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Improving energy efficiency in lower quality commercial buildings: Simulation, retrofit optimisation and uncertainty

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IMPROVING ENERGY EFFICIENCY IN LOWER QUALITY COMMERCIAL BUILDINGS: SIMULATION, RETROFIT OPTIMISATION AND UNCERTAINTY

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Abstract

Substantial reductions in the greenhouse gas emissions of modern societies are required in the near future to mitigate the projected impacts of global climate change. The best methods to achieve these cuts is a dominant issue in modern public discourse. Retrofitting of existing buildings offers significant opportunities for reducing global energy consumption and greenhouse gas emissions, and it has been recognised as one of the lowest cost options (McKinsey & Company, 2008). Whilst efficiency improvements of 15% to 30 % are typical for an energy efficiency retrofit, to make a meaningful contribution to mitigation efforts deeper cuts to consumption will be required.

The determination of the most cost-effective retrofit measures for particular projects represents a major technical challenge. Building Performance Simulation (BPS) is a valuable tool in this retrofit optimisation problem. Effective BPS requires substantial building data inputs and typically is bounded by incomplete information. This creates a reliance upon user skill and expert knowledge, and there is significant scope for error and uncertainty in predictions. Indeed, there exists a widely acknowledged 'performance gap' between actual energy consumption and predictions from BPS (Bannister, 2005; Bordass *et al.*, 2004; Menezes *et al.*, 2011; Torcellini *et al.*, 2004). This lack of confidence in findings from BPS was identified as one barrier to the uptake of energy efficiency upgrades in Australian commercial buildings (ClimateWorks Aus, 2010b).

The aim of the present study was to improve the understanding of the uncertainty in predictions from BPS for lower quality office buildings in Australia. Lower quality buildings were defined as B, C, or D Grade buildings according to the Property Council of Australia (PCA, 2011), and termed 'Secondary Grade' buildings. Secondary Grade buildings are a significant sub-set of the building stock, have previously received limited attention in the literature, are particularly affected by several barriers to retrofitting, and anecdotally may have a greater energy savings potential on a per m^2 basis than higher quality buildings.

A multi-method research approach was employed in this study, to allow methodological triangulation of findings. Quantitative analysis of three accessible databases containing building energy and energy-related information was undertaken. A qualitative investigation, which consisted of semi-structured interviews with twelve actors in the industry in Australia, was also completed. Analysis of the interview data revealed numerous challenges for BPS users, primarily related to the lack of reliable, accessible data regarding building operations and energy use. This precluded data-based decision-making and encouraged the use of simulations to inform retrofit decisions, but required the modeller to rely on assumptions and heuristics for uncertain inputs. In turn, this approach relied on the expert knowledge of the user. Simulation

based investigations were therefore undertaken to consider the impact of several sources of quantitative uncertainty.

Detailed analysis of the possible impact of climate change on the Heating, Ventilation and Air Conditioning (HVAC) energy consumption of reference commercial office buildings located in five Australian cities was undertaken. The relative magnitude of this impact was also compared to other possible future changes in the energy consumption of the buildings, such as changes in information technology. In regions of Australia where the annual cooling load was dominant, or there was a balance between heating and cooling demand, then significant increases in total building energy consumption were predicted, due to long-term rising ambient temperatures. In locations where the annual heating load was dominant, a slight increase or a decrease in energy consumption was predicted to occur. Changes in total building energy consumption of between 0.6% and 8.3%, and an increase in the total design cooling equipment capacity of 9.1% to 25.0% were predicted over the period 1990 to 2080 due to climate change in the various climate zones.

The uncertainty associated with the use of common assumptions (or default values) for variable, uncertain, or 'hard-to-measure' building and behaviour inputs to Building Performance Simulations (BPS) was then examined. A variation in predicted energy consumption of more than 50% from the baseline consumption was found for two reference buildings, when simulated with the range of input values collated from previous studies. The input parameters that most influenced energy consumption were found to be: i) cooling set-point; ii) Information and Communications Technology (ICT) power density; iii) ICT usage schedule; and iv) lighting power density. A case study of a lighting upgrade showed that the payback period could vary from 2.4 to 10.3 years depending on the simulation assumptions used. The use of default values from simulation protocols, designed to reduce the variability of these assumptions, was found to result in building energy use predictions varying by up to 13.5%, and substantially different energy end-use breakdowns.

Finally, a feasibility study of the use of 'reference buildings' for simplified BPS of existing Secondary Grade buildings in Australia was carried out, in the form of BPS of three case-study Secondary Grade commercial buildings. Reference buildings (also known as typical, template or archetypal buildings) selected from previous studies were progressively calibrated to align with detailed energy models of the case study building, validated with real building energy performance data (termed 'Baseline' models in this study). The final model calibration resulted in a predicted absolute average difference of 4.0% in base-building consumption (i.e. the consumption of the equipment and services which are under the control of the building owner in a tenanted building), and 7.9% in whole-building consumption (i.e. the base building, plus the equipment and services added and used by tenants in a tenanted building) between the

simplified ‘Calibrated Reference Building’ models and the fully detailed ‘Baseline’ models. It was found that the selection of an appropriate HVAC system and the use of an approximation of the geometric form significantly improved the accuracy of the reference buildings, with minimal increased modelling effort. This result may suggest that detailed modelling of the HVAC system is more important than detailed modelling of the geometric form of a building. The use of calibrated reference buildings for simplified BPS was found to be a potential method to improve the effectiveness of modelling and optimisation of deep retrofits to Secondary Grade buildings. Recommendations for research to further characterise this sub-sector of the stock, reduce the uncertainties identified in this study, and improve the decision process were also provided.

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Glossary and Acronyms

ABCB	Australian Building Codes Board
ABGR	Australian Building Greenhouse Rating
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineering
BA db	Building Attribute Database
BCA	Building Code of Australia
BEEC	Building Energy Efficiency Certificate
BEER	Building Energy Efficiency Register
BESTest	Building Energy Simulation Test
CBD	Central Business District
CBECS	Commercial Building Energy Consumption Survey
CIBSE	Chartered Institute of Building Services Engineers
CO_2	Carbon Dioxide
CV (RMSE)	Coefficient of Variation of the Root Mean Squared Error
DSA	Differential Sensitivity Analysis
DTS	Deemed-to-satisfy
ESC	Energy Savings Certificate
EUI	Energy use intensity
GBCA	Green Building Council of Australia
GBF	Green Building Fund
GCMs	General Circulation Models
GHG	Greenhouse Gas
ICT	Information and Communication Technology
IEQ	Internal Environment Quality
IPCC	Intergovernmental Panel on Climate Change
IWEC	International Weather for Energy Calculations
LEED	Leadership in Energy and Environmental Design
LGA	Local Governments Area
M & V	Measurement and Verification
NABERS	National Australian Built Environment Rating System
NLA	Net Lettable Area

NMBE	Normalised Mean Bias Error
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
PACU	Packaged Air Conditioning Unit
PMP	Performance Measurement Protocols
PV	Photovoltaic
RMY	Reference Meteorological Year
TMY	Typical Meteorological Year
TRY	Test Reference Year
VSD	Variable Speed Drive
WWR	Window to Wall Ratio
WYEC	Weather Year for Energy Calculations
Base Building	The equipment and services which are under the control of the building owner in a tenanted building (e.g. lifts, central plants, common lighting)
Low Grade Buildings	C, or D Grade buildings as defined by the Property Council of Australia Guide to Office Quality
Prime Grade Buildings	Premium of A Grade buildings as defined by the Property Council of Australia Guide to Office Quality
Reference Buildings	Used in this study to refer to typical, template or archetypal buildings. That is a theoretical building created to represent an average or typical building in a segment of a building stock.
Secondary Grade buildings	B, C, or D Grade buildings as defined by the Property Council of Australia Guide to Office Quality
Whole Building	The base building, plus the equipment and services added and used by tenants in a tenanted building

List of publications associated with this thesis

Chapter 2

Ma, Z, Cooper, P, Daly, D, & Ledo, L 2012, 'Existing building retrofits: Methodology and state-of-the-art', *Energy and Buildings*, vol. 55, pp 889-902.

Chapter 4

Daly, D, Cooper, P & Ma, Z (In Press). 'Qualitative Analysis of the use of Building Performance Simulation in the Australian Retrofitting Industry', *14th International Conference of the International Building Performance Simulation Association 2015*, Hyderabad, India.

Chapter 5

Daly, D, Cooper, P, & Ma, Z 2014, 'Implications of global warming for commercial building retrofitting in Australian cities', *Building and Environment*, vol. 74, pp 86-95.

Chapter 6

Daly, D, Cooper, P, & Ma, Z 2014, 'Understanding the risks and uncertainties introduced by common assumptions in energy simulations for Australian commercial buildings', *Energy and Buildings*, vol. 75, pp 382-393.

Chapter 7

Daly, D Cooper, P & Ma, Z (2014). 'The impact of default assumptions from simulation protocols on predicted energy consumption in office buildings in Australia'. In *2014 ASHRAE/IBPSA-USA Building Simulation Conference Papers*, pp. 219-226, ASHRAE, Atlanta.

1 Introduction

1.1 Background and Motivation

Human-induced climate change caused by resource over-consumption on a global scale presents a defining challenge to modern society. A substantial reduction in the greenhouse gas (GHG) emissions of developed nations is required in the near future to mitigate the projected impacts of climate change. There is broad public debate regarding the most effective methods to achieve these emissions reductions. It has been widely recognised that improving the efficiency of energy use must play a key role in any solution. Many studies (e.g. ClimateWorks Australia, 2010b; IPCC, 2007) have suggested that up to 30% of current energy use can be avoided with a net economic benefit through energy efficiency improvements across many industries.

Commercial building retrofitting has a major role to play in realising Australia's necessary emission reductions (i.e. 40-60% reduction in GHG emissions by 2030 (Climate Change Authority, 2014)). Commercial buildings account for approximately 7.5-10% of the total energy consumption in Australia (BREE, 2014; CIE, 2007; pitt&sherry, 2012b). Previous research (IPCC, 2007; Stern, 2006) has indicated that significant energy use reductions can be achieved in commercial buildings through technology upgrades/retrofitting, and organisational and behavioural modification strategies. McKinsey & Company (2008) found that commercial building retrofitting was the most cost-effective method of reducing GHG emissions in Australia. However, a significant time imperative exists. Most commercial buildings would be expected to undergo one major upgrade cycle before 2030 (Wilkinson & Reed, 2008), and given the average age of commercial buildings in the major markets is approaching 30 years (Adelaide City Council & JLL, 2007), a significant amount of upgrade action can be expected in the short term. This implies that the next building upgrade cycle must realise meaningful efficiency improvements in order to contribute to necessary emissions reductions.

At the same time, rising energy costs and an enhanced public awareness of the environmental issues are leading many organisations to examine ways to reduce their environmental impact, and their dependence on conventionally generated energy. This increased Corporate Social Responsibility, combined with government regulation and incentive programs to encourage energy efficiency in the commercial building sector, has resulted in substantial retrofit activity in Australia. In particular the National Australian Built Environment Rating System (NABERS), combined with Commercial

Building Disclosure legislation (*Building Energy Efficiency Disclosure Act 2010*, which mandates the disclosure of building energy efficiency information at the time of sale or lease) has been effective in driving retrofit activity in some sectors (IPD, 2013).

Poorer quality buildings, classified as B, C, or D Grade buildings by the Property Council of Australia (PCA, 2011), and known collectively as 'Secondary Grade' buildings, constitute between 50% and 85% of the Australia commercial building stock (NPC & Exergy, 2009), but have received little attention in previous studies. Secondary Grade buildings are typically older, in poorer condition, have poorer maintenance and repair, and are in private (rather than institutional) ownership. These buildings are also likely to have a greater energy savings potential per m^2 than Premium or A-Grade buildings (known collectively as 'Prime' Grade buildings). However, Secondary Grade buildings are more likely to be impacted by common barriers to building retrofitting, such as limited access to capital, limited access to information, lack of understanding, low business priority, lack of project scale, and other goals of decision makers (ClimateWorks Australia, 2010a). The retrofitting process for Secondary Grade buildings is also often complicated by poor documentation of construction and systems, incomplete or non-existent operation and maintenance manuals, and smaller project budgets for audit, investigation and upgrade works.

The determination of the optimal strategy to achieve a meaningful improvement to the energy efficiency of a commercial office building is a multi-objective optimisation problem, with a large number of constraints, limitations and competing priorities (Ma *et al.*, 2012). Building Performance Simulation (BPS) is a useful tool in the retrofit optimisation process, which can support the assessment of the energy and occupant comfort implications of a particular strategy prior to physical implementation. However, BPS requires a substantial amount of detailed input data. Macdonald (2002) estimated that a typical model in a modern simulation engine required over 4000 data items to describe the geometry, construction, and operation of a building. This complexity is one reason for the presence of a well-known 'performance gap' in simulation results (Bordass *et al.*, 2004; Torcellini *et al.*, 2004). The performance gap is the difference between the predicted performance of a building simulated in a BPS tool, and the actual energy consumption of the building in operation. The performance gap has been attributed to a number of causes, which may be summarised as errors in the prediction process, and variance introduced during construction or operation of the building. An important source of errors in the prediction process is the use of inappropriate simulation inputs and assumptions for unknown or variable parameters (Bordass *et al.*, 2001; Guyon, 1997; Menezes *et al.*, 2011; Simm *et al.*, 2011). The reliance on assumptions is

generally greater when simulating Secondary Grade buildings (PCA, 2011), due to both poor access to information, and limited budget for energy auditing and BPS. There is a need to develop simplified, lower cost methods of retrofit optimisation to allow Secondary Grade building owners to consider more holistic retrofit initiatives and realise the identified efficiency improvement potential.

Uncertainty and lack of confidence in predictions of energy savings from BPS was identified as an important barrier to the realisation of the significant GHG abatement and economic opportunities previously identified in the existing commercial building sector (Franconi & Nelson, 2012; IPCC, 2007; McKinsey & Company, 2008; Stern, 2006). Whilst BPS requires a large number of inputs, generally it will be a much smaller subset of these inputs that will have the most significant impact on the simulation results. Uncertainty Analysis and Sensitivity Analysis are techniques that can be used to: i) determine which inputs to a simulation are the most important, and ii) quantify the effect of an incorrect input value on the results. Sensitivity and Uncertainty Analyses are similar techniques in that both measure the change in a model output that results from a change in a model input. Unlike Uncertainty Analysis, Sensitivity Analysis is not concerned with the likely variation in the input parameters; rather all parameters of interest are perturbed by an arbitrary amount, i.e. ± 1%. Sensitivity Analysis can be used to identify key inputs for further targeted investigation or Quality Assurance. The incorporation of Uncertainty Analysis into BPS can provide decision makers with the information required for risk based decision making (Franconi & Nelson, 2012). The use of these two techniques can improve BPS predictions, allowing a move away from single figure deterministic representations of a building's performance, towards more nuanced representations of predictions as likely outcomes from probable conditions (Williamson, 2010).

1.2 Aim, Research Questions and Specific Objectives

The primary aim of this research project was to understand and quantify the uncertainty involved in BPS representations of commercial office buildings in Australia, particularly Secondary Grade buildings. In addition, the research was designed to develop ways of reducing uncertainties and complexity in the BPS process, and thereby assist in removing barriers to the use of BPS and related tools in the upgrade and retrofit optimisation of Secondary Grade buildings.

The key research questions for this study were:

1. *Is uncertainty in the predictions from Building Performance Simulation (BPS) an important issue for commercial building retrofitting in Australia, and what is the current standard practice in commercial consultancies for addressing uncertainty in BPS?*

2. *Which unknown or uncertain parameters are most significant in BPS of commercial buildings in Australia, and is the current standard practice, including heuristics and assumptions for significant inputs, an important source of uncertainty in BPS for retrofit optimisation in Secondary Grade commercial buildings in Australia?*

3. *Is the use of existing reference buildings a possible method to simplify the BPS of existing Secondary Grade commercial buildings in Australia, and thereby facilitate more effective use of BPS, including an improved representation of uncertainty in predictions for these buildings.*

The specific objectives of the study were to:

1. Conduct a review of existing literature in the areas of;
    a. Building energy retrofitting and behavioural modification strategies to minimise building energy consumption, particularly with respect to drivers, barriers and strategies;
    b. Retrofit optimisation processes, including the use of BPS for predicting energy savings from retrofit strategies, focussing particularly on the Australian commercial building sector;
    c. Characterization of the existing Australian commercial buildings stock, and relevant policy and programs.

2. Collect and analyse information on current standard and best practices for building energy efficiency retrofitting in Australia, including the attitudes and experiences of consultants and other stakeholders in the field. Scrutinize accessible data sources to gain insights into the Australian commercial building stock, and the building energy efficiency retrofitting industry.

3. Analyse the uncertainty involved in the representation of local and future weather conditions with typical weather datasets for BPS of office buildings in Australia. Examine

the relative importance of future changes to climate (over a timescale similar to the life of existing and new buildings) on building energy efficiency and the retrofit optimisation process, as compared to retrofit technologies and other possible future building utilization trends.

4. Analyse the uncertainty inherent in BPS of office buildings arising from the use of estimates of unknown, or uncertain, building characteristics and occupancy inputs. Identify key building attributes that influence energy consumption of office buildings in Australia, and identify and critique benchmark BPS inputs currently recommended by professional and government agencies.

5. Develop detailed thermodynamic models of several Secondary Grade office buildings as Case Studies. Evaluate the benefits of using existing commercial reference buildings to characterise these buildings and retrofits to such buildings. Investigate possible simplifications to the representation of these Secondary Grade buildings, and understand the implications of simplifications on uncertainties in the retrofit optimisation process.

1.3 Summary of Methodology

The research presented in this document employed a mixed-method approach to examine the research questions from numerous perspectives. The research project used Building Performance Simulations, Sensitivity and Uncertainty Analyses, along with qualitative investigations and statistical analysis of accessible data, to allow ‘triangulation’ of findings. Methodological triangulation can provide an ongoing check of the validity of the findings from each method, and enhance the contextual value of conclusions.

1.4 Structure of Thesis

The structure of the thesis is shown schematically in Figure 1-1 and an overview of each chapter is presented below.

Chapter 2 presents a review of existing literature relevant to understanding the generic building energy retrofitting process in the Australian context. It covers common methods and solutions for achieving building energy efficiency improvements, and outlines contextual factors influencing the building retrofitting industry in Australia.

Chapter 3 outlines the methods used to achieve the specific objectives stated in Section 1.2. Details are provided on: BPS tools and techniques employed, qualitative research methods used, and database analyses undertaken.

In Chapter 4 the Australian building energy retrofitting industry is investigated and described. The results from an analysis of key Australian data resources, including a qualitative analysis of expert opinions and behaviours, and a statistical review of existing data sources are presented.

Chapter 5 reports on the uncertainties introduced through the selection of different weather files on a representative commercial office building. The impact of predicted changes to future weather conditions, from climate change, on building energy performance and retrofit selection is also described.

The results of an uncertainty analysis that used BPS to investigate the impact of numerous uncertain building and occupancy inputs on commercial building energy consumption are given in Chapter 6.

In Chapter 7 the uncertainty associated with the use default values recommended by four simulation protocols to represent unknown occupancy inputs is considered.

Chapter 8 employs a number of case studies to investigate the benefits of a simplified approach to BPS evaluation of building energy efficiency. Consideration is given to the importance of modelling detail in various input sub-systems (e.g. geometry, construction, occupancy HVAC system).

The final chapter outlines the conclusions from this research project, its limitations, and recommendations for future research.

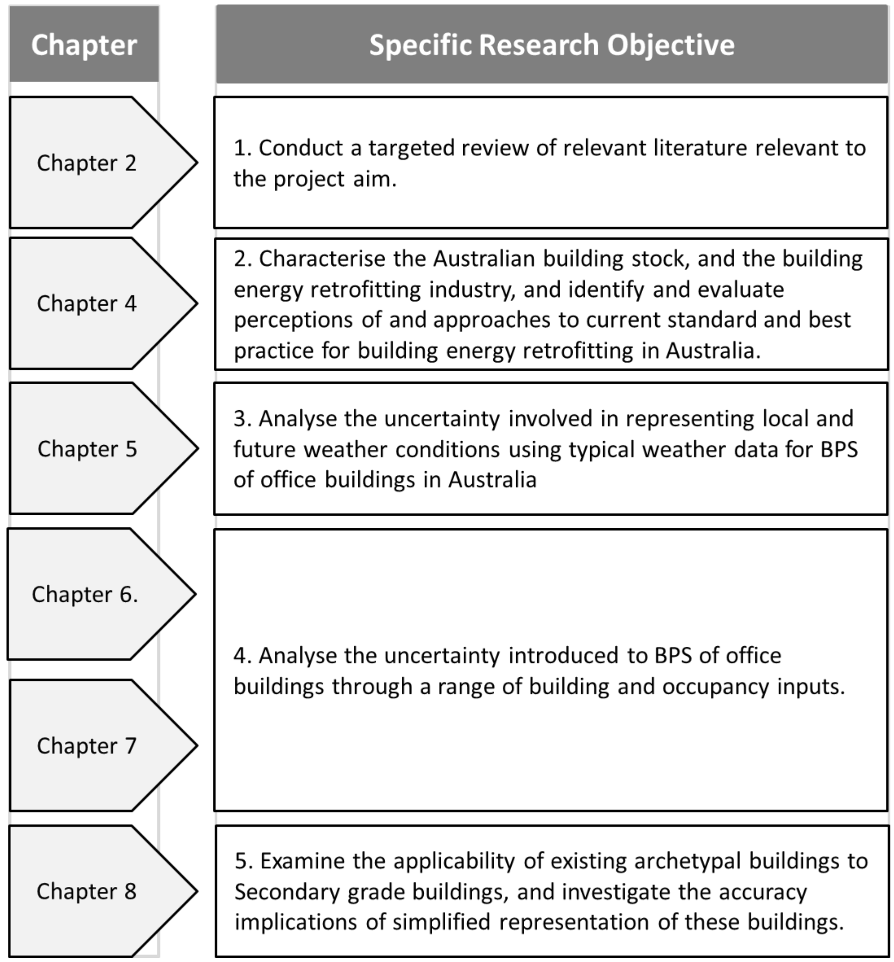


Figure 1-1 Chapter structure of this thesis, linking chapter location with specific research objectives.

2 Literature Review

The use of Building Performance Simulation (BPS) in the selection of optimal retrofit strategies is complex, and requires expert knowledge in numerous areas. Understanding how and why BPS has been applied to the problem of commercial building retrofit optimisation requires knowledge of contextual factors. This chapter provides a review of existing literature, and introduces the fundamental concepts most relevant to this research, including:

1. The generic building retrofit optimisation problem and decision making process;
2. Established techniques and technologies used for improving the energy efficiency of commercial buildings;
3. Building performance simulation tools and protocols, and;
4. Contextual factors which influence commercial building energy retrofitting in Australia, including drivers of, and barriers to, building retrofitting.

These areas of knowledge are inter-related, as illustrated schematically in Figure 2-1.

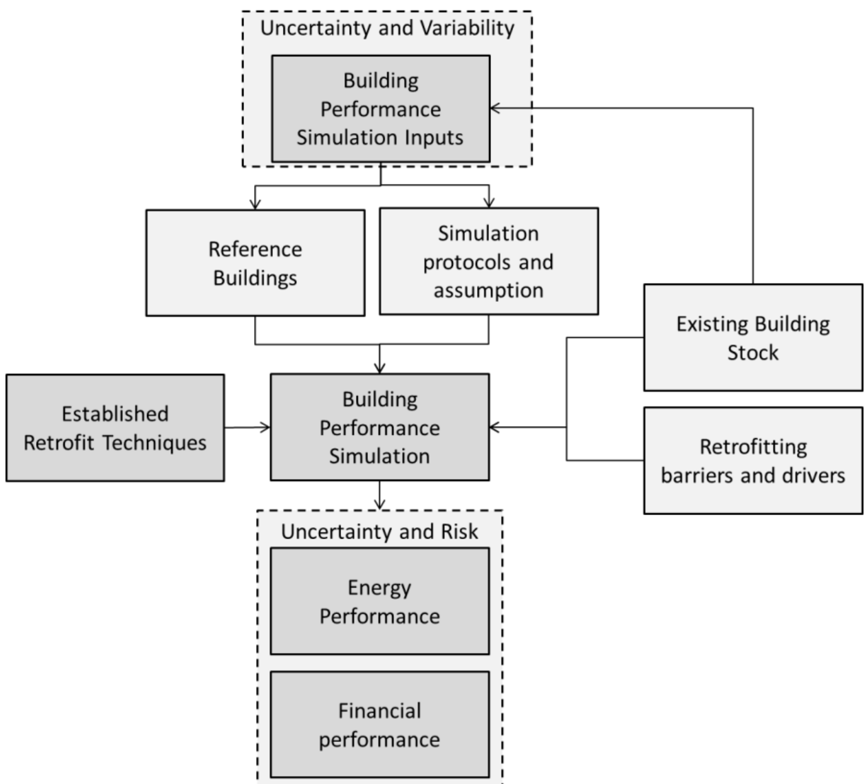


Figure 2-1 Graphical summary of the key knowledge areas for this research.

2.1 The Environmental Imperative

The extensive use of non-renewable resources to sustain and improve standards of living is the cause of many of the environmental issues faced today, including global climate change. The Stern review (Stern, 2006), a British inquiry into the economic implications of climate change concluded that, ‘the scientific evidence is now overwhelming: climate change presents serious global risks and it demands an urgent response.’ The Fifth Intergovernmental Panel on Climate Change (IPCC) assessment report (IPCC, 2013) concluded that if emissions continue, on a worst case scenario, global temperature rises of 3.2 - 5.4 ^{o}C are to be expected by the end of this century. Greenhouse gas emissions (GHG) are the driver behind climate change, and electricity generation is a key source of emissions. The Stern review found that stationary power generation and energy use account for 51% of global emissions. Other sources of emissions, which include agriculture, land-use and transport, account for the remaining emissions.

In Australia, the building sector accounts for approximately 20% of Australia’s GHG emissions, and commercial buildings are responsible for almost 50% of these emissions, between 7.5 – 10% of Australia’s total GHG emissions (BREE, 2014; CIE, 2007; pitt&sherry, 2012b). Australia has the highest per capita emissions of any OECD (Organisation for Economic Co-operation and Development) country (26.7 tCO_2-e/p/yr.) (Garnaut, 2008), and commercial building emissions have been projected to increase by 154% from 2005 to 2050 (CIE, 2007). The provision of acceptable Internal Environmental Quality (IEQ), including adequate lighting and ventilation and acceptable thermal conditions, is the major end use of energy in commercial buildings; representing between 50% and 85% of a building’s overall energy consumption (AGO, 1999; pitt&sherry, 2012a).

2.2 The Economic Imperative

Improving the energy efficiency of the existing building stock in Australia is an economically viable way to reduce emissions and has significant climate mitigation potential. The IPCC report into mitigation of climate change (IPCC, 2007) found that CO_2 emissions reductions of 30% by 2020 (against a 2004 baseline) with net economic benefit were possible in the building sector. Other studies (CIE, 2007) suggested that the building sector as a whole could reduce its energy consumption by between 20 and 40% by implementing energy efficiency measures. The Low Carbon Growth Plan for Australia (ClimateWorks Australia, 2010b) found that the building sector

could contribute 26 Mt of CO2-e emissions reductions, with 77% coming from the commercial sector. Further, the report found that 75% of the measures would offer profits to investors, at an average of $90 per tonne of CO2-e offset. The majority of the benefits, 80%, are to be achieved with the existing building stock, rather than with new builds. Figure 2-2 shows the societal marginal abatement cost for different measures. Figure 2-3 shows the cost to the investor of the identified energy efficiency improvements.

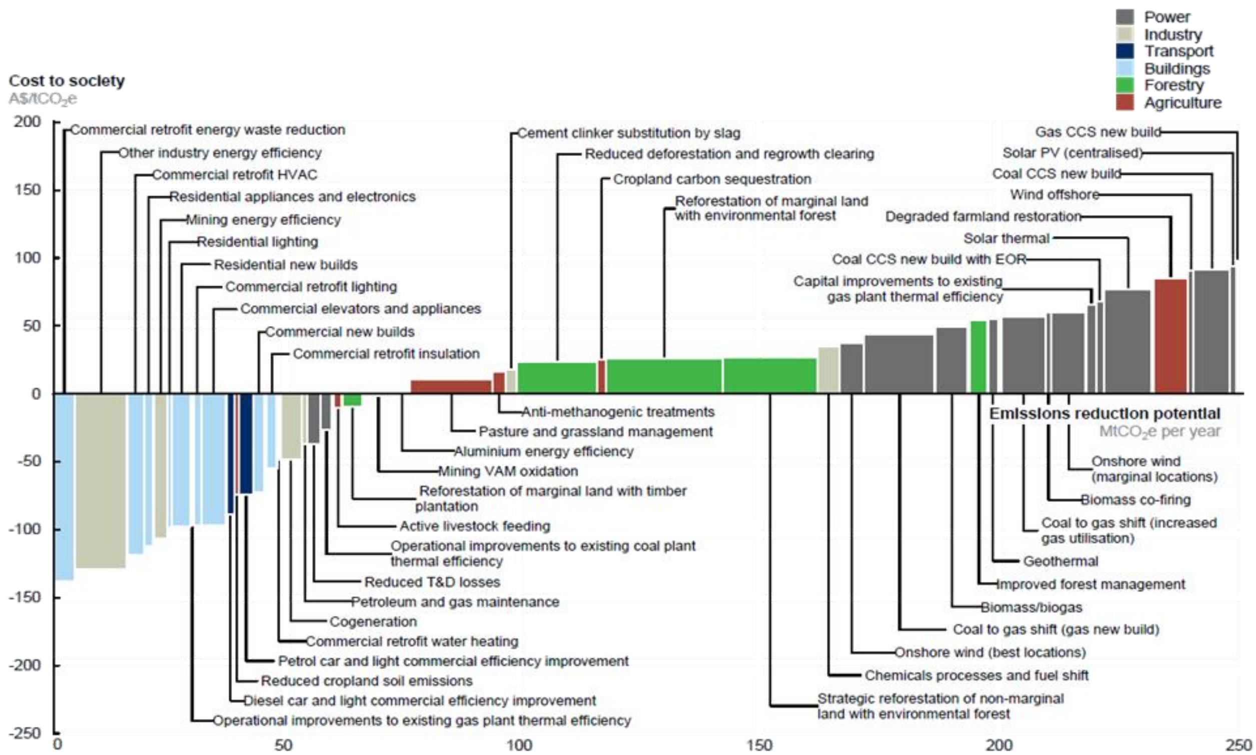


Figure 2-2 Marginal Abatement Cost curve for societal costs of various GHG reduction measures (ClimateWorks Australia, 2010b).

From the perspective of building owners, ‘green’, or energy efficient buildings, offer numerous economic advantages. Energy efficient buildings have the potential to lower costs, increase income, and minimize risk. Bowman and Wills (2008) found that industry experts expect owners of ‘green’ commercial buildings in Australia will realise average savings of $\$5/m^2$ of annual operating cost. An analysis of over 1000 properties in the investment portfolio of IPD (IPD, 2010) found that both rental and capital values increased at a higher rate for buildings with higher than average NABERS (National Australian Built Environment Rating System) ratings. The Australian Federal Government has a mandated minimum NABERS rating of 4.5 stars for space that they occupy. In Canberra, a city with a large number of government tenants, 5 star NABERS buildings attract a

21% price premium, compared to 4% for Sydney Central Business District (CBD) (Newell *et al.*, 2011). These studies are not isolated, and others e.g. (Fuerst & McAllister, 2008; GBCA, 2008; Kats, 2003; Pivo & Fisher, 2009; Miller *et al.*, 2009; RMI, 2010; Fluhrer *et al.*, 2010) supported the link between green buildings and increased property values. It follows that upgrading an existing building may allow an owner to receive higher rents, faster increasing rents, lower occupancy, and increased building value. Green buildings may also have a lower exposure to future risks, including predicted rises in utility costs.

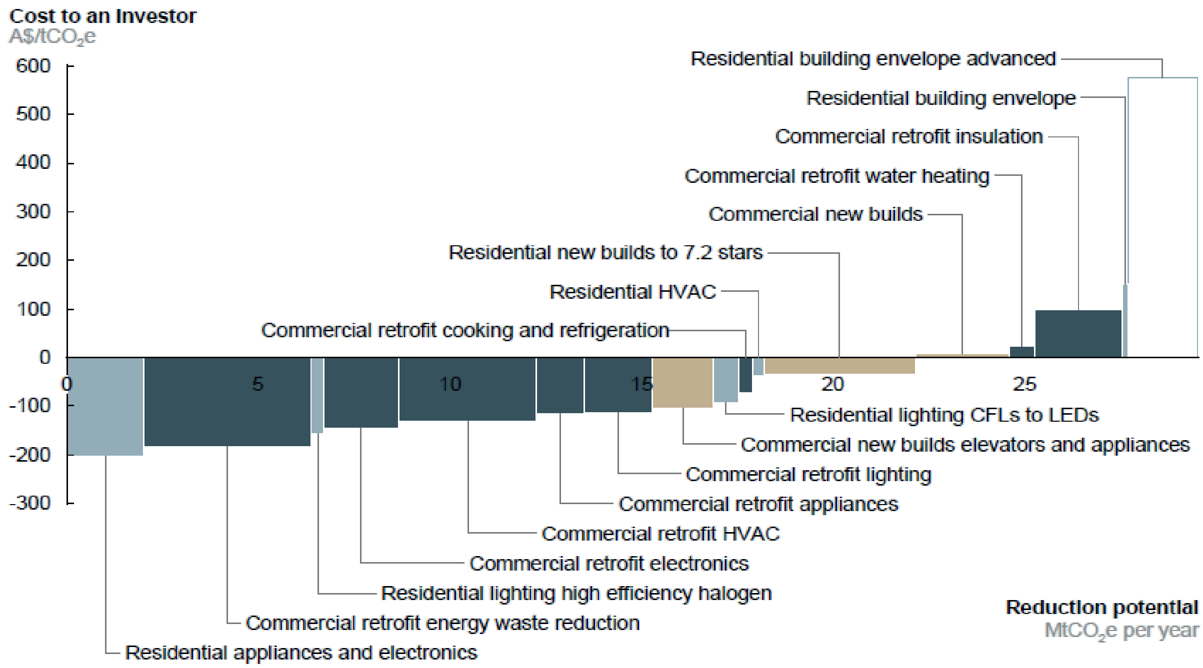


Figure 2-3 Marginal Abatement Cost curve showing the cost to an investor of various potential energy efficiency improvements (ClimateWorks Australia, 2010b).

There are many opportunities to realise further economic benefits for tenants, beyond reduced operating costs, in well-designed green buildings. A building energy retrofit offers an opportunity to deliver improved IEQ alongside energy savings, although this is not an automatic outcome of the retrofitting process. Improvement of the IEQ in buildings has been shown to increase staff productivity, reduce absenteeism, reduce staff turnover rates, and improve employee health. In a review of previous international studies, Fisk (2000) found that productivity increases of between 2-20% for simple tasks had been reported as a result of improvements in thermal environment. Kats (2003) recommended attributing between 1% and 1.5% productivity and health gain to LEED certified buildings, which is shown to correspond to a financial benefit of \$3.25 – \$51/m^2. Miller *et al.* (2009) compared the responses of tenants who have moved into LEED or Energy Star rated

buildings, and reported that employees took on average 3 less sick days per year, and showed a 4.9% increase in perceived productivity. Leaman & Bordass (1999) found that losses or gains of up to 15% of turnover in a typical office organization might be attributable to the design, management and use of the indoor environment. The benefits mentioned above can have a much greater economic impact than simple energy savings. For an average office-based business, wages account for 80-90% of a company's total expenditure (Sustainability Victoria, 2011). This means that a small increase in productivity is more economically attractive than a much larger reduction in electricity expenditure. It should be noted that any study into productivity improvements must overcome significant difficulties in measuring this index.

2.3 Retrofitting of Existing Buildings

Improving the efficiency of Australia's existing building stock has been identified in many previous studies as vitally important to reducing emissions. Existing buildings, in this case defined as buildings that were built without sustainability considerations in mind, make up 97% of Australia's building stock (GBCA, 2008). The rate of replacement of old buildings by new constructions is of order 1-3% per year (Adelaide City Council & JLL, 2007; Reed & Wilkinson, 2007) meaning that building new low energy constructions will not by itself have a significant impact on GHG emissions in Australia in the near future. Numerous studies (e.g. IPCC, 2007; McKinsey & Company, 2008; Stern, 2006) have examined the technical and economic considerations of climate change mitigation methods, and identified the refurbishment of existing buildings as the quickest and easiest method available to achieve emissions abatement. There is a significant potential for energy efficiency improvements in the commercial building stock (Chidiac *et al.*, 2011a, 2011b; Ecologic, 2015; Hampton, 2011; LBNL, 2015). The 'Low Energy High Rise' study (NPC & Exergy, 2009) found that approximately 30% of commercial energy use could be avoided, with 'only limited recourse to major technical refurbishment'. The Zero Carbon Australia Buildings Plan (ZCA, 2013) identified savings of 44% for non-residential buildings, primarily through technical refurbishment.

The embodied energy of buildings is an important factor in determining life-cycle emissions. The Preservation Green Lab (2012) found that if an existing building with an average level of energy performance was replaced with an energy-efficient new construction, it would take between 10 to 80 years of operation for the new building to realise lower life-cycle emissions. The majority of building types studied would take 20-30 years, depending on location and type, to outperform an

existing, averagely efficient building in terms of life-cycle carbon emissions. Roussac (2006) calculated that a newly built 5 star Green Star building will take 50 years to overcome the embodied energy of demolition and construction through more efficient operation, when compared to leaving an existing poorly managed 2 star building in place.

Rawlinson & Wilkes (2008) identify the following as the key advantages of building refurbishment, when compared to new build:

1. Speed to market – reduced construction time, minimised planning requirements, and the opportunity to phase works;
2. Retention of the character, development density and massing of the existing building;
3. Cost avoidance of total demolition and rebuild (at least 20% even in major upgrades);
4. Flexibility – the opportunity to tailor the extent or timing of the upgrade to market conditions.

The studies identified above have highlighted the advantages of building retrofitting. However, there are many barriers and complexities which hinder the implementation of building retrofit strategies. The barriers are often contextual; a discussion of the barriers in the Australian context is included in Section 2.10.5.

The identification and implementation of an optimal existing building energy reduction strategy is a multi-objective optimisation problem with a large number of constraints and limitations (Diakaki *et al.*, 2008; Ma *et al.*, 2012). The optimisation problem is to 'determine, implement, and apply the most cost effective retrofit technologies to achieve enhanced energy performance while maintaining satisfactory service levels and acceptable indoor thermal comfort, under a given set of operating constraints' (Ma *et al.*, 2012). Once the decision has been taken to upgrade a building, the retrofit decision maker must identify the optimal retrofit strategies. The key phases in a sustainable building retrofit program are identified in Figure 2-4 and are discussed in the following section.

