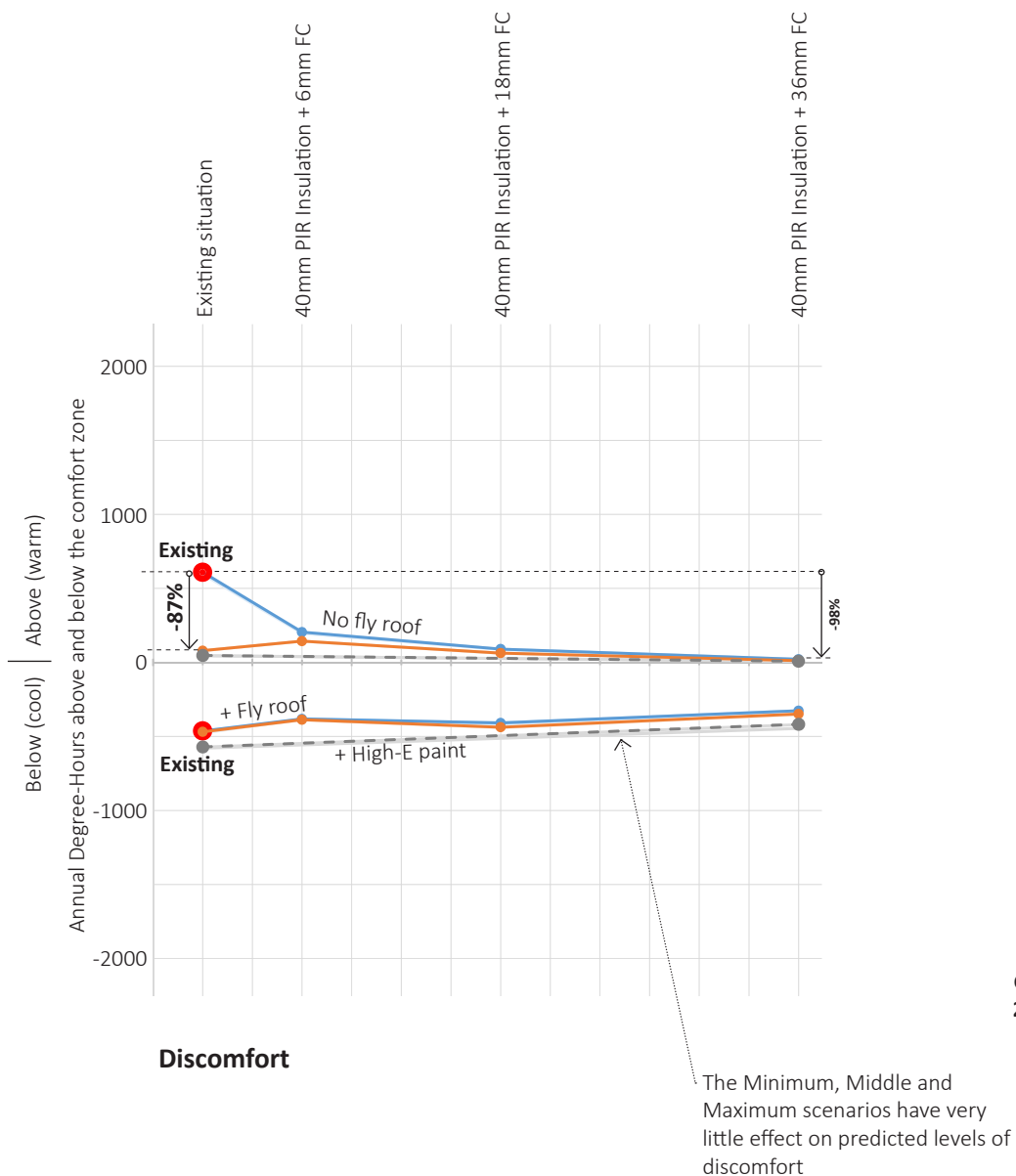


Figure 5.11a: Predicted annual thermal discomfort (degree-hours)

The impact on comfort (degree-hours) of adding insulation to the external envelope of the classroom.

CLIMATE: Coffs Harbour

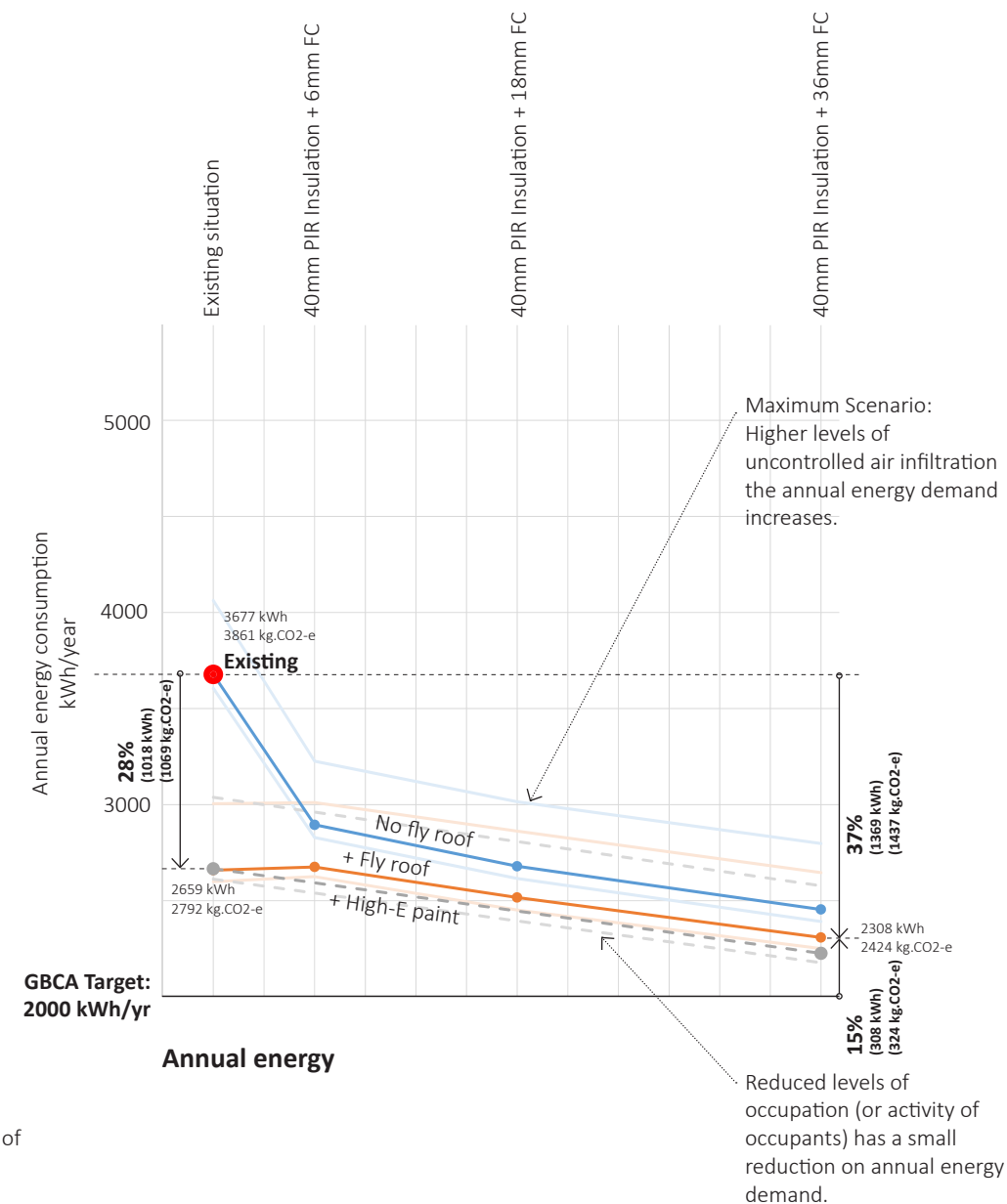


Figure 5.11b: Predicted annual energy consumption (kWh)

The impact on annual energy consumption (kWh) of adding insulation to the external envelope of the classroom.

CLIMATE: Coffs Harbour

5.2.2 Uncertainty and sensitivity

In Chapter 2 (Section 2.5) the issue of uncertainty within the simulation model as a consequence of input parameters and the modelling software was discussed, together with an analysis of the sensitivity of the model to variations in particular input parameters. This discussion resulted in three scenarios (Minimum, Middle and Maximum scenarios) being simulated for each solution Set (Table 2.12, repeated here for convenience).

Minimum simulation scenario:	Occupation: Mean metabolic output per person: Infiltration rate:	25 pupils plus one teacher 86 W Poor
Middle & primary simulation scenario:	Occupation: Mean metabolic output per person: Infiltration rate:	27 pupils plus one teacher 97 W Poor
Maximum simulation scenario:	Occupation: Mean metabolic output per person: Infiltration rate:	30 pupils plus one teacher 107 W Very Poor

The Minimum and Maximum scenarios have been indicated on the graphs (Figures 5.7- 5.11) with a pale line.

The Minimum and Middle scenarios have the same (Poor) infiltration rate (uncontrolled ventilation) but different levels of occupancy and metabolic activity (2.2 kW and 2.7 kW respectively). For these two scenarios the results for each Solution Set are very close in all five climates. The Maximum scenario increased occupancy (3.3 kW), metabolic activity and infiltration (Very Poor). The results of all the simulations for this scenario indicate significantly higher total annual energy demand, although the trend (i.e. the gradient and shape of the graph) remains the same as for the Minimum and Middle scenarios. The levels of comfort in all scenarios are similar. These results corroborate the sensitivity analysis undertaken in Section 2.5 and illustrated in Figure 2.31. These results suggest that:

- Uncontrolled infiltration of outside air is a significant problem. An observation made by others (Hopfe and Hensen, 2011, Han et al., 2015, Sadineni et al., 2011)
- The effect of the various solution sets is consistent in all three scenarios in all five climates.
- The simulation software and model is stable and, whatever inaccuracies, over or underestimations it may produce, the effect of them appears to be consistent across all scenarios evaluated in this project.

Table 2.12 (repeated): Minimum, middle and maximum simulation scenarios
The main simulation scenario and the two extreme simulation scenarios used to indicate the range of confidence

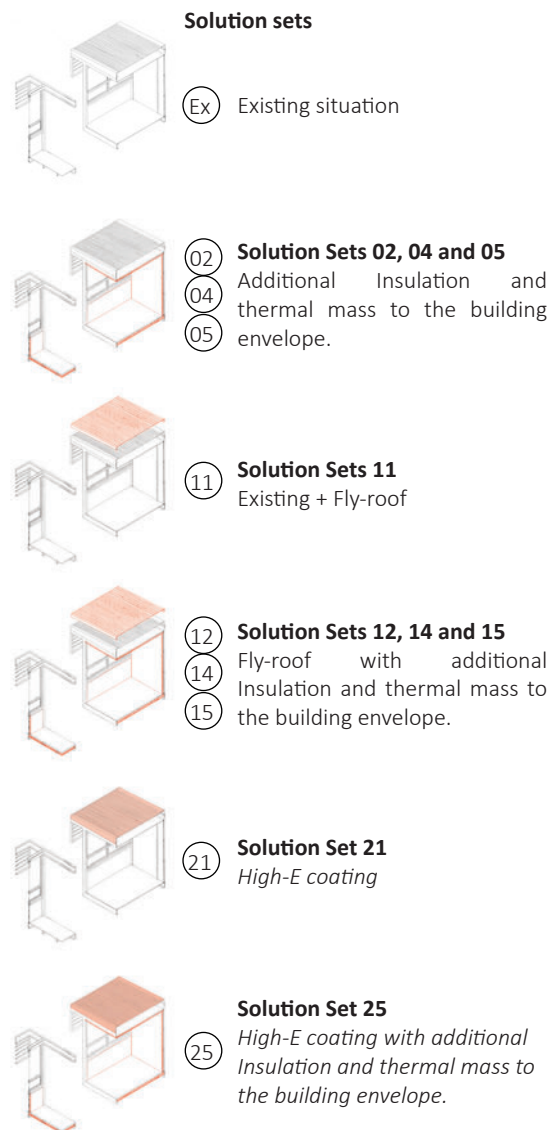


Figure 5.12: Key to Solution Sets

Solution Sets numbered, described and illustrated as exploded cut-away isometric drawings illustrating the additions with the additions shown in red.

(Drawing by author)

5.2.3 Annual performance of Solution Sets: Thermal mass, fly roofs and High-E paint

The following three strategies, introduce thermal mass, a fly roof and the addition of an external coating of High-E paint and are explored separately and in combination (Figure 5.12):

The introduction of thermal mass is done in combination with 40mm of additional insulation in the walls and ceiling since 80mm of additional insulation appears to cause no or very little benefit over 40mm of additional insulation.

The use of a fly-roof and High-E paint are simulated separately, with no other modifications to the classroom building and then with the addition of 40mm of insulation (SET 02) and then with insulation and thermal mass.

The discussion relates to figures 5.7 - 5.11.

5.2.4 Annual performance: Additional thermal mass (SET 04 and 05)

Thermal comfort

The addition of thermal mass has a small but significant effect on thermal comfort in all five climates. The addition of 36mm of fibre-cement sheet and 40mm of thermal insulation practically eliminates overheating discomfort in four out of the five climates where the classrooms were simulated, the exception being the classroom in Broken Hill. Compared to 40mm of insulation and 6mm fibre-cement sheet (SET 02) the



use of 18mm of fibre-cement sheet (SET 04) slightly increases the cold discomfort in all climates but increasing the thickness of fibre-cement sheet further to 36mm (SET 05) reverses this.

Annual Energy demand

The addition of thermal mass has a modest impact on annual energy consumption in Broken Hill and Canberra and a significantly more pronounced impact on annual energy consumption in Richmond, Williamstown and Coffs Harbour. Williamstown and Coffs Harbour are the two more moderate climates and Broken Hill and Canberra have more extreme climates. Richmond also has a challenging climate, however annual energy consumption is predicted to reduce with the addition of thermal mass following the pattern in the more moderate climates.

Design guidance (Hollo, 1986, Reardon et al., 2011) suggests that the use of thermal mass to moderate thermal discomfort and reduce energy consumption is more effective in climates with larger diurnal temperature ranges, in this case the more extreme climates of Broken Hill, Canberra and Richmond. However the results of the simulations of these classrooms do not follow this orthodoxy. The results suggest an alternative pattern: In Broken Hill and Canberra the diurnal temperature range reduces during the winter (May – August) months. In Richmond, Williamstown and Coffs Harbour the diurnal range increases during the winter months (Figure 5.13).

This correlation is intriguing but beyond the scope of this research to investigate further.

5.2.5 Annual Performance: Whole building shading (fly roof) (SET11 – 15)

Thermal Comfort

The introduction of a fly roof without any other modification to the classrooms (SET 11) causes the largest improvement in predicted thermal comfort of any of the initial Solution Sets (SET 02, 03, 11 & 21) by significantly reducing overheating in the classrooms. The fly-roof reduces the number of degree-hours above the comfort zone by 58% in Broken Hill and 70% or more in all the other locations. In Coffs Harbour the reduction is 84%. The fly roof is as effective as, or slightly more effective than, the introduction of thermal insulation (SET 02) at reducing overheating. The fly-roof has negligible influence on under-heating in all five locations with the exception of Canberra where the fly-roof creates a slight increase in cold discomfort under all scenarios (SET 01 – SET 15).

Once additional insulation and thermal mass are introduced the fly-roof has only a small and diminishing effect on thermal comfort compared to the Solution Sets without a fly roof.

Annual Energy demand

The combination of the fly-roof, insulation and increasing quantities of thermal mass (fibre-cement sheet) leads to further reductions in annual energy demand in all

locations except Canberra. In Canberra the introduction of insulation has the largest impact on annual energy consumption of all the Solution Sets, the addition of a fly roof does not reduce energy demand further.

When the fly-roof is the only intervention annual energy consumption is reduced by between 13% (Canberra) and 27% (Coffs Harbour). In absolute terms the savings range between 557 kWh/year (585 kg.CO₂-e) in Canberra and 1148 kWh/year (1205kg.CO₂-e) in Richmond. Predicted absolute savings in Coffs Harbour are almost the same as those predicted for Richmond.

5.2.6 Annual performance: High-E coatings (SET21 – 25)

The simulation model was used to model a High-E paint applied to the base case classroom with no other modifications (SET 21), and to the classroom modified with insulated floors, walls and ceiling plus 36mm of fibre-cement sheet added for thermal mass (SET 25).

The results of the simulations for all five sites indicate that the effect of the High-E paint on overheating and annual energy consumption closely matches the effect of adding a fly-roof (SET 11 & SET 15). This indicates that the High-E paint has a similar effect to completely shading the roof of the building. Both strategies

significantly reduce the impact of solar radiation on the building (Figures 5.7- 5.11).

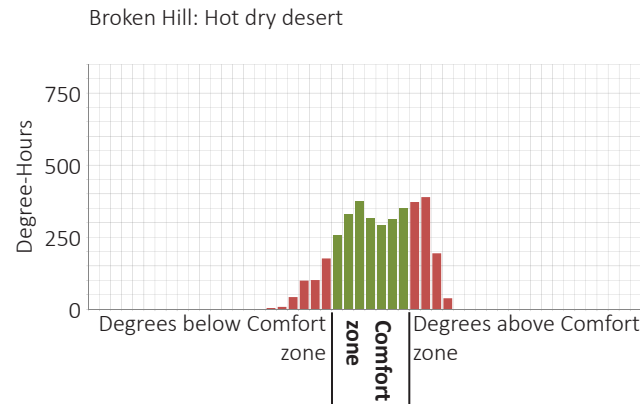
Thermal Comfort

The addition of the High-E paint results in an increase in annual cold discomfort in all five climates. The discomfort is reduced slightly when insulation and thermal mass are also added to the classroom construction, but the relative increase in cold discomfort is the same in the two simulated scenarios. This effect is most apparent in Richmond where the introduction of the High-E coating to the base-case classroom model (SET 01 – SET21) increases cold discomfort by 344 Degree-Hours (about 50%) and by 331 Degree-Hours (about 70%) when insulation and thermal mass are added (SET 05 – SET 25). This observation suggests that the increased emissivity of the external surface of the classroom is creating a cooling effect when the classroom is cool or on cold days as well as when it is too hot. A similar observation was reported by Bell et al (2003) when testing High-E coatings in lab experiments and on supermarket roofs on the Sunshine Coast in Queensland (approx. 500km north of Coffs Harbour).

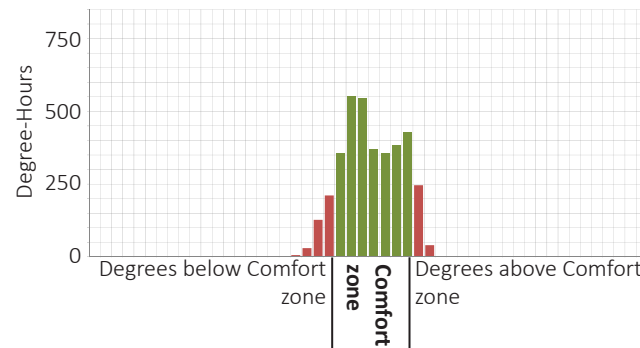
Annual Energy demand

Despite the increased heating load created by the High-E paint, when the classroom is coated in High-E paint in combination with additional insulation and thermal mass (SET 25), it uses the same or less energy compared to the most efficient of the other Solution Sets that have been modelled. In Richmond Solution Set 25 reduces energy consumption by a further 159 kWh compared to equivalent Solution Set using a fly roof (SET 15) and 315 kWh compared to the Solution Set with no fly roof (SET 05) (refer to Figure 5.9).

SET 01:
Base case
The existing classroom



SET 15:
Fly-roof, insulation and thermal mass
The existing classroom with insulation and thermal mass added to the building envelope and shaded with a fly-roof.



SET 25:
High-E paint, insulation and thermal mass
The existing classroom with insulation and thermal mass added to the building envelope. The opaque surfaces of the external envelope are coated with High-E paint.

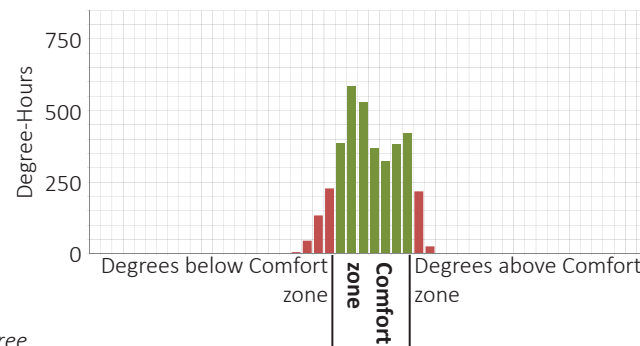


Figure 5.14: Bar charts of thermal comfort in Broken Hill
Bar charts illustrating the number of degree-hours below, within and above the comfort zone (shown green) in one degree increments for different Solution Sets.
UNITS: Bars are in one degree increments

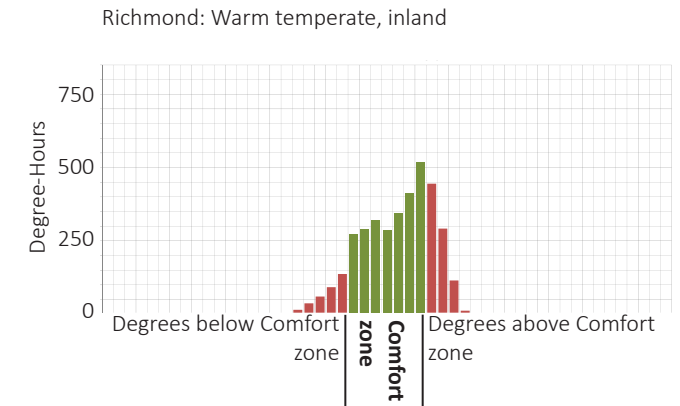
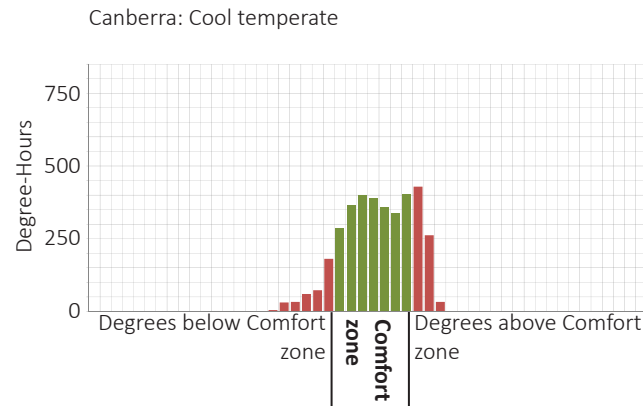
5.3 Implications of Annual comfort and energy performance of the Solution Sets

The results of the thermal simulations of the various Solution Sets indicate that it is possible to come close to eliminating overheating in NSW Demountable Classrooms in most climates. Figures 5.14, 5.15 and 5.16 Illustrate this using bar charts plotting the number of degree-hours below, within and above the comfort zone (shown green). The bars represent one degree increments (i.e . 1°C, 2°C, 3°C.... above or below the comfort zone) and illustrate predicted comfort and discomfort for the existing situation SET 01, and Solution Sets SET 15 (Fly roof, insulation & thermal mass) and SET 25 (High-E paint, insulation & thermal mass). While hot or warm discomfort is reduced by between 76% and 97% in all climates, underheating or cold discomfort remains a challenge.

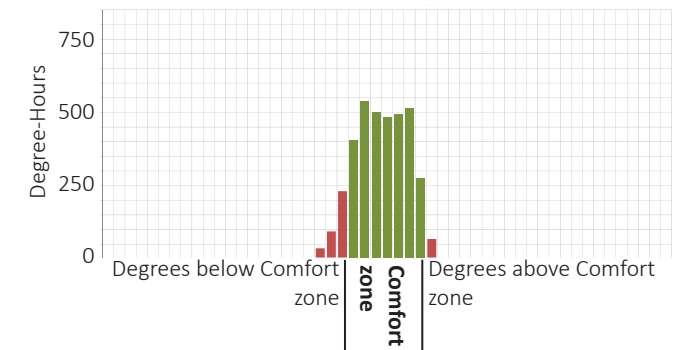
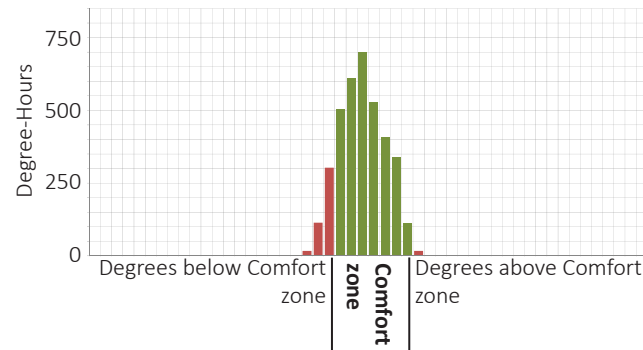
This very significant improvement in comfort is not matched by a reduction in annual energy consumption. Reductions in annual energy consumption are significant ranging from 26% to 42% depending on the climate. Assuming a unit cost of 30c/kWh¹ these savings equate to between \$358 per classroom per year (Canberra) and \$596 per classroom per year (Williamstown). However, the annual heating and cooling energy consumption of

¹ Based on Australian Energy Market Commission Final Report into 2015 Residential energy Price Trends and review of energy prices on website www.energymadeeasy.gov.au for “small businesses” fixed price offers 09/01/2017.

SET 01:
Base case
The existing classroom



SET 15:
Fly-roof, insulation and thermal mass
The existing classroom with insulation and thermal mass added to the building envelope and shaded with a fly-roof.



SET 25:
High-E paint, insulation and thermal mass
The existing classroom with insulation and thermal mass added to the building envelope. The opaque surfaces of the external envelope are coated with High-E paint.