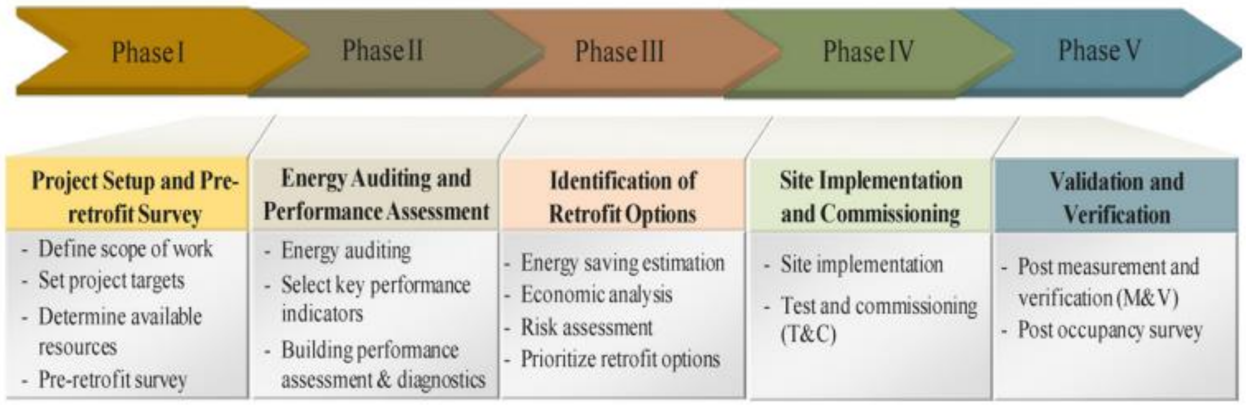


Figure 2-4 Key phases in a sustainable building retrofit program, from Ma et al. (2012).

Phase I involves the identification of targets and constraints for the retrofit. It is vital that the targets and goals for the building upgrade are clearly defined, as the success or otherwise of the upgrade will be judged against these. Phase II is to determine the baseline building performance, and identify poorly performing systems within the building. Energy auditing standard procedures, e.g. (ASHRAE, 2006, 2010b; CIBSE, 2006; Standards Australia, 2014), can be used to guide the process. It is common for a condition audit of mechanical services to be undertaken at this stage to identify items nearing end-of-life.

Phase III involves identification and prioritisation of retrofit options. Options will be identified according to building type, occupancy, climate, and services. The expected performance of retrofit options can be analysed quantitatively with the use of a range of energy, economic, and risk assessment tools, as discussed in the following section. The appropriate level of analysis will be determined largely by the upgrade targets. Simple upgrades to achieve average performance targets may be adequately assessed based on the results of a Type 2 audit (Standards Australia, 2014). Upgrades targeting higher performance, and with correspondingly higher costs, will require a more detailed analysis before implementation. The selection of appropriate upgrades for consideration will also be driven by equipment life cycles and compliance with relevant sections of the Building Code of Australia (BCA).

Phase IV is the installation and commissioning of the retrofit, which may involve significant disruption to building occupants. Phase V, the final phase, is measurement and verification (M & V) of retrofit energy savings, and post-occupancy evaluation of retrofit success. This is an opportunity for comparison of predicted energy savings with the actual energy savings. A detailed flowchart of this process is shown in Figure 2-5.

2.4 Commercial Building Retrofit Strategies

There is a range of options available for improving the energy efficiency of existing buildings, and the range is ever increasing as new technologies become commercially available. The Existing Building Survival Strategies handbook (Arup *et al.*, 2009) lists 200 different strategies to minimise electricity consumption. Harvey (2009) also provided an extensive review of retrofit measures. These efficiency improvements can be grouped into technical, organisational, and behavioural initiatives (Tripp & Dixon, 2004). A large proportion of potential energy reductions from building retrofit programs comes from resolving problems in the operation of existing components in buildings, known as recommissioning. Ma *et al*. (2012) categorised retrofit technologies into four groups, i.e. heating and cooling demand reduction, energy efficient equipment and low energy technologies, human factors, and renewable energy technologies and electrical system retrofits, as shown in Figure 2-6.

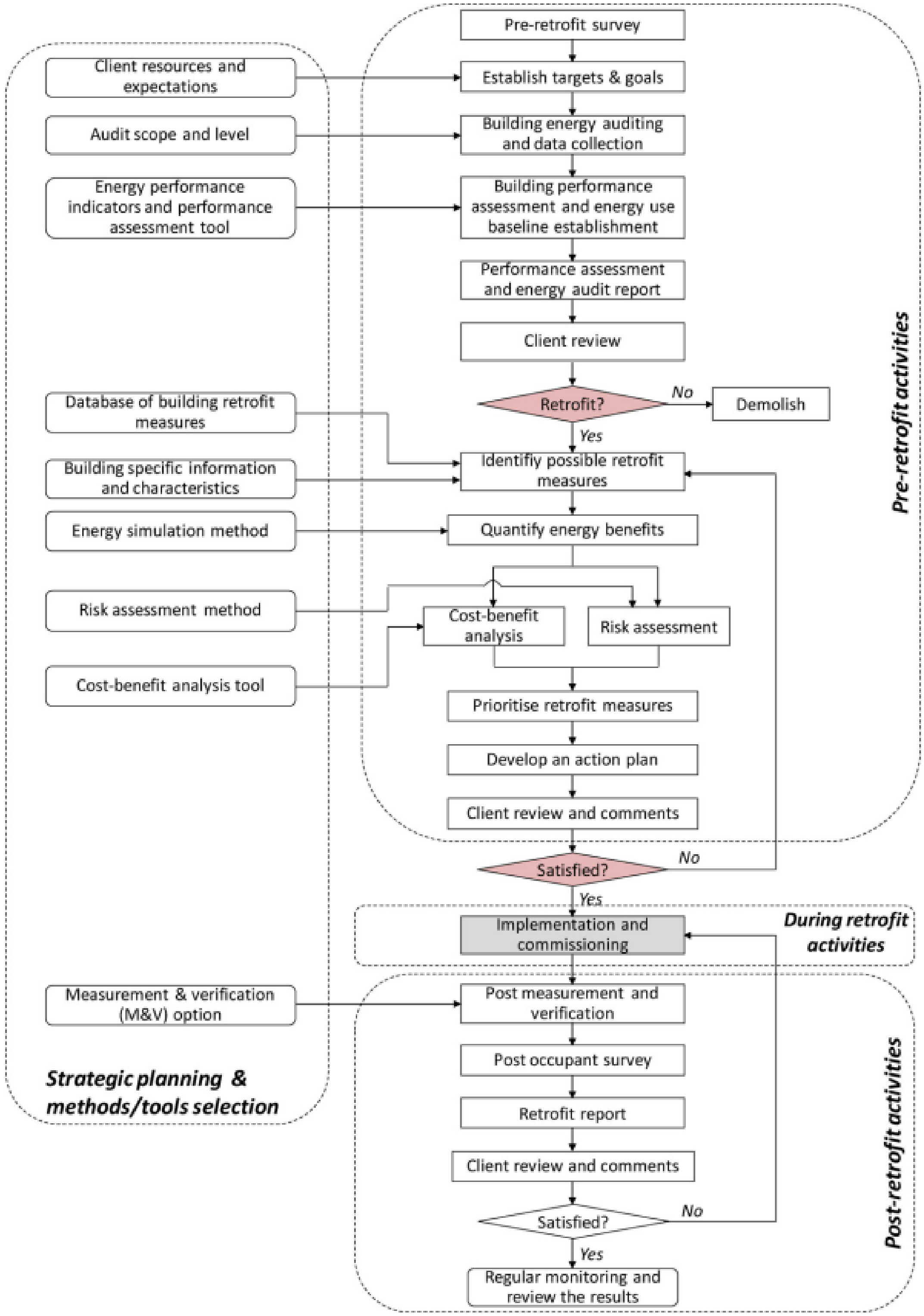


Figure 2-5 A Systematic Approach to retrofitting, outlining the key activities and tools in a building retrofit process (Ma et al., 2012).

In the field of technical improvements, retrofitting is usually aimed at improving building services, building envelope or fabric, or improving the technical aspects of the building fit-out. Efficiency improvements can be made through replacement of out-dated technology, which has become inefficient in comparison to newer technologies, or has become inefficient due to age and maintenance issues. There have been numerous studies investigating the effectiveness of technical retrofits, with a focus on HVAC (Graham, 2009; Lancashire, 2004; McIntosh, 2014; Nicol & McCartney, 2000; Saidur *et al.*, 2012; Sonmor & Lagana, 2009; Zheng & Zaheer-Uddin, 1996), lighting (Aste & Pero, 2013; Harvey, 2009; Nelson, 2010; OEH, 2012), IT (Davis, 2008; Kamilaris *et al.*, 2014), and building envelope (Huang *et al.*, 2012, 2013; Saidur, 2009).

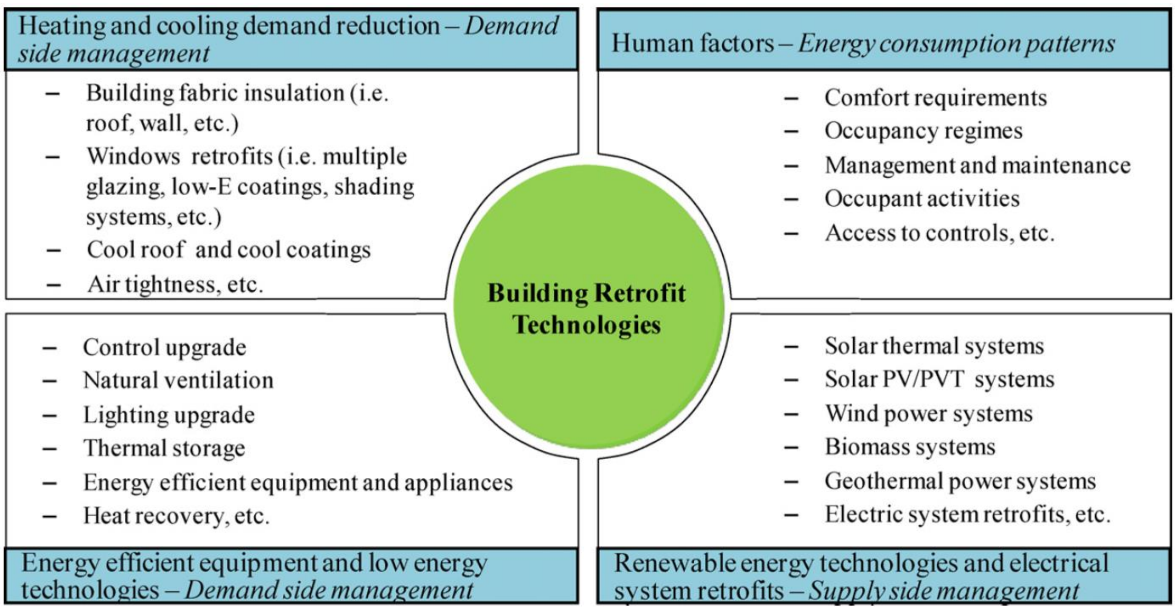


Figure 2-6 Major categories of building retrofit technologies (Ma et al., 2012).

Organisational and behavioural modifications are interrelated issues; organisational change is often necessary to promote individual behaviour to become more energy efficient (Tripp & Dixon, 2004). It is accepted in the field of cultural geography that subjectivity and identity are informed by the space inhabited by an individual, both in a physical and intellectual sense (Probyn, 2003). This means that norms of behaviour in a workplace can alter an employee’s sense of self, and therefore their actions. Put more simply, if a workplace has a culture of energy wastage, an employee who is generally energy conscious outside of work may unconsciously adopt the energy wasting behaviour associated with their work space. It is more difficult to estimate energy saving through behavioural and organisational initiatives, however numerous studies have examined this issue (Baker, 2007, 2009; Bamberg, 2003; Bannister, 2012a; Brager *et al.*, 2004; BRECSU, 2001; Chung & Burnett,

2001; Energy Saving Trust, 2013; Hargreaves, 2011; Humphreys, 1995; Hunting & Tilbury, 2006; Newsham *et al.*, 2008; Nicol, 2000; Nicol & McCartney, 2000; 2004).

2.5 Measurement and Verification of Retrofit Energy Savings

To determine the success of a retrofit strategy, and ensure economic criteria are met, it is vital that effective measurement and verification (M&V) of the energy savings is undertaken. The difficulty in determining energy savings from a retrofit scenario lies in the varying nature of energy consumption over time. It is not enough to simply compare raw pre- and post-retrofit energy consumption, and state that the difference is the saving or increase. The data must be corrected for changes in weather, occupancy, production levels, operations and maintenance conditions. It is most common to adjust the pre-retrofit data to the conditions of the post-retrofit measurement period, creating an energy use know as baseline or business as usual energy consumption. Equation 2.1 (Ma *et al.*, 2012; Schiller, 2007) shows the generic calculation required to determine energy savings from a retrofit.

$$E_{saving} = E_{pre} - E_{post} \pm E_{adj} \quad (2.1)$$

E_{saving} is the energy saving; E_{pre} is the energy use in the pre-retrofit period; E_{post} is the energy use in the post-retrofit period; E_{adj} is the difference in energy use caused by any differences in non-energy retrofit measure factors, such as weather conditions, occupancy schedules, etc. This calculation is shown graphically in Figure 2-7.

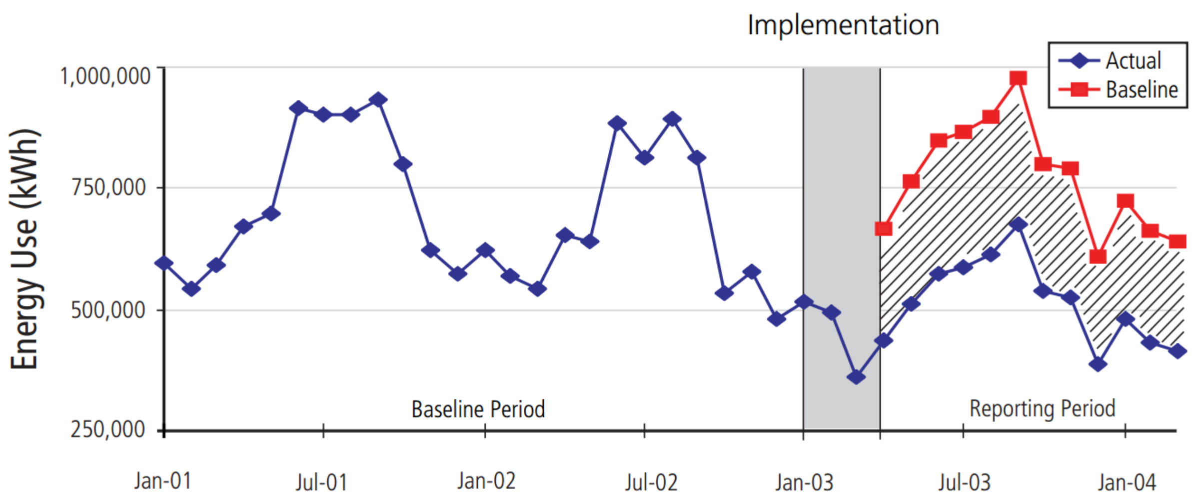


Figure 2-7 Method for determination of retrofit energy savings according to the IPMVP, image taken from Schiller (2007).

A Best Practice Guide to Measurement and Verification of Energy Savings (AEPCA, 2004) provides a summary of the International Performance Measurement & Verification Protocol (EVO, 2012) for the Australian context, and contains clear guidance on measuring energy savings from building retrofits. After highlighting the importance of effective M&V, the guide provides an in-depth discussion of four options that can be used to determine the savings from an energy conservation measure.

2.6 Building Performance Simulation

Building Performance Simulation (BPS) programs can be used to provide valuable information about the effect of a building energy retrofit on a building's thermal and energy performance. BPS programs require inputs regarding building geometry, construction material properties, electrical loads, building occupancy, HVAC equipment, and local climatic conditions. The underlying principle of whole-building BPS is illustrated in Figure 2-8.

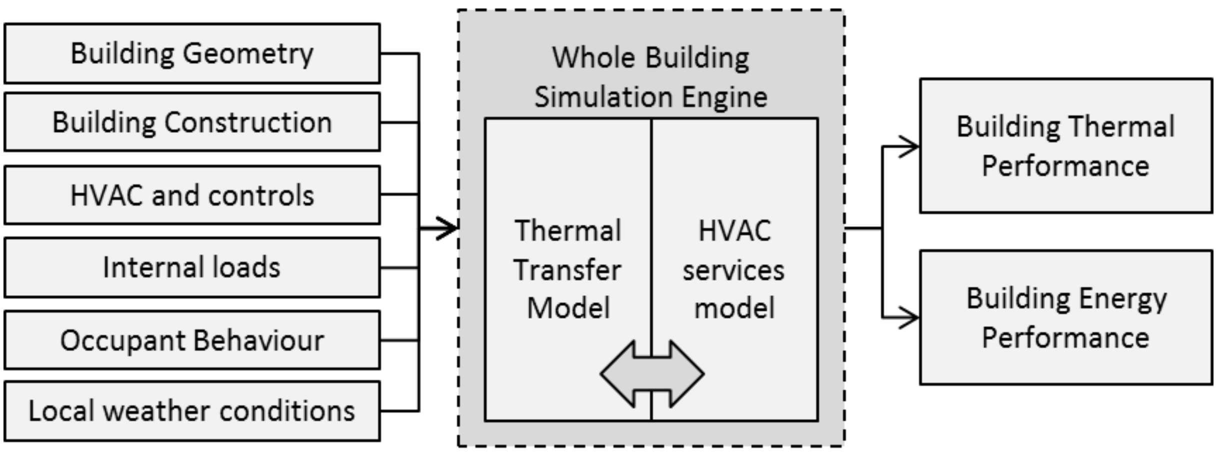


Figure 2-8 Generic whole-building simulation calculation process.

There are a large number of BPS programs that can effectively model the thermodynamic transfers and heat loads in a building. Crawley *et al.* (2008) identified twenty major simulation programs, and compared their features and capabilities. Analytical verification according to the International Energy Agency Building Energy Simulation Test (BESTest) (Judkoff & Neymark, 1995), is designed to ensure that the mathematical representations used in whole-building energy simulation programs provide valid results. Detailed discussion of the building performance simulation program selected for use in this study is given in Section 3.4.

2.6.1 Accuracy of Building Performance Simulations

Despite rigorous BPS program validation, there is a widely acknowledged ‘performance gap’ between actual energy consumption and predictions from BPS (Bannister, 2004, 2005; Bordass *et al.*, 2001, 2004; Menezes *et al.*, 2011; Newsham *et al.*, 2009; Torcellini *et al.*, 2004). Indeed, Bannister (2005) stated, ‘evidence does not support the existence of a general relationship between simulated performance and absolute performance [of buildings]’. Frankel & Turner (2008) found that although the results from energy simulation tools can be useful in predicting energy consumption, actual usage varies from the predictions by up to 25%. CarbonBuzz (RIBA & CIBSE, 2015), a UK based platform for sharing of design and performance data for new buildings showed that on average, operating buildings use between 1.5 and 2.5 times more energy than is predicted. At the time of writing, *office buildings in the database used 49% more energy than was predicted on the basis of BPS.* It is therefore important that any results from BPS programs be carefully scrutinised.

‘Garbage in = garbage out’ is a maxim of computer simulation. The accuracy of a building model is directly related to the accuracy of the simulation inputs. Whilst it may be theoretically possible to determine the characteristics of existing buildings, in practice this is often troublesome, as building documentation is often unavailable, incomplete or out-of-date (Camilleri & Babylon, 2011). Raslan and Davies (2009) identified four influential causes of variation of predictions for energy models:

- The reliability and accuracy of physical input data;
- User skill in data interpretation and tool use;
- Applicability of the tool to the building and climate being analysed;
- Ability of the tool to predict building performance/calculation method used.

The Building Simulation Performance tool used can significantly alter the predicted energy consumption for a building. Schwartz and Raslan (2013) showed that up to 35% variation in model prediction from three widely used simulation tools, all of which were verified according to the BESTest. The model user can also significantly influence energy use predictions. Guyon (1997) asked 12 expert users to predict the energy consumption of a residential building for which detailed documentation was supplied. It was found that the results from energy simulations varied by as much as 40% for inputs from different users. More recently, Berkeley (2013) found a variation of -11% to +104% for total yearly electrical consumption, and -61% to +1535% for gas

consumption when 12 professional energy modellers were asked to model a school administration building based on identical information in a constrained time period.

When BPS is used for existing buildings, it is possible to test the accuracy of a model empirically, with actual energy consumption data. Accuracy is generally defined as the degree to which predicted consumption and annual metered utility data match, at monthly or hourly intervals (ASHRAE, 2012; EVO, 2012). ASHRAE (2012) declares models to be calibrated 'if they produce MBEs (Mean Bias Errors) within ±10% and CV (RMSE) (Coefficient of Variation Root Mean Squared Error) within ±30% when using hourly data or ±5% [and] ±15% with monthly data.' There is a lack of a well-defined and widely-used method for the calibration of BPS models to meet these accuracy requirements. Reddy (2006) found that model calibration was 'highly dependent on the personal judgment of the analyst performing the calibration', and recognised the danger of 'fudging' the model on a trial-and-error basis to match the metered data. Given the large number of variables in a building energy model, it is generally possible to produce an output which matches the metered data, without truly representing the building (Bertagnolio, 2012). Raftery *et al.* (2009) presented an evidence-based methodology for calibration of whole-building energy models to mitigate this issue. This method can improve model accuracy through the use of verifiable building information in the model calibration process. The key feature of the methodology is the use of an evidence-based decision making process through a data hierarchy and modelling log.

2.6.2 Representations of Local Weather Conditions

As identified in Judkoff *et al.* (2008), accurate BPS relies on accurate input data. One key input is the information about weather conditions, such as dry bulb temperature, humidity, wind speed, etc. Whilst it is possible to simulate a building with actual weather data from a particular period, and indeed this is desirable for many applications (for instance during calibration), simulation for optimisation of building energy retrofits generally requires average weather data.

There are two methods commonly used to extract a 'typical' year from a dataset of hourly weather observations. These methods result in the Test Reference Year (TRY) and the Typical Meteorological Year (TMY) formats. A TRY is an actual year of observed data, selected from a database by progressively removing the years with particularly high or low monthly average conditions, until only one year remains. This results in a particularly mild year, with extreme events filtered out (Crawley, 1998). A TMY creates a year of representative weather data by assembling

the ‘most average month’ from the database for each calendar month. A weighted average of important parameters is created for each month, and the month which most closely matches the average is selected for the TMY. For example, a TMY might consist of the weather observations from Jan 1995, Feb 1989, March 2000, etc. whilst a TRY will be all months from 1996, say. It is recommended by Crawley (1998) that simulation users use files derived from the TMY procedure.

There is a range of typical weather years available from different sources developed with the TMY procedure, including TMY, TMY2, TMY3, Weather Year for Energy Calculations (WYEC), WYEC2, International Weather for Energy Calculations (IWEC) and Reference Meteorological Year (RMY). The differences between the various files are in the source of the base data, and the weighting given to parameters when determining the most average months. IWEC (ASHRAE, 2001a) and RMY weather files are available for Australian locations; both rely on data from the Australian Bureau of Meteorology. Historically, Australian simulations users have used TRY files obtained from ACADS-BSG. Since 2001 IWEC files have been available for Australian capital cities, and since 2006 RMY files have also been available. Issues have been raised with some RMY files (Liley *et al.*, 2013), primarily with regard to the solar radiation data. New TMY files were released in April 2014, and are discussed in Chapter 5.

Crawley (1998) conducted a relatively simple sensitivity analysis of a typical building in the US, and found that predicted annual energy consumption varied from +7% to -11% and peak demand varied from +4.9% to -4.7% between actual weather and six typical weather data sets. The average variation in annual consumption between actual and typical weather data was ± 5%, and the average difference in peak electrical demand was ± 6%. Newsham *et al.* (2009) found a maximum of 5% difference in the predicted annual energy consumption between 3 typical weather data sets and the 30 year long-term climate for a typical building in 10 U.S. climate zones.

Typical weather files, by definition, do not provide information about extreme weather events such as heat waves, as they have been processed to represent average conditions, and many studies have suggested that it is an increased incidence of extreme events that is likely to be the most disruptive aspect of climate change in the short-term (BRANZ, 2007; Garnaut, 2008). In order to study the impacts of extreme events, Lee and Ferrari (2008) suggested the definition of an extreme meteorological year, e.g. creating a single year file with the hottest summer and coolest winter in the observation period. Crawley (2007) contrasted extreme and typical weather years and found that

annual energy consumption could be expected to change by a maximum of 7% between extreme weather years and TMY years.

Swain *et al.* (2013) compared the predicted energy consumption of a reference building simulated with the TRY and the RMY weather files for all capital cities in Australia. They found an average absolute difference of 2.9%. A maximum difference of 6.2% was found for a medium-size office reference building in Canberra. The average predicted consumption in the study was 259 MJ/m^2, significantly lower than the national average for commercial buildings of 981 MJ/m^2 (Bannister, 2004).

2.6.3 Representations of Building Occupancy

The energy related behaviour of occupants in a building, including the interaction with facility managers, can have a significant effect on the energy consumption of a building and is fundamental to the determination of thermally acceptable environments. The uncertainty and variability in building occupancy has been recognised as an important source of discrepancy between predicted and actual consumption (Gunay *et al.*, 2013; Macdonald, 2002). Moreover, the influence of occupants on overall energy performance will become greater as the technological aspects building performance improves (Turner & Frankel, 2008). Various levels of resolution with respect to representations of building occupant are available, and consideration should be given to the use of appropriate representation for the purpose of a BPS exercise (Hoes *et al.*, 2009)

Historically, deterministic representations of occupant behaviour in BPS have relied upon assumptions regarding peak occupant density and fixed diversity profiles. These diversity profiles have become increasingly founded on results from field observations (Abushakra *et al.*, 2000; Duarte *et al.*, 2013).

More recently, the use of stochastic models of energy related behaviour has become common. Stochastic models provide a more nuanced representation of how building occupants interact with a building (Gunay *et al.*, 2013). A comprehensive review of previous studies that have monitored energy related occupancy behaviour was presented by Hong *et al.* (2015). Stochastic representations have been developed to represent space occupancy (Hoes *et al.*, 2009; Lam *et al.*; Wang *et al.*, 2005), as well as energy related behaviour including window opening (Haldi & Robinson, 2011; Rijal *et al.*, 2007), shade/blind usage (Haldi & Robinson, 2011; Reinhart, 2004), and lighting operation (Newsham, 1995; Reinhart, 2004). These stochastic representations have been effectively

coupled with BPS to represent the energy-related behaviour of building occupants more accurately (Bourgeois, 2005; Gunay *et al.*, 2014; Hoes *et al.*, 2009).

2.6.4 Building Performance Simulation Protocols

Given the significant uncertainty associated with energy predictions from BPS, partially due to uncertainty around input assumptions, several simulation protocols have been developed to inform and standardize uncertain inputs for BPS. There are three widely used simulation protocols specific to Australia: the BCA Section J alternative verification method (ABCB, 2013); the 'NABERS Energy – Guide to building energy estimation' (NABERS, 2011); and the Green Star 'Greenhouse Gas emissions calculator guide' (GBCA, 2013a). ASHRAE standard 90.1 'Energy Standard for Buildings Except Low-Rise Residential Buildings' (ASHRAE, 2013) is an internationally recognised simulation protocol, which is used by some consultants in Australia. These simulation protocols provide a method for simulations of the energy performance of non-domestic buildings. Each protocol has a slightly different purpose, and none claims to result in an accurate prediction of a building's energy consumption. Thus, it is expected that absolute predicted energy consumption will vary for each protocol. However, due to their prevalence and acceptance in industry these protocols can inform simulation assumptions outside of the programs for which they are mandated. The default values and schedules given in these protocols are often used in simulation studies to represent commercial buildings in Australia, which do not necessarily follow the entire protocol (ABCB, 2006a; BRANZ, 2007; Judkoff *et al.*, 2008; ZCA, 2013).

'NABERS energy: guide to building energy estimation' (NABERS, 2011) provides a guide for the use of BPS to estimate 'base' or 'whole' building energy use for a NABERS commitment agreement, a commitment from a developer of a new or refurbished building to achieve a specific NABERS star rating. Base building ratings include, a whole building rating covers both base building and consumption of tenancy equipment and services. For buildings committing to a high (4.5+ star) rating, it is a requirement that BPS is undertaken. The protocol supplies default values for use when a more accurate estimate or actual data for an input is not available. The guide acknowledges the existence of a 'performance gap' between theoretical and actual energy consumption, and hence the default values are designed to provide a conservative estimate of energy consumption. Ideally, the building is to be modelled as it will operate, i.e. the default values given in the protocol are for use when a parameter is uncertain. The intent of the NABERS protocol is to predict energy consumption of the operational building accurately.

The BCA Volume 1 (ABCB, 2013) Section J contains requirements for new buildings, and building retrofits involving extensions or changes to building use, to ensure a minimum standard of energy efficiency. Section J includes provisions that relate to all aspects of a building use and construction, including building fabric, glazing, building services, lighting, and hot water. There are two paths for Section J compliance, deemed-to-satisfy (DTS) or verification using energy modelling – the JV3 verification method. These are discussed in detail in Section 2.10.5. Verification by JV3 requires the development of two simulation models, the proposed building and a reference building modelled with DTS construction, heat gains, occupancy etc. The proposed building is approved if the annual energy consumption is not more than that of the modelled building when the proposed building is modelled with proposed services, and the proposed building is modelled with the same services as the reference building. This ensures both the building fabric and building services are assessed independently; meaning that one facet of the building cannot compensate for shortcomings in the other – both building services and fabric must achieve a minimum standard. Section J of the BCA provides detailed instructions for the inputs to the building simulation of the reference and proposed buildings. The intent of this protocol is to ensure compliance with a minimum standard of energy efficiency.

The Green Star greenhouse gas emissions calculator guide is available for the 10 different building types covered by Green Star. Office buildings generally fall under the Green Star Office v3 Greenhouse gas emissions calculator guide (GBCA, 2013c). This guide requires the building to be modelled in accordance with the NABERS energy guide to building energy estimation, specifically with the default figures, to predict the greenhouse gas emissions. However, there are provisions within the Green Star – Public Buildings greenhouse gas emissions calculator guide (GBCA, 2013a) which relate to office buildings, and which differ from the NABERS default figures. This guide is directly compared to the BCA JV3 and NABERS guide by Aherne (2011), an effort by the Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH) to harmonise the conflicting protocols. The method outlined in (GBCA, 2013a) is based on the JV3 verification method where the predicted energy consumption of the proposed building is compared to the predicted consumption of a ‘standard practice building’. For some inputs to the standard practice building, the guide stipulates default values. The intent of the Green Star modelling is to assess the potential of a building to perform efficiently.

ASHRAE standard 90.1 is the American equivalent of Australia’s Section J, and is a standard designed to set out minimum energy efficiency standards for the design of buildings other than low-

rise residential buildings. Similar to JV3, the standard applies to new buildings and extensions to existing buildings. It also applies to new systems and equipment within existing buildings. The simulation protocol included as Appendix G serves a similar purpose to the JV3 alternative solution verification, allowing the energy efficiency provision to be flexible to new designs and technologies that can be shown to improve building performance through BPS. Significant detail is included to aid energy modellers with HVAC system simulation. More accurate information is accessible regarding the energy attributes of US building stock due to large-scale projects such as the Commercial Building Energy Consumption Survey (U.S. EIA, 2015).

2.7 Sensitivity and Uncertainty Analysis

Whilst BPS requires a large number of inputs overall, typically only a much smaller subset of these inputs will influence the model outputs significantly. Uncertainty Analysis (UA) and Sensitivity Analysis (SA) are both techniques that may be used to determine which inputs are important, and the impact of not knowing the correct input value may have on the results. SA is an investigation of the change in a model output that results from perturbing input parameters by an arbitrary amount, e.g. ± 1% (Macdonald, 2002). UA is a consideration of the change in a model output that occurs when an input is varied within the probable distribution of that parameter (Macdonald, 2002). It should be noted that this distinction between terms is not always applied in the literature. SA can improve BPS of existing building through the identification of key inputs for further targeted investigation or quality assurance. Franconi and Nelson (2012) argued for the incorporation of UA into BPS to provide decision makers with the information required for risk-based decision making. The use of UA can improve the utility of predictions from BPS, allowing a move away from single-figure deterministic representations of a building's performance, towards more nuanced representations of predictions as likely outcomes from probable conditions (Williamson, 2010). The generic method for conducting a SA or UA is shown in Figure 2-9.

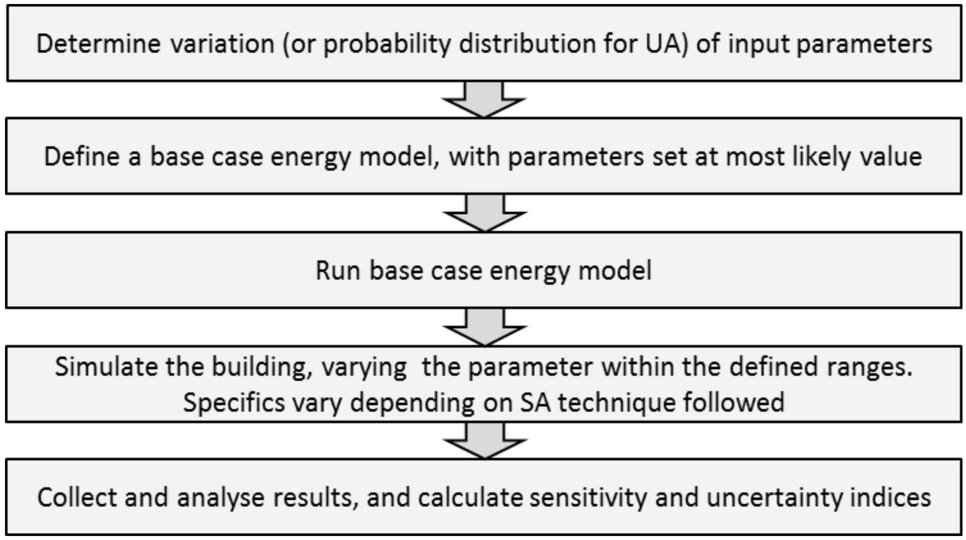


Figure 2-9 Generic Sensitivity or Uncertainty Analysis method.

There are numerous examples of SA and UA in the literature. Eisenhower *et al.* (2011) presented a comprehensive UA and SA of a drill hall, where 1009 input parameters were considered and the influence was analysed for 10 consumption outputs. Griffiths and Anderson (1994) conducted a SA of an archetypal office building in Portland, Oregon. They identified VAV airflow rate; heating set point temperature; and ICT density as the most important inputs. Mottillo (2001) analysed 10 buildings of different types in multiple Canadian locations. Thermal resistance of walls, roof, and fenestration; lighting power density; and minimum outdoor air rates were found to have the largest impact on the predicted energy savings. Lam *et al.* (2008) analysed 10 significant parameters in determining building energy use in Hong Kong high rise buildings (>10 storeys) with centralised HVAC systems. They found cooling set-point, lighting load, and equipment load were the most influential inputs. In each of the studies discussed above different parameters were highlighted as being of key importance, which was to be expected, as the relative importance of different building simulation assumptions will vary strongly with location and building specific attributes.

Few sensitivity analyses have been undertaken for commercial office buildings in Australia, and international studies are of limited benefit to Australian practitioners due to unique Australian climate and building characteristics. Samarakoon and Soebarto (2011) presented the findings of a differential sensitivity analysis of the ABCB Form A building (discussed later) with a particular focus on inputs arising from the characteristics and behaviour of building users. The window-to-wall ratio was found to have the largest impact on energy consumption, followed by equipment usage schedule, occupancy profile, thermostat set point, illuminance set point, and occupancy load

density. Other studies (e.g. Egan, 2011, 2012) have examined the influence of uncertainty in individual parameters on predicted energy consumption.

2.8 Economic and Risk Analysis

Risk assessment is an important feature in building energy retrofit optimisation, closely related to uncertainty analysis. Risk assessment provides the decision makers with information about their exposure to risk from a decision or action, i.e. the likelihood that the outcome will differ from the 'best-guess' estimate (Ma *et al.*, 2012). It is important to define risk and uncertainty in the present context. Uncertainty is the lack of certainty in that there is more than one possible outcome; whereas risk is a state of uncertainty in which one of the possible outcomes carries the potential of an undesirable outcome (Hubbard, 2007). It is possible to quantify uncertainty through the use of probability distributions, and risk may be quantified based on potential losses. Williamson (2010) highlighted the danger that risk may be concealed within simulation results.

> *… claims made by simulationists can often lead to a spurious impression of legitimacy, with 'accurate' predictions of some aspects of built environment performance being used to legitimize certain design decisions…*

Risk assessment is therefore essential to provide decision makers with a sufficient level of confidence to select and determine the best retrofit solutions (Franconi & Nelson, 2012).

Numerous studies have examined the issue of risk assessment in building energy retrofitting, and the issue is recognised in energy benchmarking tools. Heo *et al.* (2012) used calibrated models incorporating uncertainty to generate probabilistic predictions of the performance of retrofits. A method was proposed to support investment in the area, by effectively accounting for uncertainty. Similarly, Menassa (2011) presented a framework for economic evaluation of retrofits under uncertainty, based on the option-pricing method. SA or UA, discussed in detail in Section 2.6.4, are effective methods of quantifying uncertainty in energy performance. This is recognised in the NABERS tool (NABERS, 2011), and off-axis simulation is a requirement of the tool. (Off-axis studies, also known as differential sensitivity analyses, involve varying certain parameters in an energy model away from the expected value to determine the system sensitivity to individual inputs). Gustafsson (1998) presented a sensitivity analysis of energy conservation measures, and showed that life cycle cost of the building is subject to only small changes so long as optimal

strategies are chosen. The Georgia Tech Uncertainty and Risk Analysis Workbench (Lee *et al.*, 2013) is one example of an effort to support uncertainty and risk analysis in BPS.

Risk assessment in building retrofitting is closely related to economic analysis. Optimal retrofit selection is generally a compromise between capital expenditure and operational cost and energy benefits. The use of BPS to predict energy savings is in part an attempt to predict future operating costs. The economic performance of a retrofit strategy will be affected not only by the technical performance of the upgrade, but also future energy prices, and the actual capital expenditure. These economic factors also have associated uncertainty which must be factored into a risk assessment. Economic analysis of retrofit options is therefore a key part of the retrofit decision process.

Economic analysis methods used to evaluate the cost effectiveness of a single building retrofit measure include: net present value (NPV), internal rate of return, overall rate of return, benefit-cost ratio, discounted payback period, and simple payback period. More advanced economic analyses, including life cycle cost method and the levelised cost of energy may be used to evaluate the cost effectiveness of multiple retrofit alternatives. The selection of economic measures can significantly impact on the retrofit strategy selected. Remer and Nieto (1995a, 1995b) reviewed 25 methods used to analyse the economic desirability of projects. They identified five main types, i.e. Net Present Value, rate of return, ratio, payback and accounting. In an earlier study (Remer *et al.*, 1993), the authors identified a shift in 'Fortune 500' companies away from internal rate of return and payback analysis toward NPV. Previous studies have used NPV (Verbeeck & Hens, 2005), LCC (Kaynakli, 2012), simple payback (Preston & Woodbury, 2013), or a combination of measures (Mahlia *et al.*, 2011; Nikolaidis *et al.*, 2009). Nikolaidis *et al.* (2009) found that the cost optimal retrofit selection was impacted by the economic measure used. Many authors have called for more comprehensive economic assessments of retrofit projects to be undertaken (Menassa, 2011; Mullen, 2005).

Even with detailed information about a building's performance, including economic and risk information, selecting the optimal retrofitting strategy is a difficult task. At present, this decision is usually made through consultant-client collaboration, and is therefore subject to biases of the individuals, and issues of bounded rationality. Highlighting the complexity of the decision process in the retrofitting situation, Kolokotsa *et al.* (2009) identified 45 considerations identified in other literature which should be considered in selecting the optimum strategies. In order to improve the decision process, it may be desirable to utilise a decision support system (DSS), which will more effectively incorporate the diverse factors. There are numerous DSS tools available, both passive

and active, however no tool has achieved widespread usage in industry. (Arup & PCA, 2008; Diakaki *et al.*, 2008; Flourentzou *et al.*, 2002; Juan *et al.*, 2010; PNNL, 2011; Yin & Menzel, 2011; Zavadskas *et al.*, 2006).

2.9 Building Performance Simulation with Reference Buildings

One of the difficulties for any study that examines building energy retrofitting is that every building is unique, with unique characteristics that influence energy consumption and the success of a potential retrofit strategy. The modelling effort required to produce a detailed model of an individual building precludes the generation of sufficient detailed energy models to support general statements about effective retrofit techniques for a larger stock. A simplification is therefore necessary. A commonly used technique is the use of 'reference' or 'archetypal' buildings (Chidiac *et al.*, 2011a; Douglas, 2006; Guan, 2009a, 2011, 2012; Lam *et al.*, 1997; Lyons, 2008; Rongère & Gautier, 1993; Sehar *et al.*, 2012). The purpose of a reference building is to represent an average or typical building in the segment of the building stock under consideration. The underlying assumption of this approach is that whilst a representative building may not accurately represent any particular building, it will respond to an intervention in a similar manner as a building of a similar form and use, facilitating an understanding of how real buildings are likely to be affected by interventions.

Best practice studies that have developed reference buildings have used statistical data to analyse the building stock under consideration, and identify a number of reference buildings to characterise that stock to a sufficient degree, and with an acceptable level of uncertainty (Deru *et al.*, 2011; Famuyibo *et al.*, 2012; Kavgic *et al.*, 2010). Once these basic forms have been selected, detailed energy models of the buildings, including details of building geometry, construction, mechanical services and internal loads, are constructed. Evans *et al.* (2014), in the UK, have developed a method of attaching database information (including energy consumption) to 3D mapping sources, and then to create a 3D stock model with actual geometry and construction details, which can then be simulated with the use of appropriate reference services and activities.

Reference building models can be used for a variety of purposes. The energy consumption for each building type in each climate zone can be predicted with BPS, and the predicted consumption multiplied by the number of each buildings in that zone, to create a bottom-up stock model of energy consumption. Reference buildings have also been used to examine the impact of new

technologies on energy consumption (Sehar *et al.*, 2012), improved energy codes and standards (Lyons, 2008), and investigate the response to external stimuli in a manner that is 'typical' of a certain building type in a certain location (Guan, 2009a). Importantly, reference buildings can provide consistency in modelling approaches and inputs for simulation users examining different subjects.

Reference buildings do not accurately model the energy use in any particular building since every commercial building is unique, and often the energy use of a building will be heavily influenced by a particular characteristic of that building. A reference building represents a hypothetical building, often with ideal operation and high-performance services that share characteristics with other buildings of that typology. Whilst reference buildings may provide hints that a particular building is performing poorly in some areas, they are not designed to benchmark the performance of a building.

Reference buildings have been developed by numerous bodies internationally to represent the building stock, or a sub-set of the building stock, of a region. Detailed consideration is given below to the US DOE Commercial reference buildings and two reference buildings designed to represent office buildings in Australia.

2.9.1 U.S. Department of Energy Commercial Reference Buildings

Deru *et al.* (2011) reported on a major study to identify reference buildings to represent common commercial building types in the U.S. Sixteen reference building forms were identified, with three variations to each form to account for difference between new construction, post-1980 construction, and pre-1980 construction. The authors estimated that the template buildings characterised approximately 70% of the commercial building stock in the US, and may be adapted to characterise other commercial building types not directly covered. The project built on previous work (Huang *et al.*, 1991; Huang & Franconi, 1999), and relied on an extensive data resource; i.e. the Commercial Building Energy Consumption Survey (CBECS). CBECS is a nationwide survey of the characteristics and energy use of commercial buildings, undertaken by the US Department of Energy (DOE) every four years, with a sample size between 5,000 and 7,000 buildings.

The building forms identified were: Small Office, Medium Office, Large office, Primary School, Secondary School, Stand-Alone Retail, Strip Mall, Supermarket, Quick Service Restaurant, Outpatient Healthcare, Midrise Apartment, Full Service Restaurant, Small Hotel, Large Hotel,

Hospital, and Warehouse. The DOE template buildings have been used extensively in a broad range of research projects. The present literature search revealed 144 citations for the original report. Sehar *et al.* (2012) used the template models to examine the impact of ice storage on office building energy use in different US climates; Ng *et al.* (2012) simulated the template buildings for an investigation of indoor air quality; and Holmes and Reinhart (2013) use one of the template buildings in their discussion of the impact on climate change on building energy retrofitting.

2.9.2 Australian Buildings Codes Board template buildings

The most commonly used reference building forms for BPS in Australia are the Australian Building Codes Board (ABCB) template buildings. The ABCB developed several representative buildings for use in simulations for benchmarking annual energy consumption when making changes to the energy efficiency measures in the BCA, as well as to evaluate the effectiveness of possible energy saving features for buildings. The forms were designed to 'reasonably reflect prevailing standards in the diverse stock of buildings' in Australia (Donnelly, 2002). The basic building forms were developed from a review of Australian Bureau of Statistics (ABS) data for the total cost of buildings approved for construction in Australia in the years 95/96 and 99/00. Five building cost ranges were identified, and these were converted into average areas for each range with the use of typical construction cost/m^2 rates. These floor areas were then used as the basis of five basic building form definitions, representing buildings in BCA classes 2-9 (e.g. every building type except single detached dwellings). A definition of the BCA Building Classes is provided as Appendix A. It was assumed that a building form may be common to a number of BCA classes, however the construction, services and usage schedules must be selected according to the building use. No recommendations were provided by Donnelly for construction or internal loads for the representative buildings.

Form A and Form B are relevant to this study, as they represent BCA Class 5 (office) buildings. Form A is designed to approximate typical fabric and internal loads in large commercial buildings, and is stated to be representative of BCA Class 2, 3 or 5 buildings with a gross floor area greater than 2,000 m^2. Form B is designed to be representative of Class 5 buildings with a gross floor area less than 2,000 m^2, typical of offices on the fringe of CBDs. The basic details of the Form A and Form B building templates are given in Table 2-1.

Table 2-1 Form A and Form B template building forms developed by ABCB (Donnelly, 2002).

Reference ID	A	B
Typical locations	CBD of capital city or major regional town	CBD edge, major regional towns or resort centres
BCA Classes and building usage	2 = apartments 3 = hotel 5 = office tower	2 = apartments 3 = hotel 5 = office block 9 = health care building
Gross Floor Area	10,000	2,000
Net Lettable Area (NLA) (m^2)	9,000	1,800
Storeys	10	3
Aspect ratio	1:1	2:1
Length (m)	31.6	36.5
Depth (m)	31.6	18.3
Perimeter Zone depth (m)	3.6	3.6
Floor-floor height (m)	3.6	3.6
Ceiling height (m)	2.7	2.7

These basic forms have been utilised in numerous buildings simulation studies (ABCB, 2004, 2006a, 2006b; ACADS-BSG, 2002; BRANZ, 2007; Donnelly, 2004; Guan, 2009a, 2009c, 2011, 2012; Lee & Ferrari, 2008; Lyons, 2008, 2009; pitt&sherry, 2010, 2012c; Samarakoon & Soebarto, 2011) for a range of purposes, however they have been used primarily in ABCB studies used to inform BCA energy efficiency provisions. The present literature review identified 12 Australian studies that utilised Form A, and eight that used Form B, with five having used both. The ABCB, or consultants to the ABCB, have used these templates in multiple studies looking at the impact on building energy consumption of changes to the energy efficiency provisions within the BCA (ABCB, 2004, 2006a, 2006b; Bannister, 2004; Lyons, 2008, 2009). Guan (2011, 2012) and BRANZ (2007) utilised the Form A building to simulate the impact of climate change on building energy use. Samarakoon and Soebarto (2011) used the template form to test the sensitivity of building energy use to occupancy inputs. There is some inconsistency in the construction, services and occupancy input values used to simulate office buildings in these studies. A detailed review of the range of modelling assumption for key occupancy and services variables is given in Chapter 6.

2.9.3 Zero Carbon Australia Buildings Plan

The Zero Carbon Australia Buildings Plan (ZCA, 2013) set out to demonstrate how existing buildings in Australia could be effectively decarbonised, becoming net-zero energy within ten years. The researchers created template buildings for energy modelling on the basis of a multi-stage process reliant on expert input. The first step in typology development used the City of Melbourne 1200 Buildings Segmentation Study (Arup, 2009) and municipal rates collection data to develop draft typologies. Numerous workshops and individual meetings were held with experts from academia and industry to identify groupings of building characteristics. From this several typologies distinguished by building function (e.g. education), age (e.g. 1950 – 1980), and location (by climate zone) were developed. Typologies included basic detail on building size, location, geometry, fabric, services, and hours of operation. These draft typologies were presented to a larger workshop with participants from industry, government, and academia, and scrutinised for accuracy and usefulness.

Following the workshop a range of sources, most significantly the National Exposure Information System (Geoscience Australia, 2006) database, were studied to identify any building typologies that were poorly represented in the building stock, and therefore unnecessary, and any areas that had been missed. Unnecessary building types were removed, and the typologies were finalised. Twenty-two typologies were developed, including four reference office buildings, namely pre-1945 Masonry Load Bearing, 1945-1980 Curtain Wall, 1980-2000 Curtain Wall and 2000-onwards Post BCA Energy Efficiency Provisions. The four office typologies were particularly relevant to the present study, as they are held to be representative of a significant portion of the Australian commercial office stock. Further detail of the three buildings modelled is given in Table 2-2. (The post-2000 building was not modelled, as it was assumed that upgrades were management improvements and system tuning).

Table 2-2 Building typologies and energy modelling inputs developed by ZCA (2013) to represent commercial office buildings in Australia.

Parameter	Office Pre- 1945	Office 1945-1980	Office 1980-2000
Occupancy (m^2/p)	10	15	15
Ventilation (L/s/p)	7.5	7.5	7.5
Plug and Process Load (W/m^2)	15	11	11
LPD (W/m^2)	17	12	12
DHW (L/p/d)	3	3	3
Floor Area (m^2)	1566	9000	9000
Aspect Ratio	2:1	1:1	1:1
No. of Floors	6	10	10
Floor to Floor height (m)	3.6	3.6	3.6
Floor to ceiling height (m)	2.7	2.7	2.7
Glazing fraction	0.20	0.32	0.73
Infiltration (ACH)	1	1	1
Heating system	Gas boiler	Gas boiler	Gas boiler
Cooling system	Air cooled chiller, FCU COP 2.3	CV central ducted AC COP 3.0	CV central ducted AC COP 3.0

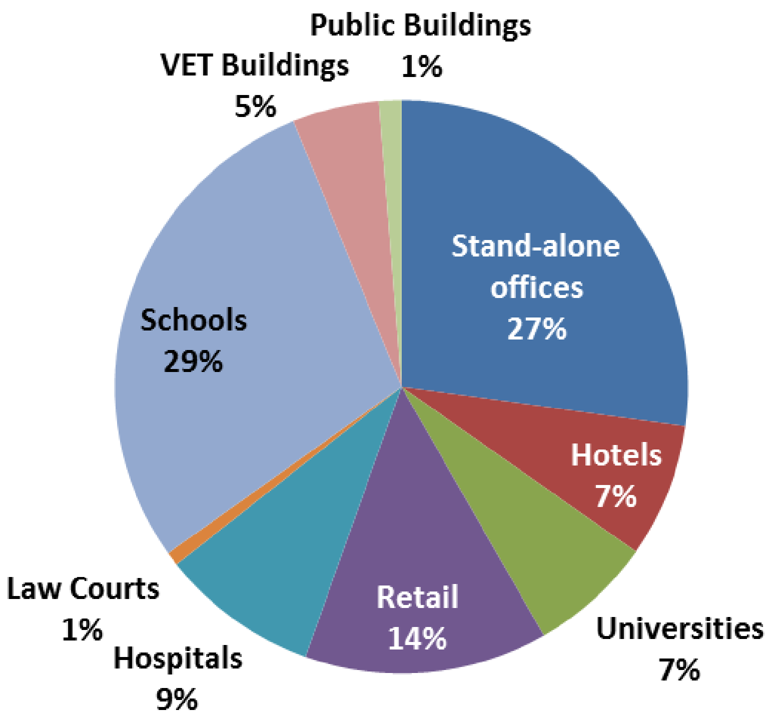
2.10 The Australian Context

This section presents a review of existing information on key features of the Australian historical, political and financial context. The existing commercial building stock is introduced, including a targeted review of information accessible on Secondary Grade buildings. Influential building rating schemes are discussed, along with a specific consideration of drivers and barriers to building retrofitting in Australia.

2.10.1 Key Features of the Commercial Building Stock in Australia

The majority of Australia's building stock was developed without consideration of energy efficiency or other environmental issues (GBCA, 2008). Wilkinson and Reed (2008) quote Australian Bureau of Statistics data that the constructed environment in Australia was worth an estimated $1,705 Billion, or approximately 44% of Australia's net worth in 2004. Kempener (2007)

found that there were 20 million m^2 of office buildings in Australia, while pitt&sherry (2012a) estimated 36.6 million m^2 to exist in 2009, and estimated that the stock was growing by 2.2% per annum. Figure 2-10 shows the calculated breakdown of non-residential, non-industrial building floor space.



Sector	Floor area ($000\ m^2$)
Offices	38,970
Hotels	10,826
Universities	9,997
Retail	19,648
Hospitals	12,790
Law Courts	1,128
Schools	41,134
VET Buildings	7,009
Public Buildings	1,800

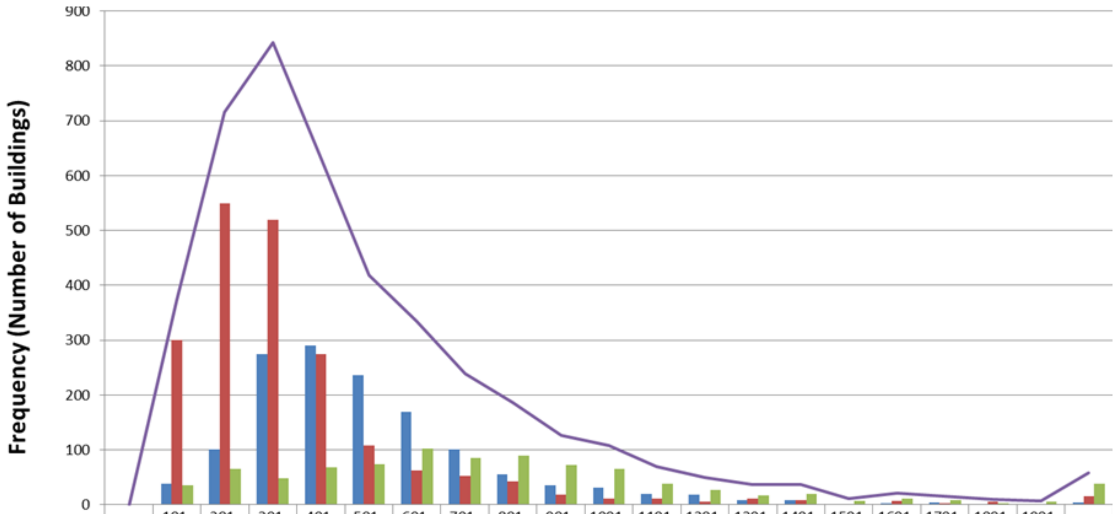
Figure 2-10 Breakdown of non-residential, non-industrial building stock by building sector Net Lettable Area (NLA) in Australia developed from pitt&sherry (2012a). VET is Vocational and Educational Training.

A Building Refurbishment Guide from Adelaide City Council and JLL (2007) reported the average age (in 2005) of the office stock in the major central business districts in Australia, reproduced in Table 2-3. Information that is more recent could not be found, and this issue was also recognised by pitt&sherry. Office buildings require refurbishment every 20-25 years (Wilkinson & Reed, 2008), therefore a large percentage of Australia's stock is entering the time when refurbishment will be considered.

Table 2-3 Age of existing commercial building stock in 2005 (Adelaide City Council & JLL, 2007)

Market (Central business district)	Average Age since Construction (years)	Average age since last refurbishment (years)
Sydney	28	19
Melbourne	31	17
Brisbane	25	13
Adelaide	31	19

Determining the average energy consumption of commercial buildings in Australia is a difficult process due to the limitations of data, which is discussed in detail in Chapter 4. There is no local equivalent of the USA's CBECS. The Commonwealth Scientific and Industrial Research Organization (CSIRO) made some efforts in this area with the launch of the Australian Building Energy Repository in 2013, however, this initiative appears to have been discontinued. The most comprehensive energy consumption database analysis to date can be found in the Commercial Building Benchmarking Study (pitt&sherry, 2012a), in which 4,308 energy consumption records (base, tenancy or whole building yearly energy consumption) for 1,715 unique buildings across Australia were compiled. Base building consumption included services under the control of the building owner (e.g. lifts, central plants); tenancy consumption included services under the tenant's control (e.g. tenancy lighting and equipment). Whole building consumption covers both base building and tenancy. For office buildings, the average whole building energy intensity was calculated at 915 kWh/m^2. The distribution of energy intensity in the database is given in Figure 2-11, which illustrates a significant spread.



	0-100	101-200	201-300	301-400	401-500	501-600	601-700	701-800	801-900	901-1000	1001-1100	1101-1200	1201-1300	1301-1400	1401-1500	1501-1600	1601-1700	1701-1800	1801-1900	1901-2000	More
Base Building	0	38	101	274	290	236	170	101	55	35	31	20	18	8	8	2	3	4	1	2	4
Tenancy	0	300	549	519	275	108	62	53	42	19	12	11	5	12	9	2	7	3	6	0	16
Whole Building	0	36	66	49	68	74	102	85	89	73	65	38	27	17	20	7	12	9	3	5	39
ALL	0	374	716	842	633	418	334	239	186	127	108	69	50	37	37	11	22	16	10	7	59

EUI (MJ/m^2 p.a)

Figure 2-11 Distribution of energy use intensity for base building, tenancy and whole building from pitt&sherry (2012b).

pitt&sherry found that regional tenancies had statistically significantly lower energy consumption than in capital cities. Similarly, government tenancies used less energy than private tenants. The average energy end use of whole office buildings, calculated from 1150 data points, is shown in Figure 2-12.

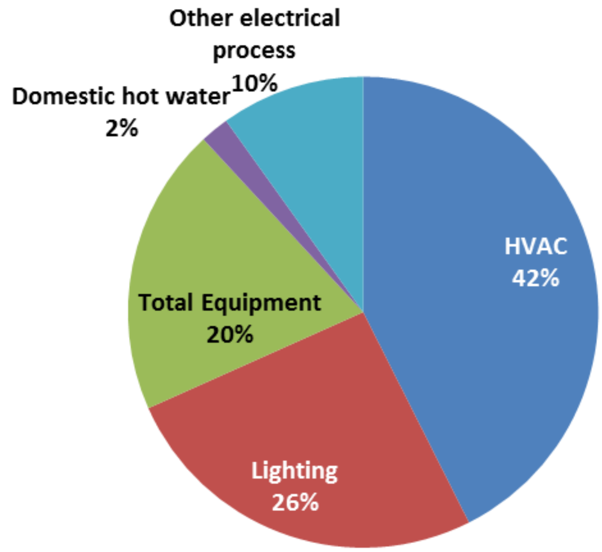


Figure 2-12 Average whole building energy end-use breakdown for Australian office buildings pitt&sherry (2012a).

2.10.2 National Australian Built Environment Rating System (NABERS)

For operational rating of commercial buildings, the most widely used tool in Australia is the National Australian Built Environment Rating System (NABERS). The NABERS scheme is administered by the NSW Office of Environment and Heritage (OEH), and there are several tools, such as NABERS office, NABERS retail, etc., which allow direct comparison against similar buildings, with similar intensity and hours of operation. To determine an energy benchmark, this rating system compares the annual energy consumption data against averages developed for different climatic areas in Australia. The benchmark values of energy intensity can be calculated from the NABERS reverse calculator (NABERS, 2015). The other important benchmarking tool in the Australian context is Green Star. Green Star is currently available for Design and As-built ratings. Green Star Performance (GBCA, 2014), which uses operational data, was launched as a pilot tool in 2013, and at the time of writing (May 2015) had seven completed ratings.

The NABERS rating scheme is a performance-based rating scheme, which has been operating in Australia since 1999. It was known initially as the Australian Building Greenhouse Rating (ABGR) scheme, and was primarily focussed on office building energy use in NSW. Over the period to 2009, the scheme expanded to include other states, and other measures of environmental performance including indoor air quality, waste and water. In 2009, the ABGR was incorporated

into NABERS as NABERS Energy for Offices. NABERS ratings are available for three rating scopes, base building, tenancy, and whole building. Bannister (2012b) identified the following as key aspects of the NABERS ratings:

1. The ratings are based on operation consumption (12 months of actual data);
2. The ratings are normalised for unavoidable operational factors, such as hours of occupancy and climate, but not building specific efficiency factors;
3. The rating scale is based on a median building achieving a rating of 2.5 stars;
4. The base building/tenancy split means 'the base building rating can be used as a generic measure of efficiency in procurement.'

As part of the NABERS process a building owner may enter into a commitment agreement; a commitment to design, build and commission or upgrade a building to a certain rating greater than 4 star. A commitment agreement allows the building owner to advertise the NABERS rating from the outset of the project, prior to a 12 months operational data being available. The rating is reviewed when the performance data is available. At the time of writing (May 2015) there were 154 commitment agreements awaiting performance rating. Commitment agreements require BPS of the development, in accordance with the simulation protocol discussed in Section 2.6.4.

Until the end of 2010 NABERS was a voluntary rating scheme; however it had a high level of adoption reaching over 50% of the national office market in 2009/10 (Bannister, 2012b). A key driver for voluntary adoption was the inclusion of NABERS base building rating requirements into government leases. By 2009, it was a requirement of all state and federal governments (except Tasmania) that leased buildings achieved a minimum 4.5 star NABERS rating. In 2010 the Building Energy Efficiency Disclosure Act was introduced, which mandated disclosure of a building's NABERS ratings in certain circumstances. Building owners are required to disclose a Building Energy Efficiency Certificate (BEEC) for sale and lease transactions of more than 2,000 m^2 of NLA. A BEEC comprise a NABERS rating, tenancy lighting assessment, and general energy efficiency guidance for the building. Mandatory disclosure is designed to improve access to information about energy efficiency of buildings and encourage potential tenants or owners to select more efficient buildings, creating pressure for building owners to improve efficiency.

Commercial building disclosure legislation has made the NABERS scheme increasingly important to businesses. The legislation is a significant driver of NABERS energy rating uptake. At the time of writing, 70% of all NABERS ratings were associated with a BEEC. Figure 2-13 shows the total

NLA of office building rated under the NABERS energy scheme, and the area weighted average rating. It can be seen that since 2005 there has been a greater than 500% increase in floor area rated under the scheme. There has also been a steady increase in the area weighted average rating. In 2013 72% of the national office market had been rated under the NABERS scheme at some point in time – 1984 individual buildings (IPD, 2013). At the time of writing (May 2015), there were 1324 current office energy ratings; 189 tenancy, 261 whole building, and 874 base building ratings.

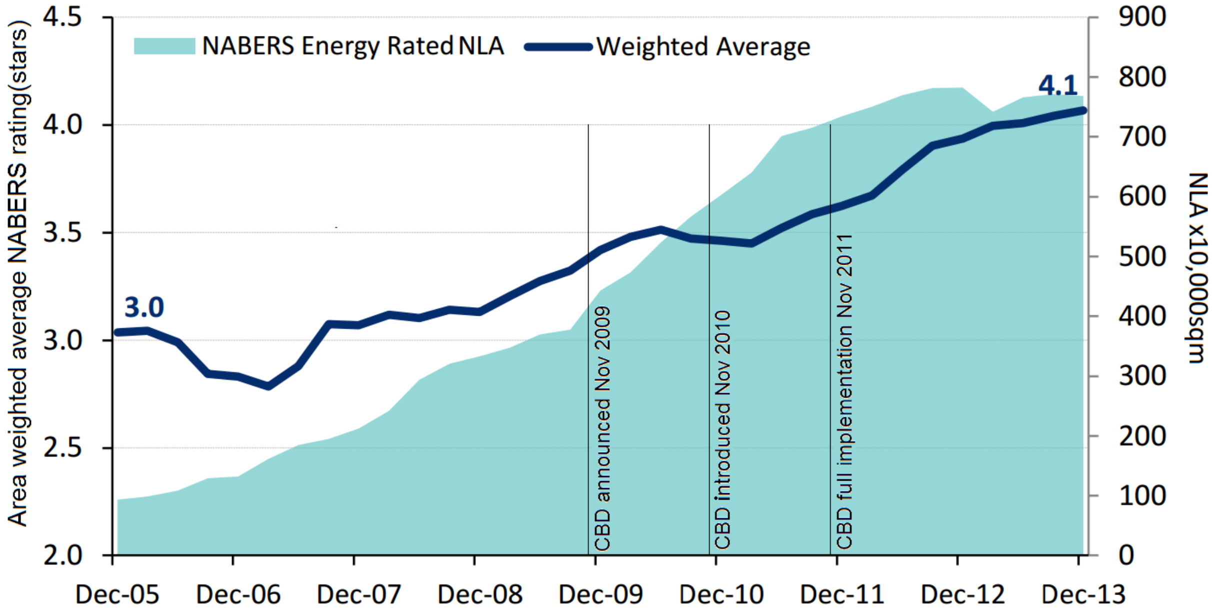


Figure 2-13 Total NLA of offices rated under the NABERS energy for offices scheme. Also shown is the area weighted average rating for the rated stock. Modified from IPD (2013).

As of December 2013, the area weighted average NABERS rating was 4.1 stars (IPD, 2013). The distribution of NABERS energy office ratings by NLA is presented in

Figure 2-14. The distribution is centred on 4.5 stars, with a long tail to lower ratings.

IPD (2013) examined the investment performance of NABERS energy-rated office assets. In general, it was found that more highly rated offices (4.5 – 6 stars) returned substantially higher capital growth, and higher total return. Income return was essentially unaffected by star rating (0.1% higher for higher ratings); Capital return was 3.1% for high ratings, 2.4% for all offices, and 1.5% for 0-4 star offices, based on a sample of 591 assets from the IPD database. Higher rated buildings also had lower vacancy rates, higher rents, and slightly longer lease terms. This re-enforces the findings from Section 2.2.

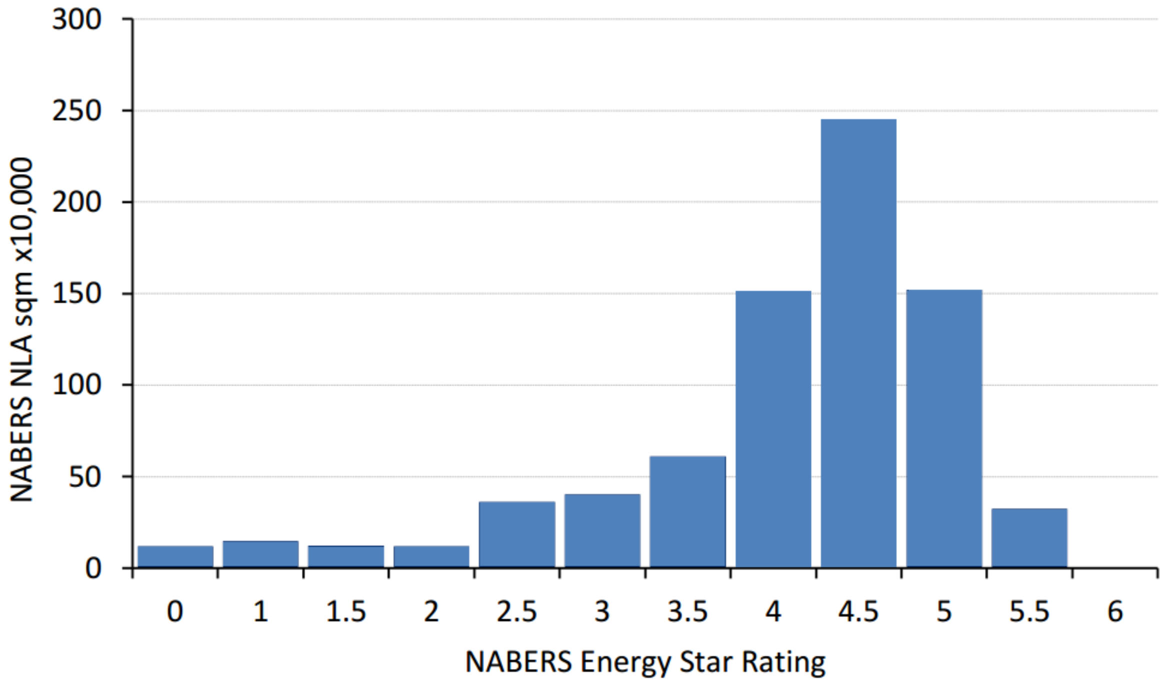


Figure 2-14 NABERS energy rated office NLA by star rating (IPD, 2013).

2.10.3 Property Council of Australia Building Rating

The Property Council of Australia (PCA) produces 'A Guide to Office Building Quality' (PCA, 2011) to allow the quality of commercial buildings, both new and existing, to be assessed. The rating is voluntary, but it is influential in Australia (Wilkinson & Reed, 2008). The guide includes an 'office quality grade matrix' for both new and existing buildings, which can be used to benchmark parameters related to building quality. Buildings are graded as Premium, A, B, C, or D Grade. A premium grade building is a 'landmark office building located in major CBD markets', whilst D Grade is classed as of 'poor quality'. Premium and A Grade building are often referred to as 'Prime Grade'; B, C, and D Grade are termed 'Secondary Grade'. Existing buildings are assessed against 60 parameters, covering items such as configuration, tenant services, building management, and parking. To qualify for a particular building grade a building must 'overwhelmingly' meet the stated criteria, although not necessarily meet every parameter. Building ratings are therefore somewhat subjective. Existing buildings are required to meet a lower standard for each parameter than new buildings. In terms of environmental performance, the PCA matrix considers NABERS energy, water, waste, and IEQ ratings. Improving the PCA Grade is possible for some buildings, and it is an often-stated target of building refurbishments (e.g. DECC & Colonial First State, 2009;

Wilkinson & Reed, 2006b). The achievable grade may be limited by the building location and original condition. Improving the office quality rating can increase rental returns and capital value of a building (Wilkinson, 2011a). Figure 2-15 shows the breakdown of Australia's existing buildings stock in terms of PCA Grade according to the number of buildings in the 2006 PCA database (NPC & Exergy, 2009), where 85% of buildings in the database are Secondary Grade.

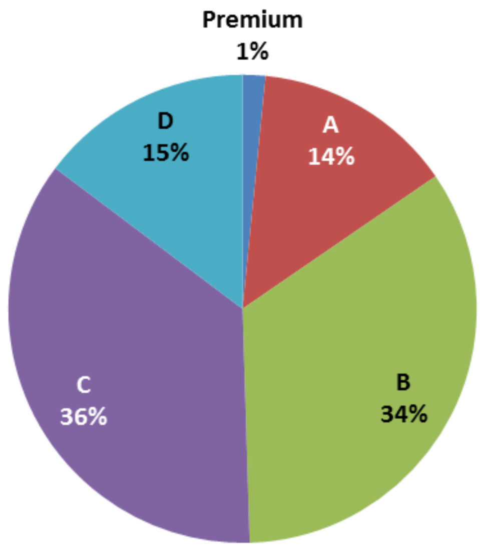


Figure 2-15 Quality of Australia's existing building stock by number of buildings in the 2006 PCA database (NPC & Exergy, 2009)

Figure 2-16 shows the average NABERS rating for each PCA office quality grade, and the amount of floor space rated for each grade from (IPD, 2013). It can be seen that there is a relationship between office quality and NABERS ratings; as expected, higher-grade buildings have a higher NABERS star rating. Over 50% of Prime Grade buildings had a NABERS rating, compared with approximately 15% of Secondary Grade buildings. As noted previously, it is a requirement that Prime Grade buildings achieve a certain rating.

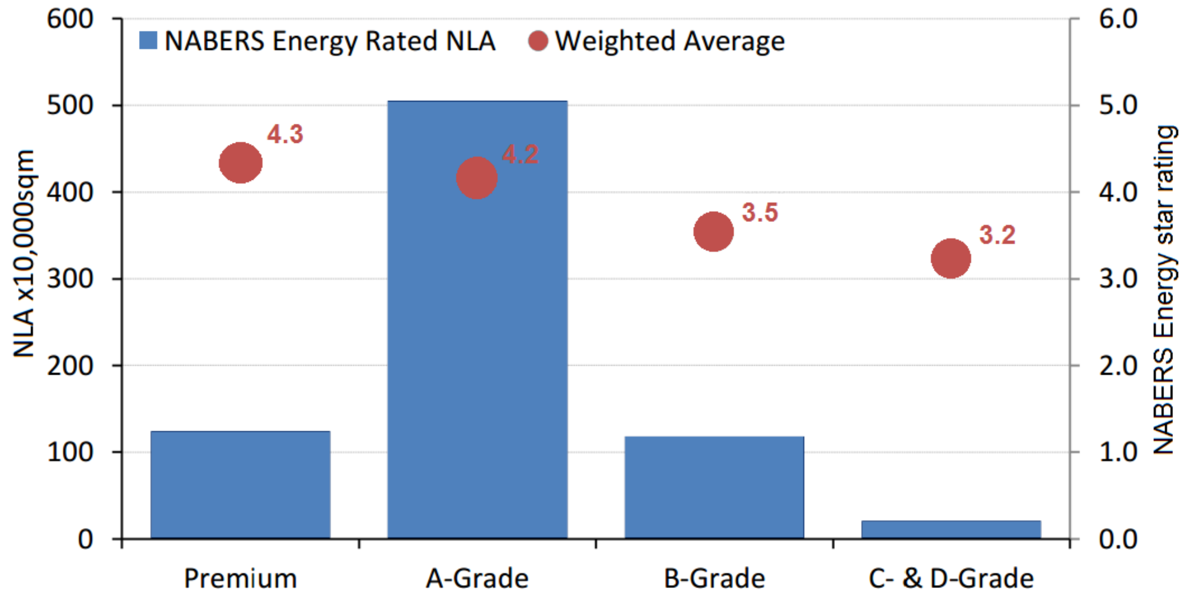


Figure 2-16 Breakdown of rated office NLA by NABERS star rating, and average star rating for each building quality grade (IPD, 2013)

2.10.4 Secondary Grade buildings

Despite the significant segment (up to 85%) of the existing stock that is Secondary Grade, there has been a limited amount of research into retrofitting and refurbishment of these buildings. Secondary Grade buildings are typically older, in poorer condition, have poorer maintenance and repair, and are more likely to be owned by individuals rather than large property groups (Wilkinson, 2011b). Large property groups are more likely than individual owners to have facility managers ensuring that the building is maintained, and viable upgrades are undertaken. Larger companies will also be more likely to respond to non-economic drivers (Wilkinson & Reed, 2008). Conversely, owners of individual buildings are more likely to be impacted by several of the barriers identified in Section 2.10.5, primarily capital availability and access to information. Secondary Grade buildings therefore have great potential for energy savings from retrofits, but have many barriers to the realisation of these savings.

Several studies have attempted to address the knowledge gap regarding Secondary Grade buildings, with limited success. The Low Energy High Rise study (NPC & Exergy, 2009) was an investigation into non-technical barriers to energy efficiency improvement in large commercial buildings, which included 30 B Grade, 5 C Grade, and no D Grade buildings in the research. This shortcoming was acknowledged and the report stated that it would have been ‘significantly more difficult and taken

even more time' to find C and D Grade building owners to participate in the survey. The report repeatedly referenced anecdotal evidence that Secondary Grade buildings have a greater energy savings potential than higher-grade buildings. It is recognised that a special focus is needed on these buildings in any initiative developed from the report. Further anecdotal evidence is referred to in the report to support the statement that C and D Grade buildings will be:

> *…older, smaller with a lower NABERS rating due to such factors as a greater proportion of T8 type lights, less instances of economy cycles and variable volume AHU's and have an older style BMS or possibly none at all…*

The report was prepared by experts in the field, with significant experience in commercial building retrofitting. The difficulty of finding willing participants highlights a key challenge facing researchers of low-grade buildings.

Geest and Erp (2011) attempted to address the knowledge gap on Secondary Grade buildings, however only two case-study buildings were identified. Again, the difficulty in accessing low-grade building owners, particularly those engaged with energy efficiency upgrade, was identified. The buildings studied were owned by institutional owners with a large portfolio of buildings. Both buildings realised approximately 60% energy savings for base building consumption, primarily through technical improvements.

There is limited information accessible about actual retrofit activity undertaken in Australia, particularly with regard to Secondary Grade buildings. There is however detailed information for the Melbourne Central Business District, which may give insights into the broader Australian building stock. Wilkinson (2011a) analysed a database of building characteristics and retrofit activity in the Melbourne CBD to determine the strength of the relationships between commercial building attributes and building refurbishment. The study found that building age, degree of attachment to other buildings, heritage listing, and floor size strongly affect building adaptation. C and D Grade buildings accounted for only 14.9% of all upgrade work, cited as possible evidence of a quality gap emerging between Prime and Secondary Grade buildings. Wilkinson and Remoy (2011) found a strong negative relationship between office quality and retrofit activity. Wilkinson (2011b) examined the physical characteristics of the C and D Grade building stock. It was found that the low-grade buildings in the database predominately had an irregular plan shape, with a brick façade in good or very good condition. The breakdown of retrofit activity by PCA Grade is shown in Figure 2-17.