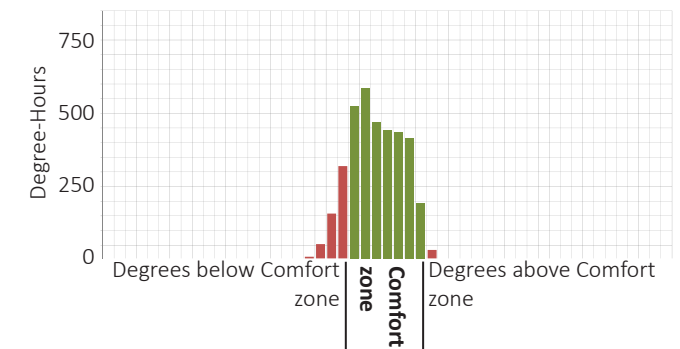
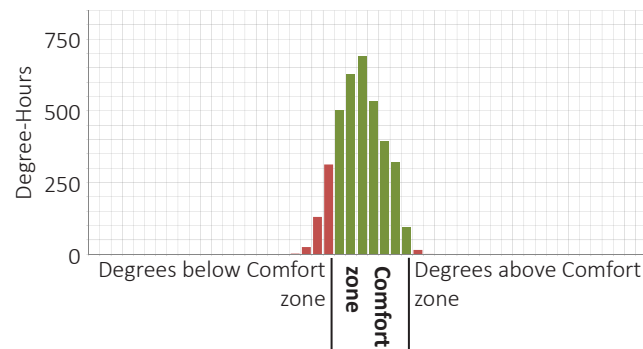
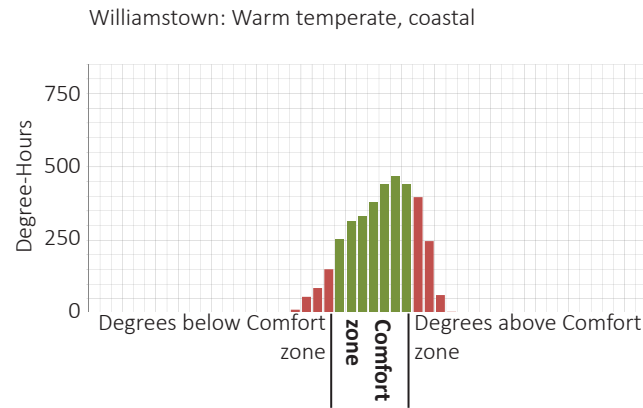


Figure 5.15: Bar charts of thermal comfort in Canberra and Richmond
Bar charts illustrating the number of degree-hours below, within and above the comfort zone (shown green) in one degree increments for different Solution Sets.
UNITS: Bars are in one degree increments

SET 01:
Base case
The existing classroom



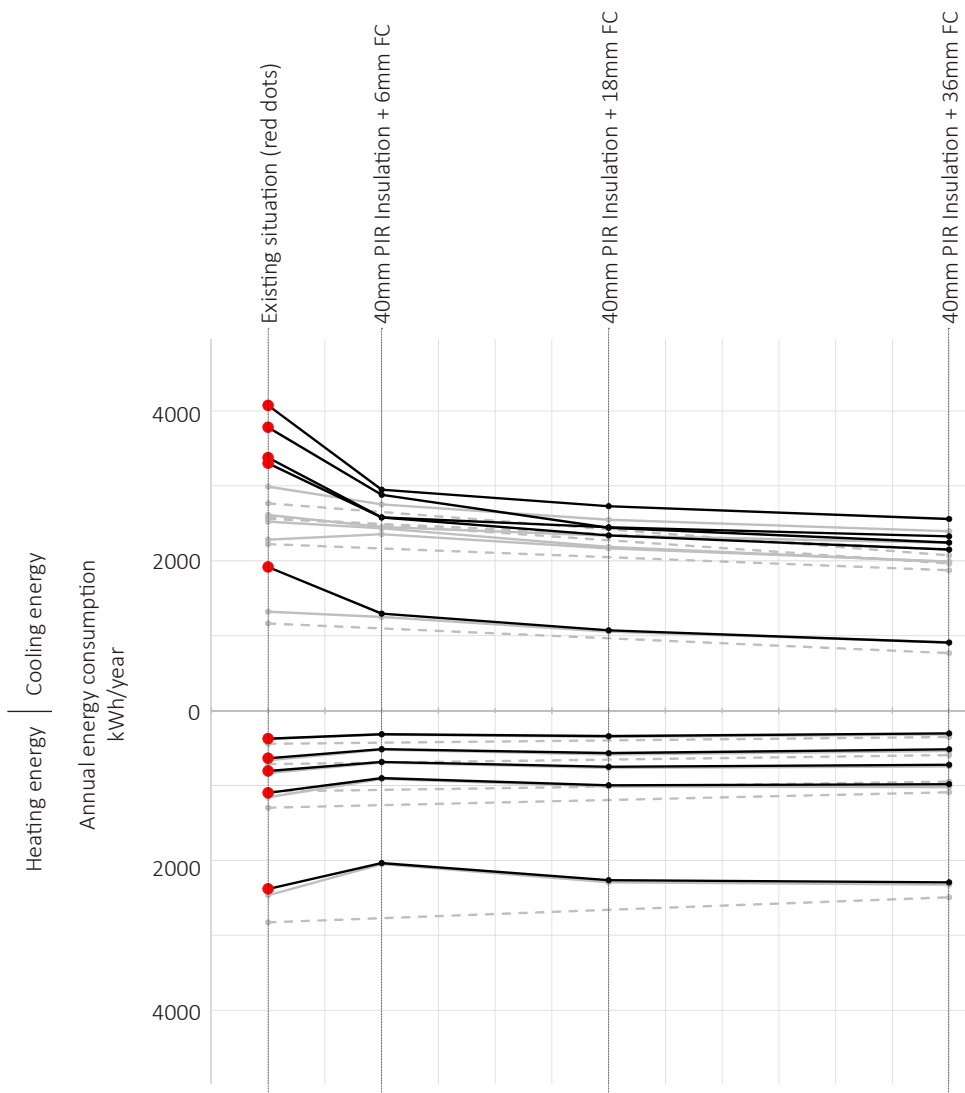


Figure 5.17: The predicted heating and cooling energy from each Solution Set in each climate.

The chart is intended to illustrate a pattern rather than provide specific readings for individual Solution Sets in particular climates. Therefore the chart differentiates between groups of Solution Sets (see table 1). Every climate and Solution Set is shown but not labelled. The Solution Set groups are:

- SET 01 series - Black
- SET 11 series: Grey
- SET 21 series: Grey dashed

The X-axis relates to increasing thickness of thermal mass (Fibre-Cement sheet).

Figure 23 shows the same data for Richmond only and labels individual Solution Sets.

CLIMATE: All climates

the classrooms remains between 33% and 81% above the GBCA target of 2000 kWh/year (26.8 kWh/year.m²) (GBCA, 2009).

5.3.1 Heating and cooling energy

Figure 5.17 shows the predicted heating and cooling energy from each Solution Set in each climate. The Chart differentiates between Solution Sets rather than climate (every climate and Solution Set is shown) and shows that the pattern of energy use and response to the various Solution Sets is similar across all climates.

The quantity of cooling energy required is generally several times the heating energy requirement. The conclusion of Chapter 2 highlighted overheating as the primary thermal comfort challenge for the Demountable Classroom. Figure 5.17 shows that the introduction, individually, of insulation, a fly-roof or High-E paint significantly reduces the cooling energy demand. However the introduction of the same Solution Sets causes only a small reduction in heating energy demand. When the Solution Sets that include a number of elements including thermal mass are used, rather than the singular strategies of insulation, fly-roof or high-E paint, the additional reductions in annual energy consumption are relatively small.

5.3.2 Thermal comfort: Reducing overheating

The analysis of the change in thermal comfort in response to the introduction of various Solution Sets indicates that

- Simple, singular interventions (e.g. fly-roof, High-E paint or insulation) to the existing classroom achieve the largest single improvement in thermal performance.
- It is by combining the Solution Sets into more complex Sets that thermal discomfort can be reduced to the point where overheating, in particular, is eliminated.

This suggests that the Solution Sets combining insulation, thermal mass and a fly-roof or High-E paint enables the air-conditioning system to create a more comfortable thermal environment in the classroom. Expressed another way the Solution Sets make the use of the air-conditioning and associated energy more effective.

Chapter 2 explained that our perception of thermal comfort is dominated by a combination of air temperature and radiant temperature, which is the mean temperature of the surrounding surfaces. This combination is called the operative temperature. Chapter 2 showed that the air-conditioning system is able to maintain the internal air temperature within the comfort zone but the high surface temperatures, particularly the ceiling, cause the radiant temperature to be high and so the operative temperature, that is the temperature we perceive, moves outside the comfort zone. Chapter 2 argued that the high internal surface

temperatures are caused by the large amounts of thermal energy landing on the classrooms from the sun and so any intervention that sets out to improve thermal comfort in the classroom will need to, “resist or deflect the enormous thermal loads imposed by the sun”.

Legend: Temperatures

- Outside air temperature
- - - External roof temperature
- Ceiling surface temperature
- - - Mean external wall temperature
- Mean internal wall temperature
- Internal air temperature
- Internal operative temperature

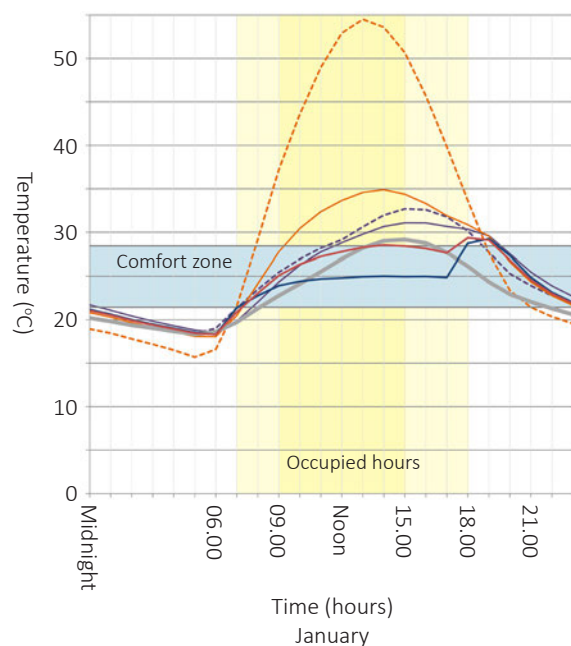


Figure 5.18a:
Mean hourly temperatures for Richmond in January (summer)
Solution Set: SET 1 Existing situation
 CLIMATE: Richmond
 SEASON: Summer (January)

Legend: Thermal flux

- Roof
- Opaque walls
- Windows
- Floor
- Ventilation
- Internal loads
- - - Air-conditioning
- ... dT inside-outside

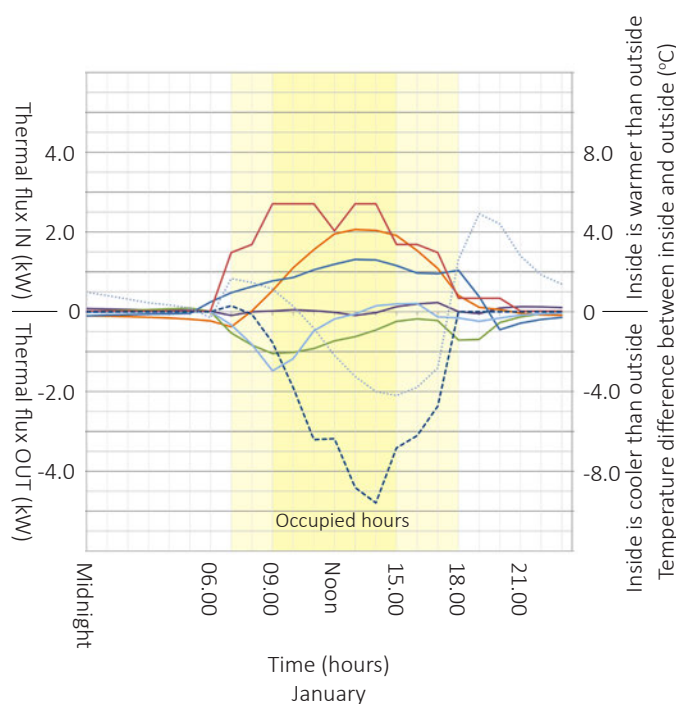


Figure 5.18b:
Mean hourly heat flux for Richmond in January (summer)
Solution Set: SET 01 Existing situation
 CLIMATE: Richmond
 SEASON: Summer (January)

5.4 Impact of Solution Sets on daily thermal comfort and energy demand

The more detailed review of the results of the thermal simulation of the various Solution Sets supports the hypothesis that the high internal surface and operative temperatures are caused by the large amounts of thermal energy landing on the classrooms from the sun. The following charts (Figure 5.18 - 5.28) illustrate the thermal flux (energy moving through the building fabric) and the temperatures in the classroom, and of different parts of the Demountable Classroom building in Richmond.

Richmond is used for the example but, as has been demonstrated above, the patterns are the same in all five of the simulated classroom buildings in the five representative climates.

5.4.1 Thermal performance and energy demand in summer

The figures illustrate the *mean hourly values* for a day in January; i.e. each point is the mean value for that hour in January meaning that there are days when values are both above and below those illustrated.

The graphs illustrate the significant impact five different Solution Sets have on the thermal performance of the classroom buildings and the consequential thermal comfort of the classroom occupants. In each case the comparison is with the base-case existing classroom building (SET 01) (Figure 5.18).

Legend: Temperatures

- Outside air temperature
- - - External roof temperature
- Ceiling surface temperature
- - - Mean external wall temperature
- Mean internal wall temperature
- Internal air temperature
- Internal operative temperature

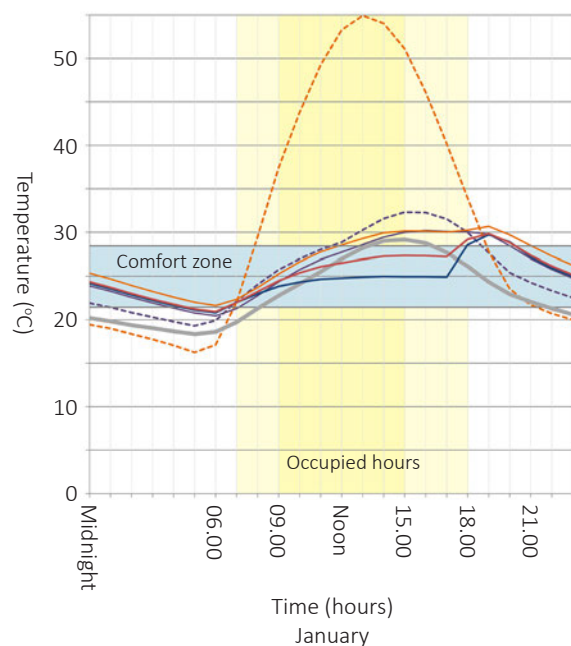


Figure 5.19a: Mean hourly temperatures for Richmond in January (summer)

Solution Set: SET 02 Additional bulk insulation

CLIMATE: Richmond

SEASON: Summer (January)

Legend: Thermal flux

- Roof
- Windows
- Opaque walls
- Floor
- Ventilation
- Internal loads
- - - Air-conditioning
- ... dT inside-outside

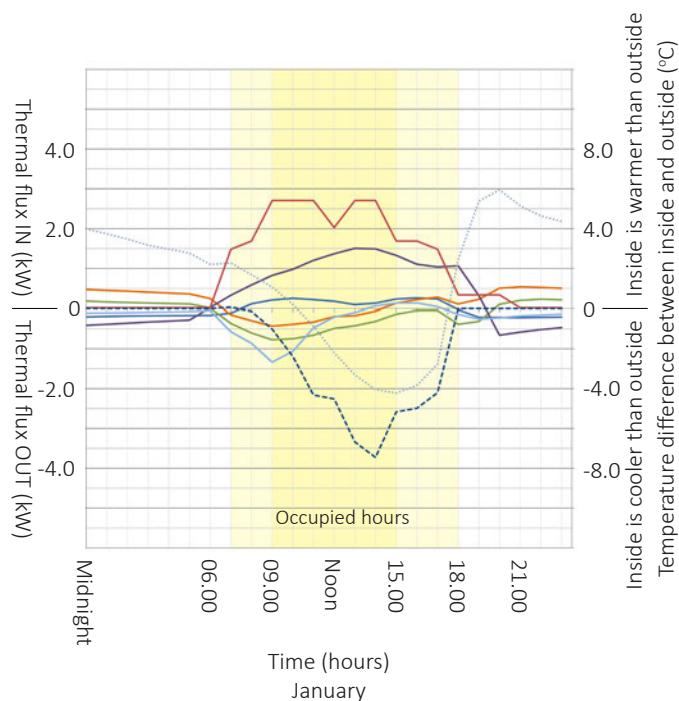


Figure 5.19b: Mean hourly heat flux for Richmond in January (summer)

Solution Set: SET 02 Additional bulk insulation

CLIMATE: Richmond

SEASON: Summer (January)

5.4.2 The addition of bulk insulation (SET 02)

Adding insulation to the floor, walls and ceiling reduces the temperature of the ceiling and significantly reduces the thermal flux through the ceiling to the extent that it becomes slightly negative (thermal energy leaving the classroom) for a large part of the working day (Figure 19b).

The temperature of the ceiling is now much closer, but still slightly above, the temperature of the walls whose temperature is also slightly reduced compared to the existing situation (Figure 5.19a). As a consequence the operative temperature is reduced and is clearly within the comfort zone. There is also a reduction in the energy load which is used entirely for cooling. The peak load reduces from 5.3 kW to 4.3 kW and overall the mean energy consumption for a day in January reduces from 30.2 to 23.2 kWh.

5.4.3 The addition of a fly-roof (SET11)

Solution Set 11 introduces a fly-roof to the NSW Demountable Classroom without any other intervention (Figures 5.20a & b). The charts illustrate the dramatic effect this has on both the external and internal surface temperatures of the roof (shown orange). The existing classroom roof reaches a mean maximum temperature of 55°C during the day in January. The mean maximum temperature of the ceiling reaches 35°C. The introduction of the fly-roof reduces the external roof temperature by up to 27°C (at the peak at 14.00). The roof surface temperature now closely follows the external air temperature and is consistently below the

Legend: Temperatures

- Outside air temperature
- - - External roof temperature
- Ceiling surface temperature
- - - Mean external wall temperature
- Mean internal wall temperature
- Internal air temperature
- Internal operative temperature

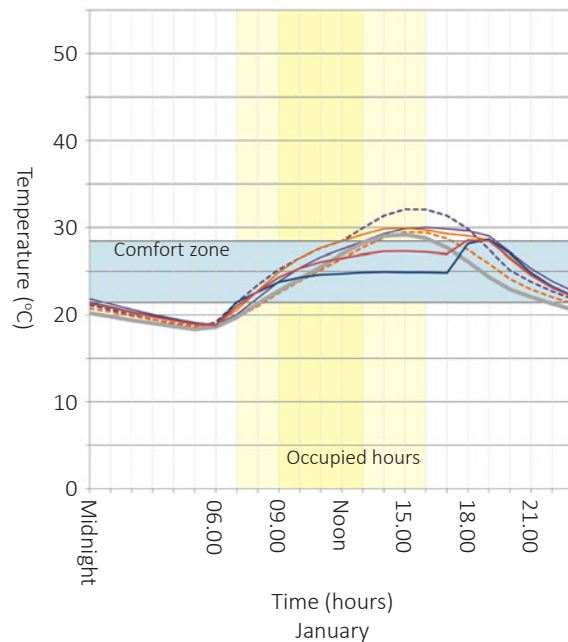


Figure 5.20a: Mean hourly temperatures for Richmond in January (summer)

Solution Set: SET 11 The addition of a fly-roof.

CLIMATE: Richmond

SEASON: Summer (January)

Legend: Thermal flux

- Roof
- Windows
- Opaque walls
- Floor
- Ventilation
- Internal loads
- - - Air-conditioning
- ... dT inside-outside

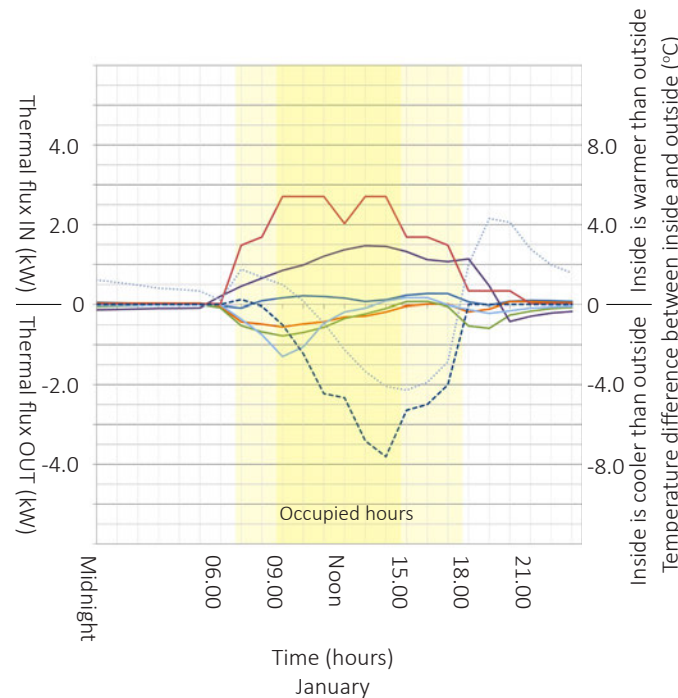


Figure 5.20b: Mean hourly heat flux for Richmond in January (summer)

Solution Set: SET 11 The addition of a fly-roof.

CLIMATE: Richmond

SEASON: Summer (January)

internal ceiling temperature. The ceiling temperature is reduced by 5°C to a maximum of 30°C during most of the afternoon and matches the mean wall temperature throughout the day. The mean temperature of the walls remains virtually unchanged compared to the existing situation (SET 01). The fly-roof does not provide any additional shade to the walls.

The introduction of the fly-roof significantly reduces the thermal flux through the roof so that it is reduced from a peak of 2.0 kW entering the classroom to a negative value for the majority of the day (thermal energy leaving the space) with a peak of -0.5 kW at 10am. The flow reverses at about 4pm.

The reduction in internal surface temperatures reduces the operative temperature during the mean January day so that it is now clearly within the comfort zone.

Legend: Temperatures

- Outside air temperature
- - - External roof temperature
- Ceiling surface temperature
- - - Mean external wall temperature
- Mean internal wall temperature
- Internal air temperature
- Internal operative temperature

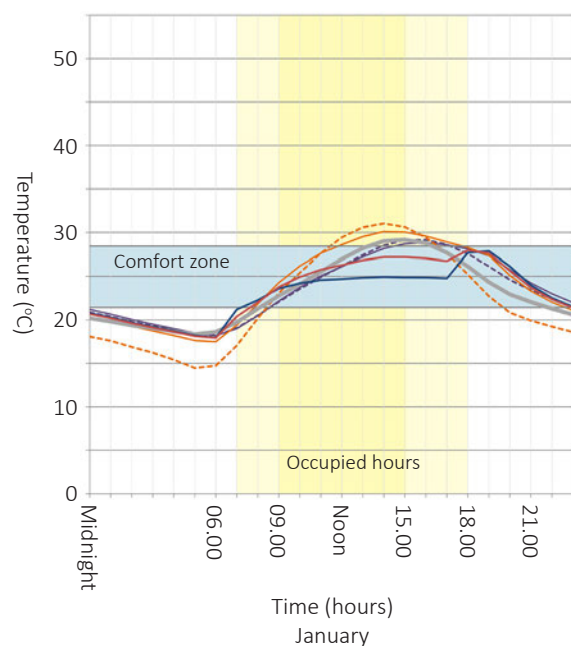


Figure 5.21a: Mean hourly temperatures for Richmond in January (summer)

Solution Set: SET 21 High-E paint

CLIMATE: Richmond

SEASON: Summer (January)

Legend: Thermal flux

- Roof
- Windows
- Opaque walls
- Floor
- Ventilation
- Internal loads
- - - Air-conditioning
- ... dT inside-outside

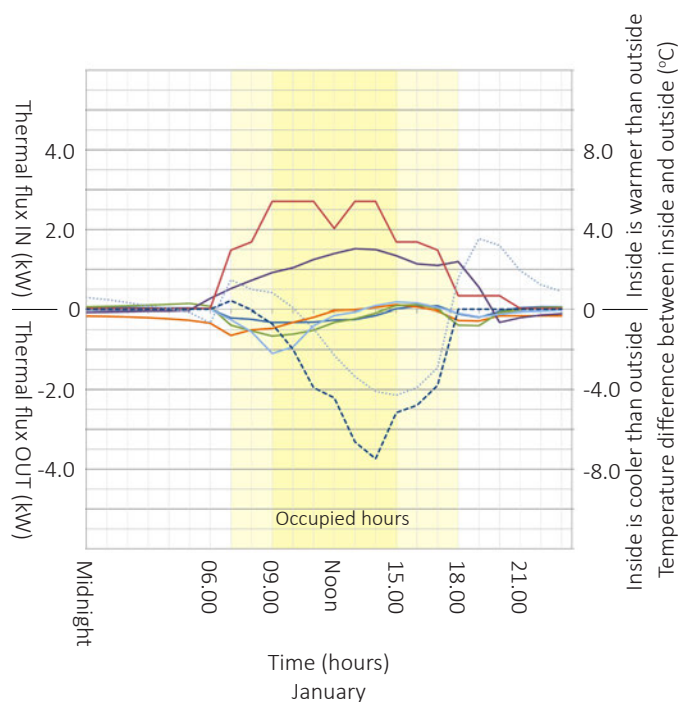


Figure 5.21b: Mean hourly heat flux for Richmond in January (summer)

Solution Set: SET 21 High-E paint

CLIMATE: Richmond

SEASON: Summer (January)

5.4.4 Using High-E paint (SET 21)

Solution Set SET 21 coats the external opaque surfaces of the NSW Demountable Classroom with a High-E paint that is highly effective at reflecting solar radiation and emitting (or dissipating) thermal radiation that is conducted to the external surface.

The consequence of the addition of the paint is a significant reduction in the external surface temperature of both the roof and the walls (Figure 5.21a). The paint causes the external roof temperature to be lower than the surface temperature of the existing 'Base-Case' by 25°C at the peak. The external roof temperature is also below the external air temperature until about 9am and after 6pm by several degrees. During the day the roof surface temperature is above the external air temperature by several degrees and slightly above the internal ceiling temperature during the hottest part of the day (11:00 – 15:00), similar to the findings of Bell et al (2003) and unlike the situation when the fly-roof Solution Set is applied (SET 11). The mean wall temperature is significantly reduced both externally and internally by the application of the High-E paint.

Thermal flux through the roof and the walls is almost entirely negative (thermal energy leaving the space) (Figure 5.21b).

The reduction in the internal surface temperatures (Figure 5.21a) reduces the operative temperature during the mean January day so that it is now clearly within the comfort zone. The mean cooling energy load

Legend: Temperatures

- Outside air temperature
- - - External roof temperature
- Ceiling surface temperature
- - - Mean external wall temperature
- Mean internal wall temperature
- Internal air temperature
- Internal operative temperature

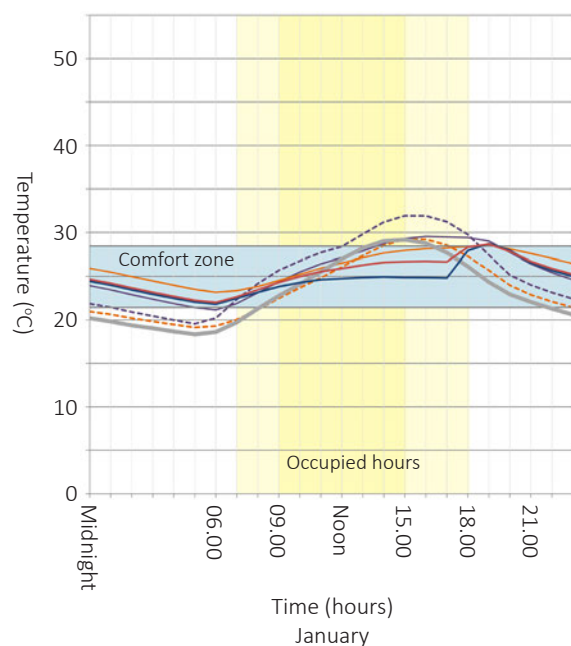


Figure 5.22a: Mean hourly temperatures for Richmond in January (summer)
Solution Set: SET 15, insulation and 36mm of fibre-cement sheet as thermal mass

CLIMATE: Richmond
 SEASON: Summer (January)

Legend: Thermal flux

- Roof
- Windows
- Opaque walls
- Floor
- Ventilation
- Internal loads
- - - Air-conditioning
- ... dT inside-outside

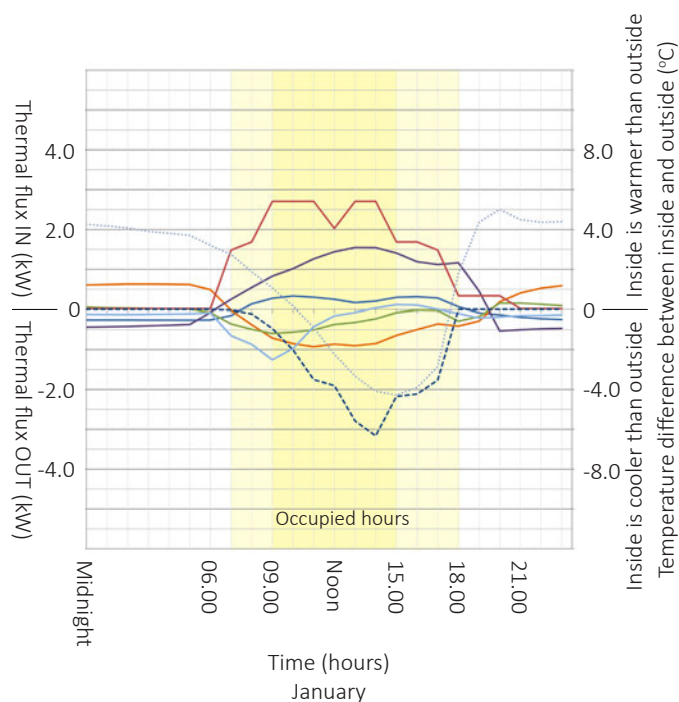


Figure 5.22b: Mean hourly heat flux for Richmond in January (summer)
Solution Set: SET 15, insulation and 36mm of fibre-cement sheet as thermal mass

CLIMATE: Richmond
 SEASON: Summer (January)

for a January day is reduced by 7.3 kWh compared to the Base-Case (SET 01) of 30.2 kWh.

5.4.5 Using a fly-roof or High-E paint combined with insulation and thermal mass (SET 15 & SET 25)

Solution Set SET 15 combines the use of a fly roof, insulation in the floor, walls and ceiling with thermal mass (36mm of FC sheet) on the walls and ceiling. Solution Set SET 25 is the same except that it omits the fly-roof and uses a High-E paint on the opaque external surfaces instead. The previous analysis showed that the use of the High-E paint (SET 21) and the fly-roof (SET 11) achieve similar overall results with slightly different detailed results. This section explores and compares the detailed results from these two Solution Sets (Figures 5.22a & b and 5.23 a & b).

The two strategies both significantly reduce the operative temperature compared to the existing situation. Compared to each other the operative temperature is practically identical with a slight but not significant divergence between the two Solution Sets of both the air temperature and operative temperature in the morning. It is notable that the previous detailed analysis of the Solution Sets showed the operative temperature and air temperature drifting below the comfort zone outside of working hours but for the two current Solution Sets both the operative and internal air temperature stay within the comfort zone for the 24 hour period.

Legend: Temperatures

- Outside air temperature
- - - External roof temperature
- Ceiling surface temperature
- - - Mean external wall temperature
- Mean internal wall temperature
- Internal air temperature
- Internal operative temperature

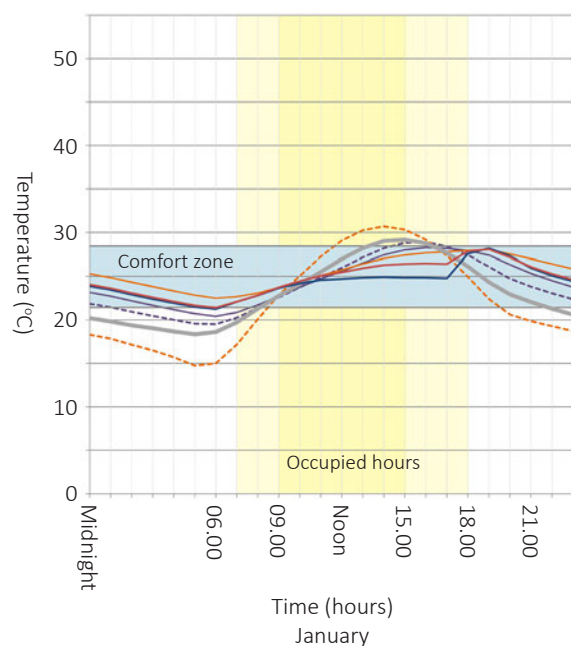


Figure 5.23a: Mean hourly temperatures for Richmond in January (summer)
Solution Set: SET 25 High-E paint, insulation and 36mm of fibre-cement sheet as thermal mass
 CLIMATE: Richmond
 SEASON: Summer (January)

Legend: Thermal flux

- Roof
- Windows
- Opaque walls
- Floor
- Ventilation
- Internal loads
- - - Air-conditioning
- ... dT inside-outside

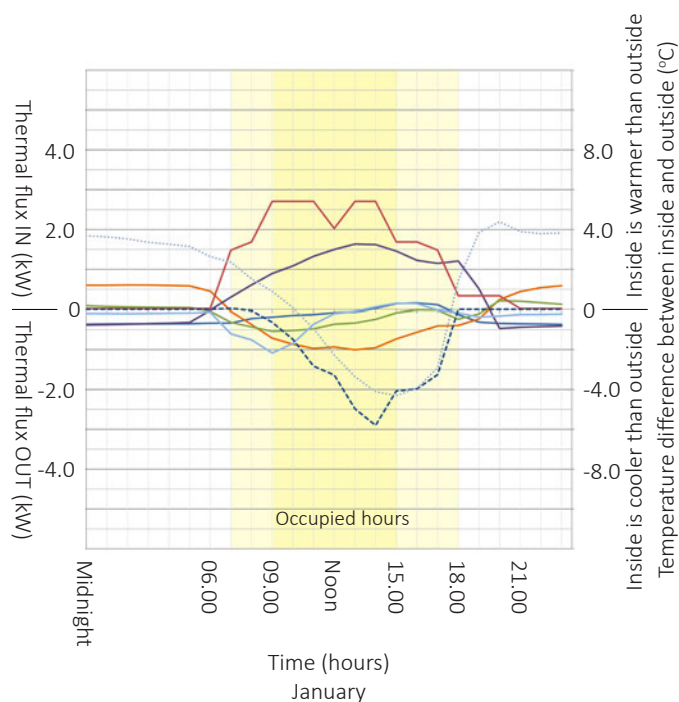
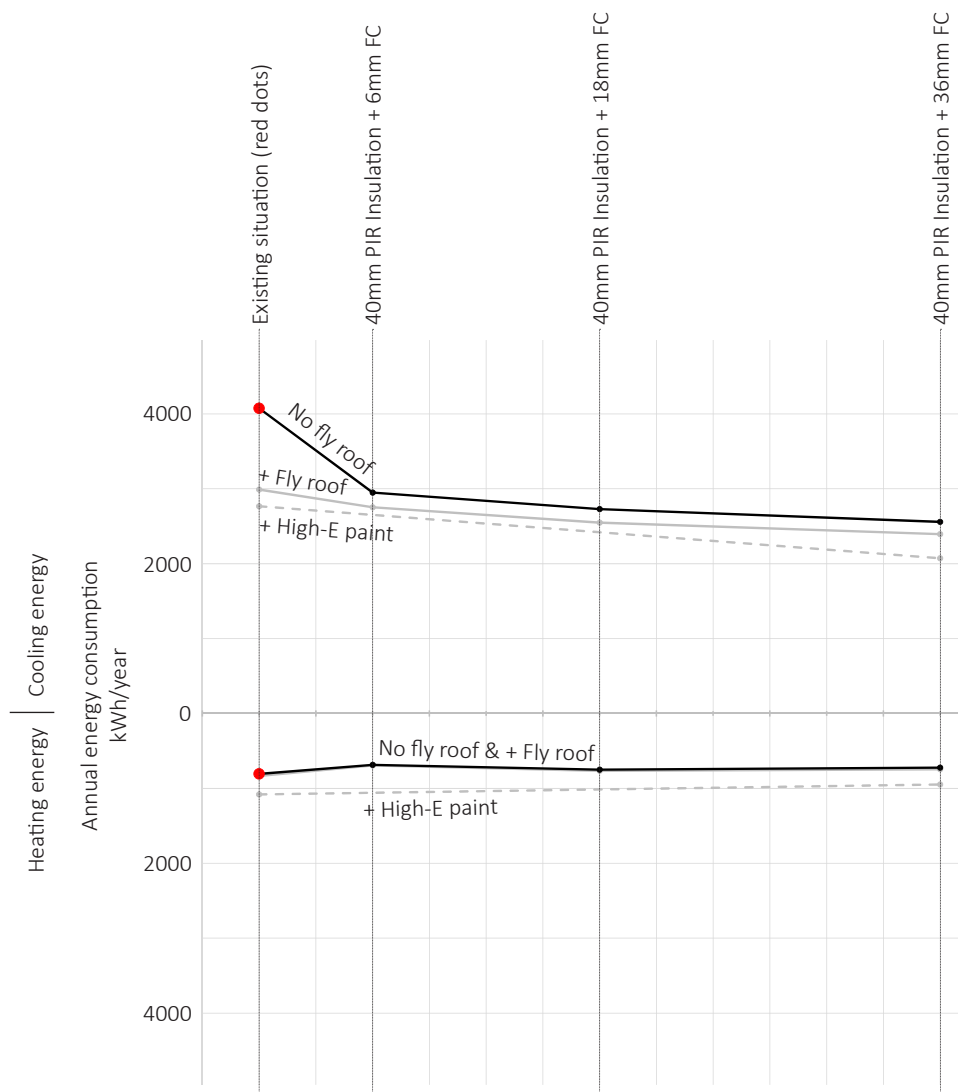


Figure 5.23b: Mean hourly heat flux for Richmond in January (summer)
Solution Set: SET 25 High-E paint, insulation and 36mm of fibre-cement sheet as thermal mass
 CLIMATE: Richmond
 SEASON: Summer (January)

The most significant difference in performance between the two Solution Sets is the external and internal surface temperatures. The external roof temperature of SET 15 with the fly-roof matches the external air temperature (as in SET 11, Figures 5.20a & 5.22a). The external roof temperature of SET 25 follows a similar track to the similar but un-insulated Solution Set (SET 21) and tracks above and below the external air temperature (Figures 5.21a & 5.23a). The internal surface temperatures of both Solution Sets are moderated by the insulation and the thermal mass. In both cases the ceiling temperature stays within the comfort zone. The mean wall temperature in SET 15 is above the comfort zone in the afternoon. With the High-E paint applied to the outside (SET 25) the mean internal wall temperature stays within the comfort zone and closely matches the ceiling temperature until the evening.

In both cases the mean cooling energy consumption for the January day is well below the existing situation of 30.2 kWh. The mean cooling energy consumption for the day is reduced to 19.9 kWh for the fly-roof Solution Set (SET 15) and 17.6 kWh for the High-E paint Solution Set (SET 25). The thermal flux through the roof is negative in both cases but through the walls it is entirely positive for the fly-roof Solution Set where the walls are not protected from the sun and positive in the afternoon when the wall is coated with High-E paint.



5.4.6 Heating and cooling energy

Figure 5.24 illustrates the impact of the Solution Sets on the annual heating and cooling energy demand of the Demountable Classroom in Richmond. The graph illustrates the points made earlier and in Figure 5.15.

A detailed review of the thermal performance of the classroom during the coldest month, July, are illustrated in Figures 5.25 - 28. The results show that the introduction of 40mm of insulation causes a reduction in the mean daily heating energy requirement of about 9% or 0.6 kWh/day. The the use of 80mm of insulation causes a further smaller reduction of 0.2 kWh/day (too small to see on the graph). The Solution Set with the fly-roof, insulation and thermal mass (SET 15) uses the same heating energy as the Base-Case while the Solution Set with the High-E coating, insulation and thermal mass (SET 25) uses 1.5 kWh/day (23%) more energy than the Base-Case (red dot).

Figures 5.24: The predicted annual heating and cooling energy from each Solution Set in Richmond

SET01 series - Black

SET11 series: Grey

SET21 series: Grey dashed

CLIMATE: Richmond

5.4.7 Thermal performance and energy demand in winter

Figures 5.25, 26 and 27 illustrate the *mean hourly values* for a day in July; i.e. each point is the mean value for that hour in July meaning that there are days when values are both above and below those illustrated. July is the coldest month.

Thermal flux

A detailed review of the thermal flux graphs for the mean day in July of the various Solution Sets shows that the heating energy is used in the morning when the temperature difference between the inside and outside is at its maximum (Figure 5.25). When the classroom is opened at 7am the external temperature is at its lowest. Following the initial period of heating the need for further heating moderates as the external air temperature increases and the number of pupils in the classroom increases. The heating load is reduced to zero during the afternoon, after about 13.00.

The addition of the various Solution Sets (Figure 5.25) all moderate the peak heating energy demand and increase the demand for heating energy later in the day. The addition of thermal mass and insulation (SET 05) illustrates this pattern most significantly. The addition of a fly-roof (SET 15) appears to have no impact on the heating demand. The addition of a High-E coating (SET 25) increases the heating energy demand compared to SET 05 at all times of the day.

In the existing classrooms thermal energy losses through the building fabric are significant (Figure 5.26). Adding 40mm of insulation to the walls (R1.9) and ceiling and 90mm of insulation to the floor (R2.5) significantly changes the flux through the floor. The flux through the walls is reduced slightly. The flux through the roof is changed both in quantity and direction: In the existing classrooms thermal energy is lost during the first few hours of the morning but by 11-00 the ceiling has become a source of radiant heat (heat gain) in the classroom. The addition of insulation reduces the losses early in the morning and prevents the ceiling from becoming a radiator later in the day. The addition of a further 40mm of insulation to the walls and ceiling has no additional or only a small impact on the flow of thermal energy.

The addition of thermal mass, fly roof or the High-E coating increases the heat losses through the roof on the mean July day. Presumably because they are preventing the thermal gains from the sun evident in the existing situation. The addition of the High-E coating also leads to a small increase in losses through the walls compared to the existing situation and other interventions.

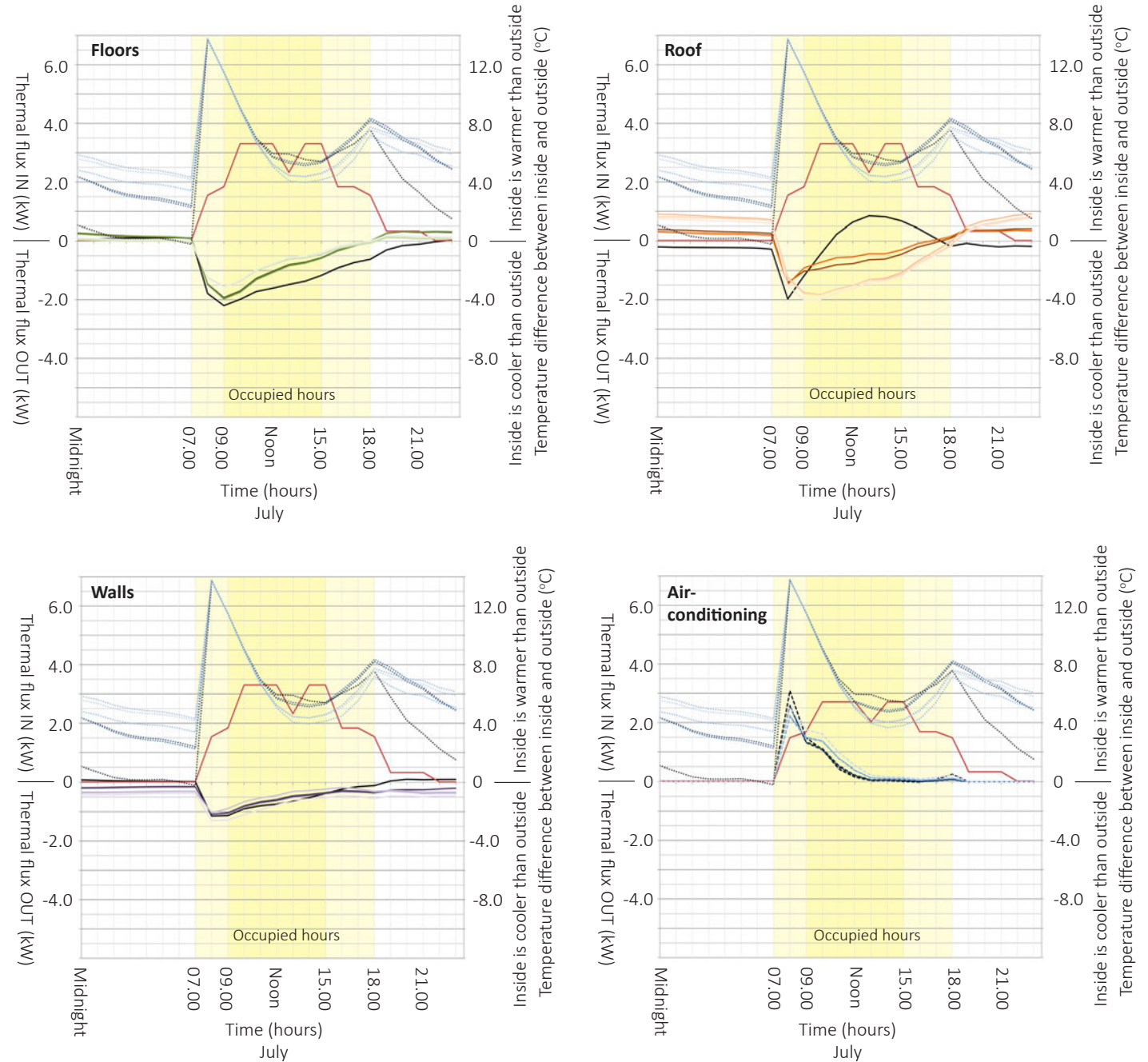
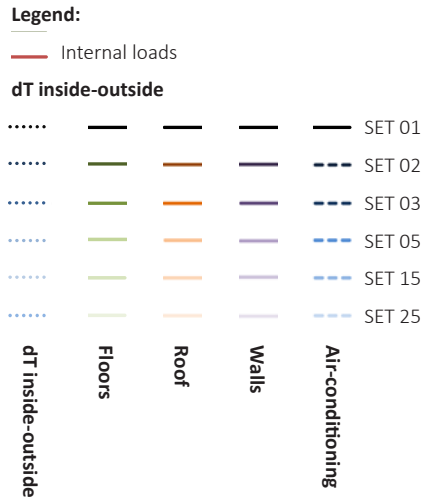


Figure 5.25: Mean hourly thermal flux for Richmond in July (winter)

Graphs show the flux through the floor, roof and walls and due to the Air-conditioning system.

Solution Sets 01, 02, 03, 05, 15 & 25 shown on all graphs with Solution Set 01 (black), SET 02 is darkest and SET 25 is lightest.

CLIMATE: Richmond

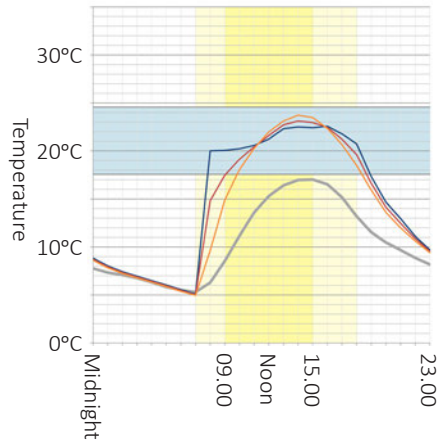
SEASON: Winter (July)

Temperature

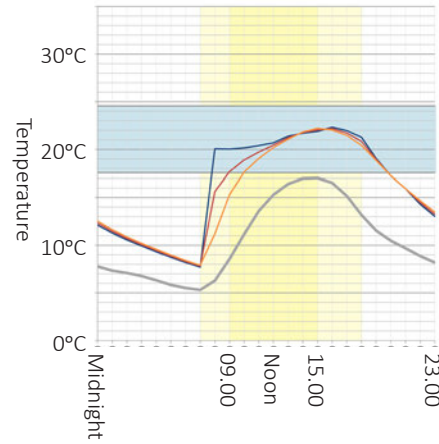
The graphs illustrating the predicted air, radiant and operative temperature in the classrooms with different configurations of Solution Sets (Figure 5.26) illustrate that the mean hourly operative temperature crosses the lower threshold of the comfort zone at the same time (09.00) in all scenarios. The various interventions contained within the Solution Sets alter the variation of the temperature during the day. The addition of insulation modifies the peak temperature and the radiant temperature. Additional insulation has no significant impact. The addition of thermal mass, a fly roof and High-E paint all cause a reduction in internal temperatures of between 1 and 2°C, the addition of the High-E paint being the most significant of these three which also significantly delays the point at which the radiant temperature in the space is within the comfort zone.

Legend: Temperatures

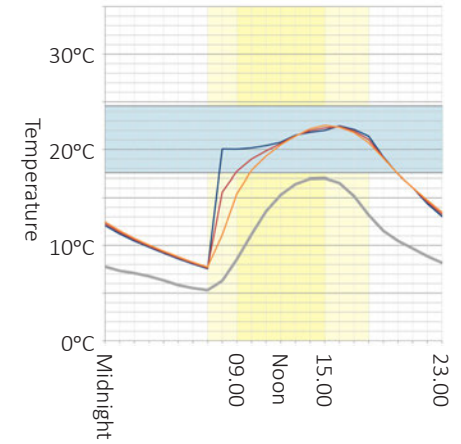
- Outside air temperature
- Internal radiant temperature
- Internal air temperature
- Internal operative temperature



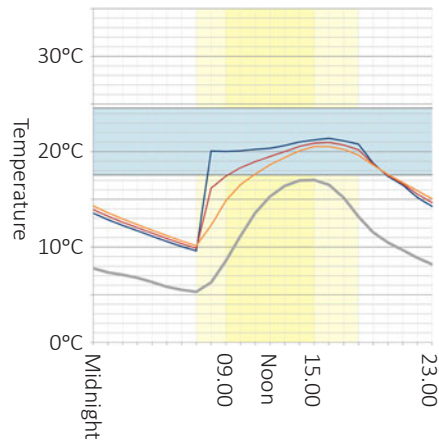
SET 01: Existing situation



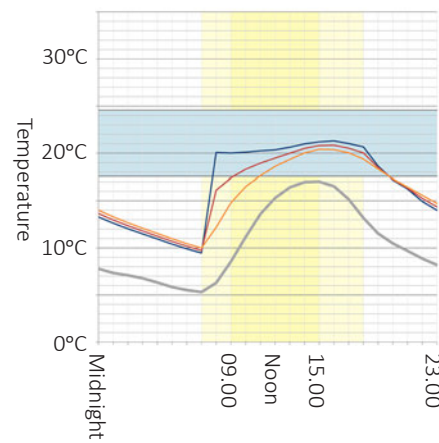
SET 02: Additional insulation (40mm)



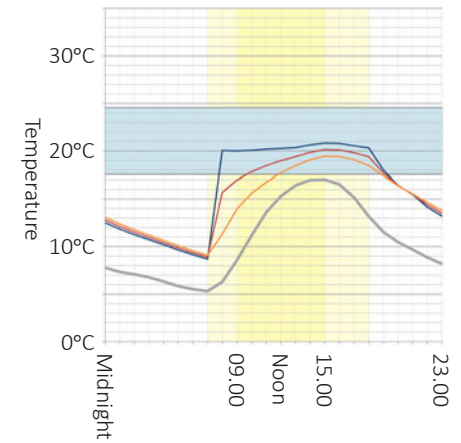
SET 03: Additional insulation (80mm)



SET 05: Additional insulation and thermal mass



SET 15: Fly-roof plus insulation & T/mass



SET 25: High-E paint plus insulation & T/mass

Figure 5.26: Predicted mean hourly temperatures in July for Solution Sets 01 (existing), 02, 03, 05, 15 & 25

CLIMATE: Richmond
SEASON: Winter (July)

Legend:

Internal loads

Thermal flux - Ventilation

SET 01

SET 02

SET 03

SET 05

SET 15

SET 25

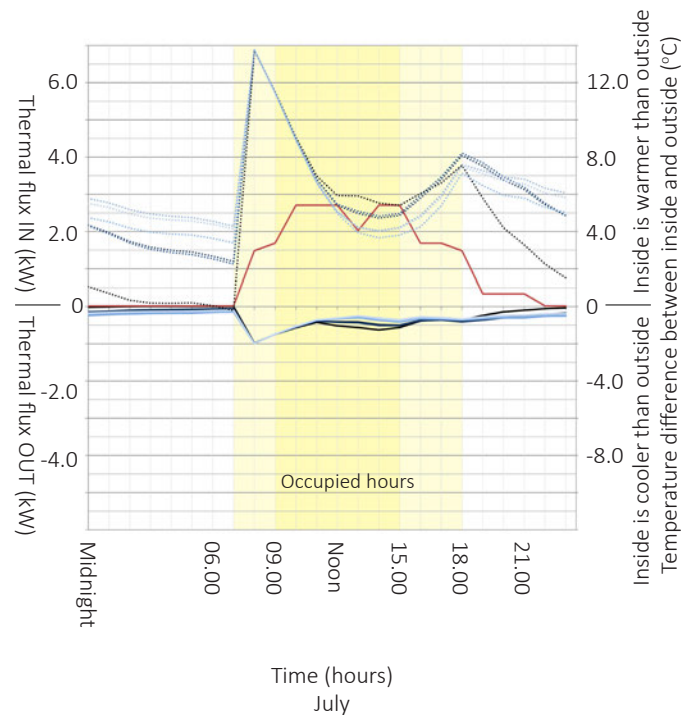


Figure 5.27: Mean hourly thermal flux due to ventilation for Richmond in July (winter)

Solution Sets 01, 02, 03, 05, 15 & 25 shown on all graphs with Solution Set 01 (black), SET 02 is darkest and SET 25 is lightest.

CLIMATE: Richmond

SEASON: Winter (July)

Ventilation

The radiant temperature of a space does not need to be within the comfort zone for the space to feel comfortable because the perception of thermal comfort is a combination of air temperature and radiant temperature. However, the absence of warm surfaces to provide a comfortable radiant temperature means that the air temperature must be raised to compensate. A ventilation rate of more than 8 L/s.person (> 4 ACH) is maintained in the classroom to ensure adequate air quality. In all scenarios, including the existing situation, the losses via ventilation are important (Figure 5.27). None of the interventions contained within the Solution Sets have a significant influence on the magnitude of these losses. When the classroom is fully occupied an air-change rate in excess of 4 air-changes/hour is required (893 m³/h). This air enters the space at the outside air temperature and the split-cycle fan coil units inside the classroom must then warm this air inside the classroom so that the air temperature is comfortable.

It is possible that the air entering the classroom may cause discomfort as a cold draft. The cool surface temperatures may also cause local discomfort. Neither of these issues are considered in the model.

5.5 Implications of the impact of Solution Sets on daily thermal comfort and energy demand

The analysis in the previous section highlights a significant challenge to achieving thermal comfort and low energy consumption in these buildings.

Thermal comfort is dominated by the relationship between the internal radiant temperature and the internal air temperature.

The results of the simulations in each of the five representative climates show that it is possible to modify the building envelope of the NSW Demountable Classroom so the envelope moderates, rather than exacerbates, the external thermal loads, so that the internal surface temperatures are close to, or within, the comfort zone (Figures 5.18 (base), 5.20, 21 & 22). This is achieved in large part by deflecting or reflecting the loads from the sun. The results have indicated that the high ventilation rate required to maintain internal air quality means that heating and cooling energy demand would still remain high. This is because when the air-conditioning is operating it must moderate the temperature of the air that has entered the classroom either above or below the thermostat set point temperature. The capacity of the split-cycle system to moderate the internal air temperature is proportional to the energy available to moderate the temperature. The predicted energy consumption of the classrooms remains well above the GBCA target of 2000 kWh/year

(Figures 5.7 - 12 & 30) after the various Solution Sets have been introduced in each climate.

Overall thermal discomfort can be significantly reduced in all five simulation climates, and predicted overheating discomfort is reduced to zero or close to zero. However under-heating discomfort remains a challenge, particularly early in the morning when the outside air temperature is well below the comfort zone (Figures 5.25 - 5.27).

This analysis is based on a simulation model embedded within which are a number of assumptions about how people perceive comfort and how the NSW Demountable Classrooms are used. Simulation models are, of necessity based on assumptions about how people behave, use things and respond to stimuli. No two teachers will use their classroom in the same way. The model is used to indicate how modifications to the classroom, and the way the classroom is used, can change the levels of thermal discomfort and the quantity of energy used by the classroom to maintain comfort in terms of magnitude, and direction, over a year or a season.

The significant assumptions that have been made in this model are

- The use of air movement to enhance comfort
- The underlying definition of comfort
- The thermostat settings for each climate

5.5.1 The use of air movement to enhance comfort

The idea that air movement can enhance our perception of comfort or make temperatures that would normally be considered too warm be considered comfortable is well established (Table 5.3) (Fountain et al., 1994, Toftum, 2004, Arens et al., 2009). Intuitively we understand that it is the cool gentle breeze through the window or under the shade of a tree on a warm day, or the ceiling fan on a hot night, that makes a space comfortable or even pleasant to be in.

Thermal comfort standards have traditionally regarded air movement as undesirable because of concern about cold drafts. Within the adaptive comfort model adopted in this study the use of air movement, of opening and closing windows, in order to manage thermal comfort is implicit as an “adaptive measure”. The use of air movement to enhance thermal comfort has been the subject of many field studies. These field studies have found that there is a common desire among building occupants for more air movement rather than less (Arens et al., 2009, Cândido et al., 2010). Xia et al and Huang et al (Xia et al., 2000, Huang et al., 2013) found that air speeds in excess of 2 m/s can be acceptable in certain circumstances and a brief literature study by Szokolay suggested the same (Szokolay, 2000).

The difference between air movement created by a fan and natural ventilation is the variation in speed and turbulence of the air in a naturally ventilated space compared to the mechanically ventilated space.

The significance of this variation has been shown by researchers such as Xia et al (2000). Xia et al showed that increasing the turbulence of the air speed (defined as the standard deviation of air velocity divided by the mean air velocity) increases the cooling effect of the air movement. i.e. Higher air turbulence allows a reduction in mean air velocity for a given cooling effect. Zhao (2007) found subjects in an experiment preferred an air flow pattern similar to natural outdoor air flow rather than the monotonous laminar airflow normally created by mechanical ventilation systems. Zhao also found that a similar effect can be established by changing the air temperature rather than the air flow pattern.