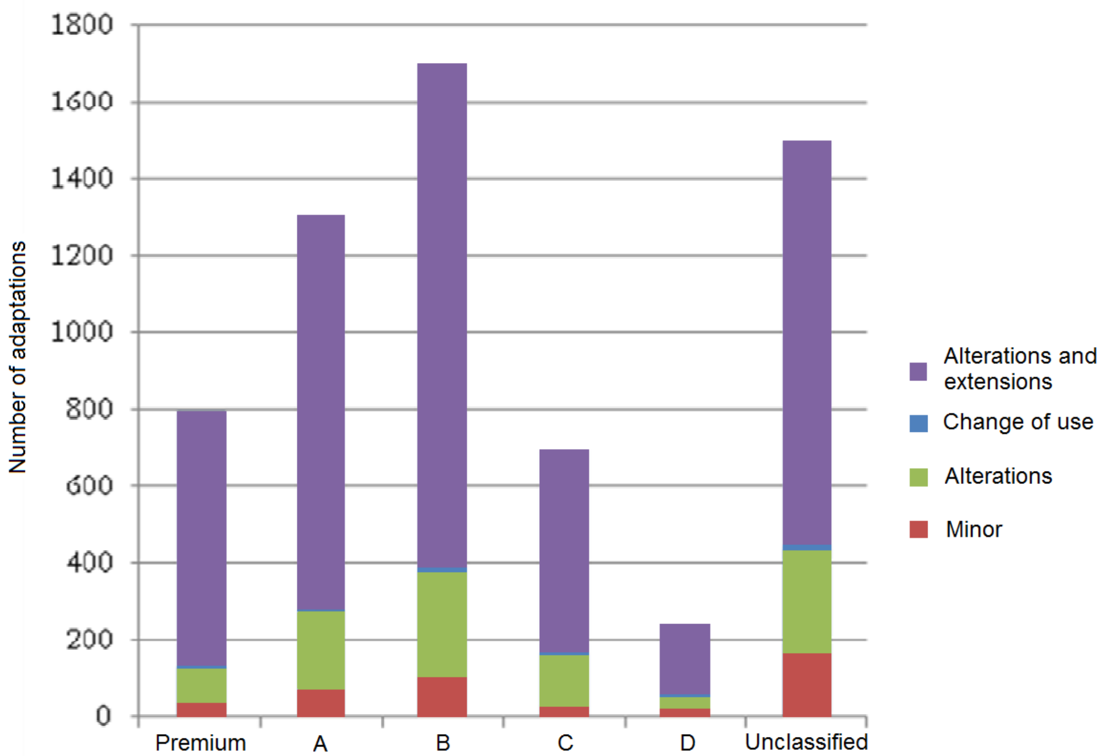


Figure 2-17 The breakdown of retrofit activity in the Melbourne Central Business District by Building quality grade and degree of intervention, from Wilkinson (2011b).

2.10.5 Building Retrofitting Drivers and Barriers

There are inherent difficulties involved in upgrading commercial buildings. The difficulty centres on the numbers of stakeholders, often with competing priorities, who have an interest in a building. Lutzenhiser and Biggart (2001) identified six key stakeholder categories in the energy retrofitting of commercial buildings, i.e.: providers of capital; developers, design and delivery firms; community/political/regulatory interests, facility management, tenants, and others (including energy service companies, product vendors, manufacturers, insurance providers). In most cases, there is no single stakeholder who must consider the entire life cycle costing of a commercial building (NPC & Exergy, 2009), meaning that long-term projects, such as energy efficiency upgrades, may be overlooked.

There are numerous reports providing in-depth analysis of the drivers for building energy retrofitting (Arup, 2009; Arup *et al.*, 2009; DEHWA, 2009; Ernst & Young, 2010; Falkenbach *et al.*, 2010; GBCA, 2008; Yates, 2001). A review of drivers for building energy retrofitting in

Australia identified the following as key factors in the decision to undertake upgrade projects, however this is not an exhaustive list:

1. Operational cost savings – Improving the energy efficiency of commercial buildings will reduce energy costs for the building owner. Increasing energy prices may increase the importance of this driver (Arup, 2009; DEHWA, 2009; 2010; GBCA, 2008).
2. Corporate Social Responsibility/Reputational – Being a 'green' company is an increasingly important tool for differentiation in the eyes of both customers and employees. This is suggested as the key non-regulatory driver of energy efficiency uptake (Arup, 2009; DEHWA, 2009; 2010; GBCA, 2008).
3. Reduced exposure to energy price volatility – given the uncertainty about energy production in the future, and the discussion around carbon pricing, reducing dependence on energy is seen as a way of 'future-proofing' a company (Ernst & Young, 2010; GBCA, 2008).
4. Government Action – government programs and funding support raises awareness and stimulates action in this area (Arup, 2009; 2010).
5. Increase tenant attraction and retention - That 'green' buildings are increasingly being perceived as necessary to ensure continued tenancy (Arup, 2009; Arup & PCA, 2008; DEHWA, 2009; GBCA, 2008; Wilkinson & Reed, 2008).
6. Legislative changes - particularly mandatory disclosure of NABERS ratings when selling or letting a commercial building, and BCA Section J (Arup, 2009; Arup & PCA, 2008).
7. Maintaining or achieving PCA office quality grade (Arup, 2009; DEHWA, 2009; Wilkinson & Reed, 2008).

Many research projects have examined barriers preventing uptake, and there is a significant resource looking at the barriers for specific stakeholders. (Productivity Commission, 2005; Sustainable Energy Authority, 2004; Ernst & Young, 2010; GBCA, 2008). For the purpose of this study, the summary from (ClimateWorks Australia, 2010a) of some of the most significant barriers, presented in Table 2-4 below, is sufficient, and has good agreement with other studies.

Table 2-4 Barriers to uptake of energy efficiency retrofits in the Australian context (ClimateWorks Australia, 2010a).

Barriers	Description
Cost of Capital	Makes marginal projects unprofitable
Interruptions in Operations	Make implementation of some technologies non-economic
Non-market Pricing	Very low energy prices decrease sensitivity to market signals
Finite access to capital	EE projects compete with other internal projects for capital
Long payback periods	EE projects offer profits, but often with very long paybacks, whereas most companies have policies for short paybacks
Investment hurdle rate	Companies often have investment opportunities with higher returns than energy efficiency projects
Access to information	Lack of awareness on energy efficiency opportunity for building owned, lack of information on impact of choices on energy bills
Lack of understanding	Low awareness; no in-house knowledge of complex processes/business case; fear of decreased performance, etc...
Low business priority	Can be caused by energy bill representing a low share of operating costs, by a focus on growth, etc...
Lack of statistical experience to prove secondary benefits	For example it is hard to put numbers on increased productivity or improved health due to more fresh air
Administrative structures	For example when building management decisions are made in an entity separate from operating costs management
Budget allocation processes	Energy savings not always taken into account (e.g. public sector), procurement policies favour low upfront vs lifecycle cost
Split incentives	Happens when building owner makes the building equipment decisions while tenants get the energy savings
Lack of project scale	Increases transaction costs, prevents dealing with ESCOs
Long decision cycles	As equipment often has long lifespan, equipment renewal/ retrofits, especially for central services, happen on long cycles
Availability of equipment, infrastructure	Energy efficient equipment is not always available (e.g. computers), lack of local expertise in some equipment
Reliability/quality of supply	E.g. issues with the reliability of savings estimates, inability for energy service companies to offer tailored service
Management tradition	E.g. long term procurement relationship
Other goals of decision makers	E.g. decision for building equipment will be driven by staff comfort

In order to overcome some of the barriers identified above, government has historically been important in this field. The overarching government program promoting energy efficiency in Australia is the National Strategy on Energy Efficiency (NSEE). The NSEE is an attempt to co-ordinate energy efficiency efforts across various levels of government, and streamline the process

for business and households. It has an overall goal to accelerate energy efficiency efforts, and one theme (out of four) is ‘Making Buildings more Energy Efficient.’ Changes to the BCA, and Commercial Building Disclosure legislation are both measures which have been implemented under this theme.

Government initiatives in the building energy retrofitting industry have experienced a high degree of flux, and therefore and exhaustive list is not supplied. Kempener (2007) provided a review of common policy instruments which relate to energy efficiency. Examples of recent policies are included, although in some cases the listed policies have been discontinued:

1. Energy efficiency standards for office equipment and base building performance (e.g. NCC Section J, Mandatory Energy and Performance Standards for appliances);
2. Voluntary energy efficiency rating programs for base buildings and tenancy (e.g. NABERS);
3. Portals for the dissemination of information on energy efficient technologies (e.g. Energy efficiency exchange (eex.gove.au), yourbuilding.org, City Switch);
4. Development of green leases and new construction contracts to overcome the principal-agent barriers between respectively owners and tenants and between owners, developers and suppliers (e.g. Environmental Upgrade Agreements);
5. Development of energy performance contracts to overcome the capital investment barriers of and lack of information on energy efficiency (e.g. Environmental Upgrade Agreements);
6. Financial incentives for building owners, property developers and tenant for energy efficient design and operation (e.g. Green Building Fund, Clean Energy Finance Company, Tax Breaks for Green Buildings, Energy Saver Scheme, Energy Efficiency for Small Business).

A government policy which is a major driver for building upgrades, not just from an energy efficiency standpoint, is compliance with the Building Code of Australia (BCA) (ABCB, 2013). Non-compliance with the building code can often trigger the need for a building upgrade, including energy efficiency measures. Once a building undergoes refurbishment, alteration or extensions, the energy efficiency requirement outlined in Section J of the BCA apply. Therefore, if a building is non-compliant in any area of the BCA, and requires upgrade works, minimum standards of energy efficiency must be achieved.

Energy Efficiency provisions in Section J of the BCA were first applied to commercial building in the 2006 BCA, and the stringency was increased substantially in 2010. Section J contains clauses which relate to; building fabric, glazing, building sealing, air-conditioning and ventilation systems, artificial lighting and power, hot water supply and swimming pool and spa pool plant, and access for maintenance and facilities for monitoring. The increased stringency is illustrated, in a simplified manner, in Table 2-5.

Table 2-5 Indicative comparison of stringency of energy efficiency clauses in BCA 2010 and BCA 2006 for Climate Zone 5, which includes Sydney. Note: values are simplifications of actual clause, and are indicative of the increased stringency only.

Element	BCA 2006	BCA 2010
Roof R-value (m^2K/W)	3.2	3.2 – 4.2[a]
Wall R-value (m^2K/W)	1.8	2.8
Floor R-value (m^2K/W)	Nil	Nil – 2.0[b]
Glazing Energy Index[c]	0.257	0.145
Lighting power density (W/m^2)	7-10	7 - 9
Fan power		Targets increased by 30%
Minimum Air cooled full load EER/part load EER	2.2/3.0	2.5/3.4
Minimum boiler efficiency (%)	75	80
Economy cycle	When AC capacity is over 50 kWr.	When AC capacity is over 35 kWr.

a – Minimum roof R-value varies depending on roof upper surface solar absorptance.
b – Minimum floor R-value varies depending on floor construction type, e.g. slab-on-ground, suspended floor.
c – Glazing energy index is a factor of glazing area and orientation, SHGC, shading, and U-value of each glazing element.

The Centre for International Economics (CIE, 2009) performed simulations to determine the impact of increased stringency in the energy efficiency provisions of the BCA. The report compared various template buildings, including two office buildings, modelled with DTS (described below) construction and services for the BCA 2009 (minor amendments from BCA 2006) and the proposed BCA 2010. The study found a predicted average decrease in the total energy consumption of office buildings of -17.2%. A decrease was predicted in all climate zones, ranging from – 5.6% in Zone 8, to -20.8% in Zone 6.

Two methods may be used to achieve compliance with BCA Section J; DTS and verification of an alternative solution. A building must comply with every relevant clause in Section J to be adjudged DTS. The increased stringency in Section J 2010 made it more difficult for a building to achieve DTS compliance, particularly clause J0 – building fabric, and J1 – glazing. CIE calculated that the new provisions for glazing reduced the allowable glazing by up to 50%, compared to BCA 2009 to achieve DTS compliance. If a building design does not met DTS provisions, an assessment of an alternative solution is required. Four alternative assessment methods may be used; documentary evidence (evidence that a material satisfies a DTS provision or performance requirement), the verification method (JV3, introduced in Section 2.6.4), comparison with DTS (showing the proposed solution is equivalent to or better than a DTS provision), and expert judgement. The verification method, JV3, involves the use of BPS to compare the performance of an alternative solution to a reference building simulated with DTS provision.

Another government policy of particular relevance to this study was Environmental Upgrade Agreements (EUA's), introduced in Victoria and NSW in 2010. EUA's were a new method of accessing capital for building refurbishment, involving local governments (LGA's), building owners and finance providers. The EUA legislation (NSW Gov., 2010) has similarities to 'Property Assessed Clean Energy' legislation operating in parts of America since 2008. A financier provides funds to a building owner for water, energy and other environmental upgrades, and this loan is repaid through a local council charge on the land, as shown in Figure 2-18.

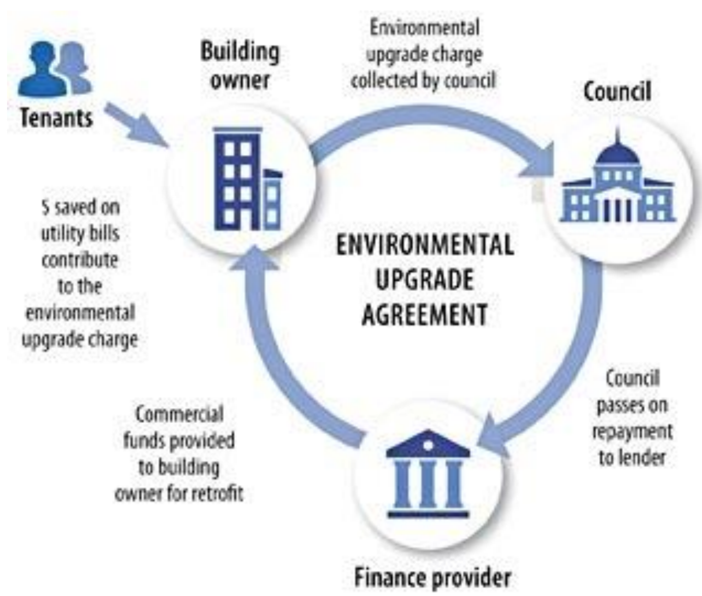


Figure 2-18 The Environmental Upgrade Agreement funding mechanism (OEH, 2013)

This legislation was designed to tackle barriers of split incentives and access to capital. It is also an attempt to stimulate environmental upgrade activity in Secondary Grade buildings. The loan is a statutory charge directly attached to the property, rather than to the building owner, and repayment is via council rates. This means loans can be offered at lower interest rates and for longer terms than commercial equivalents (Blundell, 2012), and that it is permissible for the owner to pass on some of the charge to tenants under a net lease. It also allows the debt to be transferred with the sale of the building, and provides additional security for the finance provider, as council has priority ahead of the first mortgage holder in the event of a default.

At the time of writing (May 2015) EUA's are currently offered in six LGAs. In Victorian LGA's written consent is required from the tenant before the Environmental Upgrade Charge (EUC) can be passed on, while it is not required in NSW. In both states the EUC can only be levied providing that the tenant contribution does not 'exceed a reasonable estimate of the cost savings to be made by the lessee' (unless the lessee consents otherwise) (NSW Gov., 2010).

Despite the potential benefits to a building owner, EUA's have not attracted widespread traction in the retrofitting market. Of the nine EUA's signed at the time of writing, only three involved passing on the EUC to the tenants. EUA's primarily target the Secondary Grade building market, as access to capital is not general a major barrier for institutional owners, who more commonly own Prime Grade buildings. Indeed Roussac and Bright (2012) explained how a major property group in Australia had been able to pass on costs due to environmental upgrades through effective lease contract negotiations. However, hitherto it has unanimously been institutional owners who have taken up EUAs. It is suggested in Blundell (2012) that this was due to Secondary Grade building owners lacking the 'sophistication' to engage with EUA. Blundell (2012) suggests several other reasons for the lack of widespread take-up, for example: uncertainty over how an EUA would affect property valuation; uncertainty as to repercussions from an under-performing upgrade; and how effective council will be at enforcing EUA payments. A solution to many of the issues preventing EUA's gaining traction in the Secondary Grade market is the use of Energy Performance Contracts (EPC). An EPC is a legal guarantee from a third party that the predicted savings will be realised, or equivalent compensation will be provided. From the building owners perspective, EPC reduced exposure to risk, enhances confidence in the decision making process, and allows advanced solutions to be implemented. Several retrofitting companies in Australia provide EPC for certain technologies; one EUA has included an EPC for the lighting upgrade.

2.11 Literature Summary

This chapter has provided a review of the existing literature in the major areas of knowledge related to the objectives of this study. The environmental and economic rationale for building retrofitting has been reviewed together with a detailed characterisation of current practice for commercial building energy retrofitting, including commonly implemented solutions. BPS is identified as having a key role in the retrofit optimisation process, and salient issues regarding accuracy and uncertainty of predictions from BPS were discussed. The current Australian context has also been reviewed, so as to introduce important characteristics for international readers. The interaction between the key areas of knowledge reviewed is represented in Figure 2-19.

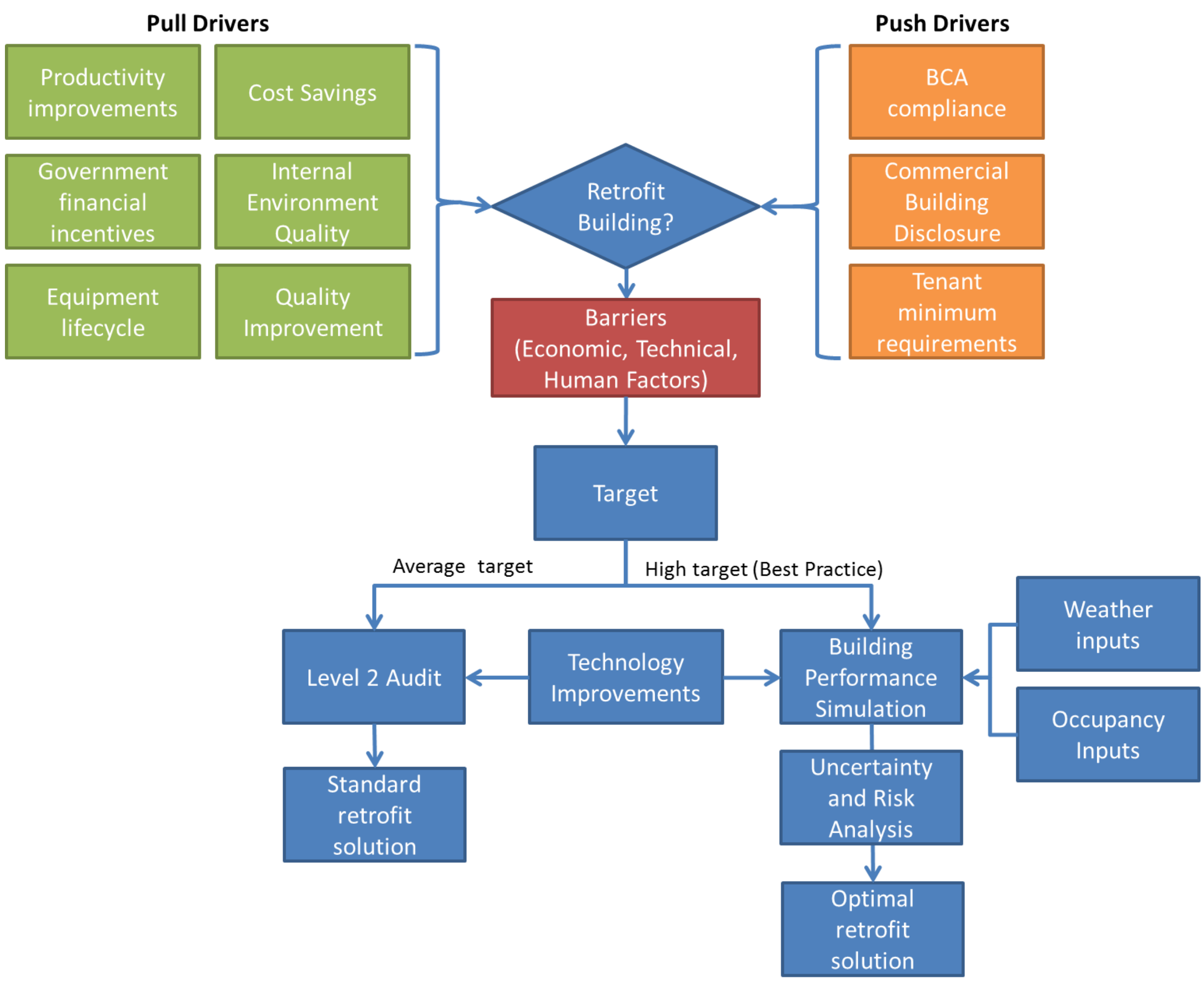


Figure 2-19 Flow chart of retrofitting process, arranged by key areas of literature

It has been shown that there are still significant knowledge gaps in this field, and that further research is required into the commercial building retrofit optimisation problem. The presence of a performance gap between actual and predicted energy consumption is evidence of the imperfect representations of buildings in BPS tools. However, the use of BPS can provide valuable insights into the likely performance of a retrofit strategy for an existing building. Further, predictions of energy savings from building retrofits are an essential component of emerging methods for financing upgrades, such as Environmental Upgrade Agreements, and Energy Performance Contracts. An understanding of the uncertainty, and therefore financial risk, involved in predictions of energy savings from BPS is important in these finance methods, and has been shown to be limited particular in relation to Australian commercial buildings. The use of assumptions and heuristics to represent uncertain inputs, and the use of default values from simulation protocols, have been highlighted as a source of uncertainty which has not been fully investigated. In addition, Secondary Grade buildings have been identified as a significant sub-sector of the existing building stock, and one that has not received much attention in the literature. Chapter 3 will present the research methodology designed to address the research objectives, which has been designed to fill these knowledge gaps.

3 Research Design

This chapter describes the overall design of this research project, to address the aim and objectives outlined in Section 1.2, and improve understanding of the knowledge gaps identified through a review of the existing literature. Detailed information regarding the specific methods employed to meet an individual objective of the project is included in the relevant chapter. In this chapter, the research need is elucidated, and limitations to the scope of this study are defined. The quantitative data sources that were collected and analysed for insights into the existing building stock in this study are introduced. This study employed a mixed-methods approach, e.g. qualitative analysis was used to aid in the characterisation of the current standard and best practice for buildings energy retrofitting in Australia. The design of the qualitative investigation is explained in this chapter, and justification for this approach is given.

An outline of the simulation approach used to investigate the quantitative uncertainty involved in the representation of weather conditions and unknown or variable building inputs, and justification for the selection of the approach is given. This includes a description of the simulation tools and reference building forms utilised, and the locations studied. A brief description of the case study buildings used to examine the applicability of reference buildings to Secondary Grade buildings, and possible simplifications to BPS representations of commercial buildings is included in this chapter. Figure 3-1 depicts the overall method followed in this research project, showing the major methods employed to meet the objectives listed in Chapter 1.

3.1 Research Need

Extensive building energy retrofitting activity is essential to the achievement of significant reductions in global GHG emissions in the near future. This task is likely to become more pressing over time as the environmental imperative becomes stronger. If current trends continue, building energy retrofitting is likely to become more economically attractive as power prices rise and energy efficient technologies become cheaper and more effective. The identification of an optimal upgrade strategy for an individual building is a multi-objective optimisation problem, which involves numerous constraints and competing priorities. At present, there is a lack of data concerning the energy use and operation of commercial office buildings in Australia, at both a stock and individual building level.

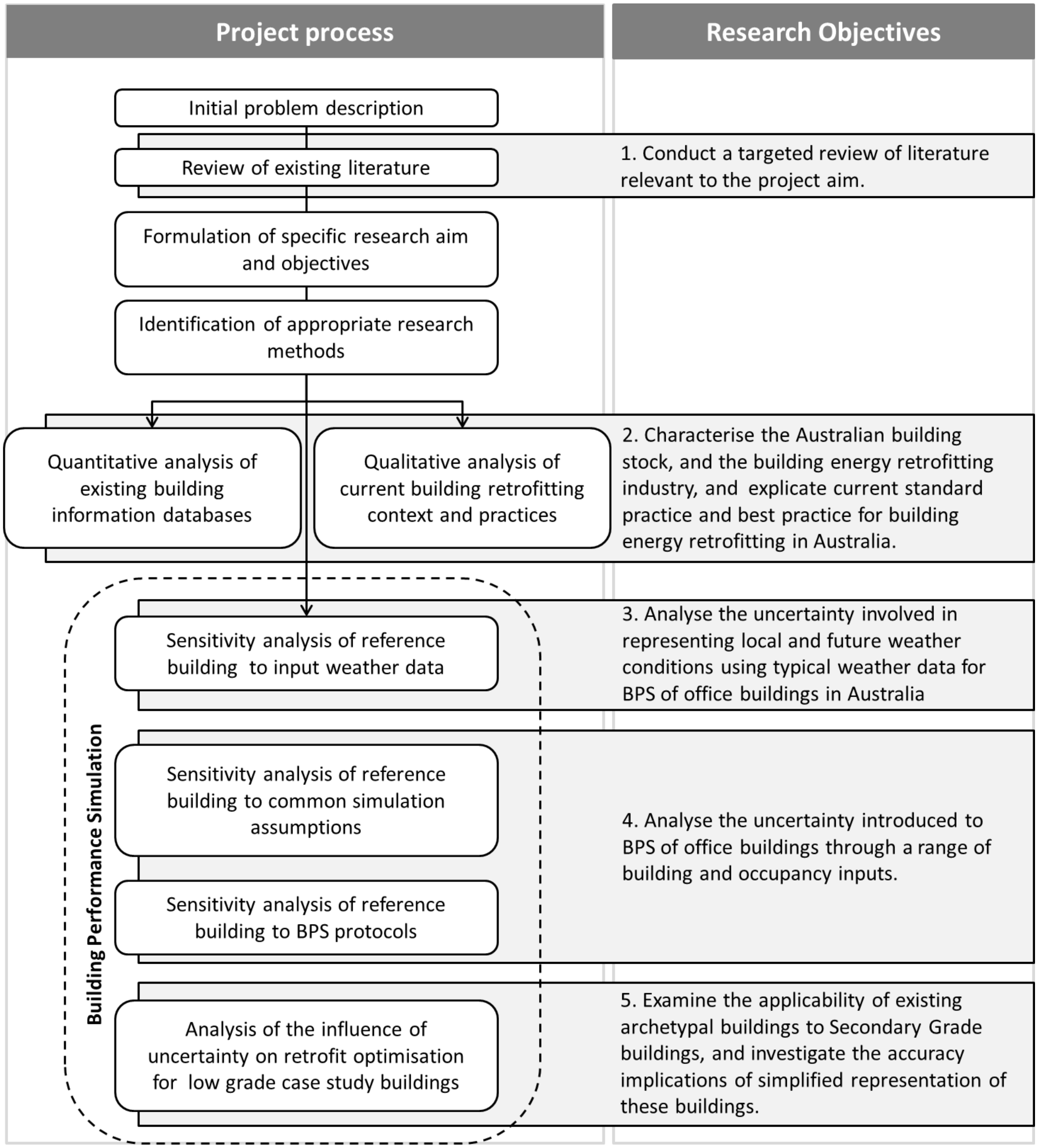


Figure 3-1 Overall research design flowchart, illustrating the mixed-methods approach to the research problem.

The retrofit optimisation decision making process is thus typically bounded by incomplete information, which can result in significant uncertainties. One of the key tools in the selection of optimal retrofit strategies is Building Performance Simulation (BPS). BPS can be used to predict energy savings from an upgrade strategy, and therefore estimate environmental and economic

performance over the full building or equipment life cycle. However, BPS requires significant user skill, expert understanding of building systems, detailed inputs regarding building attributes and occupant behaviour, and an appropriate representation of local climate conditions. There is significant scope for error and uncertainty in the results from BPS, and indeed a significant gap between predicted and actual building energy consumption has been repeatedly observed. Results from BPS of Secondary Grade buildings typically have particularly high uncertainty, as building specific information is often incomplete or non-existent. Understanding and managing this uncertainty is a key challenge for the building simulation and retrofitting industry, particularly as investment and financial risk are increasingly tied to the results of BPS.

3.2 Research Scope

The aim of this research project was to understand the uncertainty involved in BPS in the retrofit optimisation process for commercial office buildings in Australia, in particular Secondary Grade buildings.

Research in the area of building energy retrofitting involves a wide range of data sources and requires expert knowledge in numerous areas. This research project focussed on quantification of the uncertainty involved in prediction of the energy performance of commercial buildings made with the use of BPS. To achieve the aim and objective outlined in Chapter 1, the scope of this study has been limited in the following ways.

- The study was limited to Australian office buildings, defined in accordance with the BCA Class 5 definition. A Class 5 building is 'an office building used for professional or commercial purposes, excluding buildings of Class 6, 7, 8 or 9' (ABCB, 2013).
- The majority of the research in this study focused on the eight Australian state and territory capital cities. Some database analysis included records from outside the capital cities. The capitals contain the bulk of Australia's Class 5 office stock, and reflect the climatic diversity encountered across the country.
- The uncertainty explored was limited to the first two causes of variation identified in Section 2.6. The impact of the reliability and accuracy of physical input data was directly tested, whilst the impact of user data interpretation was considered in relation to decisions about uncertain or stochastic inputs. Consideration was not extended to the applicability of the tool to the building and climate, or the calculation method and underlying algorithms used in the tool. The tool employed was an industry standard tool for Class 5 buildings.

- This study considered building energy retrofitting (also termed building retrofitting), which was defined for this study as building upgrades, retrofits, and refurbishments undertaken with a principal goal of improving energy efficiency. All retrofit technologies and strategies considered were proven, commercially available technologies. Consideration was only given to energy efficiency measures. On-site generation, demand response, and power quality strategies were not considered in this study.
- This study was limited to consideration of end-use energy efficiency, in terms of actual energy use (e.g. kWh or MJ). Whilst environmental impact of energy consumption is generally considered in terms of GHG emissions, expressed as tCO_{2}-e, the varying carbon intensity of energy sources in different Australian states meant that the use of this measure would have introduced a barrier for direct comparison of retrofitting strategies and sensitivity indices between states.
- The study did not consider the uncertainty in the financial evaluation of building retrofits. The prediction of the cost of retrofit measures, the future cost of energy, and the future operating and maintenance costs associated with retrofit scenarios will all strongly affect the retrofit optimisation process, and have a strong interaction with energy performance contracting and related finance tools. However, an assessment of the uncertainty associated with each of these tasks, and the implications of the uncertainty, is a complex undertaking that was beyond the scope of the current study.

3.3 Analysis of Accessible Data

Research into the existing building stock is heavily influenced by the accessibility of data to researchers. Thuvander (2003) conceptualised this issue as shown in Figure 3-2, which illustrates that building stock data has a number of layers and determines which of those can be used. ‘Achievable’ data is all that could be known without constraints, e.g. unlimited time, money, personnel, etc. ‘Existing’ data is data that has previously been captured and ‘available data’ is existing data that is in a format that would allow use, but may not be accessible due to privacy concerns or similar issues. ‘Accessible’ data is available data without restrictions to access, available in a format compatible with the model constraints.

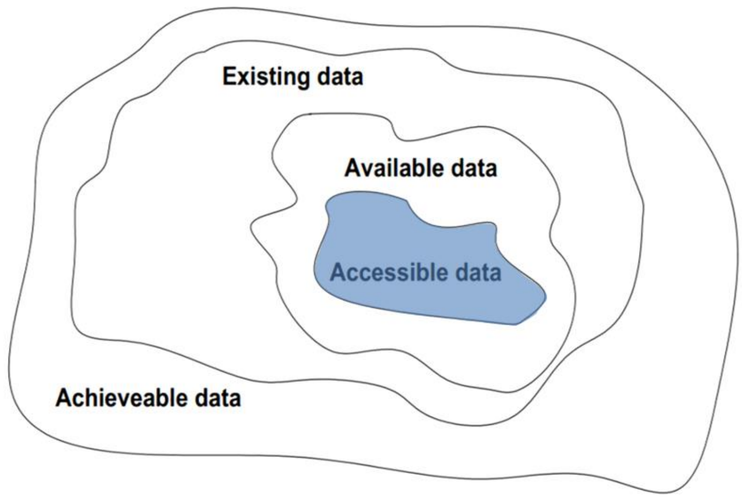


Figure 3-2 Accessible data is a subset of available, existing and achievable data sets. Various restrictions between each layer hinder research into the existing building stock (Thuvander, 2003).

A key driver for the design of this research project was the poor availability and accessibility of data related to commercial office building energy use in Australia. Attempts were made in the initial stages of this study to analyse the effectiveness of building energy retrofitting strategies through the use of real-world data. As the Australian office stock is heterogeneous, a significant data resource would be needed to make findings applicable to a large segment of the office building stock. Insufficient data was able to be collected for the present author to use this method. Access to data was partly hindered by privacy concerns of both public and private institutions. Generally, information about successful strategies implemented in Prime Grade buildings was available. However, data about poorly performing or unassessed retrofits, particularly relating to Secondary Grade buildings, was more difficult to access. A discussion of unexplored data sources is included in Section 4.2.4.

This study performed analyses of several data sources that related to the Australian retrofitting industry. Significant effort was spent in identifying and accessing all useful existing and available data sources relevant to the research question. A truncated version of Building Attributes Database, developed for the Melbourne CBD by Wilkinson (2011a) was used to help characterise existing buildings. This database was supplemented by the Building Energy Efficiency Register (BEER). This collection of Building Energy Efficiency Certificates (BEEC) from the Commercial Building Disclosure Scheme provided energy consumption information for numerous buildings. The BEER was analysed and compared to previous studies that had investigated the average energy consumption for various regions in Australia. Non-identifying data from the NSW Energy Saver

Scheme was analysed, primarily to understand currently recommended energy efficiency upgrades. A summary of the databases analysed is shown as Table 3-1.

Table 3-1 Summary of quantitative databases accessed and analysed.

	Australian Building Energy-Efficiency Register	**Building Attributes Database**	**Energy Saver Scheme Database**
Source	Federal Government	Other researcher, incorporating Victorian Government data	NSW State Government
No. of records	3190 unique buildings	6,778 events, 439 unique buildings	1983 upgrade, for 381 unique buildings
Energy information	Yes, NABERS ratings details	NABERS star rating for few buildings	No

3.4 Building Performance Simulation Program

This research project relied substantially on BPS to investigate uncertainty issues and sensitivity of building energy consumption in Secondary Grade buildings. A key assumption in this study was that the BPS tool employed was able to effectively represent the building and climate under consideration, and to predict the performance of the building, given accurate input data. This study utilised a tool widely used and accepted by the building design and retrofitting industry in DesignBuilder, a graphical user interface for the EnergyPlus thermodynamic simulation engine. A range of other tools were considered for this study (see Section 2.6); Designbuilder and EnergyPlus were considered most appropriate for this study.

EnergyPlus is a proven BPS tool in common usage in the Australian context (Asadi *et al.*, 2012; Ryan & Sanquist, 2012; Yalcintas, 2008). EnergyPlus has been used as the energy simulation software in numerous previous Australian research projects (Castleton *et al.*, 2010; Copper & Sproul, 2013; Gentle *et al.*, 2011; Rahman *et al.*, 2010). EnergyPlus was developed by numerous reputable developers, and has been tested and validated in accordance with ASHRAE Standard 140-2001 (ASHRAE, 2001b) and other analytical and comparative tests (U.S. Department of Energy, 2014). Detailed information regarding the calculations used in the EnergyPlus engine can be found in the EnergyPlus Engineering Reference (U.S. Department of Energy, 2013b).

DesignBuilder, a third-party graphical user interface for EnergyPlus, was used in this study. DesignBuilder has been used in many studies in Australia (Chowdhury *et al.*, 2008; Rahman *et al.*,

2010, 2011), and has also been verified with ASHRAE 140-2001 (ASHRAE, 2001b). The use of DesignBuilder simplifies the input of geometric building data into the EnergyPlus engine. Comprehensive details regarding DesignBuilder are available in the program documentation (DesignBuilder, 2011).

3.5 Reference Building Models

This study employed BPS to investigate uncertainty in the retrofit optimisation process. One method used to simplify modelling effort and allow generalisation to be made regarding a segment of the building stock under consideration is the use of reference buildings (also termed typical, archetypal of template buildings). In the context of this research, a ‘reference building’ is a theoretical building defined with information about the geometry, construction, and services. A reference building may also include a simplified occupancy representation. A reference building is generally developed to be representative of a common building type in a particular setting. For much of this research project, uncertainty analysis has been conducted with the use of reference, or archetypal, buildings. A review of existing reference buildings employed in Australian research projects has been presented in Section 2.6.4. The use of reference buildings means that results were not influenced by the idiosyncrasies of existing buildings, and findings were more likely to be broadly applicable. It does however introduce the need to use numerous assumptions and ‘typical’ inputs, and removes the possibility of building-specific characteristics informing the retrofit optimisation process. The final chapter considers several case study buildings to facilitate an in-depth discussion of this issue.

This study primarily utilised the Australian Buildings Codes Board (ABCB) Form A and Form B reference buildings. These two building archetypes have been used to represent office buildings in Australia in many studies (ABCB, 2004, 2006a, 2006b; ACADS-BSG, 2002; BRANZ, 2007; Donnelly, 2004; Guan, 2009a, 2009c, 2011, 2012; Lee & Ferrari, 2008; Lyons, 2008, 2009; pitt&sherry, 2010, 2012c; Samarakoon & Soebarto, 2011). The reference geometric form was originally developed by the ABCB (Donnelly, 2002). The base case information concerning services and occupancy for these buildings was taken from ACADS-BSG (2002); a detailed investigation of these assumptions forms the basis of Chapter 6.

The Form A building was designed to approximate typical fabric and internal loads in large commercial buildings, and is stated to be representative of BCA Class 2, 3 or 5 buildings with a

fully enclosed, covered area greater than 2,000 m^2. It is a 10-storey tower with a square footprint and a gross floor area of just under 10,000 m^2 (31.6 m x 31.6 m), representative of a central CBD office building. Form B was designed to be representative of Class 5 buildings with a floor area less than 2,000 m^2, typical of offices on the fringe of CBDs. It is a 3-storey building designed to represent city fringe buildings, with a 2:1 aspect ratio floor plan and a gross floor area of 2,000 m^2. For both buildings NLA was assumed to be 90% of gross floor area, i.e. 9000 m^2 and 1800 m^2, respectively. Visualisations of the buildings are shown in Figure 3-3 and Figure 3-4.

The geometric specifications of the building are displayed in Table 3-2, along with the base case inputs for the building construction, HVAC and occupancy parameters. Unless otherwise noted, these inputs were assumed for all simulations in this study, however, alternate values were used to test the building performance sensitivity in many cases.

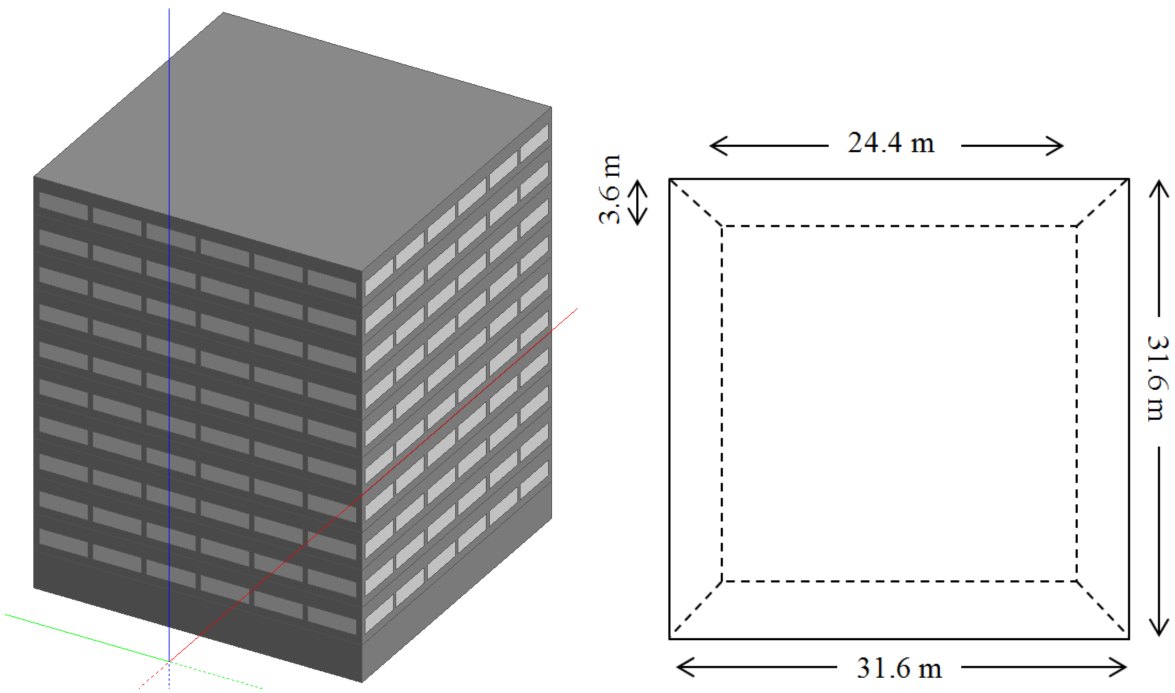


Figure 3-3 'Form A' 10-storey commercial office building as visualised in DesignBuilder.