5.5.2 The underlying definition of comfort & an alternative understanding of the perception of comfort

The concept of pleasure arising from our thermal environment is not something that features in current thermal standards (ASHRAE, 2013, ISO_7730, 2005). Existing comfort standards, including the adaptive comfort model, are derived from a methodology that measures the absence of discomfort rather than the creation of comfort (de Dear and Brager, 1998, Humphreys and Nicol, 2002, Nicol and Humphreys, 2010). The standards are written to ensure that less than 20% of people express dissatisfaction with their thermal environment rather than specifying satisfaction or pleasure. However we know from everyday lived experience that the thermal environment can cause pleasure as well as discomfort, and that our experience

Air movement enhances our perception of thermal comfort by:
- Increasing the rate of evaporation from our skin which, in turn, increases cooling through the increase in the loss of latent energy through evaporation (the change in state from liquid to gas). - Increasing heat convection which increases the opportunity of heat exchange between the body and the air. - The turbulent or transient nature of a natural breeze creates a pleasant sensation.

Table 5.3: Air movement and the perception of thermal comfort

of the thermal environment is about much more than the absence of comfort.

Lisa Heschong’s totemic book, “Thermal Delight in Architecture” (Heschong, 1979) explores our complex and multifaceted relationship with the thermal environment through four headings, only the first of which is considered within the existing comfort standards:

Necessity:	Humans physiological need to maintain life.
Delight:	Sensual stimulation and pleasure
Affection:	Emotional engagement though patterns of social activity including different gathering spaces such as the hearth, the sauna or the veranda.
Sacredness:	Cultural traditions and significance

Heschong argues that humans have evolved to perceive change and so variation within our thermal environment is stimulating while neutrality and homogeneity is monotonous.

Kuno (Kuno, 1995) argues that we cannot experience thermal pleasure until we have experienced a little discomfort and that this is why naturally ventilated buildings are more pleasant:

“Neutral environments have no pleasantness. Passive systems produce a little discomfort and therefore can bring pleasantness.”

In 2011 De Dear proposed the application of Cabanac’s theory of alliesthesia (Cabanac, 1971) to the adaptive model of thermal comfort. In essence the theory suggests that pleasure is derived from the dynamic experience of moving from discomfort to comfort (De Dear, 2011). In 2015 and 2016 Parkinson and De Dear published a series of papers that develop this idea further through argument and experiments (Parkinson and de Dear, 2015, Parkinson and de Dear, 2016, Parkinson et al., 2016). They argue that when the body’s peripheral temperature receptors (skin) sense conditions that bring the body’s temperature closer to its “set point” those conditions will be perceived as pleasant. The opposite, thermal sensations that will move the body’s temperature away from the set point, will be perceived as un-pleasant. The larger the relief from discomfort the greater the pleasure signal. Parkinson and de Dear suggest that it is this oscillation between discomfort and comfort, displeasure and pleasure that creates the positive hedonic tone or pleasure (Parkinson and de Dear, 2015). The oscillation is by definition temporal (it occurs in time) and can be generated by the physical movement of the person from one thermal environment to another (Parkinson et al., 2012) or by the variation of the thermal environment itself (Xia et al., 2000, Zhao, 2007, Parkinson and de Dear, 2016, Parkinson et al., 2016) which is why the breeze from an open window in a warm room or the warmth of direct sunlight in a



Figure 5.28: Thermal delight under the oak tree

Listening and learning on a summer afternoon: Thermal delight under the oak tree at Cumnor House School, Sussex, England. PHOTO: Cumnor House School

cool room might be pleasant. The opposite, a breeze in a cool or cold room or direct sunlight in a warm room is likely to be considered unpleasant. The pleasure of the cooling breeze or the warming sun is derived from the moderate displeasure experienced immediately before, had the displacement from thermal equilibrium not occurred the experience of pleasure could not occur.

Interestingly, in 1939 Bedford and Warner observed that, *“the air movement should be variable [because] The body is stimulated by ceaseless change in the environment”*. (Bedford and Warner, 1939)

5.5.3 Re-assessing the simulation thermostat settings

The results of this series of simulations have been assessed against the existing standards. The results have conformed to the convention of measuring the absence of discomfort rather than measuring an increase in pleasure because that is how the standards are constructed and because discomfort has been shown to be a serious problem in these classroom buildings.

The proposed modifications to the building envelope have successfully reduced thermal discomfort but, despite significant reductions, have not managed to reduce the overall energy demand to levels that are below the GBCA target.

The adaptive comfort model is posited on the understanding that thermal comfort is not something we passively receive, it is something we actively seek. Comfort is a state of mind and body. We engage with

our environment to become comfortable. We adapt ourselves and our thermal environment to improve comfort (Nicol and Humphreys, 1973, Brager et al., 2004, Arens et al., 2009, Huang et al., 2013). The incorporation of the theory of Alliesthesia into the adaptive comfort model provides an overarching framework that explains our intuitive understanding of our thermal environment. The theory reconciles and connects many of the observations of our relationship with our thermal environment, in particular, it explains how natural ventilation and a more dynamic thermal environment can enhance our thermal experience even when it is warm.

There is no standard for predicting thermal pleasure within an environment, however the principles outlined above enable us to revisit the parameters defining thermal comfort within the simulation model to account for some of the factors that will enable the occupants of the classroom to experience a more dynamic and therefore pleasant thermal environment.

The simulation model assumes that the building operates in a “mixed mode”. This means that when conditions inside and outside the classroom are within the parameters defined by the thermostat settings natural ventilation occurs, creating the dynamic thermal environment that, it is argued, is necessary for the thermal environment to be enjoyable. When the outside air temperature is above or below the thermostat settings and will not enhance comfort in the classroom the windows are closed and the air-conditioning system operates.

In the current simulation model the thermostat settings are fixed throughout the year. The lower limit is fixed at 20°C and the upper limit is defined as the neutral temperature as defined by the adaptive comfort model for the hottest month which is assumed to be January (Chen, 2016) (also see Chapter 2). This creates a fixed range of temperature between 4.2°C and 5.9°C wide compared to the dynamic 7°C band defined by the adaptive comfort model. The upper and lower limit of the adaptive comfort zone vary in response to recent mean daily temperatures. The simulation model uses the adaptive comfort model to predict comfort.

So the assumption that teachers adjust the thermostat settings in their classrooms based on their perception of comfort and recent thermal experience would be consistent with other assumptions in the model.

A broader range of temperatures during which natural ventilation is used in the classroom would reduce the use of the air-conditioning system and the associated energy demand. The discussion above also suggests that

- A wider comfort band would be acceptable and increases the opportunity for natural ventilation.
- That increased natural ventilation may enhance comfort by increasing the dynamism of the thermal environment in the classroom and so increasing opportunities for thermal pleasure, as well as displeasure.

Further evidence for changing the thermostat settings comes from recent research by Kim et al (Kim et al., 2016). Kim et al conducted a field study of thermal

comfort and the use of air-conditioning in residential buildings in NSW. The households who took part were in the Sydney region and Wollongong (on the coast south of Sydney). These two climates are broadly equivalent to the Williamstown climate used in this study, although some of the "Sydney region" climates may be closer to the Richmond climate. The research found that within the domestic setting, when people have considerably more adaptive opportunities than in an office environment (on which the adaptive comfort model is based) people are more tolerant of thermal variation and the 80% acceptability comfort zone is 2° wider than the adaptive comfort model predicts. The additional 2° are at the lower (cooler) edge of the comfort band.

Significantly for this project the use of air-conditioning was also studied: Kim et al found that 80% of people did not turn on the air-conditioning for cooling until the outdoor air temperature was 28°C or above. The number of people using air-conditioning or another appliance for heating crosses the 20% threshold (less than 80% people have the heating turned off) at an outdoor air temperature of 22°C.

The domestic setting is different from the school setting in terms of expectations for behaviour, clothing, the tasks being undertaken and all of the adaptive opportunities, or lack of opportunities, that these social conventions entail. Another study of thermal comfort in NSW classrooms also found students to be more tolerant and adaptable than the ASHRAE adaptive comfort model predicts but with a greater preference for cool conditions (de Dear et al., 2015), echoing Kim

et al's findings of a broadening of the comfort zone and preference for cooler conditions in the domestic setting. De Dear et al's findings are supported by other studies (Kwok et al., 1998, Wong and Khoo, 2003, Kwok and Chun, 2003, Hwang et al., 2009, Huang et al., 2013). De Dear et al (2015) also found that more diverse thermal experience leads to greater adaptability and tolerance of thermal diversity.

5.6 A revised simulation model: The impact of thermostat settings on thermal comfort and annual energy demand

The discussion above argues that, while the thermostat settings used in the simulation conform to current standards and prescribed practice, they may not reflect the way people use buildings, or, even if they do reflect how classrooms are used, modifying how classrooms are used may be beneficial in terms of both thermal comfort and energy use.

There are two possible strategies for re-defining the operation of the classrooms within the simulation model:

The first is to assume that the teachers will control the air-conditioning units and adjust the thermostat settings in response to recent thermal experience and so behave in a manner predicted by the adaptive comfort model.

The second is to assume that the thermostat settings are fixed but that the cooling set point and the heating set point are adjusted to broaden the period of time the classrooms operate as free running naturally ventilated buildings and so reduce the use of air-conditioning.

The question that then arises is what should the thermostat settings be? The evidence from the research by Kim et al (Kim et al., 2016) suggests that a cooling set point of 28°C and a heating set point of 22°C may

be reasonable. Huang et al (2013) argues that monthly variation set points following the adaptive comfort model are unnecessary and that the upper and lower limits for the year should be used. For Richmond this would mean a cooling set point temperature of 28.6°C and a heating set point temperature of 17.6 °C (based on the simulation climate file, BOM data gives 28.7 and 17.6 °C respectively). The current set points are 25.2 and 20 °C respectively.

Upper (cooling)	Lower (heating)	
28.7 °C	22.0 °C	Highest set point temperature of the year defined by the adaptive comfort method
28.0 °C	22.0 °C	Limits observed by Kim et al (2016)
27.0 °C	21.0 °C	
26.0 °C	21.0 °C	
25.2 °C	20.0 °C	Current set point temperatures
25.2°C	19.0 °C	
25.2°C	18.0 °C	
25.2°C	17.6 °C	Lowest set point temperature of the year defined by the adaptive comfort method
28.7 °C	17.6 °C	Upper and lower limits set by the maximum and minimum of the adaptive comfort zone during the year (ASHRAE 2013)

Table 5.4: Fixed upper and lower setpoint temperatures based on various parameters

5.6.1 Revised simulation

The review of the impact of thermostat settings on thermal comfort and annual energy consumption in Chapter 2 demonstrated that variations to the thermostat settings act independently on heating, and the associated cold discomfort, and cooling, and warm discomfort.

The model for Richmond with Solution Set SET 15 has been simulated with a series of thermostat settings based on the discussions above. The thermostat settings are illustrated in Tables 5.44 and 5.5. Table 5.4 shows the various fixed set point temperatures defined by the different arguments set out above. The model was run to test each of these scenarios and the points in between at 1°C intervals. Table 5 shows the thermostat settings defined by the 80% acceptability adaptive comfort zone.

The model using the adaptive comfort protocol was run for each month and the thermostat settings were changed manually. The results were collated to create data for a whole year.

The results of the simulations are discussed below and plotted on the scatter graphs (Figures 5.29 and 5.30).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Upper (cooling)	28.4	28.6	27.9	27.0	25.6	24.7	24.6	24.8	25.7	26.6	27.2	28.4
Lower (heating)	21.4	21.6	20.9	20.0	18.6	17.7	17.6	17.8	18.7	19.6	20.2	21.4

Table 5.5: Set point temperatures for each month in Richmond varied to follow the adaptive comfort model
Set point temperatures for each month in Richmond varied to follow the adaptive comfort model using the mean daily temperatures from the simulation weather file.

5.6.2 Results

Figure 5.29 shows each simulation plotted as a point comparing the annual energy demand against annual thermal discomfort measured as degree-hours. The existing situation, SET 01, plotted as a red dot, the results from the previous simulations of Solution Sets SET 02 – SET 25 for Richmond are plotted grey, and. The plot demonstrates the significant improvement in thermal comfort and reduction in annual energy demand the Solution Sets achieve with the thermostat settings used in the first round of simulations following the NatHERS protocol. The Solution Set used for this series of comparisons, SET 15 (insulation, thermal mass and fly-roof), has the lowest levels of discomfort and second lowest annual energy demand (dark grey).

Setting the thermostat set point temperatures to follow the upper and lower limits of the adaptive comfort zone (green) reduces energy consumption below the 2000 kWh/year target of the GBCA at the cost of significant predicted discomfort compared to the majority of the results with fixed thermostat set points. The exception is the model that follows the protocol proposed by Huang et al (2013) to use the annual maximum and minimum set points defined by the adaptive comfort zone. This scenario (yellow) uses the least amount of energy (1293 kWh/year) but at the cost of significant predicted thermal discomfort (2696 degree-hours) which is above the existing classroom's level of discomfort.

The second scatter graph (Figure 5.30) illustrates the same simulations but with energy and discomfort

separated into warm and cold discomfort and the associated cooling and heating energy. This second plot shows that the use of the adaptive comfort model or Huang et al's protocol to define heating and cooling set points significantly reduces cooling energy demand but increases overheating to close to but still below the levels found in the existing classroom. Cold discomfort also increases significantly but offers only a small reduction in heating energy demand.

Reducing the heating set point temperature (blue) below 20°C increases discomfort for a minimal saving in energy demand. As the heating thermostat set point moves further below 20°C the corresponding reduction in energy demand reduces.

Increasing the heating set point above 20°C reduces thermal discomfort at the cost of an exponential increase in heating energy demand.

In contrast adjusting the cooling set point temperature (brown) has a significant impact on both annual energy demand and discomfort, with the energy demand decreasing and discomfort increasing in response to an increase in the set point temperature.

An analysis of the variation in mean daily air, radiant and operative temperatures inside the classrooms and the outside air temperature in January and July (Figures 5.31 & 5.32) illustrates that SET 15 has significantly moderated the internal radiant temperature. The graphs also illustrate that the challenge to improving thermal comfort and reducing energy demand remains rooted in tension between moderating the internal

Legend

- The existing situation (SET 01).
- Solution Sets SET01 - SET 25 with set points at 20°C and 25.2°C (NatHERS standard)
- Heating set points REDUCED below 20°C (NatHERS standard) (SET 15)
- Cooling set points INCREASED above 25.2°C (NatHERS standard) (SET 15)
- Set Points varied monthly to follow the Adaptive Comfort protocol (SET 15)
- Set points based on findings of Kim et al 2016 (22 - 28°C) (SET 15)

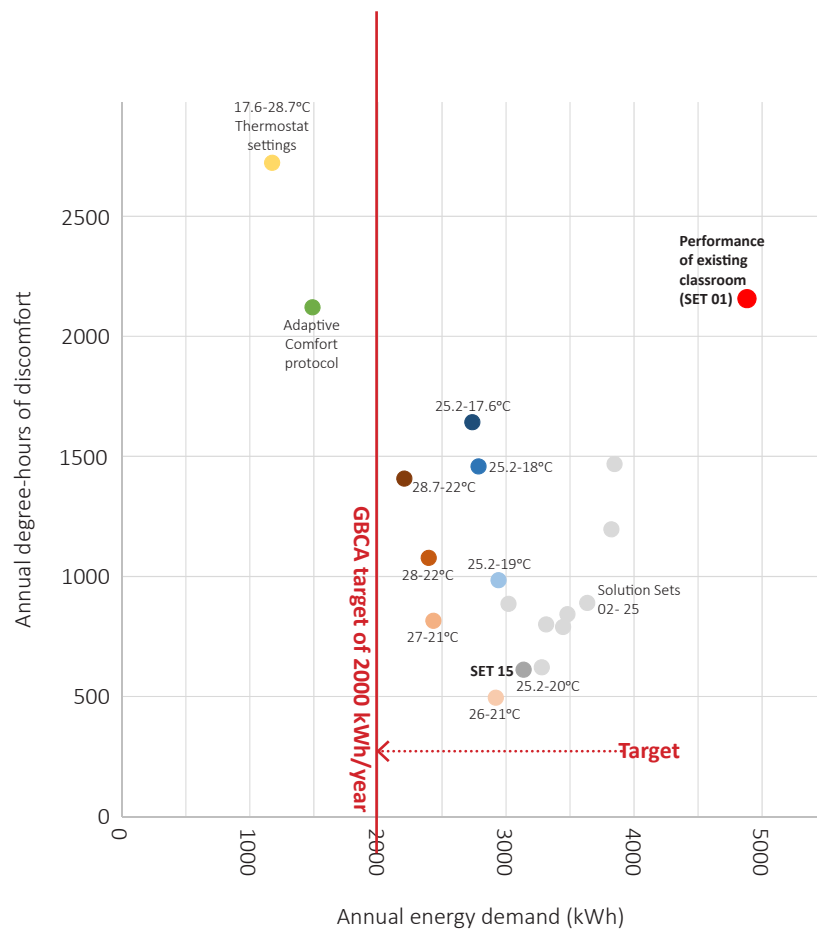


Figure 5.29: Total annual energy and thermal discomfort

Total annual energy demand plotted against total annual thermal discomfort measured as degree-hours for different thermostat settings

CLIMATE: Richmond

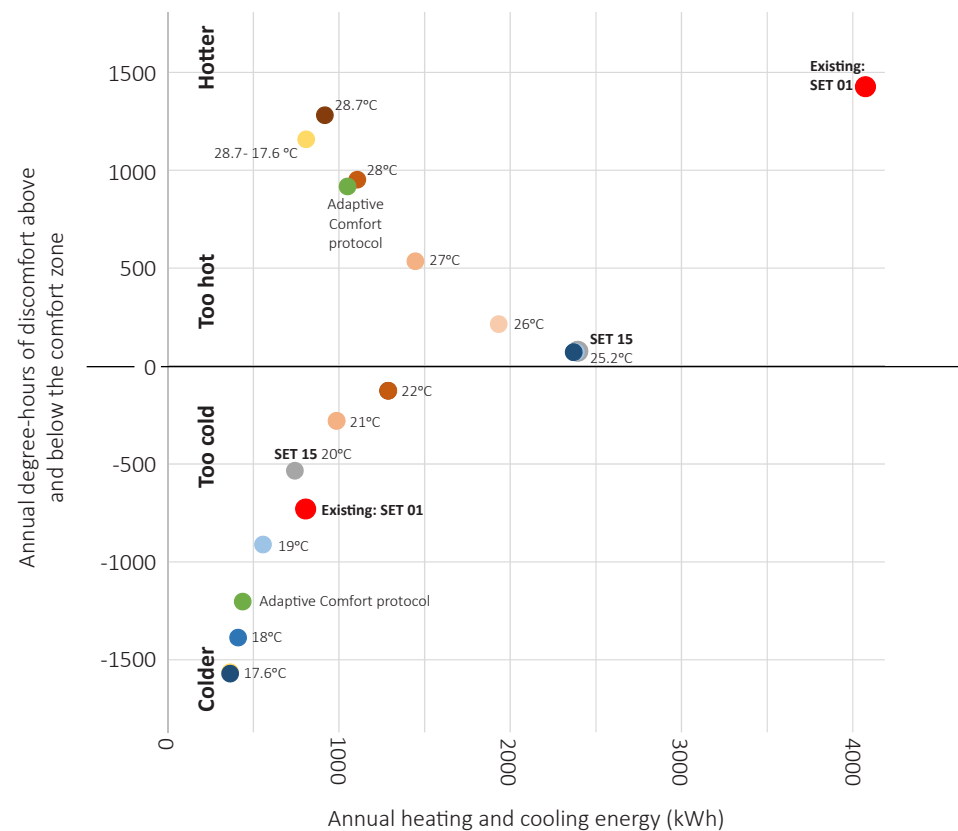


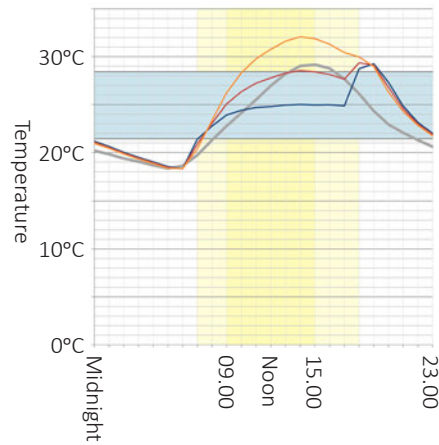
Figure 5.30: Annual thermal discomfort above and below comfort zone with annual energy demand

Annual thermal discomfort above and below comfort zone measured as degree-hours for different thermostat settings [plotted against annual heating and cooling energy demand.

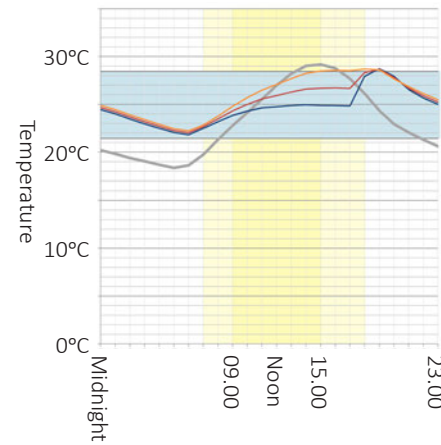
CLIMATE: Richmond

Legend: Temperatures

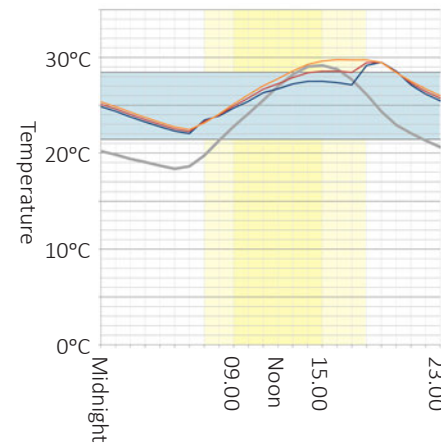
- Outside air temperature
- Internal radiant temperature
- Internal air temperature
- Internal operative temperature



Existing situation: Cooling set point temperature 25.2°C



SET 15: Cooling set point temperature 25.2°C



SET 15: Thermostat settings follow the adaptive comfort protocol. Cooling set point temperature 28.7°C

air temperature and minimising the energy needed to achieve that.

The graphs of the mean hourly temperatures for January (summer) show that raising the cooling set point temperature to 28.7°C reduces the temperature difference between the internal and external air, therefore the amount of energy needed to cool four air changes an hour is reduced. The rise in the internal air temperature also allows the internal radiant temperature to rise because the cooling effect on the internal surfaces through convection and conduction is reduced. In January the rise in air temperature and rise in radiant temperature raises the operative temperature so that the mean operative temperature for a day in January is just above the comfort zone.

Raising the heating set point temperature in July (winter) improves thermal comfort but also increases the difference between the incoming external air and the desired internal air temperature, thus increasing the heating energy demand. Reducing the heating set point temperature in winter reduces the heating demand but, because the building fabric is also cold and so the radiant temperature is low, the operative temperature (the mean of radiant and air temperature) is lowered and so cold discomfort increases.

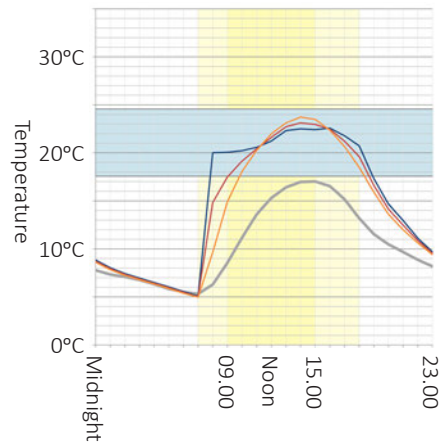
Figure 5.31: Predicted mean hourly temperatures in January using different cooling point thermostat settings.

CLIMATE: Richmond

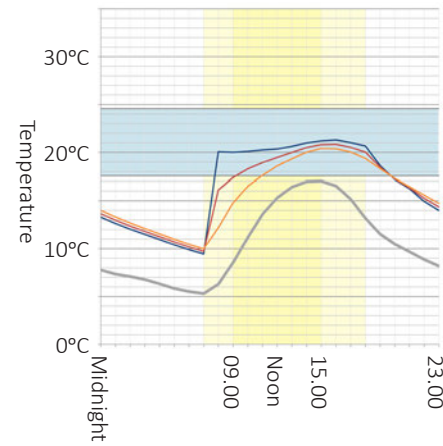
SEASON: Summer (January)

Legend: Temperatures

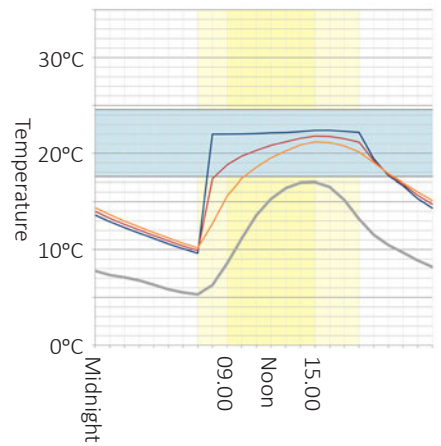
- Outside air temperature
- Internal radiant temperature
- Internal air temperature
- Internal operative temperature



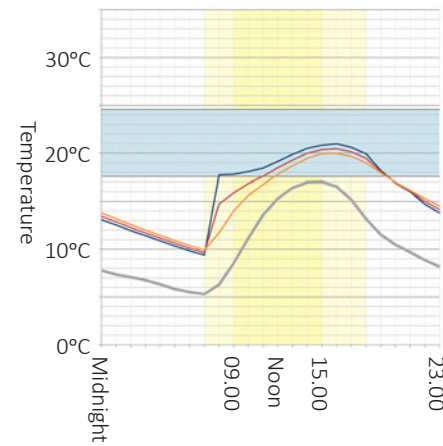
Existing situation: Heating set point temperature 20.0°C



SET 15: Heating set point temperature 20.0°C



SET 15: Heating set point temperature 22.0°C following the observations of Kim et al 2016



SET 15: Thermostat settings follow the adaptive comfort protocol. Heating set point temperature 17.6°C

Figure 5.32: Predicted mean hourly temperatures in July using different cooling point thermostat settings.

CLIMATE: Richmond
SEASON: Winter (July)

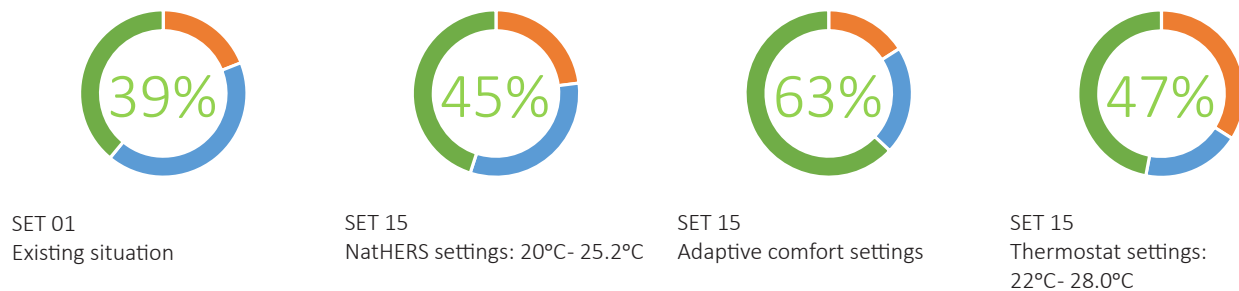


Figure 5.33: Percentage of time naturally ventilated

Proportion of annual working hours the classroom is operating as a naturally ventilated building (green), HVAC heating mode (red) or cooling mode (blue) for different scenarios.
CLIMATE: Richmond

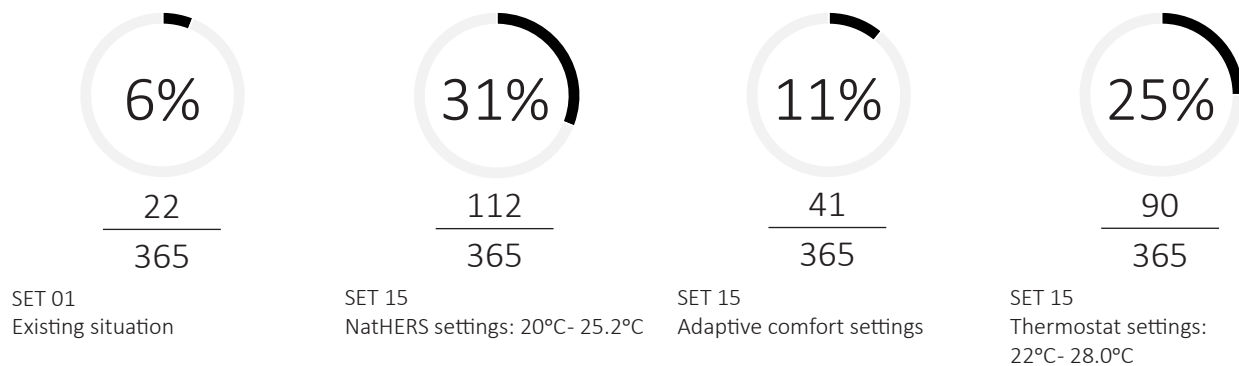


Figure 5.34: Days without any discomfort

Number of days per year the Richmond Demountable Classroom is predicted to be within the comfort zone for the entire working day.
CLIMATE: Richmond

5.6.3 Summary:

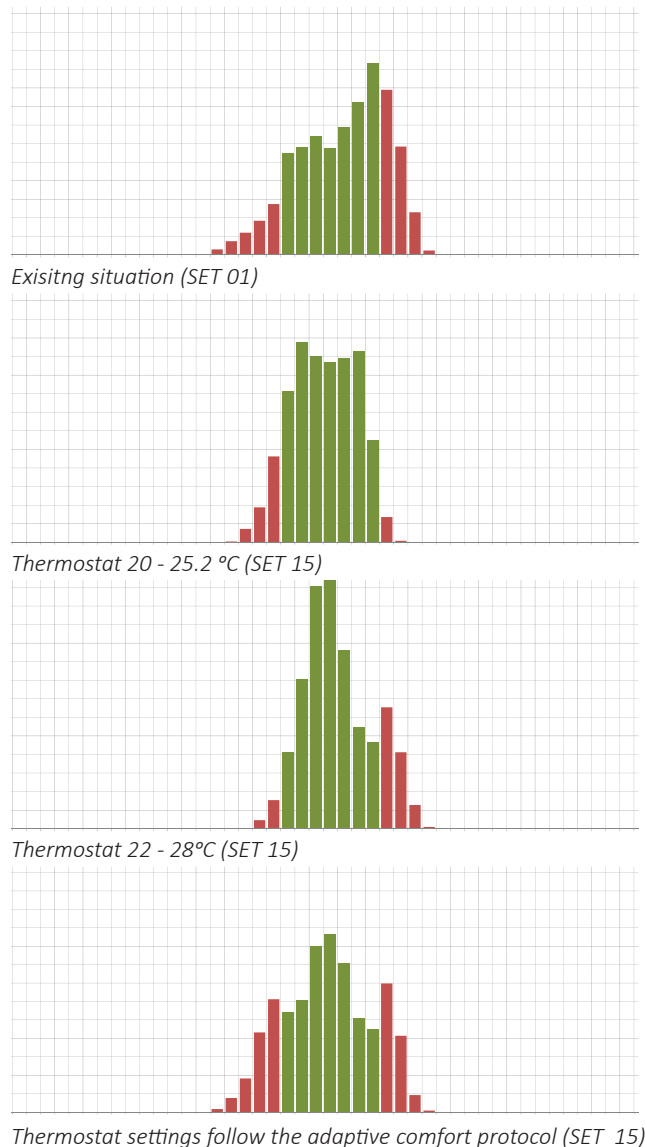
The impact of thermostat settings on thermal comfort and annual energy demand

The plots demonstrate the significant impact adjusting the thermostat settings can have on the annual energy demand of the classrooms and the thermal comfort of those who use them. How we experience and define thermal comfort is also clearly a significant factor and, as has been discussed above, an area of continuing interesting research.

Figures 5.33, 5.34 and 5.34 provide a further series of comparisons that illustrate how the modification of the fabric of the classroom, the way we use the classroom and what we perceive or accept as comfortable are all intertwined. The un-modified existing classroom is included in the comparison to illustrate the improvements that are possible and inform the discussion. Three scenarios are illustrated using Solution Set SET 15 modifications to the building fabric.

The thermostat temperatures are defined by

- The NatHERS protocol (as with the existing classroom): 20°C - 25.2°C.
- The adaptive comfort zone
- The limits observed by Kim et al (2016): 22°C - 28°C



Figures 5.35: Annual number of degree hours below, within and above the comfort zone (green)

The top chart shows the existing situation.

The lower charts show the SET 15 Solution Set with different thermostat settings.

SOLUTION SETS: SET 01 (top) and SET 15

CLIMATE: Richmond

UNITS: Bars are in one degree increments

The charts compare the number of days completely free of discomfort and the proportion of working hours the classrooms are naturally ventilated, heated or cooled.

It has already been established that the SET 15 modifications to the fabric of the classroom significantly improve the thermal performance of the classroom. These charts show that when the classroom is operated following the NatHERS protocol approximately 1/3 of days (out of 365) occur with no thermal discomfort which is significantly higher than when the classroom is operated following the protocol elaborated from the work of Kim et al (2016) or following the adaptive comfort model.

However if it is important that the users of the classroom experience and enjoy a naturally ventilated space then the NatHERS thermostat settings will be the most restrictive while the adaptive comfort model allows the classroom to be naturally ventilated for approximately 2/3 of the hours of operation. The arguments for naturally ventilated spaces revolve around a desire to create a dynamic thermal environment that may increase both pleasure and dis-pleasure, or comfort and discomfort, in order to create a more stimulating space. As noted above, field studies using the adaptive comfort model frequently report subjects expressing a preference for more air movement, a benefit of a naturally ventilated space.

Further modifications to the landscaping surrounding the classroom may also improve the thermal comfort and thermal experience of the classroom occupants.

In Chapter 4 the possibility of developing vegetated envelopes was discussed. Without repeating the discussion here it is clear that the shade and evaporation from the leaves of plants (evapo-transpiration) reduces local air temperatures and may also improve air quality (Akbari, 2002, Akbari et al., 2001). While using plants as part of the building fabric is not practical for these classrooms, it may well be practical to surround them with plants.

5.7 A third modification: introducing photo-voltaic panels

The analysis of the existing classroom buildings in Chapter 2 showed that the primary cause of thermal discomfort in the classrooms is the solar energy loads on the building envelope, thermal flux through the fabric and consequential high radiant temperature inside the classrooms. In order to solve the problem of thermal comfort within the classroom it was necessary to improve the thermal performance of the building envelope and so reduce the radiant temperature inside the classrooms. The analysis in this chapter has shown that the Solution Sets can achieve that objective, practically eliminating overheating discomfort in several climates, but they have had a relatively modest impact on annual heating and cooling energy demand.

This section investigates the potential for using the classrooms to generate energy to meet this continuing demand by Integrating photo-voltaic panels into the building shading device. This transforms the fly-roof from a passive deflector of solar energy into something that transforms the solar energy from a problem into useful electricity.

The following series of simulations illustrates the amount of power two different configurations of panels can generate in the five representative climates that have been used in this study (Figure 5.36).

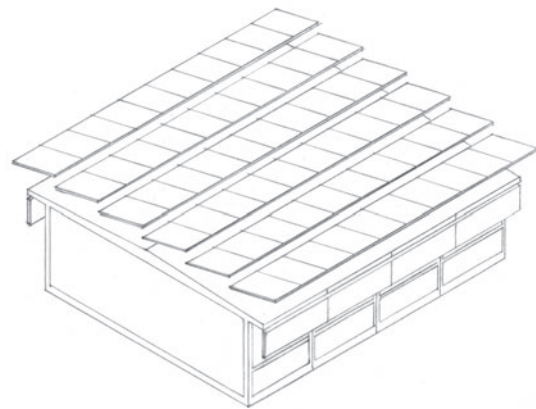


Photo Voltaic panels oriented to the North

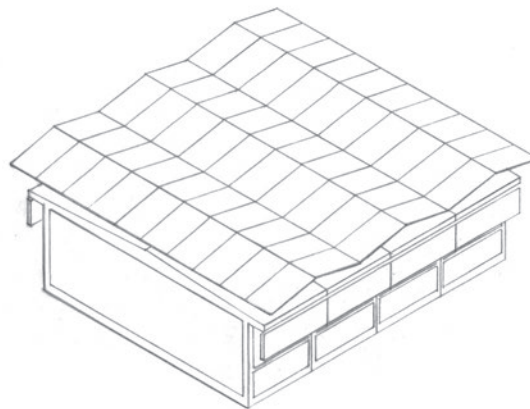


Photo Voltaic panels oriented to the East and West

Figures 5.36: Alternative configurations for photo-voltaic panels on the NSW Demountable Classroom

The north facing configuration maximises the solar energy landing on each panel. The east-west configuration maximises the number of panels, minimises self shading and maximises the shading of the classrooms below.

The classroom is oriented towards the North in both isometric drawings.

The orientation of the classroom and the panels are not inter-dependent.

5.7.1 Methodology

This brief series of parametric simulations used the National Renewable Energy Laboratory's (www.nrel.gov) System Advisor Model 2017.1.17 (NREL, 2017) to model a range of panel pitches and spacing for two configurations (Figure 5.36):

- North: All the panels face due north towards the noon sun.
- East-West: The panels are arranged in pairs of rows facing alternately east and west.

The orientation, pitch and spacing of the solar panel array is critical to the efficiency of the array. The spacing between the panels is correlated to the problem of one row overshadowing another but also the number of rows that can fit in a particular space. The pitch (angle from the horizontal) of the panels determines the angle of incidence and quantity of the sun light landing on the panel. The angle of incidence is also a function of both latitude and season and so the pitch of the panels needs to be optimised for a particular climate and location.

The first configuration is the most common and ensures that all the panels face the sun for the maximum amount of time each day provided self-shading is avoided.

The second configuration avoids self-shading by panels and increases the number of panels that can be placed on a roof space.

Both configurations were constrained by a canopy area of approximately 10m x 10m that is independent of the Demountable Classroom structure. A Jinko Solar

GCR	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Spacing (m)	16.2	8.1	5.4	4	3.2	2.7	2.3	2	1.8	1.6

Table 5.6: 'Ground Cover Ratio' and PV panel spacing

"Ground Cover Ratio" (GCR) and the corresponding spacing between rows of Photo-Voltaic panels

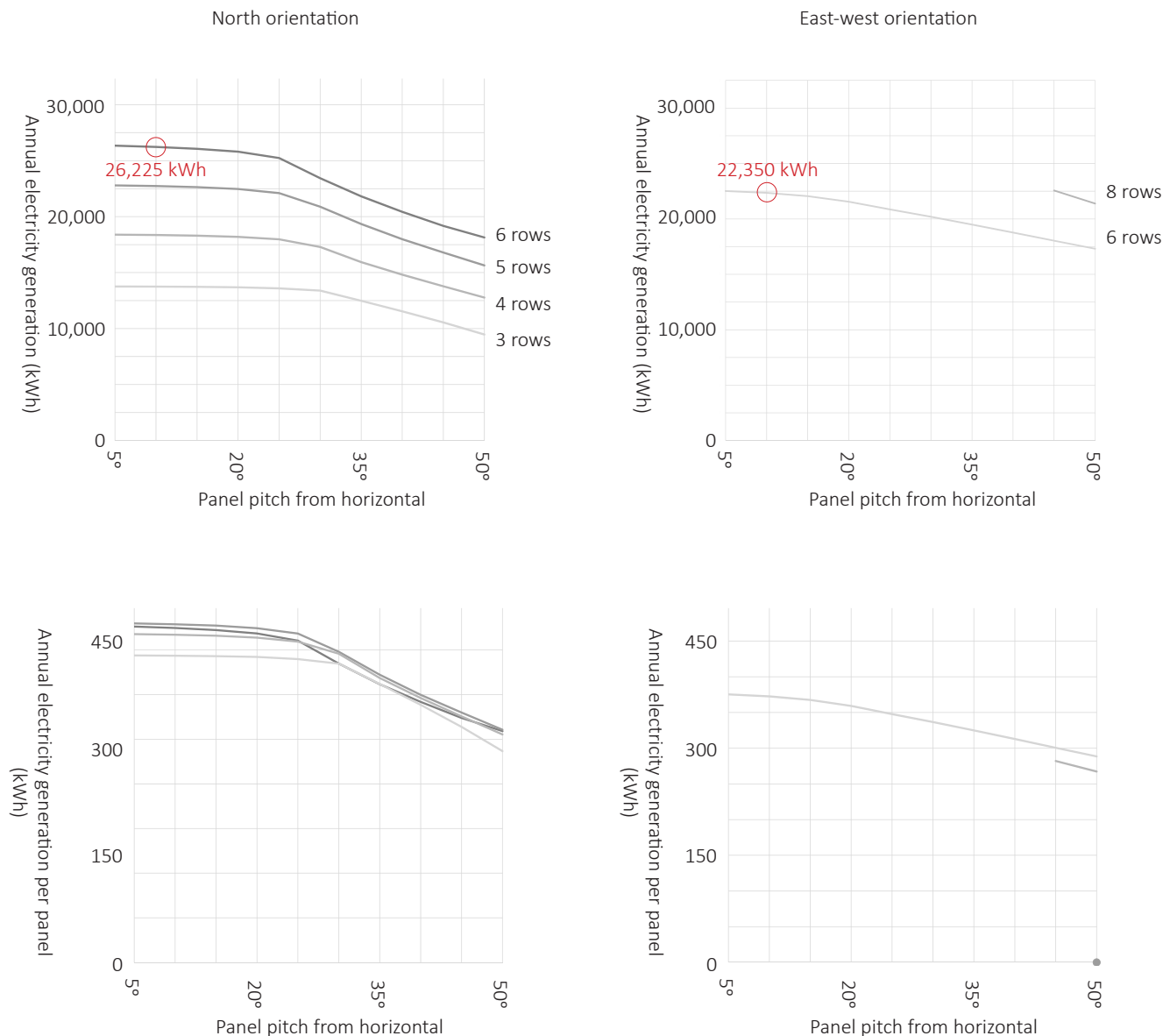


Figure 5.37: Predicted annual energy generation from PV arrays
 CLIMATE: Broken Hill:

JKM250P-60 panel was used arranged in rows of 10 as a portrait configuration. A default DC-AC inverter was used in the model.

Variation of Pitch

In both configurations the pitch of the panels was varied in 5° increments between 5° above horizontal to 50°.

Variation of spacing

The SAM software uses the “Ground Cover Ratio”(GCR) to define the distance between rows of panels. GCR is

$$\frac{\text{the area of the PV panels}}{\text{the area of the ground under the array.}}$$

The GCR was varied in increments of 0.1 between 0.1 and 1.0. as the GCR approaches 1.0 the change in spacing for each increment is significantly reduced (Table 5.6)

In the model the East and West facing arrays were modelled separately and the results combined.

The simulation mode was run using the weather data used in the Design Builder thermal simulation model. The two configurations were also modelled in Design Builder (Design Builder Ltd) using the climate in Broken Hill as a simple validation strategy. The two simulation models produce comparable results including the effect of temperature and weather on the efficiency of the PV array.

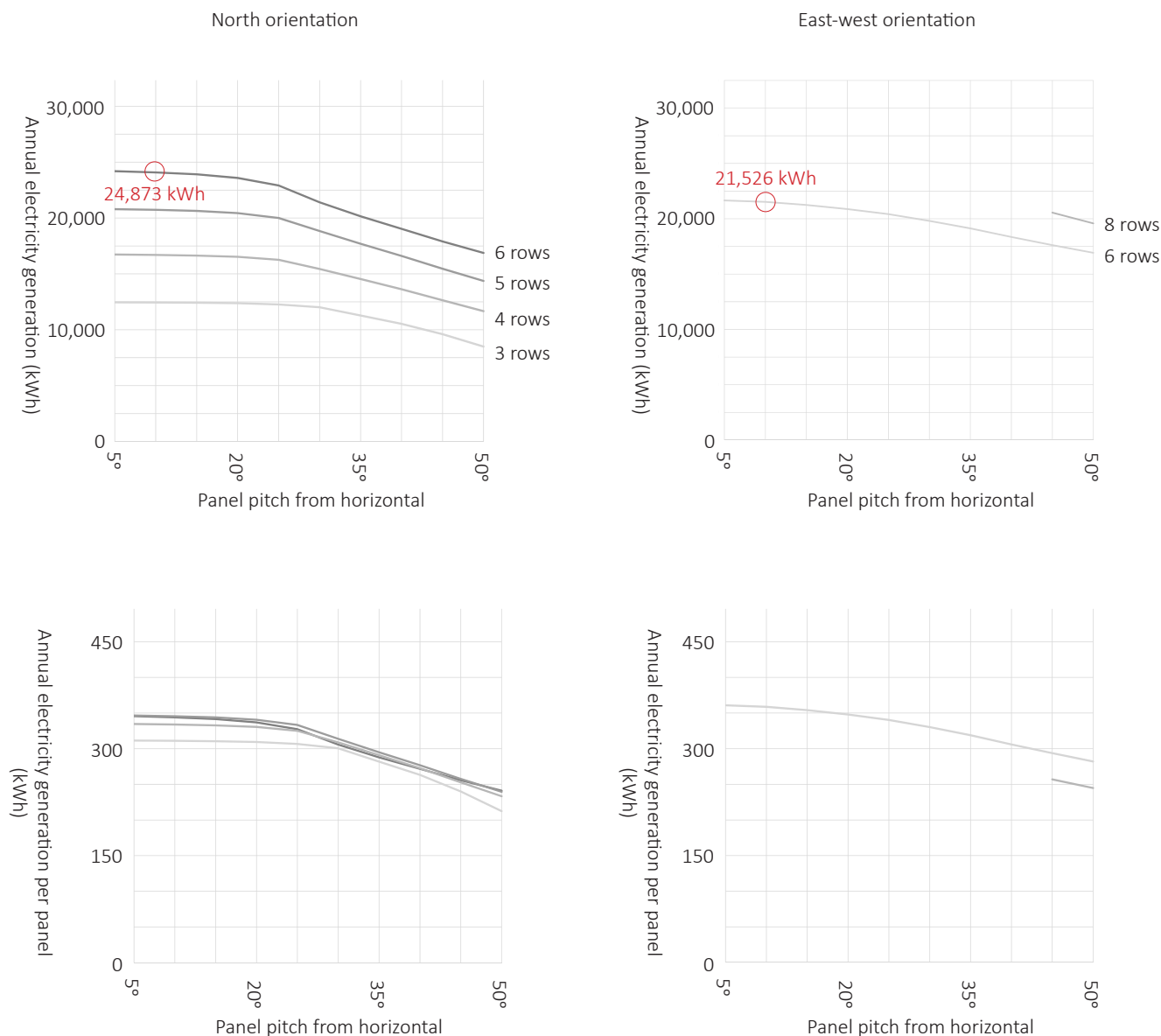


Figure 5.38: Predicted annual energy generation from PV arrays
CLIMATE: Canberra

5.7.2 Results

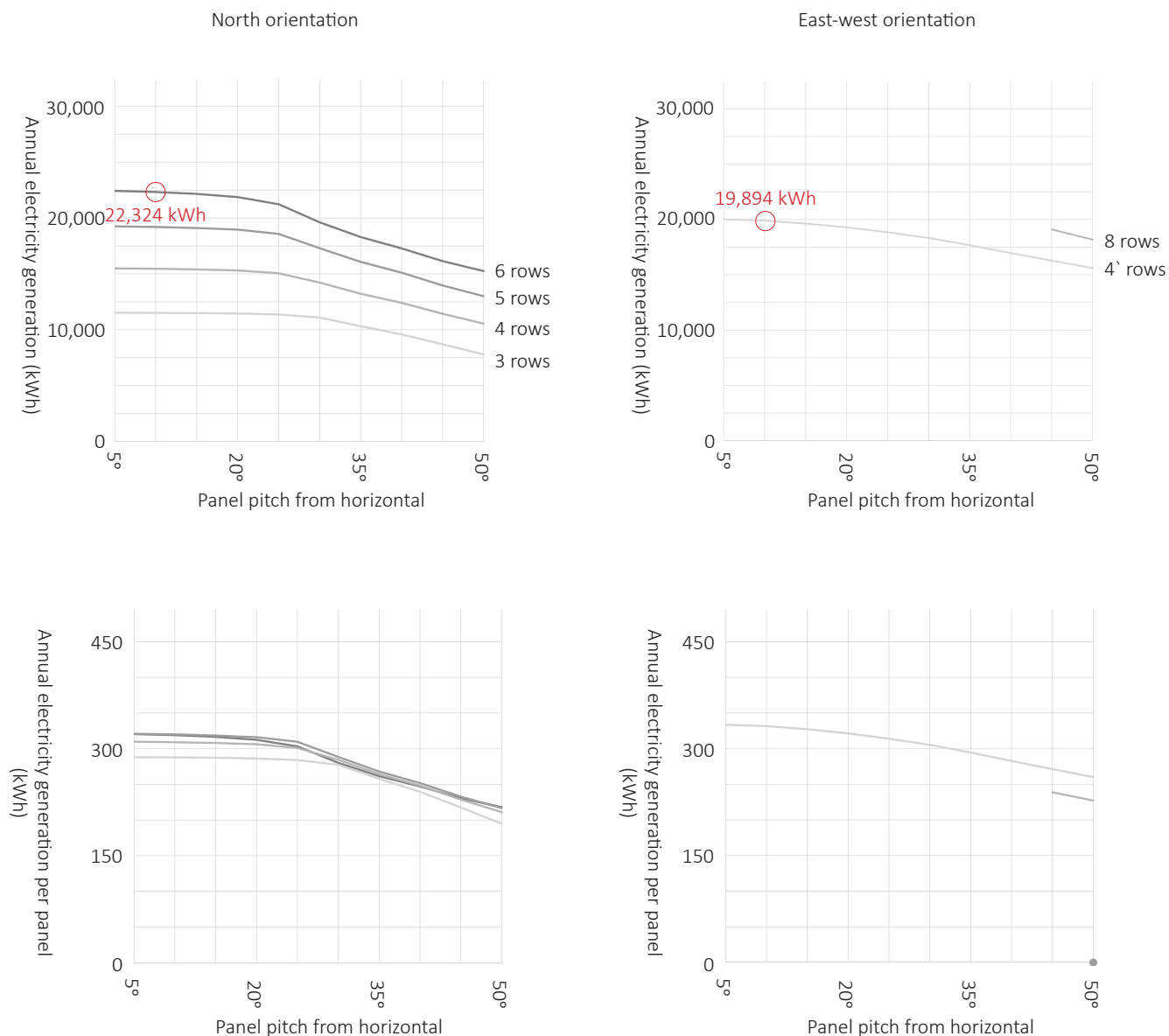
The graphs in figures 5.37 - 41 illustrate the results. It is clear that the East-West configuration generates between 9% and 15% less energy (depending on the location) than the North facing arrays.

For the North orientation the variation in the pitch of the panels between 5 and 15° has very little or no significant effect on the efficiency of the collection/generation of energy. Beyond 15° the efficiency of the system declines and beyond 25° the decline accelerates.

For the East-West configuration performance also declines with the increasing pitch of the panels. The decline in performance is more gradual than with the north facing configuration.

One of the significant constraints of any array is the number of panels that can be fitted onto the roof. The NSW Demountable Classrooms are close to square in plan and the nominal roof space for the PV array has been defined as a 10 x 10m square. In these circumstances 6 rows of panels can be arranged facing north or east and West in 3 paired rows. When the pitch of the panels is increased to 45°, 8 rows of panels (4 paired rows) can be fitted in an East-West orientation but this configuration is less productive than configurations with a lower pitch.

The results indicate that for both configurations the steepest pitch that does not lose efficiency is 10°. This pitch creates a 287mm vertical space below the panels to accommodate structure to support the panels and span over the Demountable Classrooms.



Finally, the results indicate that, depending on climate and configuration, shading the NSW Demountable Classroom with the PV array will generate multiple times the electricity required to operate the air-conditioning system in classrooms whose building fabric has been modified with the SET 15 Solution Set. Based on the data from the simulation models that assume the classrooms are used 365 days of the year the energy generated using the North facing configuration provides between 6.4 and 8.9 times the AC energy demand predicted by the Design Builder model depending on the climate (Table 5.7).

Figure 5.39: Predicted annual energy generation from PV arrays
CLIMATE: Richmond

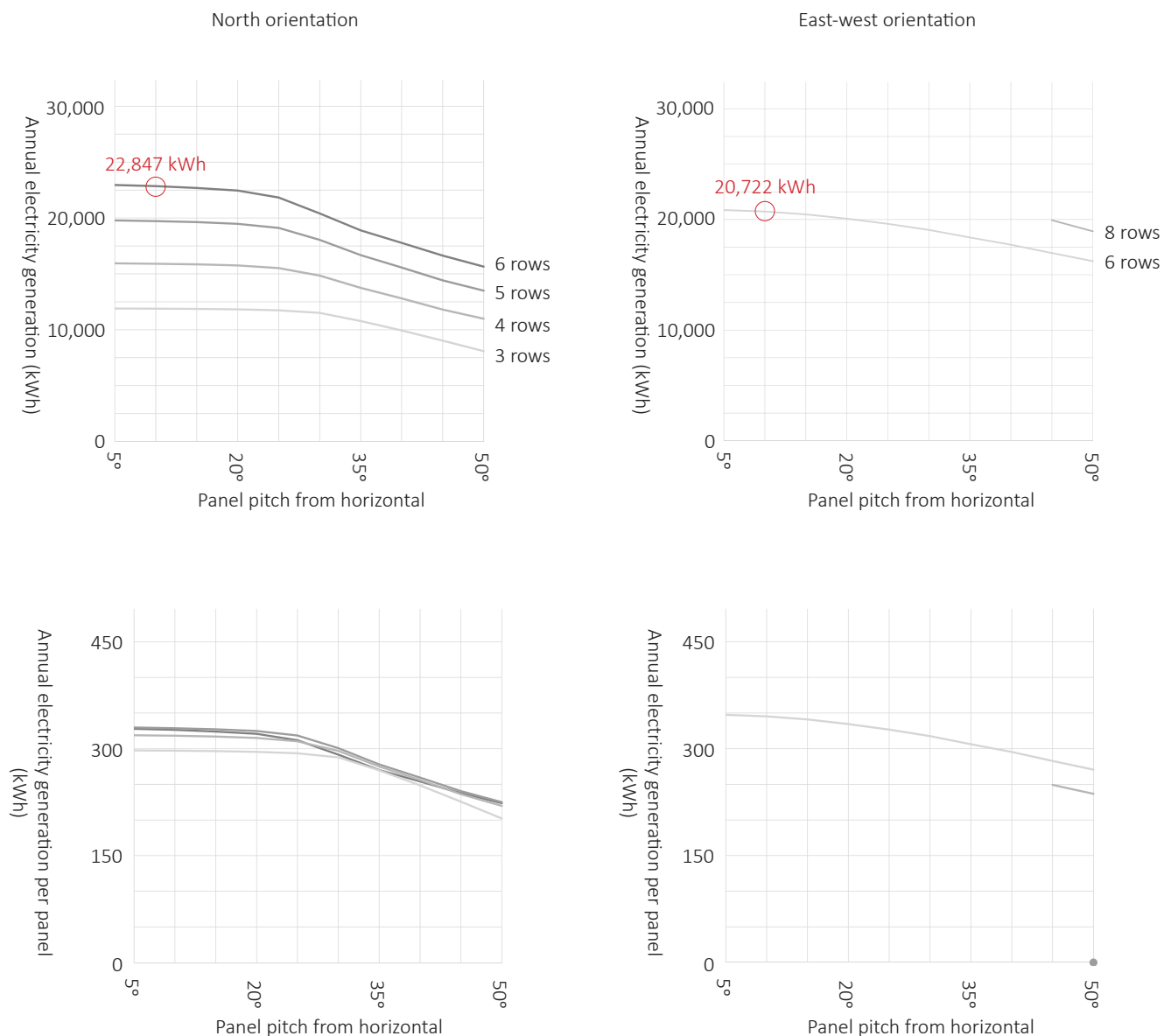


Figure 5.40: Predicted annual energy generation from PV arrays
CLIMATE: Williamstown

	Demand: AC energy	Generation: North orientation
Broken Hill	3450 kWh	760% 26,225 kWh
Canberra	3270 kWh	761% 24,873 kWh
Richmond	3472 kWh	643% 22,324 kWh
Williamstown	2785 kWh	820% 22,847 kWh
Coffs Harbour	2668 kWh	891% 23,756 kWh

Table 5.7: Comparison of predicted energy demand and generation

Comparison of predicted energy demand by the NSW Demountable Classroom retrofitted with the SET 15 Solution Sets operating 365 days a year and the potential generation capacity of PV arrays on the roof oriented North (6 rows of 10 panels) and East-West (8 rows of 10 panels alternating).