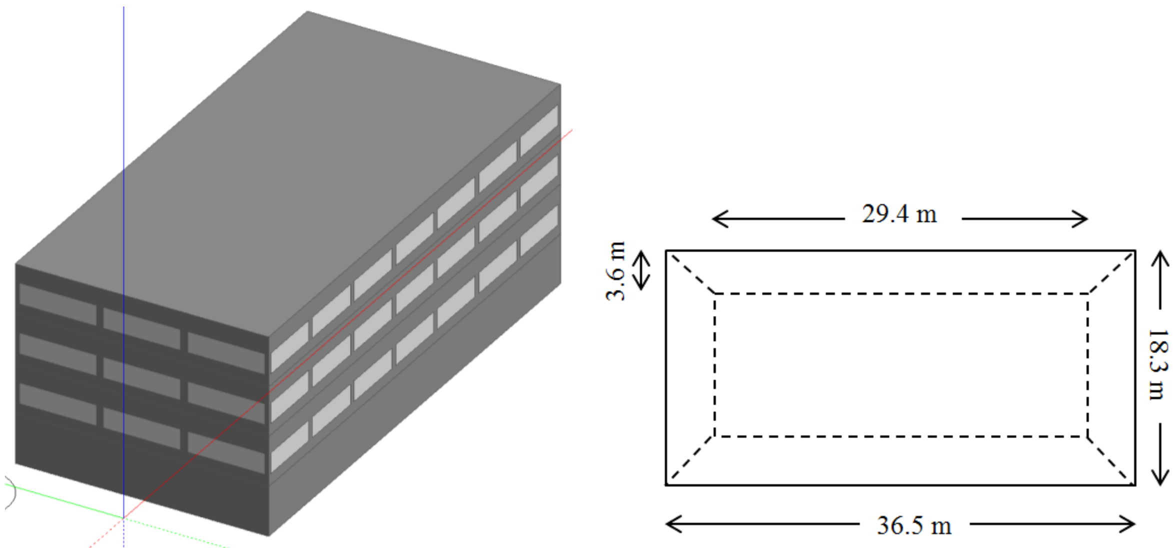


Figure 3-4 'Form B' 3-storey commercial office building as visualised in DesignBuilder.

Equipment, lighting and occupancy schedules were not stipulated in previous reports from the ABCB. Unless otherwise noted, the default equipment, lighting and occupancy schedules from NABERS (2011), discussed in Section 2.6.4 were used. An annual allowance was made for lifts and auxiliary service equipment of 8 kWh/m^2, as recommended by NABERS (2011).

Chapter 8 investigates the importance of HVAC system detail in BPS of the case study and reference buildings. For the other simulation studies, the HVAC system modelled was developed in accordance with the system used by ACADS-BSG (2002), which was a commonly implemented system for this building class (Bannister, 2004). Detailed information regarding occupancy, envelope and climate inputs is given in the relevant chapters.

Whilst the ABCB forms are the most widely used reference buildings in Australia, reference building forms developed by ZCA (2013) and the US Department of Energy (DOE) (Deru *et al.*, 2011) respectively were also considered. Further information was given for these reference buildings in Section 2.9.

Table 3-2 Building geometry and systems inputs for ABCB Form A and Form B buildings as defined by ACADS-BSG (2002).

Parameter	Form A	Form B
Total floor area (m^2)	9,985.6	2,000
Net Lettable Area (NLA) (m^2)	9,000	1,800
Floor plate configuration (m)	31.6 x 31.6	36.5 x 18.3
Number of floors	10	3
Aspect Ratio	1:1	2:1
Floor to floor height (m)	3.6	3.6
Floor to ceiling height (m)	2.7	2.7
Internal zones	3.6 Perimeter and Core	
Basement	Y	Y
Glazing fraction	0.38	0.38
Shading coefficient	0.56	0.56
Exterior walls	200 mm HW concrete, R1.5 batts, 10 mm plasterboard ($R_{overall}$ = 1.8 m^2K/W)	
Roof	Metal deck, air gap, 150 mm HW concrete, roof space, R2.0 batts, 13 mm acoustic tiles (R = 3.6 m^2K/W)	
Floors	175 mm concrete with carpet (R = 0.76 m^2K/W), exposed concrete ceilings.	
Windows	Single clear mm (U = 5.89 W/m^2K)	
HVAC system types	VAV, water cooled AC, Gas boiler	

3.6 Sensitivity Analysis Method

Sensitivity analysis is a tool commonly used in building energy research, but is an area without a well-defined or generally accepted procedure/process (Lam & Hui, 1996). Individual studies generate a specific approach suited to the particular objectives of the study. Sensitivity analysis was a key analysis tool employed in this research. A previous review (Lomas & Eppel, 1992) of commonly employed sensitivity analysis methods highlighted Differential Sensitivity Analysis as the preferred technique for research into building energy use. A detailed description of the sensitivity analysis method followed is given in each relevant chapter. Specific discussion of the DSA method is included in Chapter 6.

The generic DSA method followed for this study was consistent with previous work in this field (Molinari, 2012; Simm *et al.*, 2011; Spitler *et al.*, 1989) and is summarised as follows:

- Define a building configuration with parameters set at the most likely base case values;
- Assign minimum and maximum values for each parameter of interest

- Simulate the building in the base case configuration;
- Simulate the building and vary each parameter of interest from its minimum to maximum value, while holding all other parameters constant at their base case values;
- Analyse the results, and obtain sensitivity indices for each parameter of interest.

This study calculated the non-dimensional influence coefficient for use as a comparison index in sensitivity analyses. Simm *et al.* (2011) and Bertangnolio (2012) identified non-dimensional Influence Coefficients (also termed point elasticity, non-dimensional Type 2 Influence Coefficients, or normalised Influence Coefficients) as the most useful index for building energy studies. The general equation for this influence coefficient is shown in Equation 3.1.

$$Influence\ Coefficient\ = \frac{\frac{\Delta OP}{OP_{bc}}}{\frac{\Delta IP}{IP_{bc}}} = \frac{\%\ Change\ in\ output}{\%\ Change\ in\ input} \qquad (3.1)$$

Where ΔIP and ΔOP are the changes in input and output parameters, respectively; IP_{bc}, OP_{bc} are the base case values for output and input, respectively.

3.7 Study Locations

This study was confined to Australia, and specifically used the locations of eight state and territory capital cities. The existing building stock is likely to vary across the study locations, due to climate, history and local building practices. The locations considered for this study were geographically diverse, and represent five of the eight climate zones, namely:

- Adelaide – BCA Zone 5 (Warm temperate)
- Brisbane – BCA Zone 2 (Warm humid summer, mild winter)
- Canberra – BCA Zone 7 (Cool temperate)
- Darwin – BCA Zone 1 (High humidity summer, warm winter)
- Hobart – BCA Zone 7 (Cool temperate)
- Melbourne – BCA Zone 6 (Mild temperate)
- Perth – BCA Zone 5 (Warm temperate)
- Sydney – BCA Zone 5 (Warm temperate)

3.8 Weather Data

DesignBuilder requires hourly weather data in the EnergyPlus (.epw) file format. For a full description of the various sources and formats of typical weather files see Section 2.6.2. Over the

course of this research, the preferred weather files for use in Australia changed, due to the completion of a major error correction exercise for the RMY files (Liley *et al.*, 2013). The present study initially utilised IWEC weather files for all locations except Hobart. In Hobart there was no IWEC file available and therefore an RMY file was utilised. Once the new TMYC files became available, they were used for all locations. The impact of this change is specifically examined in Chapter 5. IWEC and TMYC files were developed according to the TMY method, which is preferable to the TRY method for energy use studies (Crawley & Huang, 1996). Specific information on the method used to generate future weather files is included in Chapter 5. Discussion of the limitations of the use of typical weather year files was included in Section 2.6.2, and is explored further in Chapter 5.

3.9 Qualitative Design

One of the objectives of this research was to understand the context of the commercial building energy retrofitting industry in Australia, and to understand current opinions and practices of various key stakeholders in the area. Building on the knowledge gained from literature reviewed in Chapter 2, semi-structured interviews were undertaken with representatives from the consulting industry, academia, relevant government organisations, and building management. This mixed-methods approach was selected in part to triangulate with the quantitative database analysis and simulation studies. The limitations of data for the Australian context, discussed in Section 3.3, provided further incentive to access this knowledge source.

The use of qualitative research, which involved human participants, meant that university ethics approval was required. This was an important aspect of the design of the qualitative research, and required the preparation of a detailed research plan. The research plan was reviewed by the University of Wollongong and Illawarra Shoalhaven Local Health District Social Sciences Human Research Ethics Committee prior to the commencement of any research activity. The committee considered the research design, along with all documentation associated with the qualitative project, including: recruitment information, Participant Information Sheets, Consent Forms, and an example topic guide. These are included in Appendix B, as are relevant excerpts from the application for approval to undertake research involving human participants. Ethics approval was granted under the Research Services Office code HE13/443, for the research activities as described below.

Prospective participants invited to participate in this research project were experts in the field of building energy retrofitting or building simulation, with experience in commercial building energy retrofitting. They were identified via networks established already by staff and students of the Sustainable Buildings Research Centre (SBRC). Participants were asked to participate in a semi-structured interview, in person or over the phone, with a duration between 30 and 60 minutes. Participants were asked about their understanding of the decision making process used to assess building retrofit strategies, including economic, technical, and attitudinal barriers and incentives. Building simulation users in commercial consulting companies were also asked about modelling practices and data sources. Specific questions were asked about how the respondent viewed current trends and practices, and general questions on what they see as important challenges for the industry going forward. A semi-structured approach was appropriate, as it allowed the participant to direct the interview towards areas they viewed as important, rather than the interviewer setting the agenda. After the interview, if necessary, participants were asked, via email, to clarify or provide further information about certain responses.

The interviews were semi-structured, and the topic guides developed varied slightly according to the interviewee. An example topic guide is included in Appendix B. Each interview was recorded to and transcribed. The transcriptions were reviewed against the audio to ensure accuracy, and then analysed.

The approach to the qualitative analysis was drawn from Creswell (2014), Saldaña (2009), and Waitt (2010). The analysis considered all the data to identify common issues and themes across sources. Initially, all transcriptions were read and clear or obvious themes were identified or noted in the margins. A fresh copy of the transcription was then re-read in detail, and first cycle coding was undertaken. In qualitative research, a code refers to ‘a word or short phrase that symbolically assigns a summative, salient, essence-capturing, and/or evocative attribute for a portion of … data’ (Saldaña, 2009). Coding is therefore the act of categorising and linking of data to ideas. QSR International’s NVivo 10 qualitative data analysis software package (QSR International Pty Ltd, 2012) was used to facilitate this coding process. Several coding cycles were completed, during which emergent themes were identified and further investigated. During the coding process, consideration was given to maintaining reflexivity (i.e. suspending pre-existing categories and responding to the text), and absorbing oneself in the texts. Comparison was made between responses from different professional groups, locations, and experiences. The responses were considered in relation to the relevant literature. A more detailed discussion of the considerations in

qualitative research and analysis has been provided by others (Creswell, 2014; Galletta, 2012; Saldaña, 2009).

3.9.1 Interview Participants

An invitation to participate in the interview process was distributed to 18 identified experts, and semi-structured interviews were undertaken with 12 participants. Interviews ranged in length from 17 to 55 minutes. The interview participants and their relevant experience is summarised in Table 3-3. It was decided to use pseudonyms within the body of this manuscript so as to provide a level of anonymity to participants, despite consent having been obtained to identify the majority of participants.

3.9.2 Positionality Statement

The identification of possible biases, values and personal interests which relate to the topic of study is an important aspect of qualitative research (Creswell, 2014). It is common for the researcher to provide a 'positionality statement' of their personal biography and views, to acknowledge any possible influence the researcher might have in the research process. The present author offers this statement as follows.

I came to this research question with great concern about climate change and the impacts of modern society on the environment. My previous research had convinced me that building energy retrofitting, including behavioural change, was an effective method of reducing GHG emissions, and should be encouraged. I do not come from a mechanical engineering background, so was interested in the topic from a sustainability perspective rather than an engineering performance perspective; however, I believe I had a sufficient understanding of mechanical systems for the project at hand. I did not have a history of working in industry, but had an academic understanding of the building energy retrofitting industry, including key barriers and drivers, and the time and financial pressures that drive many decisions. This meant that I was particularly interested in areas in which the actual practice was different to how I understood the process academically. I did not have close relationships with any of the interviewees.

Table 3-3 Semi-structured interview participant details.

Pseudonym	Interview Date	Position	Expertise
Consultant A	26/03/014	Associate Director, International engineering consultancy, Canberra based	Managing retrofits projects.
Consultant B	26/03/2014	Professional Engineer, International engineering consultancy, Canberra based	Building Performance Simulation
Consultant C	09/04/2014	Sustainability Leader, International ESD consultant, Sydney based	Managing retrofit projects, International experience
Government A	13/06/2014	EUA Program Co-ordinator, Local Government, Sydney based	EUA's
Consultant D	19/06/2014	Senior Consultant, ESD consultancy, Sydney based	Managing retrofits projects and BPS, International experience
Government B	03/07/2014	Sustainability programs co-ordinator, Local Government, Sydney based	EUA's
Consultant E	03/07/2014	Sustainability Project Manager, Energy consultancy, Sydney based	Energy audit and retrofit identification
Consultant F	03/07/2014	Director, Energy efficiency consultancy, Sydney based	Managing retrofits projects and BPS
Building Management A	05/08/2014	Building Manager, Sydney based	Building management
Building Management B	13/08/2014	Facilities Manager, Sydney based	Building management
Consultant G	20/08/2014	Principal, International ESD consultancy, Sydney based	Managing retrofits projects and BPS, International experience
Consultant H	21/08/2014	Manager, International energy consultancy, Melbourne based	Energy performance contracting

3.10 Detailed Numerical Analysis of Case Study Buildings

Three case study buildings were examined to apply the insights gained from earlier section of this study in a real world setting. The case study buildings were selected based on availability of data. To be suitable for this study a building had to be a Secondary Grade office building, with sufficient building-specific information accessible to allow an energy model to be created and validated. It proved to be extremely difficult to identify potential case studies in which the relevant party possessed, and was willing to share, the required information. In practice, this meant that the owners/tenants of the building had to be either considering, in the process of, or just finished, an energy retrofit.

The case study buildings were generally identified through intermediaries, e.g. ESD consultants known to the present author. The qualitative research process was invaluable in the identification of possible case studies. Several other buildings were identified and inspected throughout the course of

this research project. These buildings were used to develop an understanding of the auditing and retrofitting methods followed by a number of consultants, including the technical and economic considerations, project management issues, and decision-making processes. Where these buildings were not specifically considered in this study, it was generally due to data limitations, privacy concerns, or the building being of a difference BCA class or PCA Grade than the study focus. The three case study buildings were all located close to Sydney, primarily due to the pre-existing network of the investigator. The three case study buildings represented a sample of buildings contained in the category of Secondary Grade office buildings. Basic information about the three buildings studied is given in Table 3-4.

Table 3-4 Case study buildings analysed for this study.

	Building 1	**Building 2**	**Building 3**
Location	North Sydney	North Sydney	Parramatta
NLA (m^2)	7436	7343	3706
No. of storeys	5	2	7
PCA Grade	B-	B+	C-D
Most recent previous energy retrofit	1992	1991	1963

Detailed models of the case study buildings were created, and accessible data sources were used to calibrate the models. The models were validated against metered consumption data. The validated model predictions were then compared to the results from simulations of three reference building models. The influence of geometry, construction, and occupancy was explicitly explored. The reference building models were then iteratively improved to more accurately represent each case study building, and the influence of each improvement was analysed.

3.11 Chapter Summary

This chapter has presented an overview of the tools used and method followed in this research project to achieve the specific aims and objectives outlined in Section 1.2. The scope of the research has been defined, along with the locations considered in this study. The sources of building and energy use data accessible for this research were outlined, and the general analysis techniques defined. The BPS tools and general methods were introduced, to be further refined in the relevant chapters. Details of the qualitative research method used to investigate current industry practice were also given, along with justification for this approach. Chapter 4 presents the findings from the analysis of accessible data sources, and the qualitative investigation. Subsequent chapters present further detail of the specific methods employed, and the results and discussion of the original research findings.

4 Qualitative and Quantitative Characterisation of the Australian Building Energy Retrofitting Industry

An objective of this study was to characterise the current state of the existing building energy retrofitting industry in Australia. Whilst this objective was addressed to some degree through the review of the existing literature, there remained significant gaps in knowledge regarding the physical and energy-related attributes of the existing building stock, particularly Secondary Grade buildings, and actual practices and attitudes of key stakeholders in the industry. This chapter presents an examination of numerous data sources related to these knowledge gaps. The results of a qualitative analysis of interviews conducted with stakeholders in the building and retrofitting industry is included in this chapter. Three databases were analysed: i) the Building Energy Efficiency Register (BEER); ii) the Energy Saver Scheme audit database (ESS db); and iii) the Building Attributes Database (BA db). The following section present several key themes, which emerged during the 'coding' of the interview transcripts. A discussion of the interrelation of the themes, and the broader context is included in Section 4.3.

4.1 Qualitative Analysis of Drivers for and Barriers to Building Energy Retrofitting

This section describes the process and insights gained from twelve semi-structured interviews undertaken with stakeholders in the building energy retrofitting industry, including consultants, government administrators and building managers. The interviews were transcribed and coded for emergent themes with the NVivo Software, as discussed in Section 3.9. Several coding cycles were undertaken, during which time key themes emerged. The data was then re-examined to identify interrelation of codes and themes. The analysis of the interview data presented below covers the retrofit optimisation process as described by the participants, and how this differed from the model outlined by Ma *et al.* (2012). Other important topics and emergent themes from the qualitative analysis are discussed, including drivers for retrofit activity and BPS, uncertainty in simulation results, the tension between commercial pressure and accuracy, and the Environmental Upgrade Agreement (EUA) program.

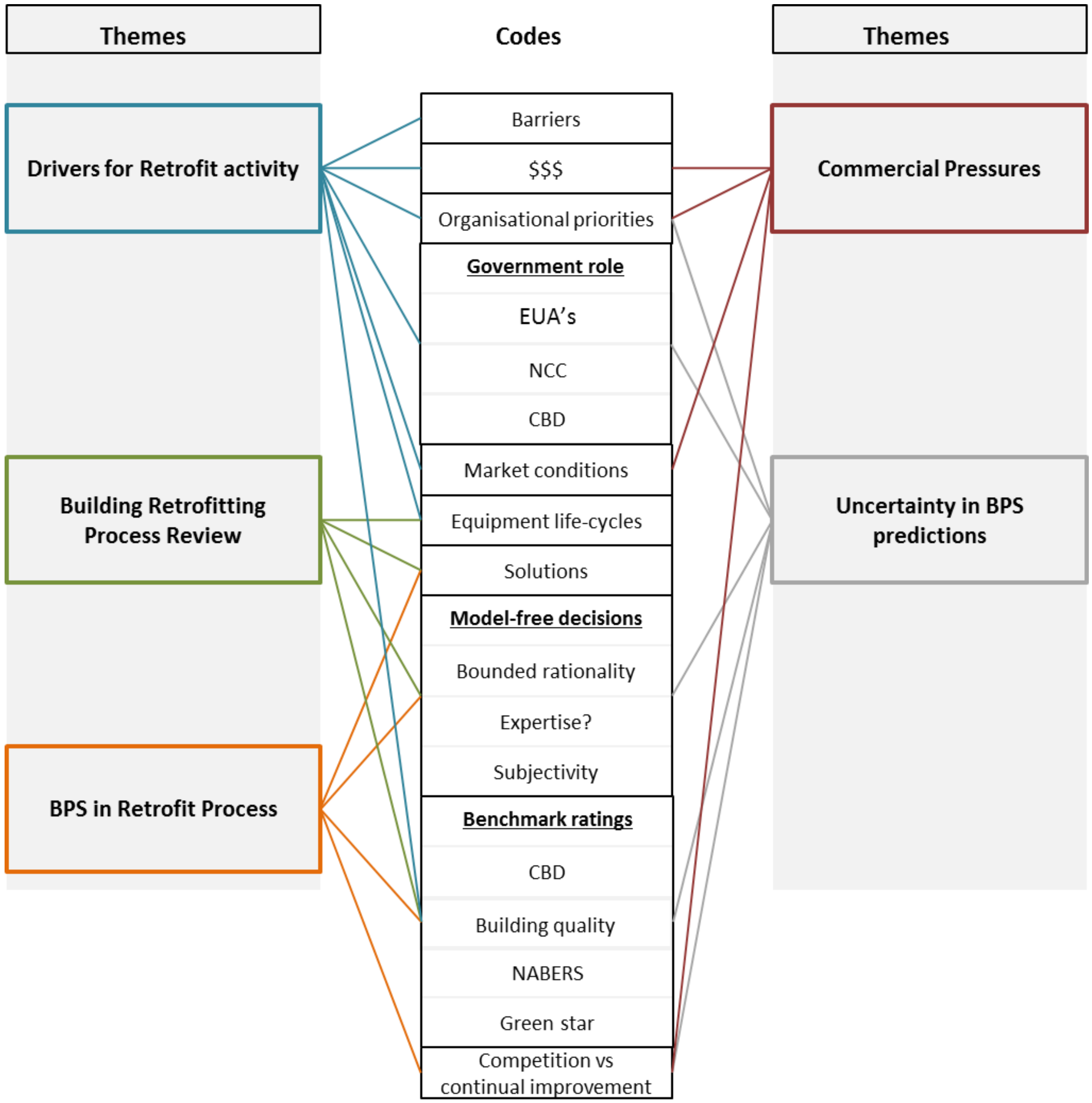


Figure 4-1 Thematic network which emerged as a result of multiple coding cycles of textual data from the expert interviews.

4.1.1 The Generic Building Energy Retrofitting Problem: a Process Review

Each interviewee was asked to explain their understanding of the building energy retrofitting process, from start to finish. The interviewer prompted the interviewee to cover issues regarding stakeholders, drivers and post retrofit involvement when appropriate. The responses were coded, as discussed in Section 3.9, and then compared to the 'Systematic Approach' to building energy retrofitting proposed by Ma *et al.* (2012) (also presented in Figure 2-5). The latter approach was

developed following an extensive literature review, and has been widely cited as a best-practice approach (Dall'O' & Sarto, 2013; Giancola *et al.*, 2014; Volvačiovas *et al.*, 2013). The figure presents a comprehensive method for 'proper selection and identification of the best retrofit options for existing buildings'. Several areas of discrepancy were identified between the Systematic Approach presented in Figure 2-5 and the interview responses.

There was strong agreement between the interviewed consultants regarding the typical process that is generally followed for a building energy retrofit project. Differences between views of individual consultants could be accounted for given the different business models of their companies, i.e. whether a company managed the practical implementation of retrofit works or simply provided the expertise to identify optimal upgrade strategies. The typical process distilled from the analysis of the interviews is shown in Figure 4-2. Note that many consultants pointed out that the process varied considerably depending on the specifics of the project. However, all respondents were able to describe what they described as a 'typical' retrofit process, which aligned closely with the process outlined in Figure 4.1, or with the major elements thereof.

There are several key differences between the systematic approach for best retrofit selection recommended by Ma *et al.* (2012), referred to from here as the 'Systematic Approach', and the 'Generic Process' identified during the interviews with stakeholders. These differences were both practices not included in the Systematic Approach, and some represented possible shortcomings in the actual practice in industry.

One aspect of the retrofit process that was not included in Systematic Approach of Ma *et al.* (2012) was a condition audit of the existing building and systems. A condition audit of the building systems includes identification of the current condition and expected remaining life of existing components, and nominates components that should be replaced as part of a comprehensive retrofit. Replacement of central plant, i.e. chillers and boilers, will often only be economically justified at the end-of-life of the existing plant. A systems condition report is also an effective method for developing a complete inventory of building equipment, and identification of energy-wasting faults and opportunities for improvements. Assessing a building's condition against the PCA Office Building Quality Matrix (see Section 2.10.3) may be important in the early stages of a retrofit project. Understanding the current quality and condition of a building allows the owner to make targeted improvements that will improve a building's quality rating. Office quality, as assessed by the PCA matrix has an influence on rental returns, capital valuation, and tenant attraction.

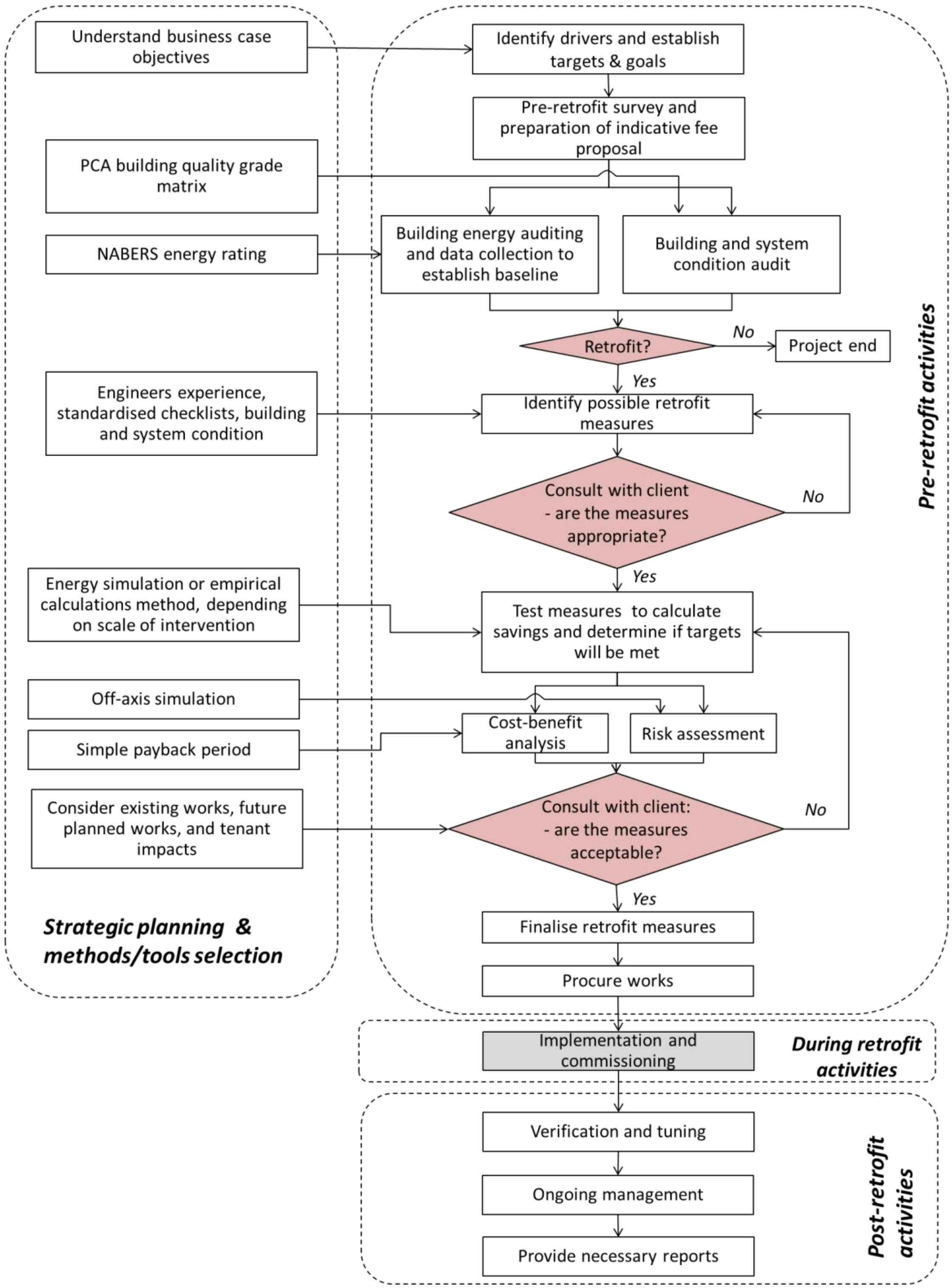


Figure 4-2 'Typical' process for building energy retrofits in Australia, developed from analysis of interviews with eight commercial retrofitting consultants.

The importance of regular client review during the development of retrofit options and the selection of the optimal retrofit strategy was highlighted repeatedly by many of the interviewees. Whilst the Systematic Approach incorporates client review at the beginning and end of the retrofit measure identification process, the interviewees' responses suggested greater client involvement is appropriate, for two reasons. Firstly, the client and building management team will generally have a deeper understanding of the building and systems than the consultant (including the manner in which the building is operated) and this is an important source of information when developing retrofit strategies. As stated by Consultant E:

> *It's really easy ... [to] ... come up with theoretical recommendations, which you then present to the owners, and ... their technicians or engineers ... and they'll just go, It's not going to work! Why have you put it here? Didn't you talk to the BMS consultant?... You look pretty stupid if you don't involve all the stakeholders.*

The second reason is that the retrofit process is not completely rational, and often the subjective views of the client may influence the particular retrofit strategies that they are prepared to consider. As identified by Consultant F, involving the client heavily in the decision making process is essential, 'so we don't spend a lot of time pursuing something that they're fundamentally uninterested in'.

Finally, the Systematic Approach suggests that the identification of possible retrofit options is informed by building-specific information and a database of building retrofit measures. The results from the present interviews analysis showed that the generation of possible strategies is grounded in the expert knowledge and experience of the consultant. For all consultants interviewed the identification of potential retrofit solutions for individual buildings was strongly influenced by their previous experience. A result of this reliance on expert knowledge was the recognition of the importance of multi-disciplinary teams by many respondents. This was seen as vital to avoid the situation of having a consultant who is limited by their previous experience, for instance 'who says, I know a bit about lighting; I know a lot about this so you'll get a lot of this and not very much lighting.'

A database, or checklist, was reported as being used by some of the interviewees, most often as a quality assurance check, to ensure that no important measures had been overlooked. As explained by Consultant C, one of the stages in the identification of retrofit measures for that company was 'using these checklists to make sure you haven't forgotten to pick up an item, which is an evolving

document that all of our … engineers contribute to.' The danger in relying on the checklist, without reference to the building characteristics was highlighted by Consultant F:

> *the problem [with relying on a standard list of measures] is people then start putting square pegs into round holes and going, Well, I'll put in a number three. Number three doesn't fit! So we prefer to have a more nuanced approach.*

Shortcomings of the retrofitting process as practiced in industry, identified through comparison with the Systematic Approach, included a simplistic approach to risk assessment, simplistic cost-benefit analysis, and a scarcity of post-occupancy evaluation studies. During the interviews these shortcomings were often identified by the consultants as representing a structural issue, i.e. the benefits of incorporating the additional assessments are known, but it is difficult to convince clients to incorporate them into the contract of engagement. For instance, when asked whether post-occupancy evaluation was common, Consultant C responded:

> *No, it's not common, in fact it's the exception. We always suggest it's a good idea to do it, but a lot of building owners are happy to effectively rely on the contractor and their obligations in the defects liability period to sort out any tuning and commissioning issues.*

Risk assessment in building energy retrofitting primarily relates to evaluation of the uncertainty in energy savings predictions. Ma *et al*. (2012) identified probability-based risk assessment methods as the most commonly employed in their reviewed literature. Risk assessment in the industry was generally limited to off-axis studies during building simulation. The consultants who discussed risk assessment raised it in the context of the NABERS energy modelling requirements for commitment agreements (NABERS, 2011). An off-axis study varying at least four factors is required for compliance with the NABERS program.

Similarly, cost-benefit analyses employed by the consultants interviewed in the present study were generally limited to simple payback period calculations. Cost-optimal retrofit selection can be impacted by the economic metric used, and more comprehensive methods than simple payback are recommended, as discussed previously in Section 2.6.4. This issue was also raised by Consultant C:

> *Some clients are also asking for ROI and NPV using discounting, so more whole life value analyses [than simple payback period]… but more often than not it's based on*

> *simple payback calculations, it does not take into account service life, repairs, maintenance. It's a pretty crude decision making criteria.*

A Revised Systematic Approach for sustainable building retrofits, built on the Systematic Approach of Ma *et al.* (2012) and incorporating the results and insights from the present interview analysis is presented in Figure 4-3.

4.1.2 Drivers for Retrofit Activity and Building Performance Simulation

A particular objective in conducting the interviews was to identify clearly the drivers of building retrofit activity in Australia, and the drivers for consultants to use Building Performance Simulation (BPS) in the process. Many drivers are contextual and the bulk of the interview data was related to New South Wales (NSW) and the Australian Capital Territory (Act) jurisdictions. However, the responses were generally nationally applicable in scope, as the experience of the consultants covered many of the national capital city markets.

Two related themes, market pressure and tenant expectations, were repeatedly identified by interviewees as drivers leading building owners to engage with ESD consultants. Fundamentally, financial considerations were the key driver for commercial building retrofit activity. However, financial considerations were mostly spoken of in the context of attracting and retaining tenants, rather than in terms of energy cost savings. This was a recognition that the primary business concern of a commercial building owner is generally to realize higher rental returns and increased capital value (IPD, 2010; Newell *et al.*, 2011). Consultant D considered the utility bill driver to be, 'not usually a great big driver, but often a driver', while Consultant G saw the role of tenant attraction as a major driver:

> *First and foremost, you've got to think, what's in it for the portfolio owners? And their business is to provide buildings for tenants. So, whatever the tenants are after, then they'll try and satisfy that, because that's their revenue stream at the end of the day, plain and simple.*

Government Administrator A concurred, and stated 'Where they [building owners] do invest, they tend to be investing in upgrades that attract tenants, so that's lighting, carpet, paint, fit-outs, and those sorts of things'.

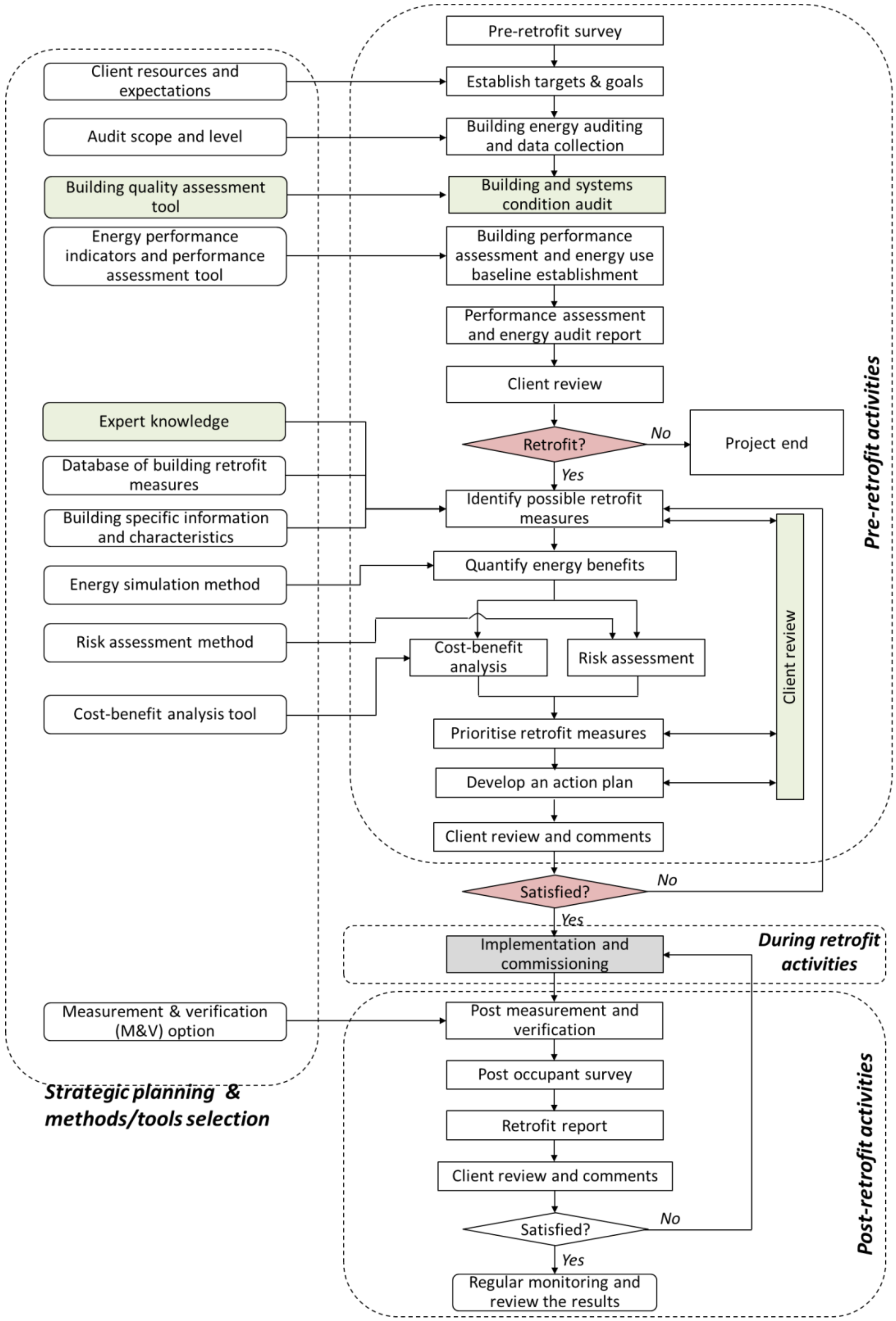


Figure 4-3 Revised Systematic Approach to sustainable building retrofits, incorporating insights from expert interviewees (changes compared to Fig. 4.1 highlighted in green boxes).

Numerous factors, both national and local in scope, create market pressure. Commercial Building Disclosure legislation is generally accepted to have created greater transparency in the industry across Australia, which in turn has provided incentives for owners of lower-performing buildings to upgrade. Similarly, expansion of the high quality building stock, for instance the forthcoming Barangaroo development (264 000 m^2 of prestige office space in development in Sydney for completion from 2015) in Sydney, creates improved market conditions for tenants, meaning building owners have to compete more strongly and improve their own offerings. In the context of this improved market for tenants, then tenant expectations become a prominent driver for building upgrades. Again, Consultant G:

> *We've gone from a world where buildings are built for profit …and tenants would come and fit in them ... to a world where buildings are being built for tenants. …to attract those tenants for a seven-year lease, you have to make your offer a bit more attractive. So I think that's driving it [building energy retrofitting activity] considerably.*

Tenant expectations relate to various building attributes; the most common attributes identified in the interviews were PCA quality and NABERS ratings. As identified previously, these two measures are somewhat intertwined as PCA A Grade requires a NABERS rating higher than 3.5 stars, and Premium Grade requires a rating higher than 4 stars. As Building Manager B related, for his project, 'The driver, was always NABERS. … everything we wanted to achieve through NABERS, it assisted us to achieve the A Grade rating we wanted.' Consultant C saw tenant expectations as common driver:

> *NABERS rating for marketability, particularly to either retain existing tenants, attract new tenants, or reposition the building as a PCA B or A Grade. The PCA guide to office building quality is another driver, connected to that trigger point of, I want to either keep my existing tenants or I've got a big vacancy and I want to attract new tenants.*

Several important intervention points were identified, where a building owner may enter discussions regarding a possible building upgrade. The trigger points identified in the previous quote from Consultant C correspond to a building owner activating a requirement to comply with mandatory disclosure legislation. That is, a building owner considering selling, or facing a vacancy in a leased space of greater than 2000 m^2. This was often raised as a reason for clients contacting

consultants. The requirement empowers the tenant, particularly those with minimum requirements for the environmental performance of spaces they will consider leasing, to drive building energy retrofitting activity. A building owner wanting to retain an existing tenant may also be compelled to upgrade, without necessarily triggering mandatory disclosure requirements, for instance in negotiations to retain an existing tenant, or to attract a tenant to lease an area below the area threshold. Consultant E stated:

> *Now … that the CBD [Commercial Building Disclosure] scheme is in place there's transparency to show that those buildings aren't performing as they should, and if you want to … attract a large tenant … if it's anything like an international company, they're going to have corporate social responsibility, and … they will have a minimum requirement [of environmental performance before they will consider leasing a space]*

Major equipment failures, or equipment reaching expected end-of-life, were repeatedly raised as a point where broader retrofit strategies could be discussed. In this scenario a building services consultant might suggest that the replacement of a major piece of equipment should be a part of a broader upgrade strategy, and advise the owner to engage an ESD consultant. It is likely that contextual issues make this particularly important. The average age of buildings in the capital cities is approaching 30 years (Adelaide City Council & JLL, 2007), which is significantly beyond the expected lifetime of chillers and many cooling towers (generally assumed to be 20 to 25 years (ASHRAE, 2011):

> *We're seeing a lot of chiller upgrades go through because … chillers have a twenty-year lifespan, so all the buildings that went through the big building booms through the eighties and nineties have got dead and dying chillers and are wildly due for an upgrade, so we can replace them with a more efficient chiller. The average efficiency of chillers has improved 35% in the last twenty years, so it's a no brainer.*

Internal changes to the building, or organisation, were another driver for consideration during building upgrades. One consultant saw this as particularly relevant in the public sector, where departmental amalgamations and changes to staff numbers were seen as more common. Proposed changes to occupancy profiles, staffing levels, or how an occupant wishes to use the space (e.g. Activity Based Working) were all identified as possible trigger points. Another key organisational change was in ownership strategy; if an organisational building owner decides to sell and become a tenant, for example. This trigger point can be highly contextual and specific to each case. It serves

to highlight the importance of subjective factors, and the complexity inherent in the building retrofit decision making process.

A final driver, which does not receive much attention in the literature, is the role of human subjectivity in driving priorities in decision making. The decision to upgrade a building is generally not entirely rational, as there are numerous restrictions on the ability to make rational decisions, such as information availability, time restrictions etc. The decision makers are also affected by personal values and priorities. As Consultant D observed, 'the drivers of … [building energy retrofitting activity are] far more related to people who are passionate about a building [than economic drivers]'. One consultant saw the industry as currently reliant on 'educated, interested, enlightened' clients driving improvement works. This human influence is very difficult to characterise, but it is an important fact or to be aware of. Consultant D stated:

> *Sometimes a person's wife works in the building, and they think it should be nicer. So, usually the decision to retrofit is … subjective rather than objective. It's nowhere near as objective as you'd like it to be.*

Representative quotes related to the key drivers for building energy retrofits, according to the interviewed stakeholders are given in Table 4-1.

Table 4-1 Various stakeholder views on key drivers for energy efficiency retrofitting.

	Example quotes
Consultants	*…It's driven by regulation or … market forces. Nowadays it's about … CBD [Commercial Building Disclosure] exposure [and] transparency in the industry which is driving it.* *…a lot of building energy retrofits are driven by the NABERS energy rating, and also I think just by cost savings.* *…CBD [Commercial Building Disclosure] definitely has been our business driver.*
Building Owners	*We started... looking at building life cycle upgrades, when the original intent was just to replace our major capital equipment... discussions about this building came up about future strategy, which hence then halted the project, changed the focus to a longer-term strategy, which was focused on NABERS.... So, NABERS became the driver... the strategy changed again for us, where we began discussions about the sale of the building... It was sold with conditions that we would refurbish the whole building and bring the building up to an A-grade, 5 star NABERS building,*
Government Administrator	*… it would be brought to [the Building Owners] attention that there were problems with [a building], or there were inefficiencies with it, or there were things they could save, or that they could improve the building and improve its yield, or its value, and that may be before they sell it, or if they're looking for tenants, or for a range of reasons.*

4.1.3 The Role of Building Performance Simulation in Retrofit Optimisation

Many of the interviews included a focus on how the interviewees used BPS in the retrofitting process. Two tiers of processes were identified in relation to the targets/objectives of the building owners. For building owners with lower targets, decisions would generally be made on the recommendations of a Level 2 audit, for owners with higher aspirations a Level 3 audit and BPS would be used.

For less ambitious projects, particularly projects that did not involve major systems replacements, often BPS was reported as not being employed. Interviewees felt that consultants then used model-free analysis or relied on 'empirical models' consisting of previously collected benchmark data to determine indicative savings likely to accrue from particular retrofits proposed. For buildings targeting a typical level of energy efficiency improvement, Consultant C relied upon 'hand calculations on a system-by-system basis'. These less extensive upgrades often will not economically justify the effectively fixed cost of a BPS exercise ($15 000 to $20 000, according to Consultant C). One consultant identified the initial cost of the energy audit as a common barrier to clients. Engaging a consultant to undertake both an energy audit and BPS exercise effectively doubles this cost barrier. Therefore, a prerequisite for BPS to be a part of the retrofit decision process is 'a dead serious client who knows that they're going to be spending a million dollars'.

There was a high level of confidence amongst the consultants interviewed that certain technologies will reliably achieve a moderate improvement in energy efficiency. For these technologies, most consultants recognised that BPS was not essential and that the energy saving opportunities can be assessed with a sufficient level of accuracy with a Level 2 energy audit. Upgrading lighting systems from T8 to T5, or to LEDs, installing Variable Speed Drives (VSDs) to fans and motors, and end-of-life chiller upgrades, to magnetic bearing chillers for example, were repeatedly identified as 'easy wins'. This is consistent with the findings from the analysis of the Energy Saver Audits described in Section 4.2.3. For Consultant C:

> *First and foremost, you look at those easy wins. Can you just do a lighting upgrade, for example? Are there VSD's on the fans that you can put in really quickly and simply? It doesn't disrupt* [the tenants] *much.*

Only one consultant raised non-technical retrofits, e.g. behavioural change campaigns and organisational changes. Quite possibly this is due to the business model of the companies the

consultants worked, which were all engineering consultancies, not organisations focussed on change management. However, non-technical changes can have significant impacts for low cost. Consultant D saw organisational changes as the first to consider:

> *If I have an R-value for this wall, and I improve it to X, then this should have this impact. But at the same time you might think, well, if I move those persons from that side of the building to the other perimeter that will have the same impact and cost nothing.*

For projects of sufficient scale to facilitate a BPS, there were several drivers for the use of simulation. These were seen to fall into three categories: compliance simulation, ‘proving-up’, and design/optimisation. Compliance incorporates BPS undertaken specifically to satisfy the requirements of a program or legislation, e.g. a NABERS Commitment Agreement, Section J Alternative Verification, or a Green Star rating. This type of simulation was mentioned by most consultants (though not generally discussed in detail). Consultants A and B, from the same company, stated that compliance was the major driver for BPS. It is likely that this is related strongly to the consultancy’s business model.

The second category of simulation was that for the purpose of ‘proving up’, where the simulation is undertaken to ‘prove’ that a particular upgrade strategy will result in a specific target being achieved. In many cases the target would have been achieving accreditation in one or more of the compliance schemes, for instance achieving a 5 Star NABERS rating. Another target of a proving-up strategy may have been sizing photovoltaic arrays to achieve net-zero energy. The crucial distinction between this type of simulation and simulation for design or optimisation is that the retrofit strategy has been decided, and BPS was used to ensure that the strategy would achieve the targets. ‘The tool validates your answer, and … proves up the strategy that you’re putting forward.’

Use of BPS as a design tool to compare different retrofit strategies was identified by several consultants, although Consultant D was the only participant for whom it was the main driver for simulation. For him ‘the main driver [for undertaking BPS] is discovering for ourselves what is the right thing to do’. This is in contrast to Consultant F, who had, ‘made most of the decisions by the time we’re doing the modelling, and the question is really, so we do all this stuff do we get to where we want to be?’ Although he saw ‘analytical enquiry rather than doing things by gut feel is becoming more prevalent.’

Consultant F described a further category of simulation; the use of reference building models to generate approximations of energy savings for interventions in smaller scale engagements where the fee would not support a full-scale model. He explains:

> *The value of simulation becomes in generating rules of thumb, or indeed in testing a specific proposition in a generic model, so…OK, are we going to, you know, fiddle around with the dead-bands? What sort of saving are we going to get from that? I'll just run it through the model. A generic modelling, not linked to that site, put it in and you go, 'Well, in Brisbane it seems to be a two percent effect. Ok, I'll allow for two percent in my model.' And that's quite cost-effective.*

Representative quotes related to the roles that BPS can play in an energy efficient retrofit, identified in the current analysis are given in Table 4-2.

Table 4-2 Indicative views on the role of BPS in energy efficiency retrofitting.

	Example quote
Compliance	*I've done a number of different models... covering 3 different applications mainly, these being NABERS prediction models, JV3 alt sols for BCA compliance, and Green star modelling under the various different tools and their guidelines.*
'Proving up'	*Most of the time it's about proving up something or other. Proving up a NABERS rating, or proving up a retrofit. It's rarely used directly as an inquisitive model. Generally we've made most of the decisions by the time we're doing the modelling, and the question is really, so we do all this stuff. Do we get to where we want to be?*
Retrofit design	*… you might be able to submit it for Green Star, or predict a NABERS result, or submit a Section J report. They're sort of by-products of wanting to... model the building. … so, use it as a design tool rather than a compliance tool.* *…it's still in a way a design tool. What we'd be able to with that energy modelling is, you know, compare two different options, for example, and as a result of those comparisons be able to show the client which one of them, for the costs, is going to get them a bigger bang for buck.*

4.1.4 Input Uncertainty in Building Performance Simulation

In analysing discussions on the information consultants use as inputs to BPS models, two themes emerged which help us understand the uncertainty in BPS. They were: i) the depth of investigations into building and systems undertaken by the consultant, and ii) the use and source of assumptions for unknown inputs. There were notable contrasts between the various consultants, largely due to the particular business models of the consultants' companies.

The availability of building information, and the depth of investigation required to access accurate information were two issues repeatedly identified, which influence the input uncertainty for BPS. These issues are tied closely with the use of assumptions, as the effort required to get data that may not be readily accessible necessitates the use of the assumptions. The issue, as seen by Consultant B, is:

> *The information on older building stock is not there, so you end up basing your model on so many assumptions that whatever results you get at the end are not results you can hang your hat on.*

One particular problem for older buildings is the lack of as-built documentation, or the documentation not reflecting the reality of the physical building. For Consultant A this was 'the biggest issue we come up against time and time again'. Consultant E, whose primary business was energy auditing, went into some detail about the effort required and methods used to get accurate information. For one project:

> *I had to dig through all the old specifications, get all the old original drawings, and then the modifications, which had taken place about twenty years ago because I think it was built in the sixties. I had to understand all those different aspects, and then it was through a conversation with some of the, not the original guys that built it, but some people who had been involved in a number of the different upgrades which had taken place. And so by pulling all that knowledge together, and also by visually inspecting different parts of the building, that's how I came up with the strategy of being able to [implement a specific upgrade].'*

He stressed the importance of talking to all key stakeholders to get the information within the time constraints imposed by the budget: 'You have to at least try to talk to everybody, because you find that stuff that you just never would have otherwise, unless you're hanging out there for a week non-stop.' This approach contrasts with the views of Consultant H (an energy performance contracting specialist) who believed: 'You really can't rely on information given at interviews. To find out what's really going on, you've got to get some hard data.'

The problem for many consultants, related to the issues discussed in Section 4.1.1, is it is difficult to get a client to pay for the collection of detailed performance data. Collection of data can also be disruptive to the operation of the building, particularly for tenancy-related information: 'It's very

difficult to get the data, because it's very…you know, it interferes with the operation of the tenant. They don't really want you there.'

This necessitates the use of assumptions, and therefore has an impact on the accuracy of the simulation predictions. A contrast exists between the typical case, where a consultancy budget will allow a short period of time on-site, and the procedure of the consultant offering guaranteed energy savings in the form of an Energy Performance Contract. It was not unusual for Consultant H's team to spend 'a week on site, and then … a couple of months back in the office doing the energy modelling… and so forth.' During the time on-site they would collect a large amount of data:

> *We might even put data logging on certain switchboards, mechanical boards, electrical boards, to get a good profile of the building, and we would put some intermittent loggers on. We might do some spot metering to determine what the loads are here and there within the building.*

and:

> *we've done jobs where we've put steam meters on, we've put water meters on, we've put clip-on current transformers, data loggers, and so forth; we've got read-outs from the building management system on energy usage throughout the facility*

and,

> *we'll look at out of hours usage, we'll look at when the mechanical plant starts up, shuts down, tenancies – when people come in, when the lights are turned off.*

This extra 'hard data' is essential for a business guaranteeing predicted savings as part of a contractual agreement, and this difference in approach is strongly related to the theme of commercial pressures, and the magnitude of projects.

Given the difficulty in accessing accurate information, the interviews investigated how the consultants dealt with uncertain inputs, generally for tenancy and occupancy loads. This was often related to the drivers for simulations to be completed. For compliance simulations assumed input values were generally driven by the requirements of the scheme, for instance, the use of 'the NABERS default profiles for lighting and computers left on'. For many consultants the NABERS defaults were commonly used for non-compliance simulation to represent unknown tenancies in a base building model. Consultant F did not view this as an issue: 'The NABERS defaults are mildly pessimistic about operating patterns, so they're not a bad sort of position, given that you're trying to prove up a base building performance.'

When simulating tenancies for whole building or tenancy assessments, the issue becomes more important, Consultant F saw it as ‘a real problem in the tenancy area, because basically you could derive a result from your assumptions.’ Lack of accurate data, and the disruptive nature of gaining information about tenant behaviours meant ‘the detail [regarding tenant behaviour in BPS]… it’s a lot of assumptions, because we’ve got absolutely no … idea at all.’ Consultant G explained how he attempted to calibrate the NABERS protocol defaults for uncertain inputs to the particular building:

> *So you have to assess, basically, on where the building is at the time. What type is it? Is it a building full of small tenants, or is it a building with a couple of large tenants on board? And then make an assumption based on that.*

An issue with the widespread use of these simple protocols, to represent an input, which can ‘vary wildly’, was recognised by Consultant D:

> *[NABERS and similar assumption sources] are fairly well-accepted across the board, and usually when models get peer-reviewed, they always ask those questions. You can say, ‘Well, model it to the NABERS protocol.’ Not necessarily assuming that that is correct, but it is an industry standard*

Universally, the consultants disclosed and discussed the assumption used in the BPS in their dealings with the client. The reason given for this was most often legal protection rather to improve the accuracy of assumption. Many respondents identified the client reaction as a variation on ‘you’re the professional, just give us the answer’. This response from the client is reasonable, but it relates to another issue identified by many of the respondents, the difficulty in distinguishing between high and low quality consultancies in the BPS field. Essentially a client is relying on a consultant to make reasonable assumptions about a building, in a situation where it is very difficult to differentiate between consultants. Consultant D related a situation where:

> *a client actually appointed two engineers to model the same building, and they had quite different results, even with very similar outputs [sic], and they engaged in a battle over it. And the main outcome of that was, the client couldn’t necessarily decide who was high or low quality*

When asked about the task of selecting between competing consultancies, Building Manager A stated ‘that’s always a lottery’. He relied on advice from others who had worked previously with the company. Building manager B selecting the consultant based on a pre-existing relationship. It is

difficult even for a professional in the field to differentiate between models. Consultant D, speaking about modelling large scale commercial buildings, said:

> *I think a lot of people just model things in all kinds of different ways, because there is nothing to compare them against, and there is nothing to pull them up on, and you can't actually prove if it was right or wrong anyway, a lot of the time.*

The comparison between 'gut-feel' decisions rooted in experience and expert knowledge, and 'more analytical enquiry' or model-based decision making is an important issue for BPS users. Understanding building systems and operations is a complex task that requires training and experience, as does representing buildings systems and operations correctly in BPS. It is difficult for consultants to balance these competing needs for employee training and development in a commercial environment. Consultant F talked at length about the issue:

> *The logical thing with a simulation that burns up a lot of hours, is that people [senior managers] put relatively inexperienced people onto doing simulations, which are now requiring increasingly complex understandings of buildings… I quality-assure the work that [the inexperienced simulation user] does, and check it and that sort of stuff, but because he spends so much time behind a computer, he has by far less practical experience looking at real buildings and how real things work than, you know, our general engineering staff. But then, our general engineering staff wouldn't know what to do with a simulation if it ran them over in the middle of the road.*

This practice could reasonably be expected to lead to uncertainty in the simulation outcomes due to modeller error, particularly in data interpretation and use of appropriate heuristics and assumptions. The converse situation was also identified, where the simulation user may pre-empt the result of the simulation to match their expectation. As identified previously, simulation is often used to prove-up a previously designed retrofit solution, and if the results are not as expected by an experienced consultant, there is a temptation to force the model to match expected outcomes. This was an issue identified by Consultant D:

> *The risk is – and this happens often – that you end up playing with it [the model] until you get the answer you expect it should be, and that's the opposite of what modelling should be.*

The usefulness of BPS is closely related to understanding the uncertainty of inputs and predictions. There was a strong contrast between Consultant D and Consultant H's comments on the utility of BPS. This is likely due to the business models, as Consultant H, who offers EPC's, is able to spend more time in data gathering. Consultant D stated:

> *When do people start modelling buildings these days? It's usually large scale commercial, and it's so complicated it's barely worth even guessing. You might as well just use a benchmark.*

Consultant H however, talked of confidence in the results from BPS:

> *We've been doing performance contracting for a long time, and part of the performance guarantee is, if you're not making the savings and you have to pay the contractor the shortfall, so far we've been…our calculations have been accurate enough that we haven't had to make any pay-back to the client, so in answer to your question, yes, we are very confident in our calculations, because it is backed with a lot of hard data.*

Table 4-3 Indicative quotes related to key sources of uncertainty identified by interviewed stakeholders.

	Example quotes
Poor documentation	*The biggest issue we come up against time and time again is the lack of documentation in old buildings*
Cost of simulation and investigation	*…the challenge with simulation is, it's [BPS] a pretty expensive exercise to undertake, so there was no way… we were ever going to engage anybody to be able to do that, so that's where you run into the challenge.*
Commercial pressures	*…fundamentally, doing a decent simulation costs a decent amount of money, and that limits its application.*
Reliance on protocol assumptions	*You can ... model it to the NABERS protocol. Not necessarily assuming that that is correct, but it is an industry standard*
Tuning to expectations	*…this happens often – that you end up playing with it [the model] until you get the answer you expect it should be …*
Building complexity	*…it's so complicated it's barely worth even guessing. You might as well just use a benchmark.*
Lack of benchmarking data	*…there is nothing to compare them against, and there is nothing to pull them up on, and you can't actually prove if it was right or wrong anyway, a lot of the time.*

4.1.5 Commercial Pressures in Building Performance Simulation

The previous section relates to a separate theme which emerged during coding of the interviews; the effect of commercial pressures on simulation accuracy. In many cases the respondents were aware that certain aspects in their retrofit decision making process may not be optimal, but felt constrained by the needs of running a viable business. This issue surfaced during the interviews in many ways.

Whilst recognising that it is logical to use junior staff for simulation (a practise he employed), Consultant F recognised:

> *There will always be some really bad simulations out there, because we still have a situation where somebody's first simulation is presented as a commercial deliverable, and that's going to be a problem.*

For other respondents the issue was discussed in terms of not being able to get the client to pay for work they saw as desirable. Consultant G saw the need to rationalize the investigative stage of the process to minimise costs:

> *The trouble with the industry at the moment is that there's not that much money in it, and timeframes for most of these projects are so short that most people don't have the luxury of trying to run a myriad of options, as is what should really be done in half of these projects. It's cut to the chase and get on designing with a very low fee.*

Similarly, Consultant E described a complex upgrade project for which BPS may have been beneficial but was not employed:

> *…a simulation would be really helpful, but the challenge with simulation is, it's a pretty expensive exercise to undertake, so there was no way, within the constraints of our budget, that we were ever going to engage anybody to be able to do that*

Consultant C expressed frustration at what he saw as unfair financial criteria being applied to energy efficiency measures by clients, restricting the scope of projects. He explained:

> *No building owner ever asks what the payback is on a bathroom refit. They're going to get marble bench tops and top-of-the-line fixtures and fittings, and they want it because it's good quality, and there's an element of prestige … It's almost an unfair evaluation criteria applied only to energy upgrades, whereas a lot of other things are just done for prestige, marketability.*

The potential for continuing improvement was also somewhat hindered by commercial realities, particularly competitiveness. Peer-review of building models was identified as a useful learning process for several consultants. Peer-review of building energy models may be included as a contractual requirement by a client, and involves a second, independent consultant reviewing the modelling approach used to represent a particular building, including any assumptions and their justifications. This was discussed in detail with Consultant D, who saw the many potential gains to be made through increased collaboration. Commercial consideration created some barriers to this though. He explained: ‘the hard part is, obviously, a lot of the people available for peer-review are in competitive organisations – so, not such a straightforward thing.’ He continued:

> *It's hard, though, because there's some people you can't work with very easily because they don't want to give up their models. Understandably, because a lot of them are full of little short-cuts that they had to take or whatever, and they don't want to be pulled up on it*

A summary of the key sources of uncertainty in BPS, as revealed through textual analysis of the interview transcripts, is shown in Table 4-3.

4.1.6 Environmental Upgrade Agreements

The take–up of EUA's has been slow, as discussed in Section 2.10. Those interviewees who had experience or views about the program were asked about them. Two EUA specialists were also interviewed, and there are some areas of contrast between their views. The issue of how uncertainty in predictions of savings is dealt with in an EUA is also explored here, via a comparison with the EPC process.

The EUA program in Australia is designed to stimulate retrofit activity in the Secondary Grade buildings sector, yet EUAs have not gained a great deal of traction to date. Consultant G put forward one reason why EUA's have not been embraced, particularly by institutional building owners:

> *all the big guys have looked at it, and it's all just too hard. From a contractual perspective more than anything else for them, for the small amount of money that they get, the amount of hoops they need to leap through, they can effectively secure their own finance for a lot less hassle. That's the sort of general message from the big guys.*

Similarly, Consultant C spoke of a perception of EUA's as a 'cheap loan':

> *EUA's haven't really got a lot of take-up. It's a cheap loan, that's all it is. Most building owners aren't short of capital, they're just reluctant to waste money. So a cheap loan is not really that useful.*

Government Administrator A recognised this perception, but did not agree with the assessment, stating:

> *... [an EUA is] not that much more difficult [than a standard upgrade], and then ... you're able to tap into the benefits of an EUA, specifically longer-term finance and tenant contributions.*

As identified in Section 2.10.5, to date it has universally been institutional owners who have engaged in EUA's. One possible explanation as to why those institutional owners who have taken up EUA's have done so, may be the reputational aspect, that is, the positive publicity associated with a well publicised innovative environmental financing model. Consultant D thought 'the EUA sort of model works more so from a reputational perspective.'

Engaging the Secondary Grade building sector is particularly challenging, due to the nature of the building ownership. Consultant G noted the difficulties in accessing the Secondary Grade buildings sector, from his experience:

> *Trying to find people who were interested in doing it [building retrofits] – all those grade 3, grade 2[sic] building owners most of the time they're not aware of these schemes because of a lack of resources. They don't really understand enough, or are happy with the buildings they've got because they're fully tenanted.*

This issue was well understood by the government administrators, indeed the EUA is an attempt to access that market. Government administrator B recognised the potential for major energy savings in this sector of the market by getting the owners to 'run your building properly … and then when your major plant equipment fails, make sure you think of this stuff [energy efficient upgrades].' However the difficulties identified by Consultant G were also echoed by Administrator B:

> *We're talking more small family trusts that don't have the property efficiency knowledge around them, and much of the available information is targeted to ... whether you've got a NABERS rating. And we're talking about 91% of these buildings*

> *not having a NABERS rating, so they don't fall within that regulatory trigger [Commercial Building Disclosure]*

Getting the information to the building owners is a challenge, as often the traditional structures that deal with this are not in place. Administrator B again:

> *[You have to go] through their intermediaries. Property managers. Mechanical contractors. For some [building owners], they don't have a property management company, so it's the mechanical guys that come out and service the plant and equipment.*

The human element in decision making is also much more prevalent in this building sector, another challenge recognised by Administrator B:

> *…how they make decisions is much more different. And the time frames. Upgrades to properties owned by a small property trusts can take a fairly long time. If you're a small family trust…this can be even longer. Life and other commitments often get in the way.*

Whilst recognising these issues, Government Administrator A thought the program would be a long-term solution:

> *I think people are sitting on the fence to see just how they work and how easy they are to do.... It's new, and with more examples, and people seeing the outcomes of them, it will become much more of a standard-type finance.*

The uncertainty associated with predictions of the potential energy savings from an upgrade project is important in an EUA project. For an EUA without an EPC, there is an amount of risk and uncertainty due to the fact that a tenant's contribution must not exceed a 'reasonable estimate' of cost savings to tenants (NSW Gov., 2010). The decision of whether upgrading a building financed with an EUA that incorporates expected tenant contributions is financially attractive must be made on predicted savings; and there is significant evidence of a 'performance gap' between predicted and actual savings, as discussed in Section 2.6. An EUA ties a potentially significant financial risk to this uncertainty in savings predictions. For the 'simple wins' retrofits, there is confidence that savings will be made. However, for deep or complex retrofits involving changes to building fabric, HVAC and controls, there is less confidence in the accuracy of predicted energy savings from BPS.

Changing occupant behaviour, building operation, or poor quality installation or commissioning of new technologies can all render predictions from a simulation inaccurate. As Consultant D noted:

> *Often the conditions that you expected the building to have are never really as when you model them. Like, the number of people using the space, for example, or how the people use the space. And then obviously all the variables of whether or not the model was right in the first place.*

Consultant E, who was involved in an EUA which involved tenant contributions discussed the complexity of:

> *How you go about determining that [predicted savings] in an appropriate way, because there are so many variables depending upon the historical situation versus what happened in the year.*

This issue is also present in an EUA with an EPC, however, the risk is clearly apportioned to the EPC provider who is also responsible for providing the prediction. As shown from the interview with Consultant H, the data collection and modelling effort involved in an EPC project is much greater than that for a regular energy simulation engagement. In an EPC there is an ongoing contractual obligation for the building owner to notify the guarantor of any major changes to building operations, so the baseline model can be updated and new saving calculated. Consultant H explains:

> *We set a baseline to start off with, and everything is measured against that baseline, so when we do an annual report, it's measured against that initial baseline. Now, if things have changed we have to modify that baseline… they need to let us know [of any major changes to the building operations] so that we can modify the baseline accordingly. …It is an obligation under the contract for the client to notify us of any major changes.*

In an EPC case the consultant has an interest in maintaining accurate baselines and estimates, as they are guaranteeing the savings. In an EUA, there is no clear mechanism for updating the baseline, and the consultant who provides the initial predictions will not necessarily be involved in maintaining the baseline and up-to-date annual savings predictions. Government administrator B outlined the reconciliation process:

> *The main follow-up mechanism is provision of an annual report, but the current format of that annual report groups savings [total actual energy savings]. What was your*

estimate? What was your actual … and there's no real compliance pathway after that, other than the responsibility agreed to by the building owner in signing the EUA to amend the estimation if it becomes no longer reasonable. So the onus is on the building owner to do that and from what I have been told by owners is that this will form a part of the existing outgoings reconciliation process.

The inaccuracy in predictions from BPS is well understood in the building simulation community; these new initiatives tie potentially significant financial risk to results generated based on these assumptions.

4.2 Statistical Analysis of Building and Energy Databases

As part of the characterisation of the Australian retrofitting industry in this research project, substantial effort was spent on identification of possible data sources to improve understanding of the energy performance of Australian commercial office building stock, particularly the Secondary Grade stock. This section presents the analysis of three databases sourced by the present author, and provides insights into the current state of the Australian building energy retrofitting industry. Whilst the databases analysed had significant limitations, they were among the best accessible at the time of writing. A discussion is included in Section 4.2.4 of other existing data that was not accessible to this study.

4.2.1 Australian Building Energy-Efficiency Register (BEER)

The Building Energy-Efficiency Register (BEER) (CBD, 2013) is a compilation of BEECs published under the Australian Commonwealth Government's Commercial Building Disclosure Program, introduced in Section 2.10.2. The Commercial Building Disclosure program mandates the disclosure of energy efficiency information of a building whenever more than 2,000 m^2 NLA of office space is advertised for sale or lease. The BEER database includes a NABERS energy rating for each building, a tenancy lighting assessment, and general guidelines for energy efficiency improvements. The tenancy lighting assessment information included in the database was collected by certified Commercial Building Disclosure assessors (who also must be accredited NABERS assessor). Lighting information was collected for every tenancy or every floor (whichever was smaller) in a building. The lighting assessed does not include supplementary tenancy lighting, e.g. feature or task lighting. The nominal lighting power density was calculated based on; nominal lamp power, ballast and transformer, number of lamps per luminaire, and an estimate of the number of

luminaires in the space. An assessment was made of the lighting control capacity, and generic guidance on potential energy efficiency improvements for building owners or building tenants was also shown on a BEEC.

The present author analysed the BEER to determine national and state average energy consumption, average energy intensity, and average Nominal Lighting Power Density (NLPD). Firstly, data was filtered to identify unique building references and unique certificate references. Buildings often had multiple references as the lighting assessment was included for each functional space in the building, and many buildings had multiple certificates for different years. The most recent records for a building were retained, even if the certificate had expired. To determine average NLPD, the data was processed to remove records flagged as ‘space not assessable’.

At the time of writing the BEER contained 52,593 records, for 1278 unique buildings across Australia. The records were primarily located in and around the capital cities, as shown in Figure 4-4. The population was a statistically representative population, calculated with the finite population size of commercial office buildings estimated in pitt&sherry (pitt&sherry, 2012b). The energy consumption data was statistically representative at the 95% confidence interval based on the sample standard deviation.

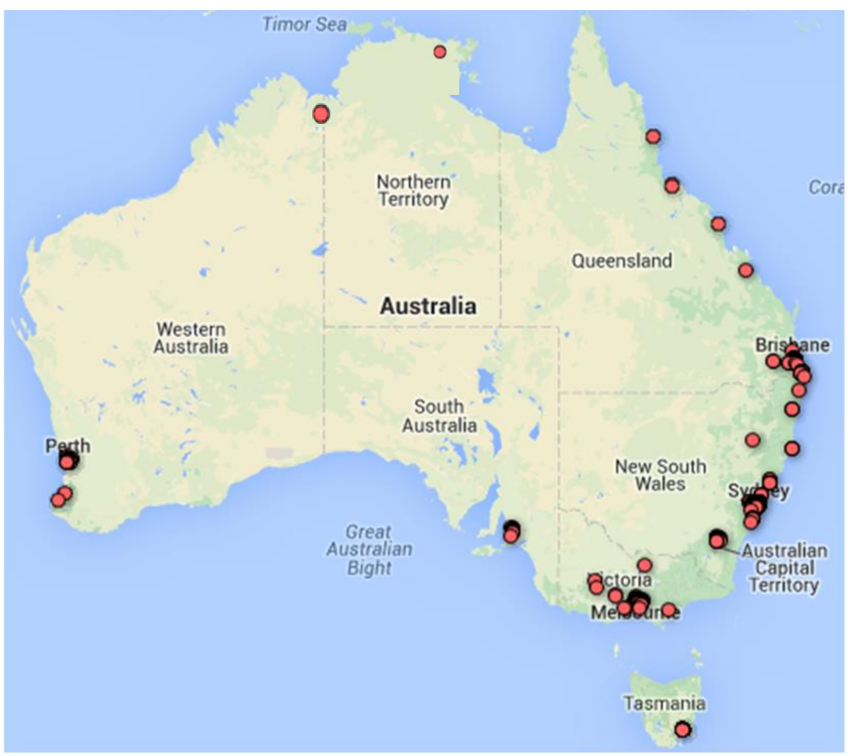


Figure 4-4 Location of unique Building Energy Efficiency Certificates

The buildings had an average NLA of 11,169 m^2 (SD = 11,158). There were records for 3190 individual certificates, 927 of the records related to valid certificates (certificates are generally valid for one year). Of the valid records 754 were for NABERS base building (central services) ratings, and 174 for NABERS whole building ratings. The average base building NABERS rating was 3.59 Stars, the average whole building NABERS rating was 2.77 stars. The NABERS ratings from the certificates are shown in Table 4-4. The trend of improving NABERS ratings was similar to that shown in Figure 2-13 from IPD office market analysis. The calculated values were slightly lower. This was as expected, as NABERS ratings undertaken not as a requirement of mandatory disclosure were likely to be for higher performing buildings.

Table 4-4 Average NABERS ratings of BEEC showing changes over time.

Time period	All records	All records (area weighted)	Base Building	Whole Building
Year to July 2014	3.44	3.94	3.59	2.77
Year to July 2013	3.37	3.91	3.54	2.59
Year to July 2012	3.12	3.62	3.20	2.75
Year to July 2011	2.90	3.46	3.11	1.94

The calculated average national and state energy consumptions are shown for base buildings and whole buildings in Figure 4-5 and Figure 4-6, respectively. The national average whole building consumption was found to be 1063.3 MJ/m^2. The calculated values agree closely with the national averages calculated by pitt&sherry (pitt&sherry, 2012a). Significant differences in base-building energy consumption at the 95% confidence interval were identified only between NSW and Victoria, Victoria and Western Australia, and Queensland and Western Australia.

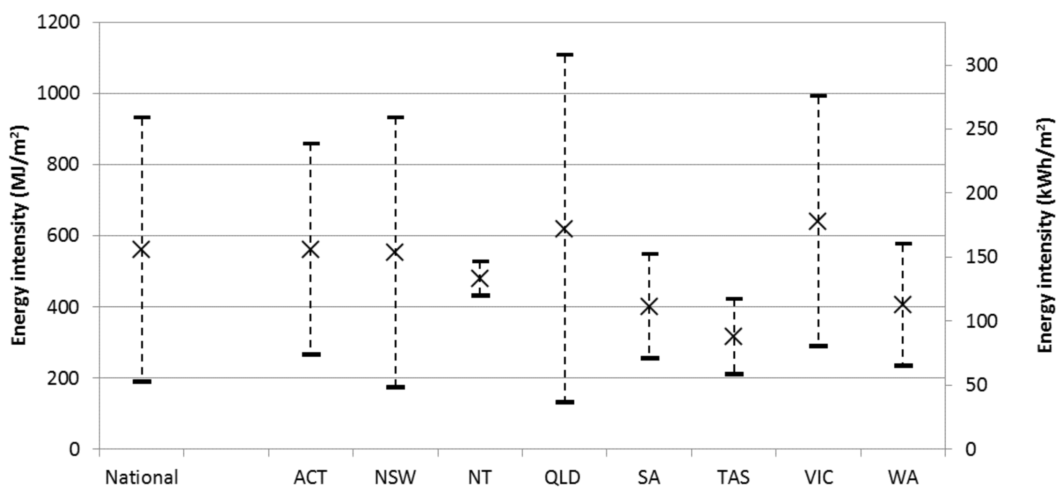


Figure 4-5 Average state and national base building energy consumption calculated from most recent BEEC for all unique building records. Note: the database contained only 2 records for Tasmania, and 6 records for NT.

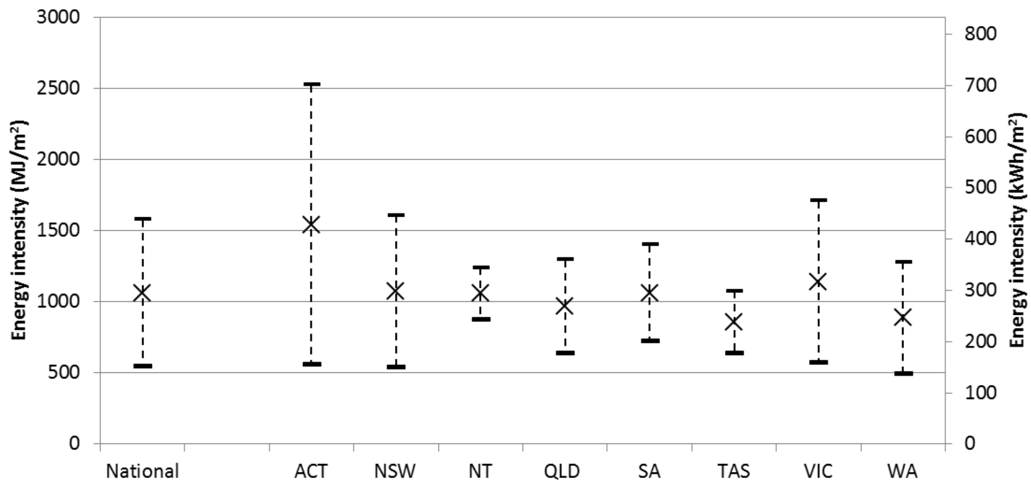


Figure 4-6 Average state and national whole building energy consumption calculated from most recent BEEC for all unique building records. Note: the database contained only 2 records for the NT, 10 records for Tasmania, and 11 records for the ACT.

Table 4-5 Mean Nominal Lighting Power Densities from the present analysis of the Australian Building Energy-Efficiency Certificate (BEEC) database.

	Mean (W/m^2)	**Standard Deviation**	***t*-test *p*-value**	**Area weighted mean (W/m^2)**
National	13.51	6.00		12.2
ACT	12.77	5.50	0.000	11.9
NSW	13.24	5.74	0.000	11.9
NT	15.74	5.57	0.003	15.8
QLD	13.31	5.96	0.027	11.9
SA	12.45	6.95	0.000	11.7
TAS	13.57	5.07	0.894	13.0
VIC	14.12	6.40	0.000	12.4
WA	14.64	6.10	0.000	13.6

Table 4-5 presents the results obtained from the analysis of the tenancy lighting assessments contained within the BEER. A p-value of less than 0.05 indicates the mean nominal lighting power density (NLPD) for that state differed significantly from the national mean. It is apparent that the current LPD assumptions recommended by Australian modelling protocols, of between 7 and 12 W/m^2 (Aherne, 2011), represent an under-prediction of LPD for a typical commercial office building. Further, the cumulative distribution function, shown in Figure 4-7, demonstrates that 73.1% of the functional spaces assessed under BEEC had an NLPD outside of the range of 7 – 12 W/m^2. For these spaces, the use of any of the modelling protocol assumptions would introduce inaccuracy into the simulation, which may significantly influence the result.