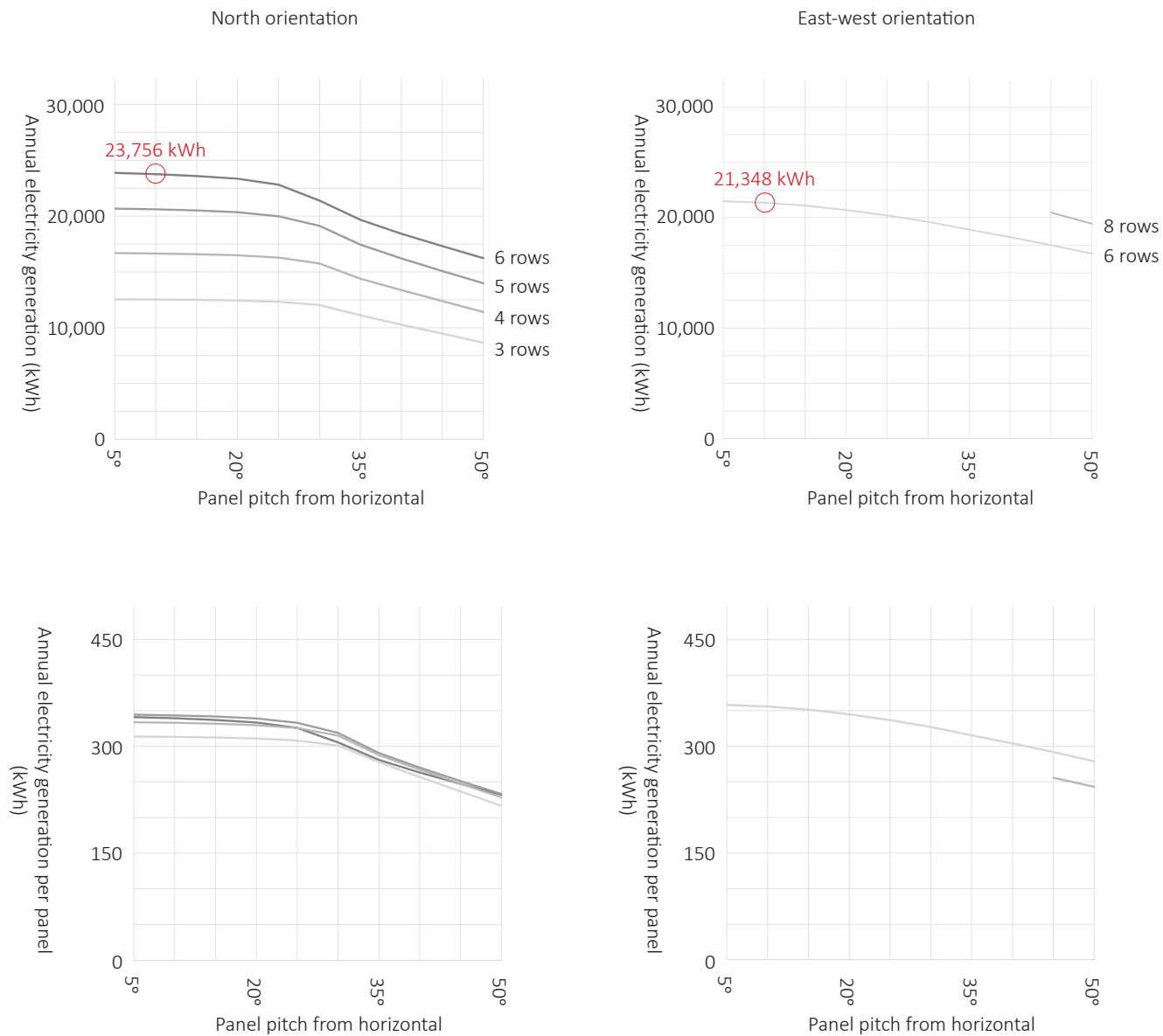


Figure 5.41: Predicted annual energy generation from PV arrays
CLIMATE: Coffs Harbour

5.8 Cost and weight

Chapter 1 concluded that the objective of this research project is to “develop socially, economically and environmentally viable proposals” for improving the thermal performance of the NSW Demountable Classroom.

This section evaluates the proposals in terms of financial cost and physical weight. Financial cost is important to all communities whether they are represented by the NSW government or a local Parent-Teachers Association. Weight is important because these classrooms are designed to be transported and easily relocated. The proposed Solution Sets must not impede the ability of the classroom modules to be rapidly relocated.

Table 5.8 sets out the costs and corresponding improvement in thermal performance of three different Solution Sets with increasing thermal mass and a fourth that uses High-E paint to replace the fly-roof used in the previous three. The table also includes the cost of adding Photo-Voltaic panels. Table 5.9 Provides a breakdown of the additional weight per module for the different Solution Sets. Table 5.10 provides a more detailed breakdown of how the costs were calculated. The following table, Table 5.11, indicates the reduction in overall discomfort and overheating discomfort for each Solution Set in each of the five representative climates, in terms of a percentage reduction in degree-hours compared to the existing situation.

Observations

The lighter-weight Solution Sets offer substantial improvements in thermal comfort but do not eliminate overheating discomfort. It is the addition of thermal mass that improves the thermal performance of the best performing Solution Sets and brings the level of overheating-discomfort close to zero. Unfortunately it is also the addition of the thermal mass, in the form of fibre-cement sheet, which adds substantial weight and financial costs to the Solution Sets in comparison to the lighter weight Solution Sets.

The additional weight of the highest performing Solution Sets is significant but does not increase the module weight above the load capacity of the trucks that transport the classrooms (Figure 5.42 and Table 5.10).

Overall the financial analysis demonstrates that significant improvements to thermal performance, reductions in energy demand and improvements in thermal comfort can be made for a relatively modest financial investment.

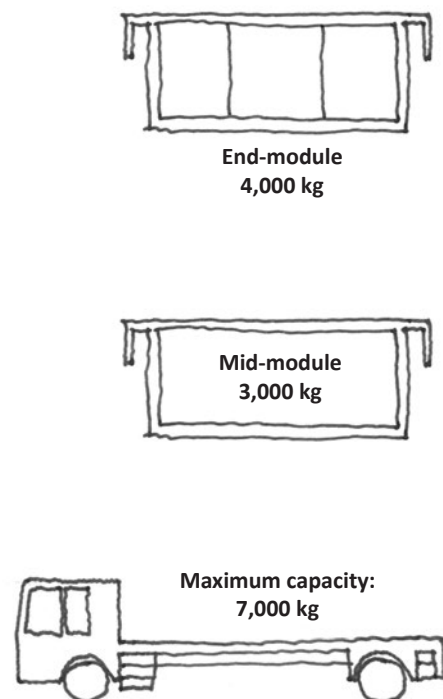


Figure 5.42: NSW Demountable Classroom existing module weights and transport truck capacity

*The weight of the existing modules and load capacity of the transportation trucks was provided to the author by the NSW Demountable Coordination Unit.
(Drawings by author)*

	Cost \$	Additional weight	Annual reduction in discomfort		
Materials			Overall	Over-heating	
SET 12 Fly-roof, 40mm PIR insulation & 6mm F/C sheet	\$7,345 + Fly-roof \$20,000	1,799 kg	86%- 94%	72%- 84%	
SET 14 Fly-roof, 40mm PIR insulation & 18mm F/C sheet	\$11,526 + Fly-roof \$20,000	3,644 kg	88%- 94%	79%- 93%	
SET 15 Fly-roof, 40mm PIR insulation & 18mm F/C sheet	\$17,206 + Fly-roof \$20,000	6,411 kg	91%- 96%	86%- 98%	
SET 25 High-E coating, 40mm PIR insulation & 18mm F/C sheet	\$17,206 + High-E coating \$4,275	6,411 kg	90%- 96%	88%- 99%	
Labour costs	\$4,880- \$6,800	3- 5 days labour for two carpenters each costing \$680/day (8 hours). SET 12 might take 3 days, Set 15 might take 4 or 5 days to complete. Alternatively the school may undertake the work themselves.			
Fly-roof	\$20,000				
High-E coating	\$4,275				
Photo Voltaic Array	\$17,400				

Table 5.8: Overall costs, weight and predicted reductions in discomfort.

Details of the sources for the costs are provided in Table 10.

The predicted reduction in discomfort shows the minimum and maximum predicted reductions in degree-hours for each Solution Set in the five representative climates. Table 9 provides this information for each climate.

	Existing situation¹	SET 12 Fly-roof, 40mm PIR insulation & 6mm F/C sheet	SET 14 Fly-roof, 40mm PIR insulation & 18mm F/C sheet	SET 15 Fly-roof, 40mm PIR insulation & 18mm F/C sheet	SET 25 High-E coating, 40mm PIR insulation & 18mm F/C sheet	
End module	4,000 kg	+520 kg	+1,095 kg	+1,957 kg	+1,957 kg	
Mid module	3,000 kg	+341kg	+624 kg	+1,050 kg	+1,050 kg	
Delivery truck capacity: 7,000 kg ¹						

Table 5.9: Existing Module and Solution Set weights

Delivery truck capacity is 7,000 kg MAXIMUM.

¹ The weight of the existing modules and load capacity of the transportation trucks was provided to the author the NSW Demountable Coordination Unit

Cost estimate breakdown	Costs per layer per classroom	Notes	Source of cost estimates
Floor			
Insulation Insulation batts R1.7 1.2 x 10m roll	\$655	Insulation installed between joists \$81.82/roll	Earth Wool underfloor insulation from Bunnings Warehouse
F/C Sheet 6mm FC sheet liner board 1.2 x 2.4m	\$874	F/C sheet installed to protect insulation \$31.22/sheet	CSR Cemintel board, Gyprock Trade Centre
End walls			
Insulation PIR insulation R1.9 (40mm 1.2x2.4m Sheet)	\$1,440	PIR insulation is supplied in sheets cut to size by the manufacturer \$89.96/m ²	Australian Urethane and Styrene Ltd. (manufactures sheets to order to specified dims) www.aus-styrene.com.au An alternative specification is 50mm of Expanded Polystyrene insulation available from Bunnings Warehouse at a similar cost per sq. m.
F/C Sheet 6mm FC sheet liner board 1.2 x 2.4m	\$500	For Solution Sets 02, 03 & 12. 16 sheets needed per classroom \$31.22/sheet	CSR Cemintel board, Gyprock Trade Centre
F/C Sheet 9mm FC sheet liner board 1.2 x 2.4	\$947 layer. classroom	For Solution Sets 04, 05, 14, 15 & 25 16 sheets needed per layer for each classroom. Multiple layers needed to make up specified thickness. \$59.16/sheet	
			Continued....

Table 5.10: Economic cost estimate breakdown

Specification, Unit cost estimate and source of cost estimates for Solution Set proposals

<i>Cost estimate breakdown</i>	Costs per layer per classroom	Notes	Source of cost estimates
Wall panels (below windows)			
Insulation PIR insulation R1.9 (40mm 1.2x2.4m Sheet)	\$720	PIR insulation is supplied in sheets cut to size by the manufacturer \$89.96/m ²	Australian Urethane and Styrene Ltd. (manufactures sheets to order to specified dims) www.aus-styrene.com.au An alternative specification is 50mm of Expanded Polystyrene insulation available from Bunnings Warehouse at a similar cost per sq. m.
F/C Sheet 6mm FC sheet liner board 1.2 x 2.4m	\$250	For Solution Sets 02, 03 & 12. 8 sheets needed per classroom \$31.22/m ²	CSR Cemintel board, Gyprock Trade Centre
F/C Sheet 9mm FC sheet liner board 1.2 x 2.4	\$473/layer. classroom	For Solution Sets 04, 05, 14, 15 & 25 8 sheets needed per layer for each classroom. Multiple layers needed to make up specified thickness. \$59.16/sheet	
			Continued....

Table 5.10 cont...: Economic cost estimate breakdown

Specification, Unit cost estimate and source of cost estimates for Solution Set proposals

Cost estimate breakdown	Costs per layer per classroom	Notes	Source of cost estimates
Ceiling			
Insulation PIR insulation R1.9 (40mm 1.2x2.4m Sheet)	\$2159	PIR insulation is supplied in sheets cut to size by the manufacturer \$89.96/m ²	Australian Urethane and Styrene Ltd. (manufactures sheets to order to specified dims) www.aus-styrene.com.au An alternative specification is 50mm of Expanded Polystyrene insulation available from Bunnings Warehouse at a similar cost per sq. m.
F/C Sheet 6mm FC sheet liner board 1.2 x 2.4m	\$249	For Solution Sets 02, 03 & 12. 24 sheets needed per classroom \$31.22/m ²	
F/C Sheet 9mm FC sheet liner board 1.2 x 2.4	\$1,420/ layer. classroom	For Solution Sets 04, 05, 14, 15 & 25 24 sheets needed per layer for each classroom. Multiple layers needed to make up specified thickness. \$59.16/sheet	CSR Cemintel board, Gyprock Trade Centre
Labour costs	\$1,360/day	Based on 2 carpenters per day @ \$85/hour incl. all overheads (excl. GST)	Costs based on current pricing from contractors in Sydney working on existing and recent construction contracts with the author
			Continued....

Table 5.10 cont...: Economic cost estimate breakdown

Specification, Unit cost estimate and source of cost estimates for Solution Set proposals

Cost estimate breakdown	Costs per layer per classroom	Notes	Source of cost estimates
Fly roof	\$20,000	Aluminium box section frame with Colorbond roof Fabrication: \$195/m ² Installation: \$85/m ²	Cost estimate from DM Projects, Sydney assuming low order numbers and off-site fabrication. Increasing order numbers will reduce the cost, possibly significantly with significant quantity due to economies of scale in setting up jigs and manufacturing processes.
High-E paint	\$4,275	Sky-Cool paint \$30/m ² Roof area: 72.1 m ² Opaque wall area: 70.3 m ²	Sky-Cool Pty Ltd. of \$30/sq.m. Costs may be reduced for multiple classrooms at a single location (telephone conversation 13/02/2017)
Photo Voltaic array	\$17,396	Supply: \$29,252 STC rebates: -\$11,856 STC rebates are Small Scale Technology Certificates that are traded on an exchange. Their value may change.	Based on the installed cost estimate available on Solar Power Australia's website (07/03/2017) www.solarpoweraustralia.com.au/grid-feed-solar-power-for-your-home

Table 5.10 cont...: Economic cost estimate breakdown

Specification, Unit cost estimate and source of cost estimates for Solution Set proposals

	Predicted annual reduction in discomfort									
	Broken Hill		Canberra		Richmond		Williamstown		Coffs Harbour	
	Overall	Over heating	Overall	Over heating	Overall	Over heating	Overall	Over heating	Overall	Over heating
Solution Set										
SET 11 Fly-roof	86%	58%	93%	82%	87%	70%	88%	63%	87%	87%
SET 12 Fly-roof, 40mm PIR insulation & 6mm F/C sheet	90%	69%	94%	82%	91%	85%	92%	85%	87%	76%
SET 14 Fly-roof, 40mm PIR insulation & 18mm F/C sheet	90%	75%	94%	82%	91%	90%	93%	95%	88%	90%
SET 15 Fly-roof, 40mm PIR insulation & 18mm F/C sheet	93%	83%	96%	98%	93%	95%	96%	98%	91%	98%
SET 25 High-E coating, 40mm PIR insulation & 18mm F/C sheet	92%	86%	96%	98%	90%	97%	95%	98%	90%	99%

Table 5.11: Predicted overall reduction in thermal discomfort

Predicted overall reduction in thermal discomfort (based on degree-hours) as a result of the implementation of each Solution Set

5.9 Conclusion: Evaluation of the Solution Sets

This chapter has evaluated the various Solution Sets proposed to improve the thermal performance of the NSW Demountable Classroom in five climates representative of the diverse climates that exist across the state.

Thermal comfort and thermal performance

It is clear that the thermal performance of the classrooms and the consequential thermal comfort of the pupils and teachers who use them can be significantly improved in all of the climates that have been simulated. In four out of five climates overheating discomfort was practically eliminated by the highest performing Solution Sets. Cold discomfort remains a challenge, particularly in the early morning when the outside air temperature and the temperature of the building's fabric are at their lowest.

The Solution Sets significantly reduce the annual energy demand of the classrooms but the annual energy demand remains significantly above the target of 2000 kWh (26.8 kWh/m².year) set by the Green Building Council of Australia (GBCA, 2009). It has been shown that the problem of high energy demand is due to the need to heat and cool the large volume of air that enters the classroom for ventilation from outside. This air is required to maintain appropriate internal air conditions but must be heated or cooled when the outside air temperature is above or below the appropriate comfort

limits in order to maintain thermal comfort for the people in the classroom.

Thermostat settings and concepts of comfort

In the simulation model the heating and cooling set point temperatures for maintaining thermal comfort are based on the protocol defined by the NatHERS standard (NatHERS, 2012, Chen, 2016). A further study was undertaken to explore how alternative thermostat settings based on the findings of other research might affect both the annual energy demand of the classrooms and the thermal comfort of those who use the classrooms. These simulations showed that changing the thermostat settings would reduce annual energy demand. Adjusting the thermostat settings would also increase the amount of time the classroom is outside the comfort zone defined by the adaptive comfort model and increase the amount of time the classrooms are naturally ventilated. The research these adjustments were based on suggests that increasing the opportunity for natural ventilation may be beneficial because it increases the dynamic variation in the thermal environment and so thermal stimulation. However the extent of the benefit of increased natural ventilation outside of the established comfort zone is not known.

CO₂-e cost and zero carbon generation

The reason high energy demand is a particular problem in NSW is that the majority of the electricity generated in the state comes from coal fired power stations and consequently has a high CO₂-e cost (1.05kg.CO₂-e/kWh) (BREE, 2013, Department for climate change,

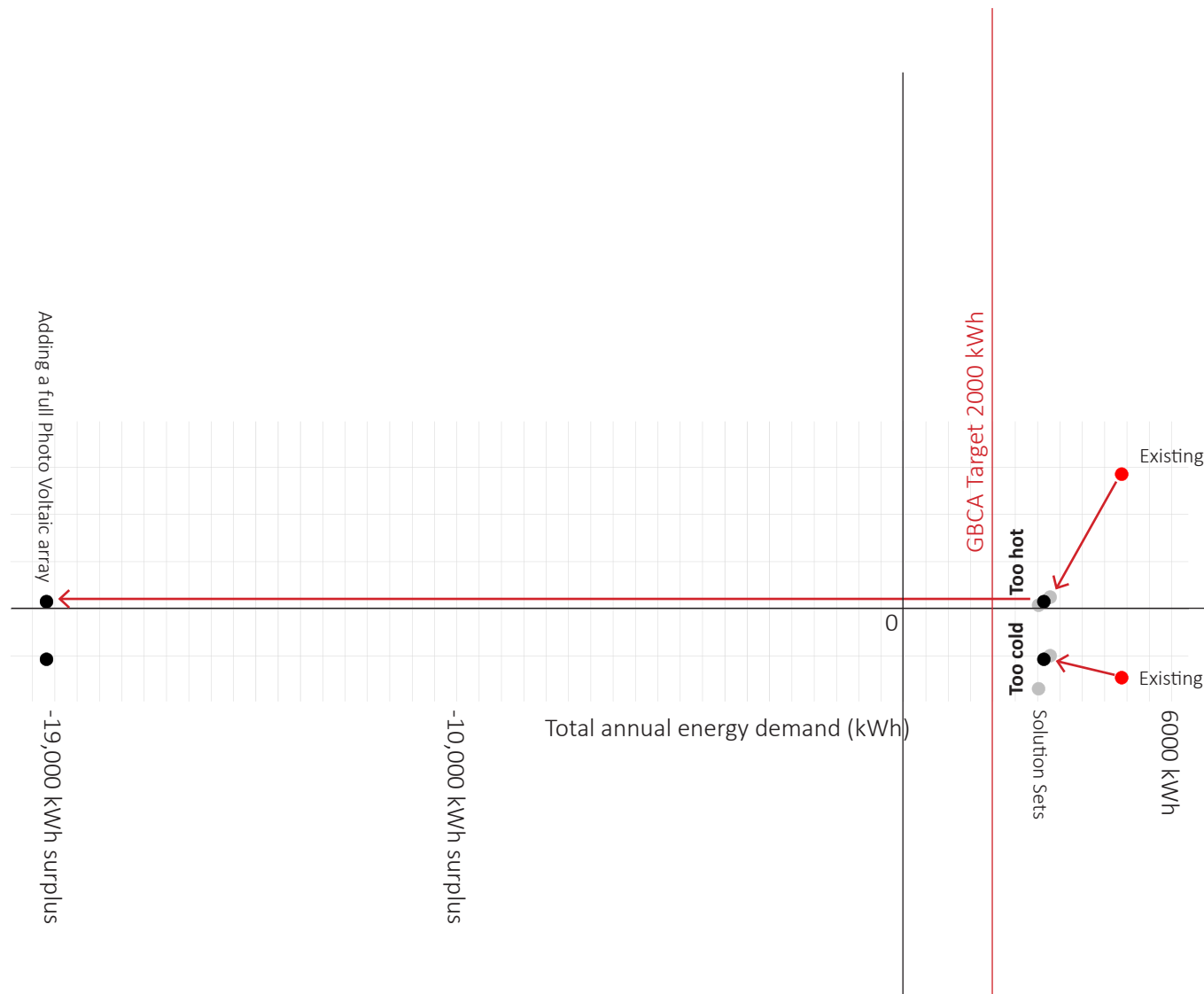


Figure 5.43: Potential improvements in thermal comfort, annual energy demand and potential zero-carbon energy generation
 Annual thermal discomfort above and below comfort zone measured as degree-hours for different thermostat settings plotted against annual heating and cooling energy demand. The impact on energy demand, and potential for zero-carbon energy generation is also shown.
 CLIMATE: Richmond

2013). Overall, the analysis of the thermal performance of the classrooms has shown that the primary cause of thermal discomfort is the large amounts of thermal radiation landing on the building envelope. An analysis exploring the potential for this radiation to be converted into electricity using a Photovoltaic array that also helps to shade the building indicates that it is possible to generate several times the operational energy demand of the classrooms over the year, allowing the classrooms to become net generators of zero carbon electricity for the school and possibly broader community (Figure 5.43).

Financial costs and implications on relocation

The final analysis reviewed the impact of the proposed Solution Sets on the ability to relocate the classrooms by calculating the additional weight the various Solution Sets add to the classrooms. This analysis also looked at the cost of implementing the Solution Sets. The analysis showed that most effective Solution Sets were considerably heavier and more expensive than the lighter-weight Solution Sets. The lighter-weight Solution Sets achieve significant reductions in thermal discomfort and annual energy demand but it is only the Solution Sets with the most thermal mass (36mm of fibre-cement sheet) that come close to eliminating overheating discomfort.

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The Conclusion: What improving the thermal performance of the NSW Demountable Classroom might achieve



Figure 6.1: A Mk 1 Demountable Classroom

Image from the NSW Government Architects Office construction drawings collection.

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6.1 Introduction

This thesis set out to understand how the 6000 Demountable Classrooms across the state of New South Wales might be transformed to improve the thermal performance of the buildings and the thermal comfort of those who use them.

Chapter 1 showed that while the NSW Demountable Classroom is regarded as a second rate teaching facility by many, it continues to fulfil the objectives it was originally designed for. The NSW Demountable Classroom enables schools to expand and contract their teaching facilities at a low or minimal financial and environmental cost and entire new schools can be constructed in just a few weeks (NSW Department for Education, 2016).

Chapter 1 and Chapter 2 also showed the reasons communities regard these buildings as unsuitable teaching environments, or even as an obsolete building typology. The problem is complex and engages with social, economic and environmental issues of sustainability and pedagogy. The perception of social value, politics, aesthetics and their impermanence all play a part (Vinson et al., 2002). But it is their thermal performance and the consequential discomfort of those who use them that was identified as the most significant problem.

Schools and school buildings are part of a complex social and economic system. Their value is determined by more than their technical performance: Their value

is also determined by the values they communicate, or are perceived to communicate, to the communities they serve. In his forward to “Schools for the future” Sanoff (2015) observes that:

“School facilities are powerful indicators of community values and aspirations. They not only support the academic needs of students they serve, but can also address the social, educational, recreational, and personal needs of the members of the broader community. It has been argued that successful schools strengthen a community’s sense of identity and coherence” (p.V)

Vinson et al (2002) made similar observations relating to NSW schools and the NSW Demountable Classroom in particular, identifying both their poor thermal performance and “insubstantial character” as significant challenges to the perception of their value, the value of education and the relative value of the community within the broader society of NSW.

Improving the thermal performance of the classroom is perhaps the least complicated of these challenges because it is technical rather than social.

This thesis argues that because it is the least complicated of the problems but has a significant impact on the perception of the classrooms by the communities who use them, and because it can be solved, the process of solving it, of significantly improving the thermal performance of these classrooms, creates an opportunity to engage with many of these other social challenges. Empowering school communities to



Figure 6.2: Collage

*The NSW Demountable Classroom refurbished to create a comfortable carbon positive classroom for the 21st century based on an image from the NSW Government Architects Office construction drawings collection
(Drawing by the author)*

engage in improving the thermal and environmental performance of the Demountable Classrooms in their schools will allow them to demonstrate the value the community places on creating and maintaining a space that is appropriate for teaching and the aspiration for a more socially inclusive and environmentally responsible future.

In response to this challenge the thesis has identified the need for the Solution Sets (strategies or collections of strategies) to be socially, economically and environmentally viable, to be simple and affordable so that they can be implemented while the classrooms are on-site within schools.

The conclusion to this thesis is in three parts: The first part identifies the primary findings of the thesis. The second part identifies opportunities for further research that develop out of the findings. The third part discusses the significance of those findings.

6.2 Findings

The findings of this thesis challenge some of the assumptions and orthodoxies that exist within climate-responsive design praxis and design guidance. The orthodox view of climate-responsive design suggests that the Solution Sets should be tailored to each climate and so change depending on the location of the classroom (or building). There is also an assumption within practice and guidance that if something is ‘good’ then lots of that thing must be ‘better’. Within the research literature there are many papers that seek to ‘optimise’ the building envelope: to find the ideal construction for a particular climate based on some form of cost-benefit analysis.

Rather than seeking an ideal or optimal construction system, or accepting the premise that more of a good thing must be better, this thesis has asked “how much is enough?”, or, “how much do we need?” to significantly improve the thermal performance of the classrooms. The results suggest that more is not necessarily better and that relatively small quantities of thermal insulation and thermal mass, together with other simple strategies, can make a significant difference to the thermal comfort of those who use the classrooms and the annual energy demand of the classrooms. In contravention of the orthodoxies of bio-climatic design these Solution Sets are effective in all five of the diverse climates used in the simulations.

The following sections provide a brief summary of the key findings:

Solution Sets work in all climates

The data has shown that the improvement in thermal performance and thermal comfort caused by the introduction of the different Solution Sets is similar in all 5 climates used in the simulations. While the magnitude of the improvements in terms of degree-hours of discomfort or kWh of energy demand is different in each climate, the pattern of improvement, or the relative and proportional improvement, within each climate is similar across the five climates.

The defensive envelope: deflecting or reflecting solar energy load

Chapter 2 identified the thermal energy loads from the sun as a significant challenge for the thermal performance of the Demountable Classroom building. The research has shown that the relatively simple strategies for deflecting or reflecting solar energy by shading the classrooms or coating them with a High-Emissivity paint (e.g. SkyCool) is the single most effective strategy for both improving comfort and reducing annual energy demand. The strategy has the additional benefit of having no impact on the inside of the classroom buildings.

The construction of a fly-roof, possibly incorporating PV panels, creates a shade structure that will be useful after the classroom building has been relocated. The use of the High-E paint is the least expensive of all the Solution Sets.