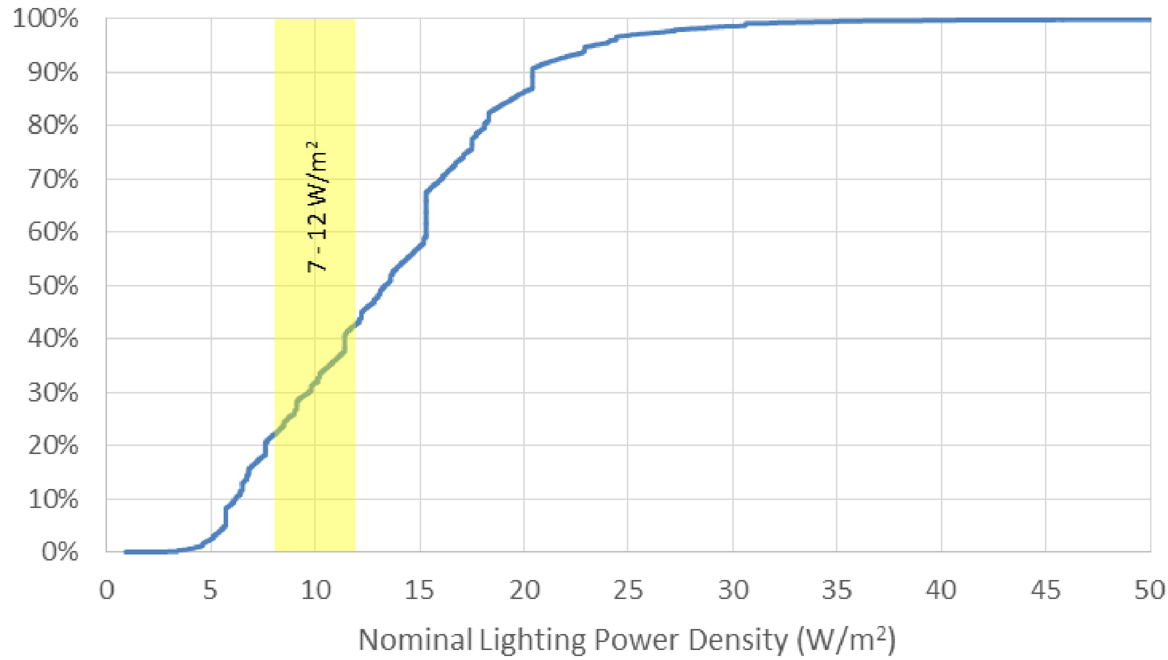


Figure 4-7 Cumulative distribution of the Nominal Lighting Power Density for functional spaces assessed under the Commercial Building Disclosure scheme.

4.2.2 Building Attributes Database (BA db)

A database of building attributes of buildings in the Melbourne CBD, developed by Wilkinson (2011a), and introduced in Section 3.3, was utilised in this study. The database was developed to examine the relationship between building adaptation, defined as any intervention to adjust, reuse, or upgrade a building to suit new conditions or requirements (Douglas, 2006), and property attributes through the use of principal component analysis. Wilkinson examined records of buildings that had previously undergone an upgrade, to identify the existence and the strength of any relationship between adaptation and property-specific attributes. The database was limited to buildings in the Melbourne CBD. The full database was developed from multiple data sources, primarily: the 'City Scope' commercial database; the LANDATA property database; and the Building Commission of Victoria Building Permits Register. The database information was verified by Wilkinson, and extra information was collected through the use of internet software 'Google Maps' and physical walkthrough surveys. Information was collected for 57 attributes related to seven factors defined by Wilkinson: physical, economic, environmental, adaptation, land use, legal, and social. There were 1,053 buildings included in the database, and information regarding 7,393 building adaptation events. For a full description of the development of the database and all attributes considered, refer to Wilkinson (2011a).

A truncated version of the database was made accessible to the present author. Information was provided for 24 building attributes relevant to this study for all BCA class 5 buildings in the database. The majority of the entries in the truncated database, referred in this study as the Building Attribute Database (BA db), related to physical and environmental factors. The BA db represents a significant information resource regarding the existing building stock in the Melbourne CBD. Whilst there are likely to be differences compared to other state capitals, the information included was considered likely to provide insights relevant to the broader Australian building stock.

The truncated database contained records for 6,778 adaptation events within the Melbourne CBD. The first stage of the database analysis was to process the records to retain only the most recent record of an adaptation event, creating a database with 439 records referring to unique buildings. Wilkinson and Reed (2006a) attempted to incorporate energy consumption information into the full database. However, the attempt was limited by a lack of data; the analysis in Wilkinson and Reed (2006a) relied on survey results from 14 buildings. Within the BA db most records identified whether a NABERS or ABGR existed for the building, but only a small proportion gave the rating. It was also considered likely what ratings were recorded could be outdated, as the database was compiled prior to mandatory disclosure legislation. The truncated database was therefore supplemented with the BEER database and other publicly accessible NABERS ratings for buildings in the BA db with valid ratings. Information was accessible from these sources regarding NLA, annual GHG emissions and energy consumption, consumption intensity, lighting power density, and NABERS rating. For the present study, energy consumption information was identified for 103 records, 80 records had a BEEC, and the remainder had a NABERS rating.

Consideration was given as to whether the BA db records for unique buildings were representative of the broader building stock in Australia. The database was created with a census approach to building adaptation events: all events in the Melbourne CBD in the studied period were incorporated. The BA db can therefore be said to be representative of the Melbourne CBD building stock that underwent adaptation between 1998 and 2008. Without further information about the broader buildings stock, it was difficult to assess whether the BA db sample was representative of the broader stock. Wilkinson (2011a) states: ‘The Melbourne CBD is similar to other Australian CBDs and also to CBDs outside Australia’, and:

Given its maturation over 175 years of continuous occupation within Australia, Melbourne is deemed to be representative of a modern urbanised city in a developed country.

It is likely that the historical, cultural, and climatic context of other Australian and international cities will have resulted in some variation in the attributes of the building stock (for instance, construction, cladding materials, building height, etc.). However, it likely that insights gained in the Melbourne CBD may be cautiously applied to other Australian cities.

Analysis of the 439 unique records provided some insights into the differences between Prime and Secondary Grade buildings. The analysis supports the anecdotal evidence cited in the Low Energy High Rise Study (NPC & Exergy, 2009). A breakdown of records by various attributes is shown in Figures 4-8 to 4-13, and summarised in Table 4-6.

Table 4-6 Summary of differences between Prime and Secondary Grade buildings

	All records	**Prime**	**Secondary**	**Ungraded**
Number of storeys	13	26	11	10
Age in 2010 (years)	53	29	58	57
Gross Floor Area (m^2)	18,026	46, 477	11, 993	14, 976
Building Cladding*	Concrete	Curtain Wall (glass)	Stone	Concrete
Plan Shape*	Deep plan	Deep plan	Deep plan	Deep plan
Ownership*	Private	Institutional	Private	Private

* *Modal record*

Prime Grade buildings are significantly larger, newer, and with more stories than Secondary Grade buildings at the 95% confidence interval. Prime Grade building are significantly more likely to have glass curtain walls, Secondary Grade buildings are more likely to have brick or stone construction. Secondary Grade buildings are also more likely to have an irregular plan shape, Prime Grade buildings are predominately deep-plan. The majority of Prime Grade buildings have institutional owners; Secondary Grade buildings are primarily privately owned. These nominal differences were tested for significance with the Chi Squared test. These characteristics all affect the retrofit optimisation process, and relate to retrofitting drivers and barriers highlighted in Section 2.10.5

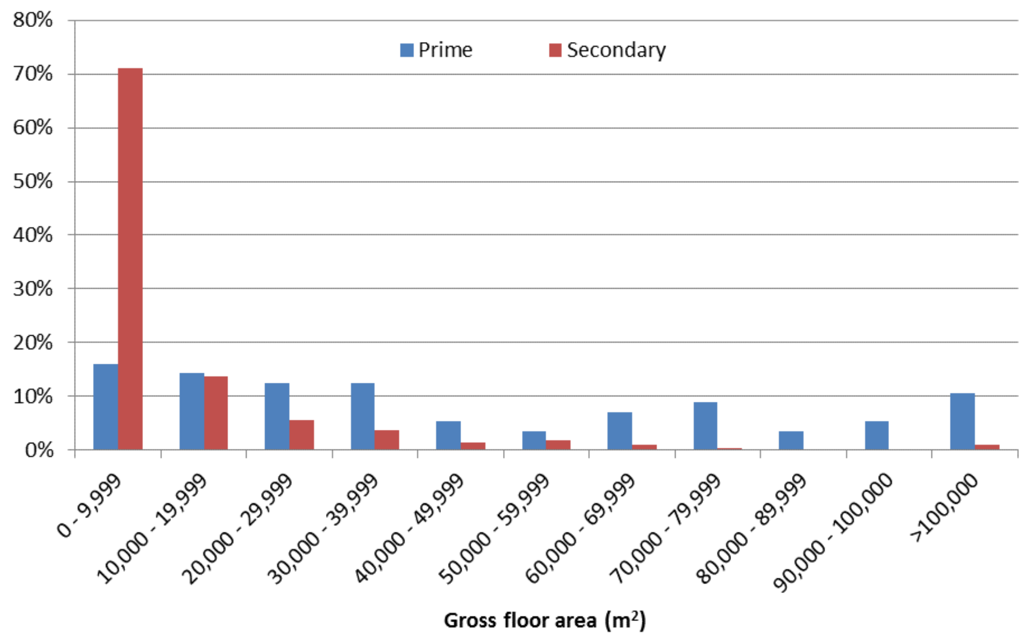


Figure 4-8 Number of records in BA db by Gross Floor Area of Prime and Secondary Grade buildings

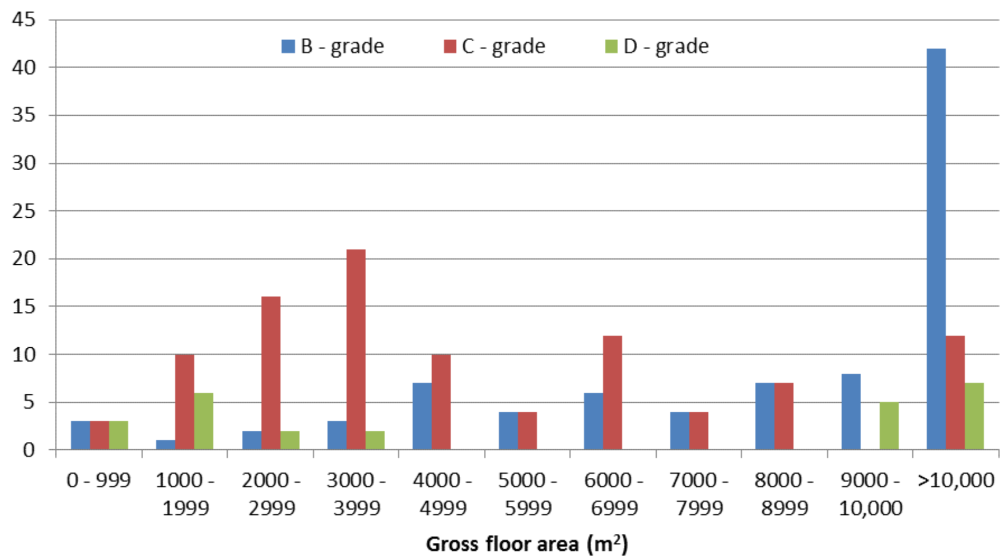


Figure 4-9 Number of records by Gross Floor Area for B, C, and D Grade buildings in Melbourne CBD.

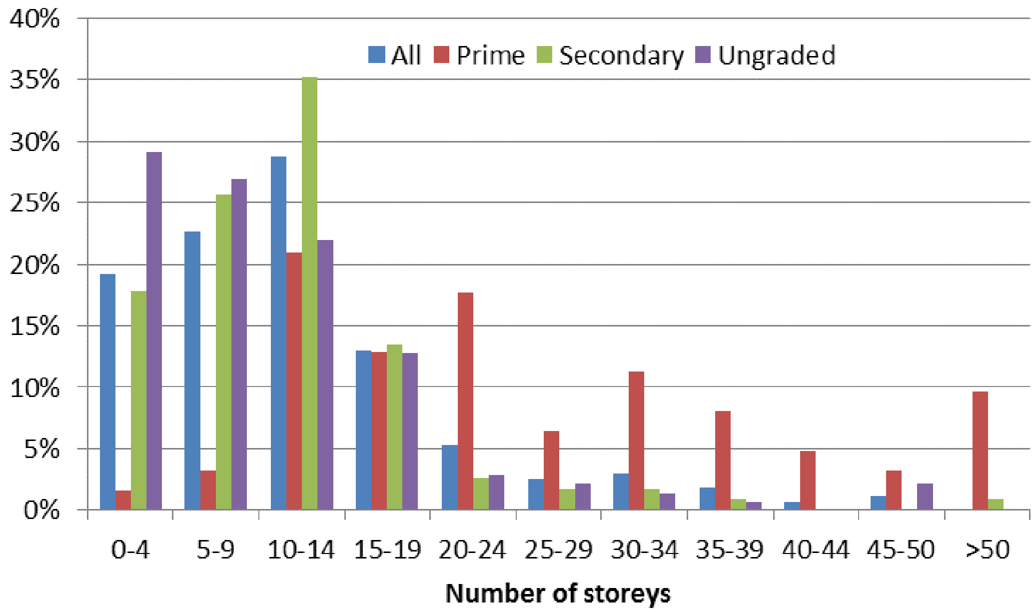


Figure 4-10 Number of records by number of stories for Prime, Secondary, and ungraded buildings in the BA db.

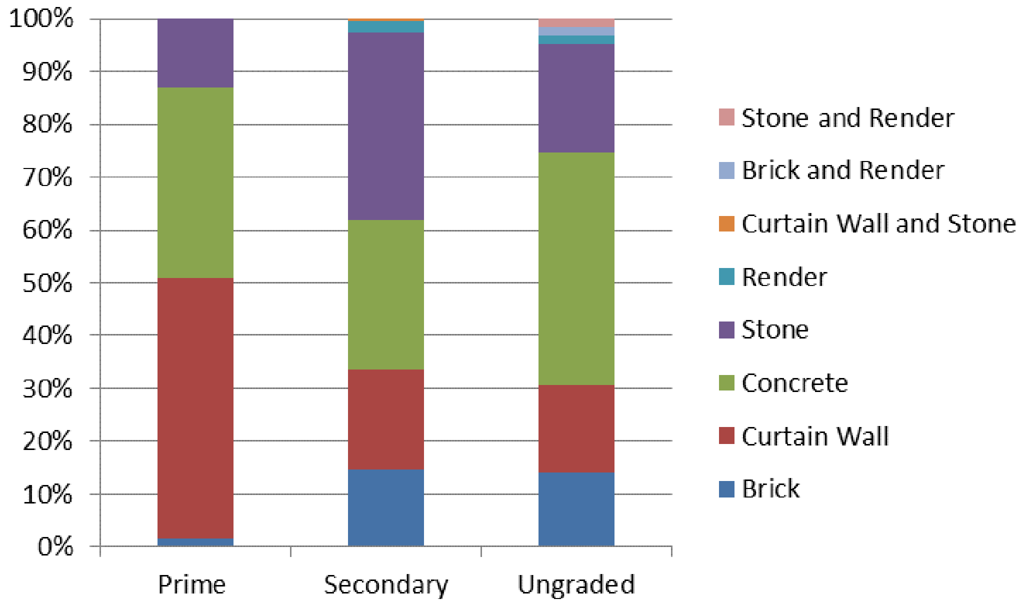


Figure 4-11 Building construction comparison of Prime and Secondary Grade buildings

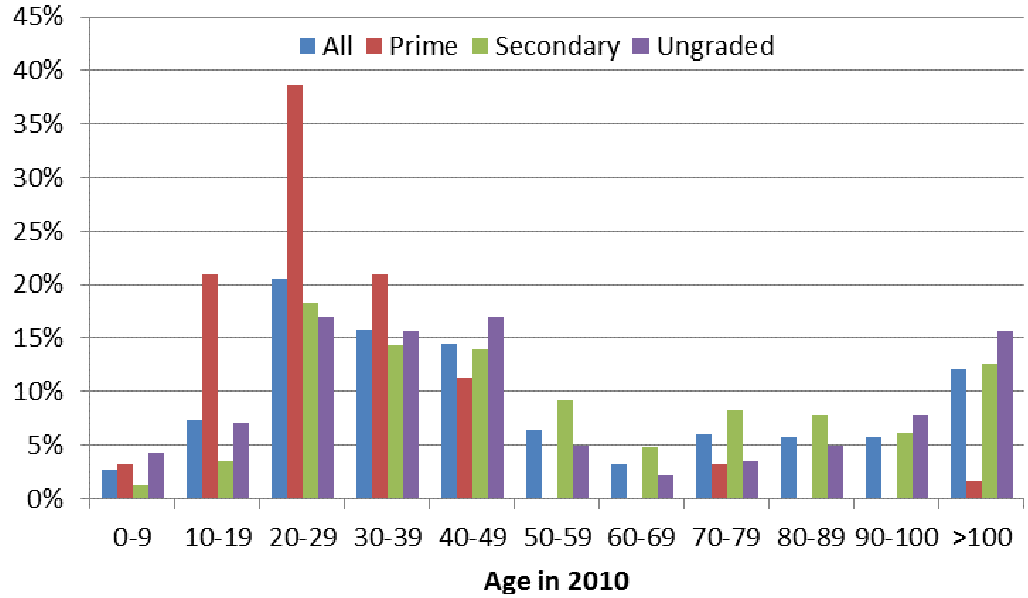


Figure 4-12 Count of records by Age in 2010 for Prime, Secondary and ungraded buildings in the BA db.

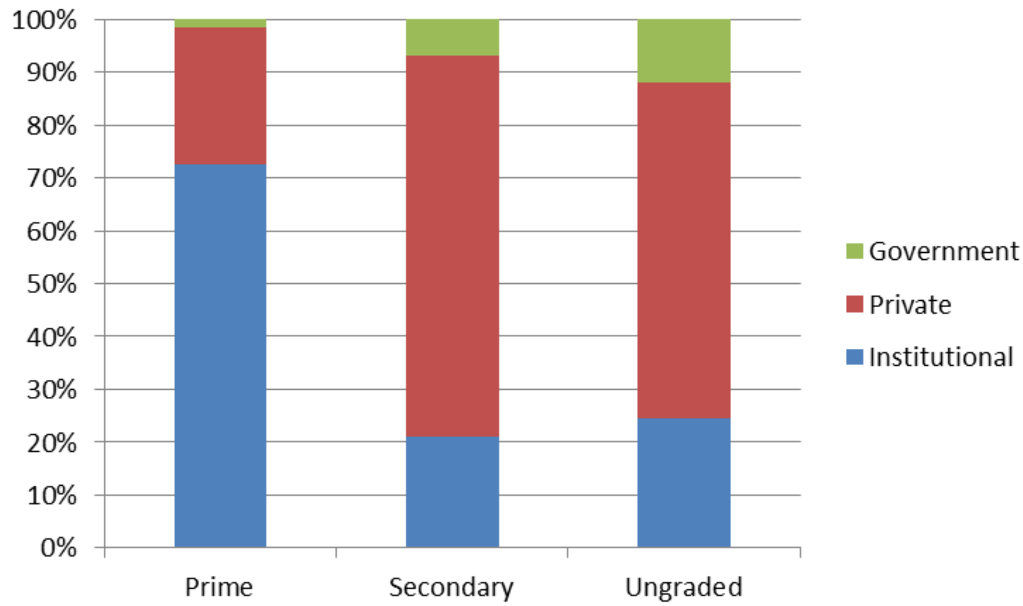


Figure 4-13 Tenant classification for Prime and Secondary Grade buildings in the BA db.

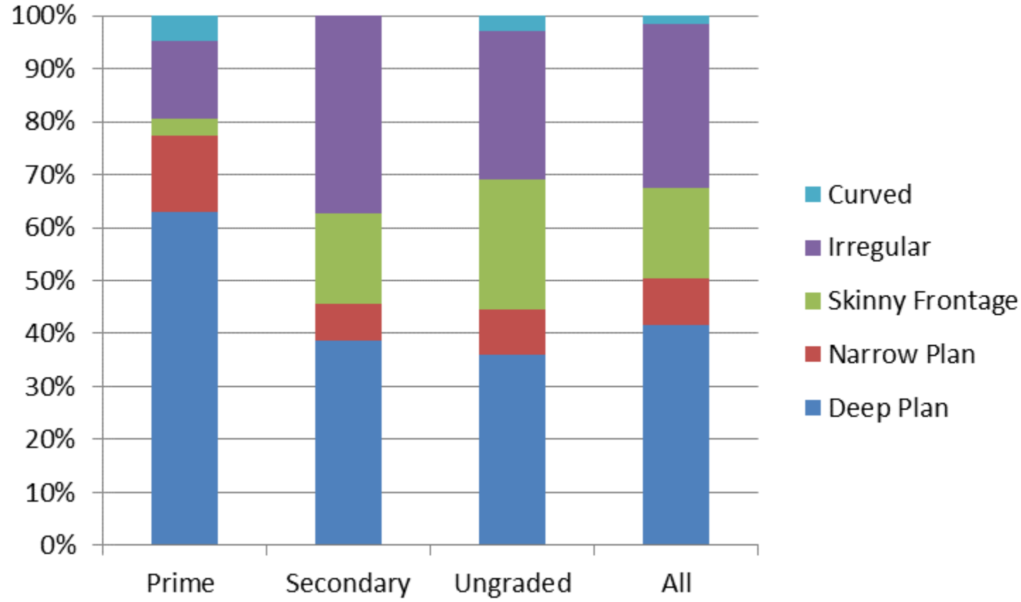


Figure 4-14 Count of records by plan shape for Prime and Secondary Grade buildings in the BA db.

Of the 103 records for which energy consumption data was available, the sample size for base building energy consumption data (the largest sub-set of data) falls short of the minimum sample size required for the data to be statistically representative, as calculated by pitt&sherry (2012b). It is worth noting that NRBuild, the database analysed by pitt&sherry (2012b) also does not meet this minimum sample size. A two sample z-test was undertaken to determine if the sample analysed in this study was significantly different from the samples analysed in previous studies. The base building energy consumption data was not significantly different from the sample population from pitt&sherry (pitt&sherry, 2012a) or Bannister (Bannister, 2004) at 95% confidence interval.

Of the 103 records with energy consumption information, 81 records related to base building consumption, 7 to tenancy consumption, and 15 records for whole building consumption. The average base building energy intensity was 610.0 MJ/m^2 (SD = 255.9), average tenancy energy intensity was 392.9 MJ/m^2 (SD = 165.7), and average whole building energy intensity was 1151.6 MJ/m^2 (SD = 287.2) (15 records). Analysis of the base building records revealed a significantly higher energy consumption intensity for Secondary Grade buildings at the 95% confidence interval. Average consumptions are displayed in Table 4-7. The sample size was not large enough to identify a significant difference between individual building grades (e.g. between A and B Grade)

Table 4-7 Average energy consumption intensity for all records base building consumption data in the BA db.

Building grade	Average Energy Intensity (MJ/m^2)	Standard Deviation	Number of records
Prime	563.4	258.2	31
Secondary	671.8	230.4	30
Ungraded	589.5	281.7	20
Premium	497.3	179.2	7
A	582.7	277.2	24
B	640.4	236.8	20
C	812.7	212.6	7
D	552.3	27.1	3
Ungraded	589.5	281.7	20
All records	**610.0**	**255.9**	**81**

The Nominal Lighting Power Density (NLPD) calculated as part of the BEEC assessment was also attached to building records in the BA db. As the lighting assessment was undertaken for individual functional spaces within each building, an area weighted average NLPD was calculated for each record. The lighting assessment considers all lighting in a space that could be reasonably expected to remain in place once the tenant leaves. Therefore all records (e.g. not limited to base building records) were included in the analysis. The difference shown in Table 4-8 was not significant at the 95% confidence interval. A larger sample size would be required to establish any relationship.

Table 4-8 Average NLPD for Prime and Secondary Grade buildings.

Building grade	Average NLPD (W/m^2)	Standard Deviation	Number of records
Prime	14.5	4.5	31
Secondary	15.8	5.0	35
Ungraded	12.7	3.8	21
All records	14.6	4.6	87

Analysis of the BA db augmented by BEEC records confirmed previously reported anecdotal evidence, that Secondary Grade buildings are older, smaller, and more energy intensive than Prime Grade buildings. It has also highlighted potentially important differences in the building attributes that will affect the retrofit optimisation process. Secondary Grade buildings, particularly C and D Grade, tend to be very small, and in private ownership. This makes the task of promoting retrofitting of these buildings difficult; a large number of individual decision makers need to be engaged. It also raises questions about the applicability of the reference buildings introduced in Section 2.6.4 to the whole of the Australian building stock. Only one reference building was used to

represent the office tower stock. This analysis highlights significant variation between Prime and Secondary Grade buildings; the Form A building appears to be more representative of the Secondary Grade office stock (10 storey, concrete construction). However, the Secondary Grade stock has been shown to be diverse in plan shape (37% irregular plan shape compared to 63% deep plan for Prime buildings) which cannot be not reflected in a single archetype.

4.2.3 Energy Saver Scheme Database (ESS db)

The Energy Saver Scheme was a New South Wales (NSW) state government initiative offering support to businesses to increase the efficiency of their operations. The scheme offered eligible businesses spending more than $60,000 on electricity every year a 50% subsidy on energy audits, advice on retrofit business case development, technical support to aid implementation of environmental upgrades, and assistance with accessing other government schemes. The scheme operated from 2009 to 2013. Non-identifying pre-processed data from the energy audits completed under the energy saver scheme were made accessible by the NSW Office of Environment and Heritage for the period up to April 2013. The data consisted of site data for 381 buildings in NSW, and energy efficiency opportunity data for 1983 upgrades, collected in a Microsoft Excel database. Site data included building type, postcode, floor area, energy use, energy end use breakdown, energy time of use breakdown, and tariff information. The opportunity data includes information about energy saving upgrades identified in the building audit, including opportunity description, status of upgrade, the sub-system impacted, and the status of the upgrade.

All records were analysed as there were insufficient records in the database to limit the analysis to Class 5 office buildings. Given the paucity of database information related to office building energy use, it was assumed that insights into all building classes may provide insights for office buildings, for instance on preferred lighting technologies being recommended and installed. Any identifying data was removed from each record, and the entries were coded according to building type, e.g. Accommodation, Club, Office, etc. The breakdown of building type is shown in Figure 4-15. Figure 4-16 shows the location of the buildings, according to the postcode data.

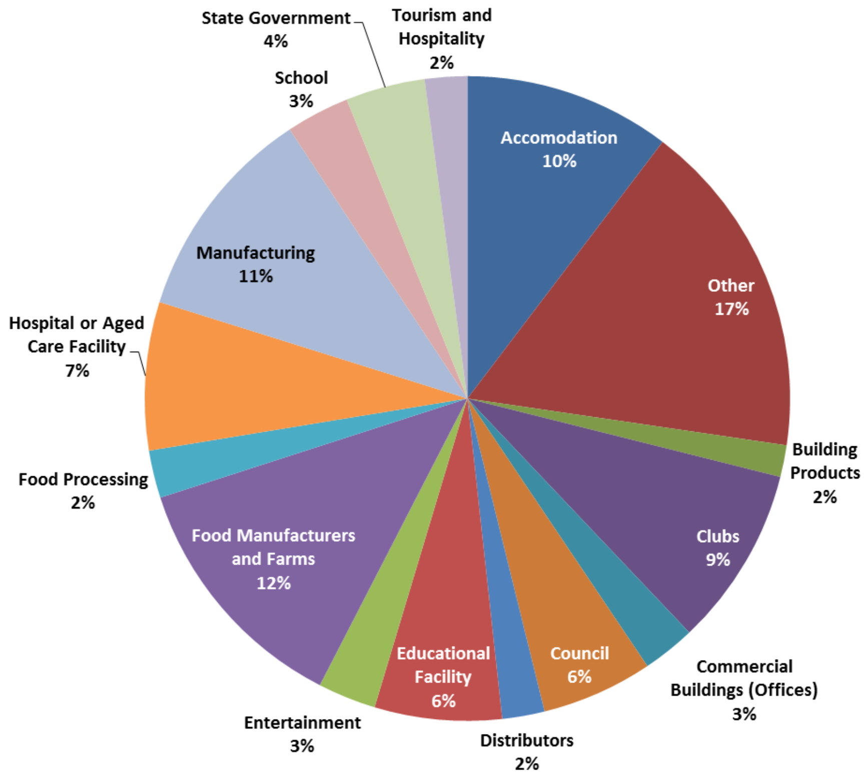


Figure 4-15 Building types represented in the Energy Saver Level 2 energy audit database for NSW.

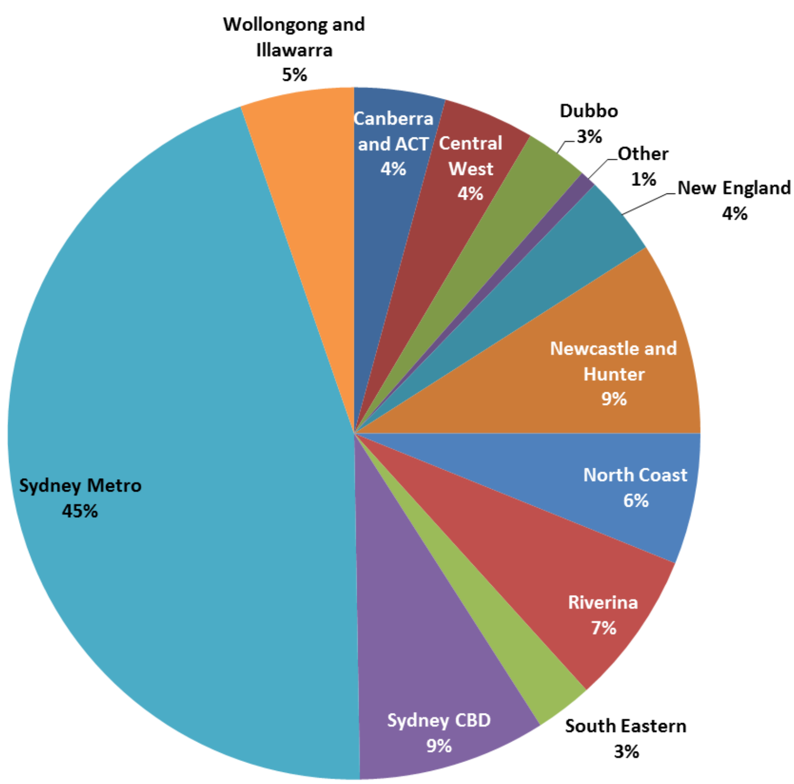


Figure 4-16 Location of Energy Saver audits in NSW sorted by postcode.

Food manufacturing and farms, manufacturing, accommodation, and clubs represent the largest subsets within the database. Only 2.56% of the site records are for office buildings, a total of 10 records. 54% of the audits occurred in Sydney CBD or the Greater Sydney region. 61.2% of the audits occurred in metropolitan areas, the remainder occurred in rural regions as defined by Department of Agriculture (2014). The average energy intensity of the records with both energy and floor area (156 records) was 237 kWh/m^2, 7.5% lower than the average for office buildings calculated in Section 4.2.1. There was a large variance in the recorded values; the minimum value was 5.8 kWh/m^2, and the maximum was 979.1 kWh/m^2. The standard deviation was 182.9 kWh/m^2. Without access to the raw unprocessed data it was difficult to verify the accuracy. During the interview process, discussed in Section 4.1, Consultant C noted that the energy saver audit process was:

> *A really rigorous process to go through. Having effectively a third party [OEH] critiquing your work and saying, no, we need more evidence here, we need more back up behind this energy savings estimate. It was a lot more work than a regular energy audit, so they were very good quality audits that came out of that process*

Given the small sample size, the energy saver audit data was of limited value in investigating the retrofitting of office buildings. Despite this, it was of interest to understand the recommended retrofits, and the status of the refurbishments, to understand current technologies being installed, and evaluate the effectiveness of the intervention.

A total of 1983 energy efficiency upgrades were recommended for implementation through the energy saver audits, an average of 5 upgrades per building. In many cases, an identical upgrade strategy was recommended for numerous locations within one building. An analysis of the opportunity data revealed the great majority of recommended upgrades were upgrades to lighting, as shown in Figure 4-17. Of the upgrades recommended in the reports, 55% have either been completed or are currently in progress, and 33% are still being considered (listed as potential). Only 9% of projects were abandoned, and less than 1% were deferred. The status of the recommended upgrades is shown in Figure 4-18, listed by upgrade type. HVAC projects had the highest completion rate (25%), compared to lighting (25%), hot water (15%), VSD (11%), and photovoltaic projects (11%). Photovoltaic projects had the highest abandonment rate (16%), possibly due to the suspension of the Solar Bonus (feed-in tariff) Scheme in April 2011.

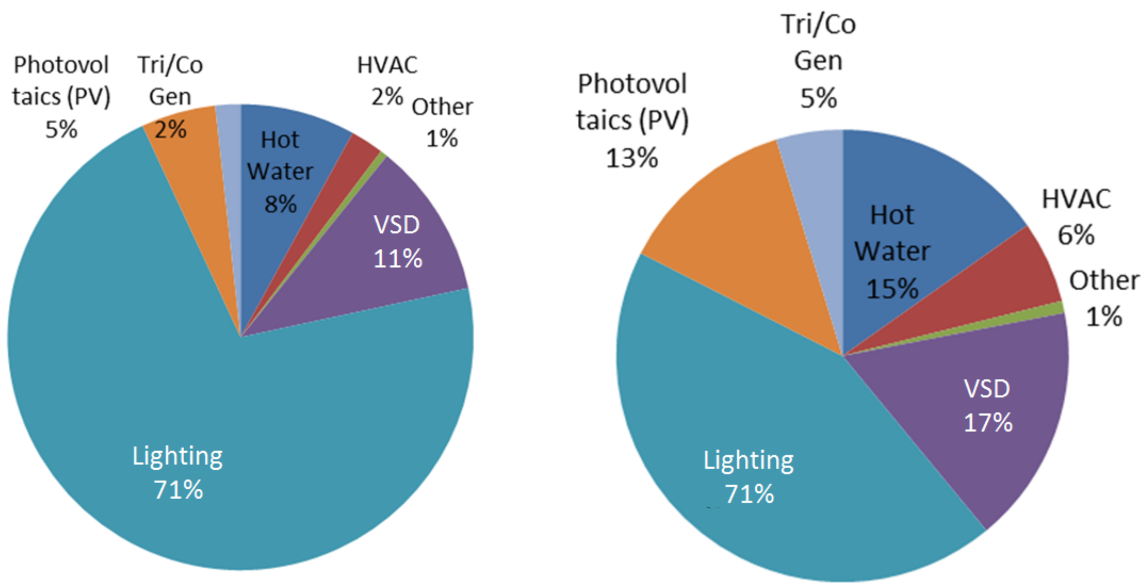


Figure 4-17 Breakdown of recommended energy efficiency upgrades from the Energy Saver scheme. The first chart shows the breakdown of all opportunity entries possible, including multiple records for upgrades to different sections of one building. The chart on the right shows opportunity entries at the building level, i.e. no duplication of upgrades in different spaces.

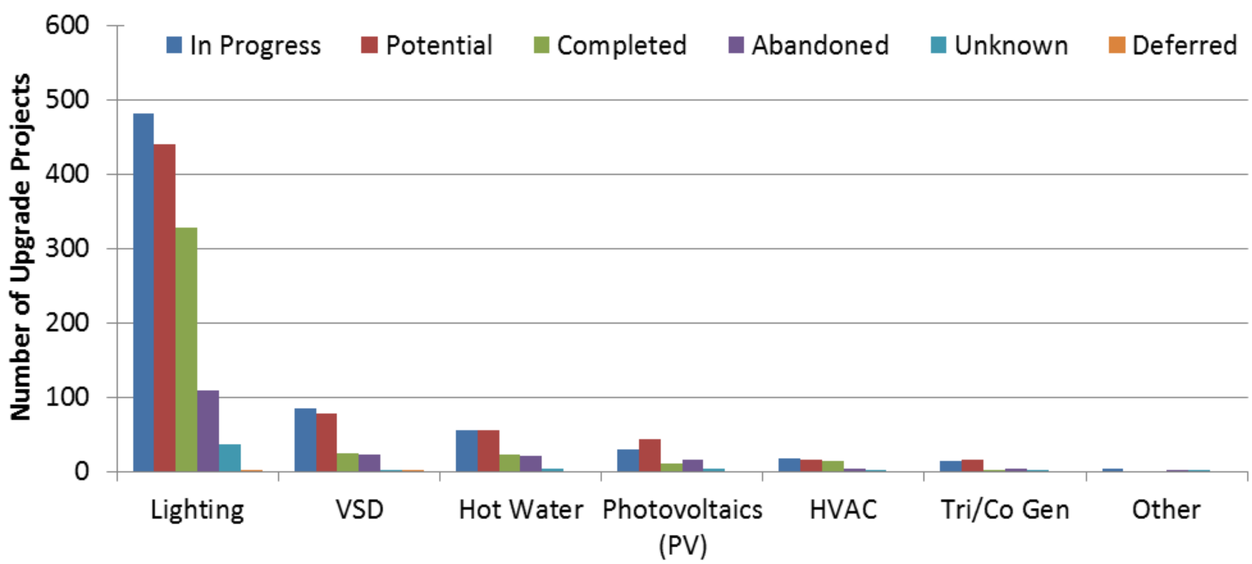


Figure 4-18 Status of energy efficiency projects recommended by the Energy Saver scheme, current in February 2014. This data was for all opportunity data; there may be several entries for lighting upgrade for a single building, as the upgrades take place in different spaces.

The technologies recommended for implementation in the category of lighting are shown in Figure 4-19. Installing LEDs was the most common recommendation, followed by T5 fluorescent tubes. This contrasts with the comments from the qualitative research that T5 was still the preferred

technology for lighting upgrades for most consultants. These two technologies represent 65% of the recommended upgrades, being 40% LED and 25% T5. The abandonment rate of LED and T5 upgrades are within 1%; the rate for T5's was 9.3% and for LED's was 8.4%.