Insulation

The simulation results showed that insulating the walls, ceiling and floor makes a significant difference to the thermal comfort and annual energy demand in all five climates. However doubling the insulation in the walls and ceiling from 40mm to 80mm of PIR insulation has no significant impact on either comfort or energy demand. The project did not investigate whether or not less than 40mm of PIR insulation would be adequate but it is reasonable to suggest that it may be and deserves further investigation. It is clear that for the Demountable Classroom in the climates of NSW there is a limit to the quantity of insulation that is needed to improve environmental performance.

Thermal mass

The results from the simulations support the proposition that the additional benefit of increasing the quantity of thermal mass in the space reduces with increasing quantities of thermal mass (Slee et al., 2014). The results show that very modest quantities of thermal mass (18mm F/C sheet) can make a significant difference to the thermal comfort in the space. Doubling the quantity of thermal mass improved the performance but at a more modest rate than moving from 6mm to 18mm of F/C sheet.

36mm of F/C sheet is itself a small quantity of thermal mass. The quantity of thermal mass added to a space is often determined by the unit dimensions of the mass itself, often a brick or concrete block wall, 110 or 100mm+ wide respectively. The results of these

simulations show that 1/3 of that thickness can significantly improve the thermal comfort and thermal performance of a space.

Finally, the results showed that while the addition of thermal mass improved thermal comfort in all five climates, it only reduced annual energy demand in three of the five climates. The results suggested that there may be a connection between the way in which the mean diurnal temperature range changes during the year and the influence of the thermal mass on thermal performance. This is beyond the scope of this study but is certainly an area that deserves further investigation.

The Significance of air temperature and thermostat settings on perception of comfort

The simplicity of the Demountable Classroom building allows the relationship between thermal comfort, indoor air quality (IAQ) and energy demand to be revealed clearly. This relationship is not new knowledge but it is important in the development of high performance buildings, that is, buildings that are both comfortable and have low or zero energy demand.

The thesis explored the impact of varying the parameters that define air temperature and thermostat settings and the research that underpins the ideas, physiology and psychology of comfort. The modelling in the thesis shows that it is possible to reduce the annual energy demand and associated CO₂-e emissions by broadening the band within which the air temperature is allowed to fluctuate, and by increasing opportunities for natural

ventilation, but that this comes at the cost of increasing discomfort as defined by the adaptive comfort model. So the increase in the range of conditions that are considered comfortable or acceptable will depend in large part on the attitude of the teacher in charge of the classroom, the tolerance of the pupils and expectations of parents.

The analysis of the research underpinning the definition of comfort showed that comfort is a dynamic concept and that it is considerably more complicated than temperature measurements. Chappells and Shove, who are sociologists rather than building scientists, observe that, *“comfort is a dynamic and socially negotiated exercise involving both building designers and users.”*(Chappells and Shove, 2003)

In another paper Chappells and Shove illustrate this point using an example relevant to this thesis:

“In the early 1900s, campaigners in the US argued that school children should study outdoors, fresh air being essential for the development of healthy bodies and minds. By contrast, those who design and specify air-conditioned offices now conclude that productivity and comfort can best be achieved by limiting exposure to the elements.” (Chappells and Shove, 2005)

The work of Parkinson and De Dear (Parkinson and de Dear, 2015) illustrates that a dynamic thermal environment, implicit in the adaptive comfort model, may be beneficial beyond creating an acceptable environment, rather creating thermal environments

that are delightful. Surveys carried out in NSW by Kim et al (2016), Deuble and De Dear (2012) (2014) and De Dear et al (2015) in domestic, office and school environments respectively illustrate that the perception of comfort can be different from what is predicted by the standards; that the perception of comfort is contingent on agency, aspiration and people’s perception of their social responsibilities as well as the air or operative temperature.

These observations open up valuable opportunities and areas for further research if the core proposals in this thesis are implemented.

Opportunity to generate energy locally (far more than is needed even for the energy intensive Demountable Classroom)

The simulation results show that while the implementation of the Solution Sets can significantly improve thermal comfort and reduce energy demand, energy demand remains high. The final modelling exercise illustrated that using photo-voltaic panels on the roofs of the Demountable Classrooms can generate multiple times the annual energy demand of these relatively inefficient classroom buildings.

This is not necessarily an innovative observation, rather it is a useful illustration of the opportunities that exist to use the roof shading strategy in the Solution Sets to also generate significant quantities of zero-carbon energy in the heart of communities across the state and the nation.

Uncertainty and sensitivity

The thesis included an analysis and discussion of the uncertainty intrinsic to the computer simulation model and the sensitivity of the model outputs to variations in the input parameters that are either variable or uncertain themselves (Chapter 2, Section 2.5 and Chapter 5, Section 5.2.3).

Computer Software

The software itself may over or underestimate the energy demand and temperature inside the classroom. The BESTEST/ASHRAE Standard 140 validation results (Henninger and Witte, 2014) suggest that Energy Plus underestimates energy demand compared to its peer Building Energy Simulation software packages. In particular for heating energy demand. There are also small variations in predicted temperature with Energy Plus slightly underestimating extreme internal temperatures and over estimating annual mean temperature (Table 2.11, Figure 2.32). However the overall trend, tendency and patterns illustrated by the model appear to be consistent across all simulation scenarios suggesting that the core propositions of the research are sound.

Orientation

The analysis of the impact of the solar orientation of the NSW Demountable Classroom concluded that solar orientation is likely to affect overheating discomfort and cooling energy demand (Figure 2.28). The analysis indicated that the deal orientation is for the windows

to face North or North East. The improvements as a consequence of implementing the Solution Sets are much larger than any improvement as a consequence of classroom solar orientation.

Class Size (occupancy) and metabolic activity

The analysis indicates that the overall occupancy and level of metabolic activity in the classroom does not affect thermal performance. In line with the analysis above this suggests that other factors, such as the energy load from the sun, are more significant. The total metabolic energy load in the classrooms was simulated at 2.2kW (Minimum), 2.7 kW (Middle) and 3.3 kW (Maximum). The maximum hourly incident solar radiation on the walls, roof and floor in Williamstown ranges from a monthly mean of 48.1 kWh in July to 75.1 kWh in January, between 15 and 31 times the total internal metabolic energy output of the pupils and teacher.

Air infiltration

The rate of uncontrolled air infiltration into the classroom was shown to have a significant effect on annual energy demand but not on thermal discomfort. This suggests that the air-conditioning system compensates for the additional thermal loads imposed by the infiltration of air at the outside air temperature (hot or cold).

6.3 Further research

The implementation of these proposals creates a number of opportunities to improve our understanding of a range of issues.

There are 6000 almost identical Demountable Classroom buildings spread across a wide range of climates and serving an even wider range of communities in New South Wales. Implementing the proposals across the state creates an opportunity to create a significant research project that is able to gather substantial and useful empirical data in a range of specific research areas:

- The perception of comfort by children.
- The impact of comfort on students ability to learn.
- The impact of the various Solution Sets on the thermal performance of the building envelope in different climates.
- Understanding the social value of schools and the value and perception of the NSW Demountable Classroom.
- Understanding the impact of the social perception of teaching spaces on learning.
- Understanding the impact of co-design and community implementation projects on self-perception and learning within school communities.

In several of these areas there is limited existing data, in others the data is commonly from unoccupied “test cells” in a limited range of climates or a single climate.

6.4 Outcomes

The outcome of this thesis can be articulated at five levels:

- i. The opportunity to improve the thermal performance of the NSW Demountable Classroom
- ii. The opportunity to create high performance lightweight construction systems in warm and hot climates.
- iii. An interrogation of the (perceived) orthodoxies of bio-climatic building design.
- iv. The value and utility of a design-led research methodology.
- v. The implementation of the proposals creates opportunities to transform the classrooms and the community.

The opportunity to improve the thermal performance of the NSW Demountable Classroom

It is established that poor internal environments in classrooms adversely effects academic performance (Mendell and Heath, 2005, Wargocki and Wyon, 2007). The thermal environment and indoor air quality (ventilation rates) are particularly important.

Improving the thermal performance and internal air quality of the NSW Demountable Classroom is significant because they account for 12% of all government school classrooms across the state, they fulfil an essential role within the infrastructure of state education and represent a capital asset of about \$840 million.* However the NSW Demountable Classroom is widely regarded as second rate.

The thesis demonstrates that it is possible to significantly improve the utility of the Demountable Classrooms across the state of NSW, and the comfort of those who teach and learn in them, by implementing a series of low cost, practical strategies. These strategies, or Solution Sets, will extend the utility of these assets, possibly indefinitely, and simultaneously creates an opportunity to significantly improve communities' perception of these classroom buildings.

The opportunity to create high performance lightweight construction systems in warm and hot climates.

This thesis project was initiated by a desire to understand whether or not it is possible to construct high performance buildings in the warm and hot climates of NSW and Australia more generally using lightweight construction systems. There are numerous vernacular examples of lightweight construction systems and building designs from across Australia, notably the archetypal "Queenslander" (Hyde, 2000). However contemporary building designs, lightweight construction systems and social expectations appear to

ignore many of the principles these systems rely on and use air conditioning systems to solve the problems of poor thermal performance.

This thesis has shown that there are a number of simple strategies that can be employed to significantly improve the thermal performance of these lightweight construction systems and building designs using readily available materials to create comfortable, low energy or even energy generating buildings, in warm or hot climates across Australia, or worldwide.

Interrogation of the (perceived) orthodoxies of bio-climatic building design.

The results illustrate a need to interrogate, or re-interrogate, the assumptions and orthodoxies that exist within the bio-climatic design paradigm. Classic reference books such as *Warm House Cool House* (Hollo, 1986) or the *Your Home Design Guide* (Reardon, 2001) emphasise the need to tailor environmental design strategies to a specific climate zone. These guides also suggest that more insulation provides "better thermal performance" (Mosher et al., 2013), and recommend passive solar design, including the use of substantial quantities of thermal mass, in all climates except tropical climates (Reardon et al., 2011).

The results from this thesis suggest that climate, insulation and thermal mass are all important but that modest quantities of each are effective. The results suggest that the performance of the construction system may not be as dependent on a particular climate

**See Chapter 1 Section 6.*

Costs based on Rawlinsons 2016 cost for classrooms including A/C of \$1,750/m² (p.73).

Sq.m rates range from \$1,435/m² and \$1,815m² excl. A/C.

A/C is costed as an additional \$11 - \$11.50/m².

Regional loadings as multiples of the metropolitan Sydney costs quoted range from 1.01 in Newcastle, 1.05 in Coffs Harbour, 1.08 in Canberra to 1.26 in Broken Hill and up to 1.35 in Wilcannia.

In this exercise metropolitan Sydney costs have been used for all estimates.

(Rawlinsons, 2016)

The internal floor area of the classrooms is 74 m², the roof area, including overhangs and shading devices, is 86 m².



Figure 6.3: Collage

*The NSW Demountable Classroom refurbished to create a comfortable carbon positive classroom for the 21st century based on an image from the NSW Government Architects Office construction drawings collection.
(Drawing by the author)*

as has been suggested previously, or, alternatively, that a single factor within the climate may dominate the performance of a construction system. In the example used in this thesis, the dominant factor is the quantity of incident solar energy on the lightweight construction system. So while climates may vary significantly they may share a common factor that dominates the thermal performance of lightweight buildings or other construction systems.

The value and utility of a design-led research methodology.

The thesis is a demonstration of how a research methodology founded in the design-led tradition of architectural praxis can solve an intrinsically complex problem that exists within other complex social, economic and environmental systems. The methodology embraced the complexity of the problem and used social and scientific research methodologies in combination with design strategies to explore the problem and develop social, economic and physical propositions. Those propositions were then tested and evaluated qualitatively through argument and quantitatively using scientific models and methods.

The implementation of the proposals creates opportunities to transform the classrooms and the community.

The Solution Sets that have been developed are simple and the materials are readily available and relatively low cost. This enables schools to undertake the transformation of these classrooms themselves, enabling and empowering those who are directly affected by the poor performance of the Demountable Classroom buildings to affect their transformation.

If the implementation of the Solution Sets is undertaken with the involvement of pupils and teachers then the process of transformation, and the consequential improvement, becomes a pedagogical tool itself by creating a broad range of both “hard” and “soft” pedagogical opportunities. Students could learn about building performance, physics, maths and other “traditional” subjects. Importantly and significantly the process of implementation and subsequent monitoring could create opportunities to learn and engage with “soft” skills including leadership, negotiation, cooperation, team work, presentation, problem solving, interdisciplinary thinking and political engagement. The process creates opportunities for reciprocal learning, and broader community engagement and integration (Wake, 2015, Cole, 2014, Wake and Eames, 2013, Parnell et al., 2008, Flutter, 2006, Hübner, 2005).

Buildings are not just passive “containers” for teaching, they can be the “lesson” in themselves (Hübner, 2005). These ideas are, strictly, beyond the scope of this thesis

which is focussed on the thermal performance of the Demountable Classrooms. The ideas are discussed in more detail in an epilogue to the thesis. They emerge from an understanding and appreciation of the social significance of the problem and the significance of schools within their communities that is illustrated in the first chapter of the thesis.

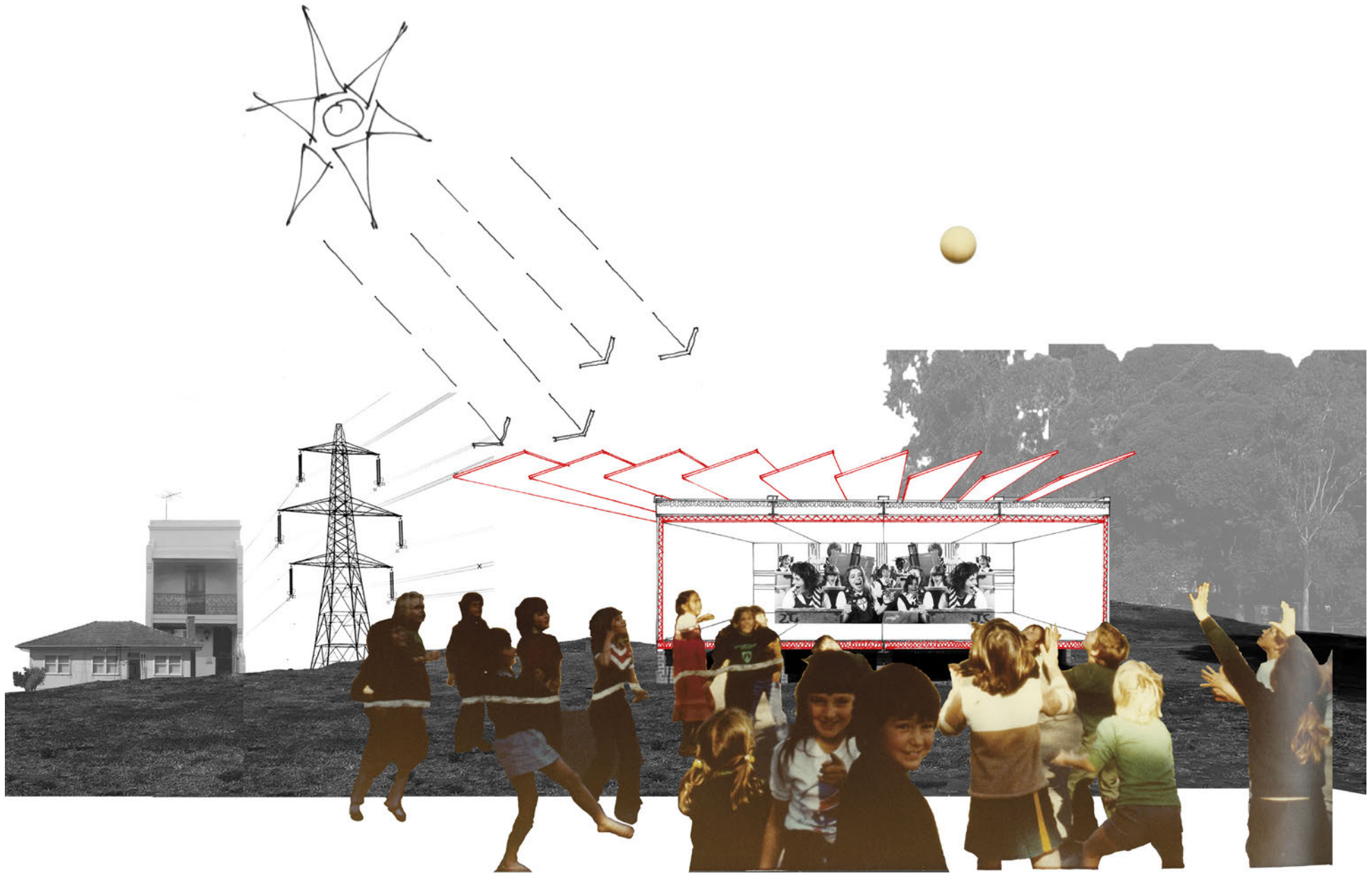


Figure 6.4: Collage

*The NSW Demountable Classroom refurbished to create a comfortable carbon positive classroom for the 21st century
(Drawing by the author)*

The NSW Demountable Classroom re-imagined as a catalyst for change



Figure 7.1: Collage

The NSW Demountable Classroom refurbished to create a comfortable carbon positive classroom for the 21st century

This epilogue reflects upon the potential social implications of implementing the proposed Solution Sets through community led projects. These ideas are beyond the scope of the research in this thesis, but develop out of the research, and offer an exciting suggestion of what might be possible.

One of the themes that recurs within the literature in this thesis is the social significance of the schools to their pupils' and communities' collective understanding of their own value and significance, and the value of education (Vinson et al., 2002, OECD, 2001, Sanoff, 2015). In her excellent paper "This place could help you" Flutter (2006) observes that

"for students, the physical conditions of school are often the familiar face of a much deeper set of issues about respect — feeling that you matter in school, that you belong, that it is 'your school' and that you have something to contribute."

Undertaking community engagement and co-design projects is not without risk (Parnell et al., 2008, Wheeler, 2009). However, carefully facilitated and integrated into the school curriculum, student participation in design and construction projects has been shown to be enormously positive and fits with contemporary pedagogical theory. The way in which we educate the

children in our communities is changing from a didactic, teacher-centred, instruction-focussed pedagogy to a “Constructivist” pedagogy that is student-centred, investigative and project based. This contemporary pedagogy recognises that education must equip our children with the practical, ethical and moral skills they need for the environmental, social and economic challenges they will face, so that they can become active, engaged citizens (OECD, 2001, Wheeler, 2009, Wake and Eames, 2013). There are many examples of projects that illustrate the opportunities for shared learning and for engagement with the wider community:

In the United States the SEED Collaborative (The SEED Collaborative) uses a co-design process to design and construct self-sufficient relocatable classroom buildings that create “*inspiring, healthy, and restorative*” learning environments with on-going opportunities for experiential learning. When the classrooms are no longer needed they can be given to another school that does need them, extending the social impact and benefit of the project.

In the UK the Sorrell Foundation facilitates small and large scale student led projects to improve schools through better design in a wide variety of schools and communities across the country (Sorrell Foundation).

Wake and Eames (2013) report on a specific project to build a new classroom in a school in New Zealand, while Wake (2015) reports on a similar project focussing on improving the outdoor spaces in a school. In both projects the reciprocal benefits for the teachers,

professionals and students are highlighted as well as the empowerment of, and engagement with, the wider community, and the longer term benefits for the pupils who have learnt to become politically engaged.

The opportunities for using collaborative co-design and construction projects, and the NSW Demountable Classroom, to develop a broader social impact are exemplified by the work of Peter Hubner, in Germany (Blundell Jones, 2007). For Hubner building is a communal activity:

“Physical involvement in building is not just a technical, but a social process. For millennia, building was a community process, neighbourhood help and an initiation ritual, and was tied into a society and its traditional practices.” (Hubner, 2015)

Hubner has helped to initiate, enable and develop multiple co-design and construction projects with community groups where the projects, and the spaces they create, help to develop cultural understanding and links between different groups in the wider community through the process of design and construction. It is the engagement in the process that is frequently cited as the most beneficial and significant element of these projects (Flutter, 2006, Parnell et al., 2008, Wake and Eames, 2013, Wake, 2015). Describing one of Hubner’s schools Blundell-Jones explains that

“[the school is] more than just an educational instrument, the school/village was conceived as a catalyst for the locality, giving people help as well as hope and inspiration” (Blundell-Jones, 2005)

The NSW Demountable Classrooms are regarded by many as 'second rate' or 'obsolete'; that they demonstrate that education and the community are not valued. By empowering those directly affected by the thermal performance problems of the Demountables to affect change it is hoped that the classrooms will be transformed from "a pejorative" into inspirational buildings that engender pride.

Classroom refurbishment projects have the potential to tackle broader issues within society as well. As a society we face enormous moral and ethical challenges about our relationships with each other and our environment, in particular the way in which we consume natural resources and produce CO₂ and other greenhouse gasses. In his philosophical exploration of student co-design and collaboration projects in the UK, Wheeler (2009) observes that

"One of the realisations of climate change is how intimately our future is bound to those of others..... It is a pedagogical problem with a philosophical complexity."

This observation directly addresses questions raised by Chappells and Shove (2003) and Kemp (2010) who argue that sustainable development means we must fundamentally change the systems for the provision of resources (physical infrastructure), and ways of thinking about the consumption of resources (social infrastructure), within society.

The NSW Demountable Classroom presents a radical alternative to the traditional conception of buildings

as permanent structures, literally embedded in our landscapes. The relocatable Demountable Classroom means that buildings, and the resources embedded in our buildings, can be used, and reused, by different communities. They can be shared.

The proposals in this thesis include the suggestion that the NSW Demountable Classrooms, and by extension schools themselves, become generators of energy embedded at the heart of communities. Thus, through their schools, communities become the producer of their own zero-carbon energy.

The retrofitting of the NSW Demountable Classroom by school communities creates an opportunity to become a catalyst for changing the social and physical infrastructure of schools, school communities and the communities that surround schools. Actively engaging the school community and the wider community in the process has the potential to help build connections between different parts of the community, which may be ethnically, intergenerationally or economically separated. The process enables debate and discussion. It demonstrates that what was regarded as obsolete can become a source of pride; a zero-carbon, energy positive, comfortable and inspirational building.

Interview records

The following pages contain the record of a series of open ended discursive interviews that were conducted with people associated with the design, maintenance and administration of the NSW Demountable Classroom program. Participants in the interviews were selected because of their particular expertise and were often found at the suggestion and introduction of other interviewees due to their particular expertise or experience with an aspect of the design, maintenance, management or administration of the NSW Demountable Classroom as a civil servant. The interviewees have experience of managing Demountable Classrooms stretching over 35 years.

The author conducted the interviews and took notes. Those notes were transcribed and emailed to the participants who had the opportunity to accept, reject or amend the notes or aspects of the notes. The agreed versions of the notes are presented here. The names and role of the participants have not been revealed in line with the requirements of the ethics approval process.

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These interviews were carried out in compliance with the University of Sydney ethics guidelines. Approval was granted by the Human Ethics Research Committee on the 12th of August 2014.

Ethics approval project reference: 2014/544

The project was also carried out in compliance with the NSW Government Department for Education and Communities guidelines.

Project reference: SERAP 2014169

Ethics approval letter



Research Integrity
Human Research Ethics Committee

Tuesday, 12 August 2014

Dr Richard Hyde
Architectural & Design Science; Faculty of Architecture, Design & Planning
Email: richard.hyde@sydney.edu.au

Dear Richard

I am pleased to inform you that the University of Sydney Human Research Ethics Committee (HREC) has approved your project entitled **"Demountable classrooms in NSW and environmental performance"**.

Details of the approval are as follows:

Project No.: 2014/544
Approval Date: 7 August 2014
First Annual Report Due: 7 August 2015
Authorised Personnel: Hyde Richard; Slee Benedict;

Documents Approved:

Date Uploaded	Type	Document Name
16/06/2014	Interview Questions	Semi-Structured interview format
29/07/2014	Other Type	Introduction email
29/07/2014	Other Type	Introduction letter
16/06/2014	Other Type	Letter - Interviewee review
16/06/2014	Participant Consent Form	Participant Consent form
16/06/2014	Participant Info Statement	Participant Information sheet

HREC approval is valid for four (4) years from the approval date stated in this letter and is granted pending the following conditions being met:

Condition/s of Approval

- Continuing compliance with the National Statement on Ethical Conduct in Research Involving Humans.
- Provision of an annual report on this research to the Human Research Ethics Committee from the approval date and at the completion of the study. Failure to submit reports will result in withdrawal of ethics approval for the project.
- All serious and unexpected adverse events should be reported to the HREC within 72 hours.
- All unforeseen events that might affect continued ethical acceptability of the project should be reported to the HREC as soon as possible.

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ABN 15 211 513 464
CRICOS 00026A



- Any changes to the project including changes to research personnel must be approved by the HREC before the research project can proceed.
- Note that for student research projects, a copy of this letter must be included in the candidate's thesis.

Chief Investigator / Supervisor's responsibilities:

- You must retain copies of all signed Consent Forms (if applicable) and provide these to the HREC on request.
- It is your responsibility to provide a copy of this letter to any internal/external granting agencies if requested.

Please do not hesitate to contact Research Integrity (Human Ethics) should you require further information or clarification.

Yours sincerely

Dr Stephen Assinder
Chair
Human Research Ethics Committee

This HREC is constituted and operates in accordance with the National Health and Medical Research Council's (NHMRC) National Statement on Ethical Conduct in Human Research (2007), NHMRC and Universities Australia Australian Code for the Responsible Conduct of Research (2007) and the CPMP/ICH Note for Guidance on Good Clinical Practice.

Semi-structured interview

Demountable classrooms research project

Date and time: 26th September 2014

Interviewees 2

Current and previous roles: Sustainability
Design
Administration

1.0 History

1.1 When were demountable classrooms first used?

-

1.2 Who designed them?

Public works

1.3 What were the original design criteria?

- **Cost?**
- **Environmental performance?**
- **Transport?**
- **Erection time? –**
- **Social purpose?**

Cope with demand quickly

1.4 A brief history of environmental standards for classrooms in NSW?

There was a "research group" to investigate sustainability in classrooms in NSW – See Alan/Eric
Following the end of the group the Sustainability Officer looked after used Sustainability of classrooms.

Used to be "Schools Facility Standards" (SFS) now revised and issued as "Educational Facilities Standards and Guidelines" (EFSG)
New standard is performance based.

1.5 How have the expectations of teachers, students and parents changed over the 30/40 years since Demountable classrooms started to be used?

- **Comfort/thermal performance/IEQ**
- **Technical expectations (digital display etc.)**

Recently a report has been prepared by Sydney University for the DfE (de Dear et al).

Part of the thermal Comfort Resource efficiency programme – contains lots of info on history and current research on A/C in classrooms.

1.6 Discussion:
Can you explain how the demountable classrooms have contributed to NSW communities over the last 40 years? Please discuss this in as holistic manner as possible and, if possible, offer some examples (case studies?) of how they offer a robust and reusable resource.

Standards have "crept in" over the last 10 years.

Last 2 years seen the greatest change the revision of the SFS to create the EFSG.

Standards developed in 1970's in response to school building boom of 70's.

Old copies in State library? Gov. Architects Office? NSW Public Works?

2.0 Present

2.1 What is the definition of the “hot zone” or climate line and what is its origin?

“Heat Stress Zone” – AT to email definition and map

2.2 The understanding of thermal comfort has changed over the last 40 years, for instance the development of “adaptive comfort” standards. Are there plans to or have you changed the definition of acceptable thermal comfort conditions for classrooms?

“Heat Stress Zone” remains as the definition line between A/C and Nat. vent in permanent school buildings.

2.3 What is the current definition or standard describing acceptable thermal comfort in a classroom?

There is no definition for day to day temperatures in classrooms.

2.4 How often are demountable classrooms refurbished?

-

2.5 How long will a demountable classroom stay on a site after it is deployed? Is there a maximum timeframe?

-

2.6 What are the current NSW design standards for classroom Size?

See EPSG

2.7 What are the current NSW design standards for Thermal performance/IEQ/sound?

See EPSG:
New standards for acoustics and ventilation.
Requirement for minimum standards – e.g. cross ventilation etc.
No requirement for min. ventilation rate per hour etc.

2.8 What are the current NSW design standards for Technical performance (IT etc.)?

No standards for glare/brightness etc. – “a work in progress”

There used to be a requirement for skylights but moving towards light tubes.

3.0 Future

The concept of obsolescence:

Building Obsolescence occurs when the gap between the expectations or requirements of the building users and the amenity that the building actually provides becomes unacceptable.

Obsolescence does not mean that the building itself is failing or deteriorating but that it no longer meets the requirements of users, for instance it lacks IT facilities.

It is not possible to predict the future, but it is possible to speculate.

3.1 What are the strengths, weaknesses, opportunities and threats to existing demountable and permanent classrooms (SWOT)? And how might these change in the future?

You may wish to consider

Extrinsic factors: Things that change around the classroom, e.g. Climate or population demographic.

Intrinsic factors: Things that are part of the classroom itself, e.g. The thermal performance of the building and the associated changing expectations of the users.

Aims, Objectives, Processes, Outcomes

3.1.a Strengths?

- “Bomb proof chassis”
- Mobile
- More robust than the Modular Design Range (MDR) that can only be relocated once or twice.

3.1.b Opportunities?

- Match the performance of the MDR range.
- Significantly improve the thermal performance of the current demountables.
- Permanent buildings built off-site (prefab technology/systems) – eg. Cairnsfoot school (NBRS architects)

3.1.c Threats?

Nothing – “we will always need them for, at the very least, disaster recovery”

3.1.d Weaknesses?

- “Core-plus” model has changed – demographic and rate of change in inner cities is changing.
- This is due to commuting/travel costs, lifestyle expectations etc.
-

Semi-structured interview

Demountable classrooms research project

Date and time:	8 th September 2014
Interviewees	1
Current and previous roles:	Retired Previously General Manager of Properties which covered demountables Also carried out a research project looking at managing the population of schools. Design Administration

1.0 History

1.1 When were demountable classrooms first used?

Wooden relocatables used in 50's and 60's
Current demountables in late 60's/70's – a response to rapid growth in school populations

- Wyndham Scheme
- ROSLA – K12 retention – the school leaving age was raised
- Large housing commission estates being built – Mt. Druitt and Green Valley etc.
- A requirement for access to a housing commission house was couple + 2 children – leads to huge demographic problem in schools (see thesis)

1.2 Who designed them?

George Conomy – Director of properties in education - Public Works Department

1.3 What were the original design criteria?

- o **Cost?**
no info – may be in Public works department records
- o **Environmental performance?**
N/A
- o **Transport?**
Modules on flat back trucks
- o **Erection time?** –
1 – 2 days
JB replaced an entire school in 10 days for 300 – 400 children
- o **Social purpose?**
Deal with Demographic change – “the baby boomers”

1.4 A brief history of environmental standards for classrooms in NSW?

Many design methods tried – school design changed.
Superseded by A/C
Now trying to move away from A/C – e.g. Camden school with nat. ventilation and shading (2000)

1.5 How have the expectations of teachers, students and parents changed over the 30/40 years since Demountable classrooms started to be used?

- o **Comfort/thermal performance/IEQ**
- o **Technical expectations (digital display etc.)**

Expectations for A/C in schools have increased as domestic use of AC has increased. – i.e. community standards have changed.
Expectation of the number of students per class has decreased – 1953 – 40 -48 per class.
now – 25 per class
Maintenance of demountables on site is a problem.

Around 2000 all demountables to be refurbished were fitted with A/C.
As a result demountables are often now more popular than old classrooms without A/C.

Old/Permanent classrooms only receive A/C from government if mean max. T in January >30 deg. C

1.6 Discussion:

Can you explain how the demountable classrooms have contributed to NSW communities over the last 40 years? Please discuss this in as holistic manner as possible and, if possible, offer some examples (case studies?) of how they offer a robust and reusable resource.

Provides accommodation for peak enrolment – currently approx.. 5,900 demountable buildings – mostly classrooms.

Approx. 90% in schools – 10% being repaired/stored – costs \$20m p/annum.
12% of Classrooms are demountables.
Demountable replacement program – long-term classrooms/libraries and admin buildings.
500 – 800 classrooms moved each January – most timely – wet weather problem.
Response to fire/emergency (flood?) – entire school in 10 days.
Lightweight construction building systems were introduced in 2000 to provided a low cost classroom solution. This includes prefab systems that were part of the demountables program.

2.0 Present

2.1 What is the definition of the “hot zone” or climate line and what is its origin?

Hot zone – isotherm where mean max T in January > 30deg.C
Now covering larger parts of the state including parts of Sydney!

A method for determining whether should have A/C given state gov. stringent financial constraints.

2.2 The understanding of thermal comfort has changed over the last 40 years, for instance the development of “adaptive comfort” standards. Are there plans to or have you changed the definition of acceptable thermal comfort conditions for classrooms?

N/A – current but changes on-going over 1990's and 2000's.
Community expectations change – private schools et. Have A/C.

2.3 What is the current definition or standard describing acceptable thermal comfort in a classroom?

N/A

2.4 How often are demountable classrooms refurbished?

On-going/as required with Cessnock Corrective Services.
Refurbishment before 2000 was often on-site – led to problems.
After 2000 “proper” refurbishment program initiated.

2.5 How long will a demountable classroom stay on a site after it is deployed? Is there a maximum timeframe?

No maximum – depends on demographics.
Schools like the space and therefore are reluctant too let the classrooms be removed.
\$100M recently to replace demountables with l/w permanent buildings.

2.6 What are the current NSW design standards for classroom Size?

80 sq.m for permanent primary school classroom.
(65 sq.m teaching + office and storage space.)

2.7 What are the current NSW design standards for Thermal performance/IEQ/sound?

2.8 What are the current NSW design standards for Technical performance (IT etc.)?

3.0 Future

The concept of obsolescence:

Building Obsolescence occurs when the gap between the expectations or requirements of the building users and the amenity that the building actually provides becomes unacceptable.

Obsolescence does not mean that the building itself is failing or deteriorating but that it no longer meets the requirements of users, for instance it lacks IT facilities.

It is not possible to predict the future, but it is possible to speculate.

3.1 What are the strengths, weaknesses, opportunities and threats to existing demountable and permanent classrooms (SWOT)? And how might these change in the future?

You may wish to consider

Extrinsic factors: Things that change around the classroom, e.g. Climate or population demographic.

Intrinsic factors: Things that are part of the classroom itself, e.g. The thermal performance of the building and

the associated changing expectations of the users.

Aims, Objectives, Processes, Outcomes

3.1.a Strengths?

- Longevity
- Adaptability and immense flexibility
- -Eg. Library, canteen, office
- A/C has been a game changer and allows deployment in all climates.
- Can be extended to create larger spaces, special spces (Kitchen, toilets etc.)
- DET owns them – replacement cost is \$150K/classroom

3.1.b Opportunities?

- Can be improved in terms of environmental performance
- Integration into schools can be improved – i.e. organisation of corridors/ covered walkways, orientation and location within the school.
- Integration into school plans for new schools – i.e. plan to include demountables!
- Visual amenity – beauty!
- Limit to 20% on a site

3.1.c Threats?

- Lack of proper maintenance
- Lack of funds for replacement
- Community perception

3.1.d Weaknesses?

- Community perception – “demountable” is a pejorative!

Semi-structured interview

Demountable classrooms research project

Date and time:	26 th September 2014
Interviewees	2
Current and previous roles:	Project Officer – Demountables programme Design Administration

1.0 History

1.1 When were demountable classrooms first used?

First built and commissioned in 1960's (mk.1)

1.2 Who designed them?

GAO or Dep. Of Public Works – Old System Drawings Available

1.3 What were the original design criteria?

- Cost?
- Environmental performance?
- Transport?
- Robust and transportable
- Erection time? –
- Social purpose?

1.4 A brief history of environmental standards for classrooms in NSW?

1.5 How have the expectations of teachers, students and parents changed over the 30/40 years since Demountable classrooms started to be used?

- Comfort/thermal performance/IEQ
- Technical expectations (digital display etc.)

There is an expectation for a fully air-conditioned classroom (or building)

White boards & IT equipment are purchased separately by the school. There is an expectation for fully interactive white boards in the classroom.

1.6 Discussion:

Can you explain how the demountable classrooms have contributed to NSW communities over the last 40 years? Please discuss this in as holistic manner as possible and, if possible, offer some examples (case studies?) of how they offer a robust and reusable resource.

Helped communities and the NSW Government deal with

- Emergency needs
- Re-building schools
- Used for other government activities – e.g. the Sydney Olympics when they were borrowed to provide various types of accommodation
- Unexpected growth in school populations

A/C in all classrooms is a relatively new innovation

Classrooms now arrive re-furbished – they used to arrive shabby – this improves their reception.

Questions:

IT & Interactive whiteboards – do they need their own supporting structure?

A/C location – where is the best place to put the A/C systems and what is an appropriate size system?

2.0 Present

2.1 What is the definition of the “hot zone” or climate line and what is its origin?

2.2 The understanding of thermal comfort has changed over the last 40 years, for instance the development of “adaptive comfort” standards. Are there plans to or have you changed the definition of acceptable thermal comfort conditions for classrooms?

2.3 What is the current definition or standard describing acceptable thermal comfort in a classroom?

2.4 How often are demountable classrooms refurbished?

10- 20 years in theory – to a certain extent it depends on current funding.

**2.5 How long will a demountable classroom stay on a site after it is deployed?
Is there a maximum timeframe?**

Data is available post 1995

Buildings are maintained on-site unless they are structurally unsound:
Re-roofing/re-cladding/over-sheeting to deal with leaks. Repairs are removed when the building is re-located/removed.

2.6 What are the current NSW design standards for classroom Size?

Meant to be:
60 sq.m Teaching space
17 sq.m practical activity space
6 sq.m store
8 sq. m "withdrawal" (quiet space/group space)

(total 102 sq.m)

2.7 What are the current NSW design standards for Thermal performance/IEQ/sound?

2.8 What are the current NSW design standards for Technical performance (IT etc.)?

4 data outlets per classroom (including phone)
All secondary schools have wireless networks.

2.9 Discussion

Heavy growth in use in the Sydney metro area – 300 deployed last year.

High energy use due to A/C systems – 2 x 6.5KW split cycle per classroom.

Roof cladding profile – currently span deck. Apparently due to large roof traffic during installation and relocation. Is there an alternative profile?

3.0 Future

The concept of obsolescence:

Building Obsolescence occurs when the gap between the expectations or requirements of the building users and the amenity that the building actually provides becomes unacceptable.

Obsolescence does not mean that the building itself is failing or deteriorating but that it no longer meets the requirements of users, for instance it lacks IT facilities.

It is not possible to predict the future, but it is possible to speculate.

**3.1 What are the strengths, weaknesses, opportunities and threats to existing demountable and permanent classrooms (SWOT)?
And how might these change in the future?**

You may wish to consider

Extrinsic factors: Things that change around the classroom, e.g. Climate or population demographic.

Intrinsic factors: Things that are part of the classroom itself, e.g. The thermal performance of the building and the associated changing expectations of the users.

Aims, Objectives, Processes, Outcomes

3.1.a Strengths?

- Transportability
- Robust construction
- Speed of installation
- Emergency needs – delivery in 1 – 2 weeks, St Clair high school – 20 classrooms in 2 weeks!
- Use to increase the size of existing schools

3.1.b Opportunities?

- Population growth data suggests that schools will be increasing in size over the next 5 years.
- Reduce energy (electricity) consumption

3.1.c Threats?

3.1.d Weaknesses?

- Limitation of unit size: height is a big issue (bridges etc.) which restricts transportation routes.
- Trying to accommodate all NSW climates in, or with, one building design.
- High energy consumption from A/C systems.

Semi-structured interview

Demountable classrooms research project

Date and time: 6th November 2014

Interviewees 2

Current and previous roles: Manager, Compliance and safety DfE) – 10 years
Analyst – Education facilities research group.
Retired
Principal Engineer – Mechanical services and sustainability – department of Public Works

1.0 History

1.1 When were demountable classrooms first used?

- (late) 1960's – (plans in Public Works Plan Room?)
- 1980's – Mk.2 version

1.2 Who designed them?

Public works, Government Architects office & Department for Education

1.3 What were the original design criteria?

- **Cost?**
-
- **Environmental performance?**
Natural lighting etc. The new system introduced increased insulation levels.
- **Transport?**
Major determinate – ordinary flatbed truck.
Mk.2 requires an articulated truck with a low bed because they are higher.
- **Erection time? –**
Speed – v. fast – e.g. Kelso High School built in 2 weeks after arson 19/08/2005.
(not 4 – 6 as predicted -
<http://www.smh.com.au/news/national/sniffer-dogs-called-in-to-check-school-fire/2005/08/20/1124435175732.html>)

- **Social purpose?**
Delivery of education
Immediate response to lack of facilities"

In order:

1. Provide a space/place where education and be given and received.
2. Provide an easily transported and erected classroom at a reasonable cost.

1.4 A brief history of environmental standards for classrooms in NSW?

Improvements have been incremental since 1970's:
Insulation was not used in permanent school buildings until 2000.
Prior to 2000 spending on schools v. tight (reason for no insulation?)

Objectives –
Good lighting
Layout of space
Temperature
Window shading – depends on orientation

1.5 How have the expectations of teachers, students and parents changed over the 30/40 years since Demountable classrooms started to be used?

- **Comfort/thermal performance/IEQ**
- **Technical expectations (digital display etc.)**

Formaldehyde has been banned for the last 30 years (1985) –
Driver for schools comes from domestic experience.
See School Facility Standards

Used to be least desired space. Now all A/C and maybe only A/C space in the school.

All IT is now wifi – has transformed technical IT requirements (since 2000?) – Digital Education Revolution since 2007.

1.6 Discussion: Can you explain how the demountable classrooms have contributed to NSW communities over the last 40 years? Please discuss this in as holistic manner as possible and, if possible, offer some examples (case studies?) of how they offer a robust and reusable resource.

Technology
Because it is always changing requirements keep changing – e.g cabling is now obsolete because of WiFi.

A/C brought comfort experience in line with expectations.

Emergency replacement:
Newcastle Earthquake

3.1.c Threats?

- Big building programs – eg. “Building the Education Revolution” – Labor government policy in wake of 2008 global financial crisis.
- Politics
- Comfort conditions/energy cost
- A single critical event – e.g. a fire and death.
- Existing design may restrict the opportunities for improvement
- Concepts of teaching are changing dramatically (pedagogy) – eg. Need for open spaces, student led teaching (acoustics?)
- Traditional “talk and chalk” teaching methods are being overtaken./replaced.

3.1.d Weaknesses?

- Multiple types
- Mk.2 better for size but worse for transport – some locations can not take larger trucks.
- Thermal bridging (thermal performance)

Thermal Comfort Program:

Heating and cooling policies were treated separately
Research has been carried out – “Thermal Comfort Program” – leading to a more holistic policy –

- Requires proposition and testing (?)
- Planning a strategy for implementation
- Higher management

See DEC for current position

2.3 What is the current definition or standard describing acceptable thermal comfort in a classroom?

There is no definition
Schools are defined as “habitable spaces with natural ventilation” in BCA – BCA compliant means opening windows.

2.4 How often are demountable classrooms refurbished?

Ask Demountables Unit/check data base:
Refurbishment based on condition – classroom modules west of the divide last a lot longer than those closer to the ocean (east of the divide).

**2.5 How long will a demountable classroom stay on a site after it is deployed?
Is there a maximum timeframe?**

Months – 10+ years.
15+ would indicate a need for a permanent classroom (Capital works).

2.6 What are the current NSW design standards for classroom Size?

See School Facility Standards and guidelines
Government Architects Office
Eg. Component design range for primary schools – 25 years of POE studies 1992- 2005.

2.7 What are the current NSW design standards for Thermal performance/IEQ/sound?

“Thermal comfort Framework”

2.8 What are the current NSW design standards for Technical performance (IT etc.)?

The development of the MDR (Modular Design Range) – Talk to Government Architects Office

3.0 Future**The concept of obsolescence:**

Building Obsolescence occurs when the gap between the expectations or requirements of the building users and the amenity that the building actually provides becomes unacceptable.

Obsolescence does not mean that the building itself is failing or deteriorating but that it no longer meets the requirements of users, for instance it lacks IT facilities.

It is not possible to predict the future, but it is possible to speculate.

**3.1 What are the strengths, weaknesses, opportunities and threats to existing demountable and permanent classrooms (SWOT)?
And how might these change in the future?**

You may wish to consider

Extrinsic factors: Things that change around the classroom, e.g. Climate or population demographic.

Intrinsic factors: Things that are part of the classroom itself, e.g. The thermal performance of the building and the associated changing expectations of the users.

Aims, Objectives, Processes, Outcomes

3.1.a Strengths?

Utility!

- Speed of delivery - 1 complete high school is always kept in storage ready for an emergency.
- Response to demographics (core plus etc.)
- Flexibility – they can be used for anything – not just classrooms.
- Construction – they last.

3.1.b Opportunities?

- Develop a new one based
 - A. on the existing
 - B. a brand new one.
- Use them as government offices (they are already)
- Can the existing design be improved to make it into a high performance building?

3.1.c Threats?

- Big building programs – eg. “Building the Education Revolution” – Labor government policy in wake of 2008 global financial crisis.
 - Politics
 - Comfort conditions/energy cost
 - A single critical event – e.g. a fire and death.
 - Existing design may restrict the opportunities for improvement
 - Concepts of teaching are changing dramatically (pedagogy) – eg. Need for open spaces, student led teaching (acoustics?)
 - Traditional “talk and chalk” teaching methods are being overtaken./replaced.
-

3.1.d Weaknesses?

- Multiple types
- Mk.2 better for size but worse for transport – some locations can not take larger trucks.
- Thermal bridging (thermal performance)

Semi-structured interview

Demountable classrooms research project

Date and time:	13 th February 2015
Interviewees	1
Current and previous roles:	Architect with the NSW Government Architects Office 25 years Expertise Leader Architectural Services Managing a team of Architects providing architectural and sub-consultancy services to DEC

1.0 History

1.1 When were demountable classrooms first used?

- DEC to advise

1.2 Who designed them?

Government Architects/Public works? - DEC to advise

Drawings signed of by Government Architect

1.3 What were the original design criteria?

- o **Cost?**
- o **Environmental performance?**
- o **Transport?**
- o **Erection time?** –
- o **Social purpose?**

1.4 A brief history of environmental standards for classrooms in NSW?

Now EFSG (Environmental Facilities Standards and Guidelines)

1.5 How have the expectations of teachers, students and parents changed over the 30/40 years since Demountable classrooms started to be used?

- o **Comfort/thermal performance/IEQ**

Expectations of Thermal, acoustic and glare conditions have

increased over decades: people “are much more savvy”.

In terms of expectations of the provision of appropriate

environmental conditions for students / staff.

A/C retrofitted to classrooms.

Note: There is a policy of naturally ventilating all classrooms –

but natural ventilation requires someone to open the windows –

and in many cases they don't!

Demountables today tend to be fitted with AC irrespective of their geographic location in NSW.

- o **Technical expectations (digital display etc.)**

1.6 Discussion: Can you explain how the demountable classrooms have contributed to NSW communities over the last 40 years? Please discuss this in as holistic manner as possible and, if possible, offer some examples (case studies?) of how they offer a robust and reusable resource.

History of Social stigma:

- Demountables generally regarded as 2nd rate facilities compared to permanent accommodation.
- Deemed not as good as bricks and mortar in terms of aesthetics, thermal mas, maintenance, functionality.
- A/C has been retrofitted to all classrooms.

Between about 1995 and 2005 the NSW government instituted a “demountables replacement program”.

Recent/current projects include:

Chatswood primary school on the Chatswood high school site – known as the “Bush School” to accommodate the increase in student numbers of primary school, temporary demountable classrooms were used to establish the primary school on the High school site.

An advantage of demountables used to be that they may not require DA approval – This is subject to councils planning laws

	and the location of the demountables.
	Can provide immediate accommodation solutions for increase in student number or if a school is fire damaged and classrooms are required quickly, demountables are a suitable response.
2.0 Present	
2.1	What is the definition of the “hot zone” or climate line and what is its origin?
	-
2.2	The understanding of thermal comfort has changed over the last 40 years, for instance the development of “adaptive comfort” standards. Are there plans to or have you changed the definition of acceptable thermal comfort conditions for classrooms?
	Current practice is to install AC to demountable classrooms. DEC to confirm
2.3	What is the current definition or standard describing acceptable thermal comfort in a classroom?
	- G.A.O use digital models of buildings to predict comfort. - Policy to use natural ventilation in all schools (dependant on geographic location). - Use Facilities Standards and Australian Standards and BCA
2.4	How often are demountable classrooms refurbished?
	DEC to advise
2.5	How long will a demountable classroom stay on a site after it is deployed? Is there a maximum timeframe?
	Some may have been on a site for 25+ years. DEC to advise.
2.6	What are the current NSW design standards for classroom Size?
	EFSG states a PS classroom is 60sqm (excl PA and Stores) HS General Learning Space is 60sqm
2.7	What are the current NSW design standards for Thermal performance/IEQ/sound?
	EFSG and relevant AS / BCA Standards.

2.8	What are the current NSW design standards for Technical performance (IT etc.)?
	Current NSW Government Architects Policy for designing new schools includes detailed presentation and discussion with key stakeholders (School Principals, P & C Reps, Students, Staff, DEC Head Office Directors and Educationalists.).
	Anecdotal evidence suggests that the issues of critical concern and interest are - Ensuring there is natural ventilation - Sustainability - Recycling as part of the construction process. - Accessibility
	Currently public schools are designed as permanent buildings with room for expansion rather than the Core-plus model that included a number of demountables. School construction is often staged subject to the demographic needs of the school or possibly logistics of construction.
	Flexibility of teaching spaces to adapt to current / future pedagogical requirements

3.0 Future

The concept of obsolescence: <i>Building Obsolescence occurs when the gap between the expectations or requirements of the building users and the amenity that the building actually provides becomes unacceptable.</i>	
<i>Obsolescence does not mean that the building itself is failing or deteriorating but that it no longer meets the requirements of users, for instance it lacks IT facilities.</i>	
It is not possible to predict the future, but it is possible to speculate.	
3.1	What are the strengths, weaknesses, opportunities and threats to existing demountable and permanent classrooms (SWOT)? And how might these change in the future?
	You may wish to consider
Extrinsic factors:	Things that change around the classroom, e.g. Climate or population demographic.
Intrinsic factors:	Things that are part of the classroom itself, e.g. The thermal performance of the building

	and the associated changing expectations of the users.
	Aims, Objectives, Processes, Outcomes
3.1.a	Strengths?
	- “Equity” – they are all the same so everyone gets the same classroom in N/S/E/W of the state. - Rapid fix to demographic problems. - Local environmental impact very limited – small pad foundations can avoid roots of trees etc. - Relatively easy to transport.
3.1.b	Opportunities?
	- Deal with tight urban sites – efficient use of space.... - Stack them go two or three stories? - Roof as play space? - Comfort - Possibly develop a kit of parts to tailor demountables to school sites e.g. heritage.
	Improve the flexibility of the spaces to allow adaption to a variety of teaching styles (pedagogy). E.g. - Allow for sliding walls between classrooms - Allow external walls to open up to outside – create inside/outside space. - Enable multiple uses of space
3.1.c	Threats?
	- MDR (Modular Design Range) (see below) -possibly provide an alternative option providing a more substantial building. - Fire rating on tight sites - Lack of flexibility in use and organisation of spaces to suit new/current pedagogical thinking – e.g. Joining classrooms or opening to the outside. - Some users see the demountable as a lesser / limited quality teaching space compared to the new schools being built comprising contemporary learning spaces.
3.1.d	Weaknesses?
	- Public perception – Stigma - Thermal comfort - Acoustics - Accessibility – need for ramps etc. to provide access of disabled students and teachers. - Siting limitations as crane access governs locations. - Use on Heritage sites could pose a problem in terms of aesthetics / suitability to heritage environments

The MDR range – Modular Design Range

Developed in 2003

- Prefabricated modular buildings
- Developed at the request of the government to provide rapid construction of classrooms.
- Ideally sited where they do not need to be moved but can be moved up to 2 or three times.
- Craned off trucks.
- Maximum height from truck bed to highest ridge 4m
- Wider and longer than classic demountable – requiring more substantial articulated truck.
- Light weight construction
- Higher performance than “classic demountable”
- “not cheap”
- Thermal comfort has been a problem depending on orientation.
- Site locations depend on crane access which may affect the best place for the MDR.
- E/W orientation can affect thermal performance but there may be limited options on some sites due to installation access requirements.
- Designs more compliant with EFSG criteria and substantial in terms of aesthetics when compared to the traditional demountables. Two storey possible.

Appendix B:

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Appendix C:

Publications

The following list documents the various publications and interviews by or with the Author in connection with this thesis.

Publications

SLEE, B. & HYDE, P. R. 2014. Towards a New Framework for Improving the Environmental Performance of Demountable Classrooms. A Study in New South Wales, Australia. In: F. MADEO AND M. A. SCHNABEL (ed.) Across: Architectural Research through to Practice: 48th International Conference of the Architectural Science Association Genoa, Italy: Architectural Science Association.

SLEE, B., HYDE, P. R., BLAIR, J. & JUNGHANS, L. 2014a. The NSW Demountable classroom: A review of existing research and a proposed methodology for future research. 2014 Asia-Pacific solar Research Conference. UNSW, Sydney, Australia.

SLEE, B. & HYDE, R. 2015a. A Base Line Study for Improving the Environmental Performance of Demountable Classrooms. 3rd Annual International Conference on Architecture and Civil Engineering (ACE 2015). Singapore.

SLEE, B. & HYDE, R. 2015b. The NSW demountable classroom: an analytical study to improve this radical building solution for education. In: STEPHAN, R. H. C. A. A. (ed.) Living and Learning: Research for a Better Built Environment: 49th International Conference of the Architectural Science Association 2015,. Melbourne: The Architectural Science Association and The University of Melbourne.

SLEE, B. & HYDE, R. 2016. Improving the thermal performance and energy efficiency of NSW Demountable classrooms using a community led retrofitting strategy. A proposal for Broken Hill. Proceedings of 9th Windsor Conference: Making Comfort Relevant Windsor, UK: Network for Comfort and Energy Use in Buildings, <http://nceub.org.uk>.

SLEE, B. 2016a. IMPROVING THE THERMAL PERFORMANCE OF THE NSW DEMOUNTABLE CLASSROOM USING WHOLE BUILDING SHADING. In: RAFAEL TUTS, P. M. I., PROF. SUSANNE GAMPFER (ed.) SFC 2016 - Sustainable Futures Conference - Architecture and Construction in the Global South. UNITED NATIONS HEADQUARTERS IN AFRICA NAIROBI, KENYA.

SLEE, B. 2016b. Simple strategies for improving the thermal performance of the NSW demountable classroom in four climates. In: J. ZUO, L. D., V. SOEBARTO (ed.) Fifty years later: Revisiting the role of architectural science in design and practice: 50th International Conference of the Architectural Science Association 2016. Adelaide: The Architectural Science Association and The University of Adelaide.

Radio interviews and programs

- BISSET, C. 2015. Blueprint for Living: The NSW Demountable. In: ABC RADIO NATIONAL (ed.) Blueprint for Living: Iconic Australian Buildings (based on information supplied by Ben Slee).
- SLEE, B. 2015. ABC 702 Mornings with Deborah Knight - NSW Demountable classrooms. In: KNIGHT, D. (ed.) ABC 702 Mornings with Deborah Knight. ABC 702 Radio Live.
- SLEE, B. 2017a. ABC Broken Hill Far West News - Feature. In: WAINWRIGHT, S. (ed.) ABC Broken Hill Far West News. ABC Broken Hill.
- SLEE, B. 2017b. ABC Newcastle - Drive. In: BEVAN, P. (ed.) ABC Newcastle- Drive- Paul Bevan. ABC Newcastle: ABC.
- SLEE, B. 2017c. ABC South East _ Breakfast. In: LAUDER, S. (ed.) ABC South East Breakfast. ABC Newcastle: ABC.

Relevant research preceding the thesis

Relevant research and publications into thermal mass that preceded and helped lead to this thesis

- SLEE, B., PARKINSON, T. & HYDE, R. 2014b. Quantifying useful thermal mass: how much thermal mass do you need? Architectural Science Review, 57, 271-285.
- SLEE, B., UPADHYAY, A. & HYDE, R. 2014c. Evaluating the influence of thermal mass and window size in a direct gain system on the annual and lifetime energy consumption of domestic Australian light weight construction. 8th Windsor Conference: Counting the Cost of Comfort in a changing world Cumberland Lodge, Windsor, UK: Network for Comfort and Energy Use in Buildings, .
- SLEE, B. & HYDE, R. 2015c. Using Thermal Mass in Timber-framed Buildings, Australia, Forest and Wood Products Australia.