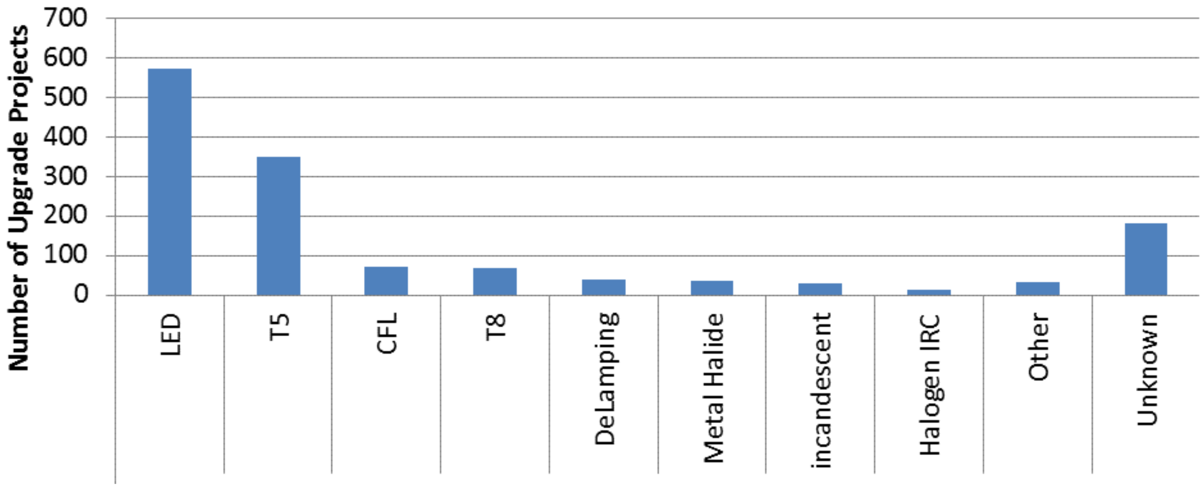


Figure 4-19 Lighting technology upgrades recommended by Energy Saver level 2 audits.

4.2.4 Data Limitations

Several potentially important data resources were identified but not fully explored due to accessibility issues or privacy concerns. A brief description of each data source is given below.

- The Green Building Fund (GBF) was an Australian Government grant program in operation for 5 years from Oct 2008. The program provided grants between $50,000 and $500,000 to help fund energy upgrades of commercial buildings, primarily offices. $119.3 million of funding was provided to 318 buildings in 7 rounds over the life of the program. Many of the best practice examples of energy efficient upgrades were beneficiaries of the GBF. As a requirement of the grant funding the building owner was required to provide certain information to AusIndustry, the managing organisation. Of particular interest to researchers in this field are end-of-project reports, which detail expected and actual expenditure on various aspects of the upgrade works, and a post-project report detailing; actual GHG savings for the 12 months post upgrade, actual energy savings (as compared to the previous 12 months) and a comparison of predicted and actual energy savings. Predicted savings were one of three key factors in allocating the grant funding. Having this information accessible in the public domain would be invaluable in developing the business case for building energy retrofitting, and in the identification of cost and energy

optimal retrofits from real-world applications. A request was made for access to the data, however it was denied due to privacy concerns. Ausindustry has signalled it will be evaluating the project in the 2014/15 financial year, and some data may become public following the review.

- A comprehensive energy consumption database was created for the pitt&sherry benchmarking report (pitt&sherry, 2012a), discussed in Section 2.9. The database, titled NRBuild, contains records for 1715 commercial buildings in Australia. The report repeatedly refers the author to the NRBuild model for further information. A summary 'de-identified' version of the model is publicly accessible; the fully specified model will not be published due to privacy concerns. The information contained within the summary database was primarily averaged data, which does not encourage further statistical analysis.

- NSW Government Energy Saver scheme. Whilst this study did make use of some information from this scheme (discussed below), a significant data resource was still unexplored. The template level 2 audit document supplied as part of the Energy Saver project includes information on:
    - Total building floor area (NLA or GFA) and number of stories
    - Major construction materials for Walls, Floor, Roofs
    - Occupancy (m^2/person) and occupancy schedule
    - Lighting system description (e.g. T8) and usage schedule
    - IT equipment load and schedule
    - HVAC System description and usage schedule
    - Control System Description
    - Building use classification
    - Baseline energy consumption, including monthly and average daily
    - Sub-metered energy loads (load breakdown) where available
    - Recommended upgrades
    - Predicted saving from upgrades

Some of this information was made accessible for this study, however the more detailed, and likely more interesting, data was not supplied due to staffing limitations and privacy concerns.

4.3 Discussion

Through the qualitative analysis of the interview data and the analysis of accessible databases, numerous considerations were identified that relate to the use of BPS in Australia. The main issues centred on a lack of reliable and accessible data regarding building energy use and building operation in Australia. This lack of data encourages the use of simulation to inform decisions, but requires the modeller to use a lot of assumptions, and heuristics, to develop the model. This makes the interrogation of a BPS model very difficult, and necessitates reliance on the expert knowledge of the simulation user. However, at present there is no well-recognised accreditation process for energy modellers in Australia, and due to commercial pressures, many companies rely on inexperienced simulation users. A summary of the issues was put by Consultant D during the interviews:

> *[BPS for large scale commercial buildings is] so complicated it's barely worth even guessing. You might as well just use a benchmark. But because the data doesn't actually exist, or a lot of it doesn't exist, or a lot of it's so bespoke that it's hard to benchmark against, you don't end up with a tool that necessarily gives you a result that's anywhere near accurate. And for that reason I think a lot of people just model things in all kinds of different ways, because there is nothing to compare them against, and there is nothing to pull them up on, and you can't actually prove if it was right or wrong anyway, a lot of the time.*

The interview with Consultant H, whose business offered EPC's on the basis of BPS predictions, illustrated that BPS can be used to predict the energy savings from a given upgrade strategy to a building and/or systems with sufficient confidence for an ESCO to enter into an EPC. However, ESCO's also routinely de-rate the predicted savings to account for uncertainties, sometimes by more than 50% (Charles *et al.*, 2002). Further, the depth of the data collection exercise that was involved in developing and validating the detailed models for an EPC is cost prohibitive for most commercial modelling engagements. The accuracy and reliability of BPS results from commercial engagements is therefore reliant on the consultant's judgement of the relative importance of inputs. The interpretive position of the modeller is shown in Figure 4-20.

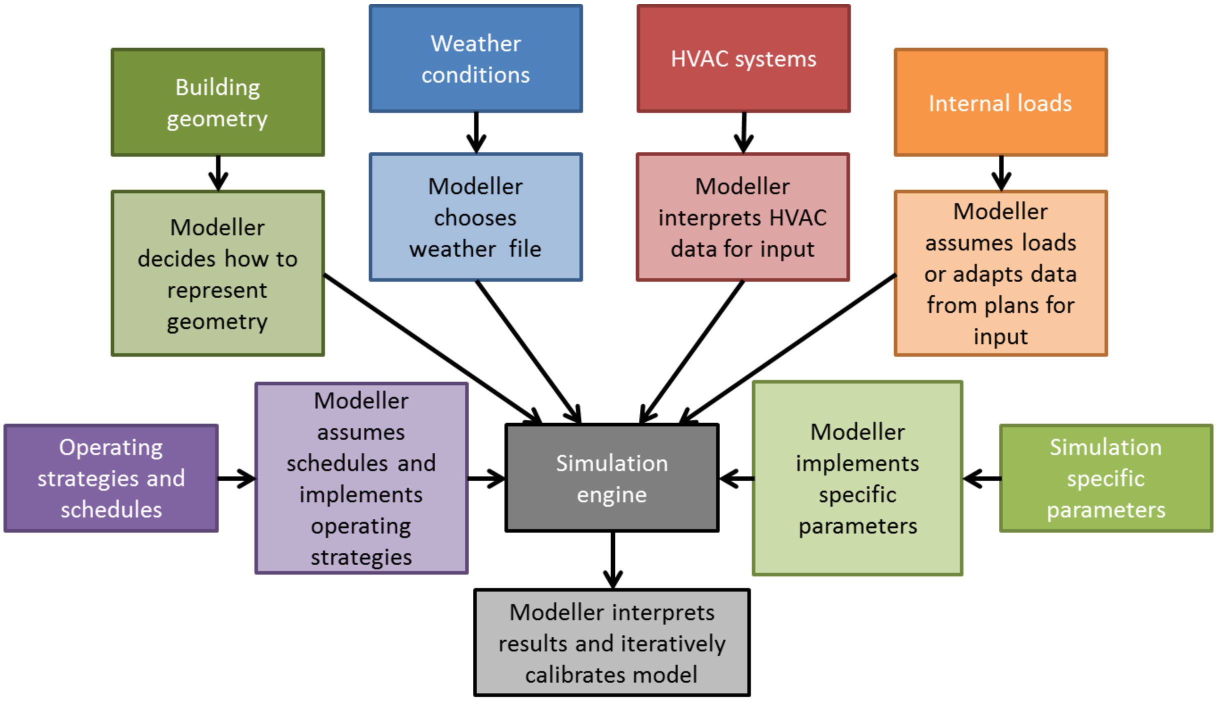


Figure 4-20 The interpretive role of the modeller in the simulation process, adapted from Berkeley (2013).

Figure 4-3 depicts an expert system, requiring significant experience and understanding of a complex system. The practice, identified by Consultant F, of using inexperienced staff to run the labour-intensive modelling software is therefore problematic. The use of peer-review and quality assurance techniques can help avoid many issues, however, the nature of BPS programs makes error-checking itself a challenging task. The difficulty in determining whether a model is sufficiently accurate becomes important for any scheme in which predictions of savings are tied to a financial reward. This was discussed in Section 4.1.5 in relation to EUA's, but applies equally to the Australian Government's Emissions Reduction Fund (ERF), and any competitive grant scheme that requires predicted energy savings. Relying on predictions from BPS to assess competing bids may incentivise the over-estimation of energy savings, with the understanding that the complexity of prediction and M&V of energy savings will make compliance difficult.

The issue above is compounded by the lack of a universally recognised accreditation scheme for energy modelling professionals in Australia. It is recognised that it is difficult educate people to be good modellers due to the complex nature of the understanding required. Testing this understanding is also difficult. In the USA, ASHRAE successfully administer the Building Energy Modelling Professional certification, which tests and register professional who have shown the necessary

knowledge to model a commercial building in an appropriate manner. In Australia, the Energy Efficiency Council have recently launched an Energy Efficiency Certification scheme for professionals who have experience working on energy efficiency retrofits for commercial buildings. However, it does not specifically test energy modelling ability and understanding. NABERS and Green Star also have accreditation systems; again, these do not certify the ability to use BPS. Without a unifying accreditation, professionals need numerous certifications for different schemes, with associated costs. Until a robust BPS accreditation scheme is developed, and included as a standard requirement for energy modelling contracts, particular government initiatives (i.e. EUA's, ERF), industry concerns are that certification will simply represent an additional cost (AIRAH, 2013).

A possible improvement is the development and use of a standardised, evidence-based modelling protocol, supported and updated from regular data collection exercises, similar to ASHRAE 90.1 (2013). The analysis of the existing database in this chapter highlighted that a significant data collection exercise would be needed before this resource could be created.

The findings of this chapter provide the background for much of the following chapters. The lack of data availability informed the approach for the simulation studies to follow. It will be shown that variability in simulation inputs and assumptions can significantly influence energy use predictions. The feasibility of using Reference buildings for simplified simulations, identified during the interview process, will be explored in Chapter 8 and consideration given to the usefulness of this approach for Secondary Grade buildings.

5 Impact of Typical Weather File Selection and Climate Change on Commercial Building Retrofitting in Australian Cities

As identified in Section 2.6.2 differences between actual weather at a building location and the statistical weather input used to represent the external conditions is a key source of uncertainty in Building Performance Simulation (BPS). There are several possible causes for this error, including annual variation in weather, local topographic effects (e.g. urban heat island), and longer-term changes to climates. The use of 'typical year' weather files is an attempt to minimise the error due to annual variation in weather, however, these files are developed based on historic data from weather stations at discrete locations. One of the fundamental drivers for all action on building energy use is concern about global warming, or changes to the Earth's climate system caused by human actions (see Section 2.1). There is a large body of research focussing on the prediction of future climate conditions under various emissions scenarios (CSIRO, 2007; Garnaut, 2008; IPCC, 2007), and much research has also focussed on the predicted reductions of emissions from retrofit strategies to improve building energy efficiency (ClimateWorks Australia, 2010b; Ma *et al.*, 2012; McKinsey & Company, 2008; NPC & Exergy, 2009).

In Australia, climate change is indirectly a key driver for building energy retrofitting, through government programs and incentives, for example. However, there has been only very limited research reported on what effect, if any, global warming will have on building energy use and the selection of retrofit strategies for commercial buildings in Australia. As retrofitted buildings will operate in a changing climate, there is a need to consider the impact of climate change on the effectiveness of retrofit strategies and the selection of optimal strategies.

In the Australian context, the 'Existing buildings survival strategies' retrofitting guide (Arup & PCA, 2008) is considered to be one of the best practice guidelines available to the retrofitting industry. The guidelines are representative of current practice in Australia and make only passing mention of climate change as a driver for building owners to consider retrofitting, with no advice provided on the likely magnitude of the impact, if any, climate change is likely to have on the selection of retrofit strategies and building performance improvements. This chapter provides an Uncertainty Analysis of the impact of the selection of typical weather files on annual energy consumption, and the impact of predicted climate change on energy use and retrofit selection.

5.1 Future Climate Predictions

To understand the impact of future climate change on the selection of retrofit strategies, a detailed prediction of future weather conditions was required. Numerous global and local studies have examined this issue (CSIRO, 2007; Garnaut, 2008; IPCC, 2007). The most comprehensive studies to date have been the IPCC assessments (IPCC, 2007). These reports have collated projections from General Circulation Models (GCMs) developed by meteorological research groups around the world so as to estimate the probable impacts of climate change, and the associated uncertainty in such predictions. The various individual GCMs lead to a range of climate impacts held by the authors concerned to be correct within a given range of uncertainty. The emissions scenarios (e.g. A1, A1F1) define different technological, cultural and social scenarios in the future. The IPCC Third Assessment Report (2007) predicted that mean temperature will increase by between 1 ^{o}C and 6 ^{o}C by 2100, with the ranges shown in Figure 5-1.

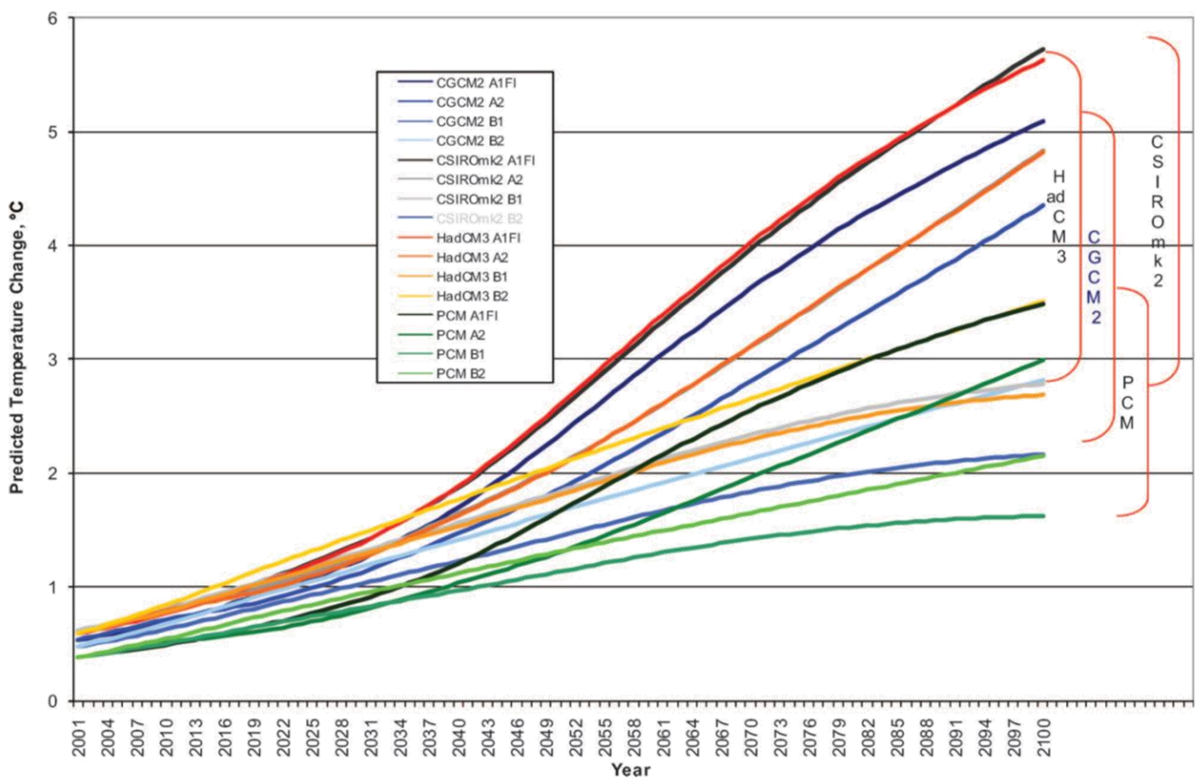


Figure 5-1 Global annual average temperature change predicted by four major Global Circulation Models (Crawley, 2007). The acronyms on the right refer to Global Circulation Models from different organisations. CSIRO is Commonwealth Scientific and Industrial Research Organisation, PCM refers to the National Center for Atmospheric Research's Parallel Climate Model 1, CGCM2 is the second version of the Canadian Centre for Climate Modelling and Analysis's Coupled Global Climate Model, HadCM3 is version 3 of the Hadley Centre's Coupled Model. A1F1, A2, B1, B2 refer to IPCC emissions scenarios (IPCC, 2007).

Globally, Australia is not amongst the nations most exposed to global warming (IPCC, 2007), however, it can expect to experience significant temperature increases. Table 5-1 shows the range of predicted changes to significant climate variables for Australia, developed from the climate change scenarios in the report 'An Assessment of the Need to Adapt Buildings for the Unavoidable Consequences of Climate Change' (BRANZ, 2007).

Table 5-1 Predicted changes to major climate variables in Australia, developed from BRANZ (2007).

Factor	**Parameter**	**Change**	
		2030	**2070**
Temperature	Annual Average	+0.4 to +2.0°C	+1.0 to +6.0°C
	Extreme events, above 35^{O}C	+10 to +100%	+20 to +600%
	Extreme events below 0^{O}C	-20 to -80%	-50 to -100%
Rainfall	Summer/Autumn	-10 to +10%	-35 to +35%
	Winter/Spring	-10 to +5%	-35 to +10%
Relative Humidity	Annual and Seasonal Average	-3 to 0%	-9 to 0%
Radiation	Annual Average	-5 to 0%	-15 to 0%

5.2 Review of Climate Change and Building Energy Use

Numerous international studies have examined what impact climate change will have on building energy use (Crawley, 2003; Cullen, 2001; Degelman, 2002; Nik & Kalagasidis, 2013; Ouedraogo *et al.*, 2012; Ren *et al.*, 2011), however, there was only limited research into the impact predicted climate changes could have on building energy use and indoor thermal comfort in Australia. The most extensive study to date into climate change adaptation in Australia's building stock was 'An Assessment of the Need to Adapt Buildings for the Unavoidable Consequences of Climate Change' (BRANZ, 2007) undertaken by Building Research Association New Zealand (BRANZ) for the Australian Greenhouse Office. This report had a broad scope, and investigated issues such as flood and bushfire safety, as well as energy and comfort. For residential buildings, the report found that climate change will broadly increase cooling energy consumption and increase the risk of overheating. An archetypal commercial building was used to examine the impacts on commercial building energy consumption. The results showed that the energy use in this commercial building archetype could increase by up to 18% by 2070 as a result of increased temperatures. The report

suggested adaption options for each predicted climate change issue, but did not provide an assessment of predicted energy savings or efficacy of the adaptation.

Guan (2009a, 2012) examined the impact of warmer weather on the design and performance of air-conditioned office buildings in Australia, looking both at increases in cooling loads, and increased incidence of overheating due to undersized HVAC systems. A maximum increase in cooling load of 28-59% was predicted for all capital cities, under a 'high' scenario with weather files generated with the CSIRO GCM (Guan, 2009b). Guan (2012) also provided basic parametric analysis of the performance of several possible adaption strategies.

Wang *et al.* (2010, 2011) investigated the impact of global warming on the energy consumption of residential buildings. It was found that the heating and cooling energy of a 5 star Nationwide House Energy Rating Scheme (NatHERS) house could vary by between -26% and 101% by 2050, and -48% to 350% by 2100, depending on the location. The large range can be partially explained by the variation in GCMs used and the particular scenario selected, but was primarily due to changes to regional climates.

Previous studies into climate change and building energy use in Australia have not considered the performance of commercial building energy retrofit strategies under a changing climate, with the exception of Guan (2012). This chapter therefore presents detailed energy simulations of a typical commercial building to investigate energy used and total design cooling requirements before and after realistic building retrofits are applied, in the predicted future climatic conditions from an alternate GCM to Guan (2012), for five Australian capital cities for 2020, 2050, and 2080. Various possible trends in retrofit technology implementation are considered, and the implications of the simulation results on the retrofit decision making process are discussed.

5.3 Research Method

5.3.1 Generation of Future Weather Files

It was necessary to generate appropriate weather files to represent future climate conditions. 'Morphed' weather files were produced based on the shifts predicted by the HadCM3 GCM, operating the A2 scenario (i.e. regionally oriented economic growth, continually increasing population, and slower technological change) (IPCC, 2007). Morphing is the alteration of an existing TMY weather file to account for the changes which have been predicted by GCMs at the

nearest geographic grid points. Guan (2009b) identified four methods which have been used previously to generate future hourly weather data files, i.e.: the extrapolating statistic method; the imposed offset method; the stochastic weather model; and global climate models. The author concluded that the imposed offset method, also known as 'morphing', was the most suitable compromise for building simulation studies. The imposed offset method provides a reasonable compromise between simplicity (e.g. extrapolating statistic method) and complexity (e.g. stochastic weather models and global climate models) for use in building simulation studies. Belcher *et al.* (2005) outlined the method and algorithms to be used for creating morphed future weather files.

The changes predicted in the GCM are applied to the existing TMY file as either a;

- 'Shift' - the monthly mean (x_o) for a parameter is offset by the absolute change (Δx_m);

$$x = x_0 + \Delta x_m \tag{5.1}$$

- 'Stretch' – the monthly mean (x_o) is multiplied by the fractional change (α_m) in the parameter;

$$x = x_0 \alpha_m \tag{5.2}$$

- 'Stretch and Shift' – A combination of the two approaches.

$$x = x_0 + \Delta x_m + \alpha_m (x_0 - (x_0)_m) \tag{5.3}$$

The morphing procedure does not take account of any feedback interdependence between climate variables. For example, increased radiation may result in increased temperatures due to interaction with the ground and atmosphere, which as stated in Colombo *et al.* (1999) is an important simplification of the real situation. Guan *et al.* (2007) showed that there is strong linear correlation between several specific weather variables through statistical analysis of 10 years of weather data in Australia.

Any study of projected climatic conditions includes a level of built-in uncertainty due to our incomplete understanding of the complex global and local climate systems, and of our inability to represent these perfectly with GCMs. There is also uncertainty associated with our understanding of societal emissions and adaptive responses to climate change. There is an inherent interdependence between future improvements made to the building stock and predictions of future emissions. The A2 scenario makes certain assumptions about the performance of the building stock in the future, which may be contradictory to some of the building adaptation assumptions in the present study, for example. However, detailed consideration of this interdependence was taken to be outside the scope of the current study as it was not expected to affect the simulation results significantly. Confidence

in predictions can be increased through the use of a variety of emissions scenarios. For the present study the A2 scenario, representing a mid-to-high impact, has been used. This scenario has also been utilised in the NSW/ACT Regional Climate Modelling project (NARCliM) (Evans, JP *et al.*, 2014), a government effort to develop improved predictive weather data incorporating local climatic influences.

The weather data morphing process utilised in the present study made use of data from the four nearest locations for which GCM prediction were available. However, the GCM spatial grid was coarse (typically 100 – 400km resolution) and did not include local topographic effects such as urban heat island effects, which can have a significant impact on extreme events. Greening Australia (2007) compared the number of days above 35^{o}C for Central Sydney (Observatory Hill, Darling Harbour) and Western Sydney (Prospect Reservoir), and found localised effects have led to a 250% increase in extreme heat events for Western Sydney compared to 22% increase for Sydney, for example. Numerous studies have considered the impact of urban heat island (UHI) effects on cooling and total energy consumption in commercial buildings (Bordass *et al.*, 2004; Bordass *et al.*, 2001; Guan, 2011; Menezes *et al.*, 2011). Hirano and Fujita (2012) found electricity consumption for cooling loads could be expected to increase by 27.5% due to UHI, whilst overall energy use would increase by 1% in a commercial office in Tokyo. Kolokotroni et al. (2012) predicted an 11-13% increase in annual electricity consumption for cooling for an office building in London due to UHI, increasing to 13-18% by 2050.

Peak load can be significantly impacted by extreme weather events and this can have major (Evans *et al.*, 2014) repercussions for HVAC sizing and energy-supply systems. It is likely that new summer design temperatures will be required for HVAC design in future climates, however, this issue is beyond the scope of the present study. It is likely that the morphing algorithms used, while providing a good estimate of representative future weather conditions, may under-predict the frequency and magnitude of extreme events, and therefore the impact of these events on energy consumption. These issues are a key driver behind the NARCliM project and the new climate projection may provide useful insights for future research.

5.3.2 Building and System Description

The simulated building was the ABCB Form A reference building; detail of the geometry and construction was given in Section 3.5. This form was used by BRANZ (2007) in an assessment of

the consequences of climate change, described above. Table 5-2 identifies the assumed value and sources for other relevant modelling parameters.

Table 5-2 Key assumptions and sources used in commercial office building archetype modelling.

Parameter	Input value	Source
Geometry	31.6 x 31.6	ACADS BSG (ACADS-BSG, 2002)
Construction Materials	Heavyweight concrete	ACADS BSG (ACADS-BSG, 2002)
Occupant Density and Schedule	1 per 15 m^2	NABERS (NABERS, 2011)
Equipment Load and Schedule	11 W/m^2	NABERS (NABERS, 2011)
Lighting Load and Schedule	12 W/m^2	NABERS (NABERS, 2011)
HVAC	VAV with central water cooled chiller and gas fired boiler.	ACADS BSG (ACADS-BSG, 2002) Bannister (Bannister, 2004) BRANZ (BRANZ, 2007)
HVAC set points	20 - 24^{o}C	ACADS BSG (ACADS-BSG, 2002)
Infiltration	1 ACH	ACADS BSG (ACADS-BSG, 2002) Bannister (Bannister, 2004) Egan (Egan, 2011)

The equipment and occupancy schedules used were the default values given by the National Australian Built Environment Rating System (NABERS) (2011), for use when insufficient information is available to more precisely specify more exact loads and schedules. The schedules assume 15% of lights, and 50% of office equipment remain on during unoccupied hours. An allowance of 1 W/m^2 was made for lifts and auxiliary service equipment, as recommended in NABERS (2011). A variable air volume system with a central water cooled chiller with COP of 2.8, and a gas-fired condensing boiler was modelled, with no heat recovery, and no economy cycle. The arrangement was selected as being representative of a commonly implemented system for this building type (Bannister, 2004). The cooling system COP used was equivalent to that defined in the initial ACADS BSG study (ACADS-BSG, 2002). A key point of difference between the BRANZ (2007) report and our approach was in local variations to building construction. The BRANZ study used the BCA 'deemed-to-satisfy' approach to define the envelope construction of the modelled building at each location. As the present study was focussed on retrofitting, our assumption was that the building was older, and likely not to be compliant with BCA energy efficiency requirements. The building envelope was simulated as originally defined by ACADS-BSG (2002) allowing direct comparison of the impact of climate change across all locations.

5.3.3 Simulation approach

The first BPS analysis undertaken was to determine the sensitivity of the reference building to the various 'typical' weather files available for use in the Australian climate, i.e. RMY, TMY and IWEC, introduced in Section 2.6.2. The building was then simulated using the morphed weather files, created from IWEC files, for 2020, 2050 and 2080. To understand the relative magnitude of the change in predicted energy consumption due to a changing climate, several possible changes to the archetypal building's energy profile were then simulated, as shown in Table 5-3. The simulation approach is illustrated in Figure 5-2.

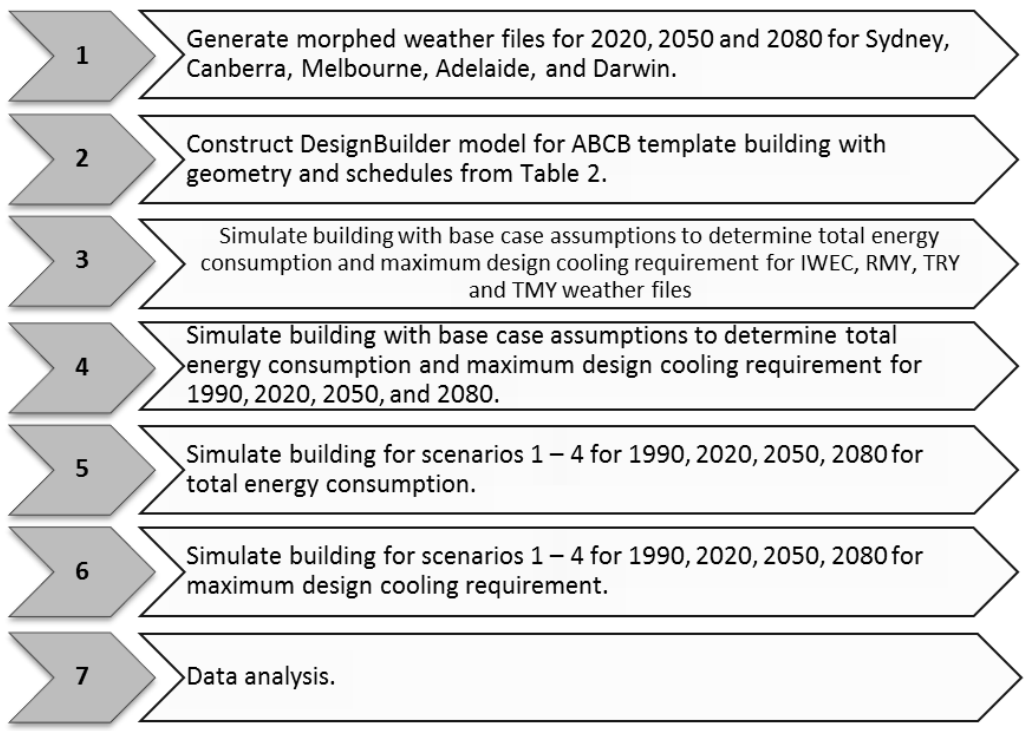


Figure 5-2 Schematic of the modelling procedure employed in the present study.

The scenarios in Table 5-3 represent commonly implemented retrofits, and possible variations in internal loads for an office building. Upgrading lighting in commercial office buildings to LED lighting is an emerging technology in Australia, considered by many to be an effective retrofit solution for lighting (Donnelly, 2004; Johnston *et al.*, 2011; ZCA, 2013), the lighting power density for LED lighting was calculated from (General Electric, 2012/2013). Changes to equipment power density are predicted according to two divergent future scenarios for equipment use, envisaged by Johnston *et al.* (2011).

1. A scenario ‘where minimising carbon pollution drives the Information and Communications Technology (ICT) acquisition policy’ with a resultant low energy intensity,
2. A scenario ‘where maximising productivity ‘drives ICT acquisition, with a resultant profusion of ICT equipment, and high energy intensity.

The upgrades to the building envelope are indicative of potential future fabric changes, identified by many as an effective retrofitting strategy (ABCB, 2004; Arup & PCA, 2008; ZCA, 2013). Wall U-value improvement was an increase of the thermal resistance of the wall element to R-3 (R = 3 m^2K/W), roof element thermal resistance was upgraded to R-4 (R = 4 m^2K/W), glazing was upgraded to double glazed 3 mm clear glass with 13 mm air gap (SHGC = 0.76 and U-value = 2.76 W /m^2K)

Table 5-3 Building performance simulation inputs for energy retrofit scenarios.

	Lighting power density (W/m^2)	**Equipment load density (W/m^2)**	**U – Value (W/m^2K)**		
			Wall	**Roof**	**Windows**
Base (pre-retrofit) building	12	11	0.55	0.278	5.8
Scenario 1 - LED lighting upgrade	5	11	0.55	0.278	5.8
Scenario 2 - ‘Energy conscious office equipment efficiency upgrade’ (Johnston *et al.*, 2011)	12	5	0.55	0.278	5.8
Scenario 3 - ‘Techno explosion’ (Johnston *et al.*, 2011)	12	15	0.55	0.278	5.8
Scenario 4 – Upgrade to envelope	12	11	0.33	0.25	2.76

5.4 Results and Discussion

5.4.1 Sensitivity of Building Energy Use to Typical Weather File Selection

The template building was simulated with three typical year weather files, TMY, RMY and IWEC, for all capital cities in Australia. The results are displayed in Figure 5-3. Compared against the RMY weather files, the average absolute difference in whole-building energy consumption was 0.44% for the IWEC files, and 0.76% for the TMY files. The greatest difference for the IWEC was +1.01% in Melbourne, for the TMY files the greatest difference was -3.45% in Canberra. The predicted energy performance of the reference building is therefore relatively insensitive to the selection of typical weather year data file.

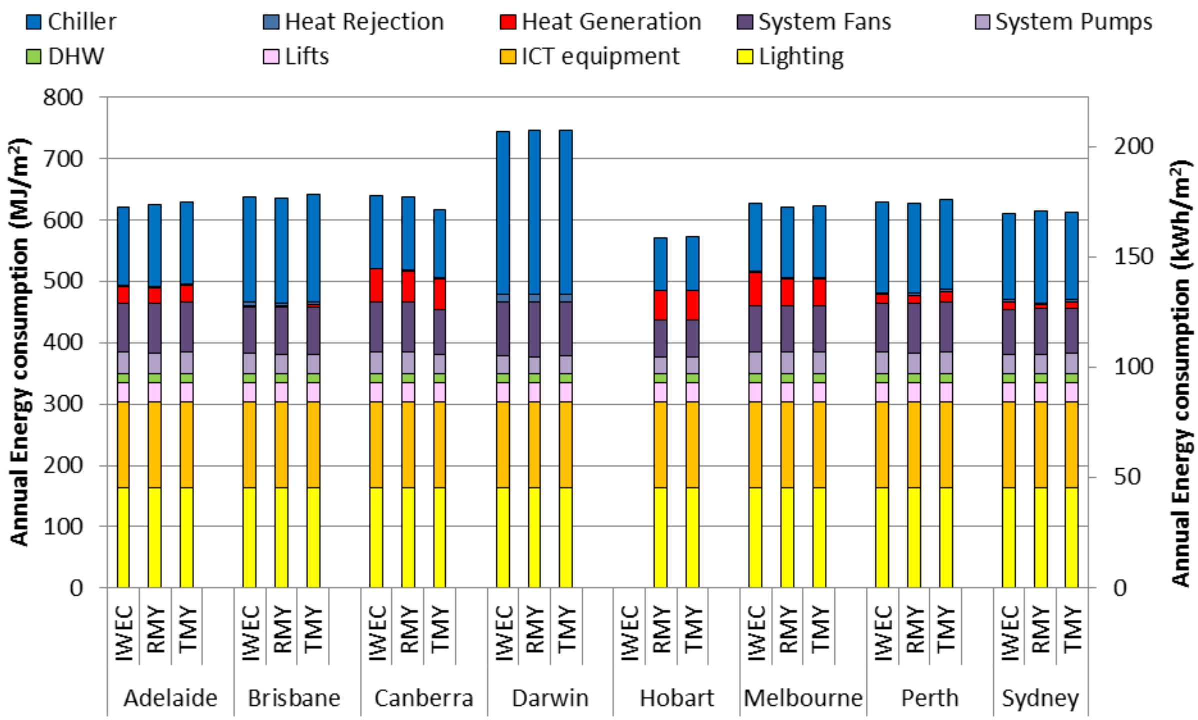


Figure 5-3 Sensitivity of building energy consumption to typical weather input file for the ABCB Form A commercial building for all capital cities in Australia.

5.4.2 Future Weather File Analysis

Future weather files were produced with the morphing procedure on currently available TMY files with one year of hourly data for all key weather parameters. The weather files were analysed to identify the predicted changes introduced by the morphing procedure. The projected hourly dry bulb temperature (DBT), dew point temperature (DPT), relative humidity (RH) and absolute humidity (AH) data were binned in frequency bins for five capital cities in Australia covering five major climate zones (BCA zones 1,2,5,6 and 7). The present author developed a visualisation tool to overlay these results on a standard Psychrometric Chart, as shown in Figure 5-4. The general trend that was observed was that the weather will become warmer and more humid, which was consistent with the predictions from previous studies (BRANZ, 2007; CSIRO, 2007; IPCC, 2007).

The mean DBT for all locations was predicted to increase from 1990 to 2080 by 3.0 °C (Standard Deviation (SD) = 0.6 °C); the mean DPT increase was 2.1 °C (SD = 0.9 °C), RH was predicted to decrease by a mean of 3.0% (SD = 2.2%) for all locations, whilst the mean AH increased by 0.0016 g/kg (0.0012 g/kg). These average changes are at the low end of the spectrum, compared to the predictions from the CSIRO GCM (Guan, 2009a). The morphed weather data files predicted an

increase in the number of hours with extreme temperatures greater than 35 °C of 170 hours/year. This value was in large part due to the predicted increase of 911 hrs/year in Darwin. The average increase in temperatures greater than 40 °C was 7 hrs/year. This information is summarised in Table 5-4, all values are significant at the 95% confidence interval.

Table 5-4 Changes to key climate variables predicted by morphed yearly weather files 1990 to 2080.

	Mean predicted change to						
	DBT (^{O}C)	**DPT (^{O}C)**	**RH (%)**	**AH (kg/kg)**	**Hours >30 ^{O}C**	**Hours >35 ^{O}C**	**Hours >40 ^{O}C**
Adelaide	2.5	1.9	-1.2	0.0010	261	100	5
Brisbane	3.7	3.1	-1.7	0.0024	916	32	0
Canberra	3.3	1.2	-7.0	0.0007	226	83	3
Darwin	4.1	3.8	-0.5	0.0042	4344	911	2
Hobart	2.0	1.6	-1.8	0.0007	16	3	1
Melbourne	2.7	1.2	-5.6	0.0006	233	62	19
Perth	3.0	2.4	-1.4	0.0014	407	115	18
Sydney	3.2	1.9	-4.4	0.0013	327	53	11
Mean	3.0	2.1	-3.0	0.0016	841	170	7

A key area of uncertainty in the generation of future weather files is the treatment of extreme heat events. The use of TMY files has a significant moderating effect on the predictions of extreme events. To create a TMY file from a given dataset of observed weather, a weighted average of important parameters is created for each calendar month, and the 12 'most average' months of actual weather data are collated as the TMY. Extreme events are therefore likely to have been filtered out, and therefore be under-predicted. The morphed weather files developed for this analysis indicated an increase in extreme days that compared well with the range of predictions from CSIRO (2007) and BRANZ (2007). However, as discussed in Section 5.3.1 morphing simply shifts and stretches the daily temperature values on the basis of predicted monthly average changes from the GCM's. In reality, a large increase in maximum daily temperature can occur with only a small resultant increase in the monthly average temperature, and these extreme events can have a large impact on energy consumption and thermal comfort in buildings. It is uncertain whether predicted increases in mean temperatures will occur as a constant warming throughout the period, or as an increase in the frequency of extreme heat events (Belcher *et al.*, 2005).

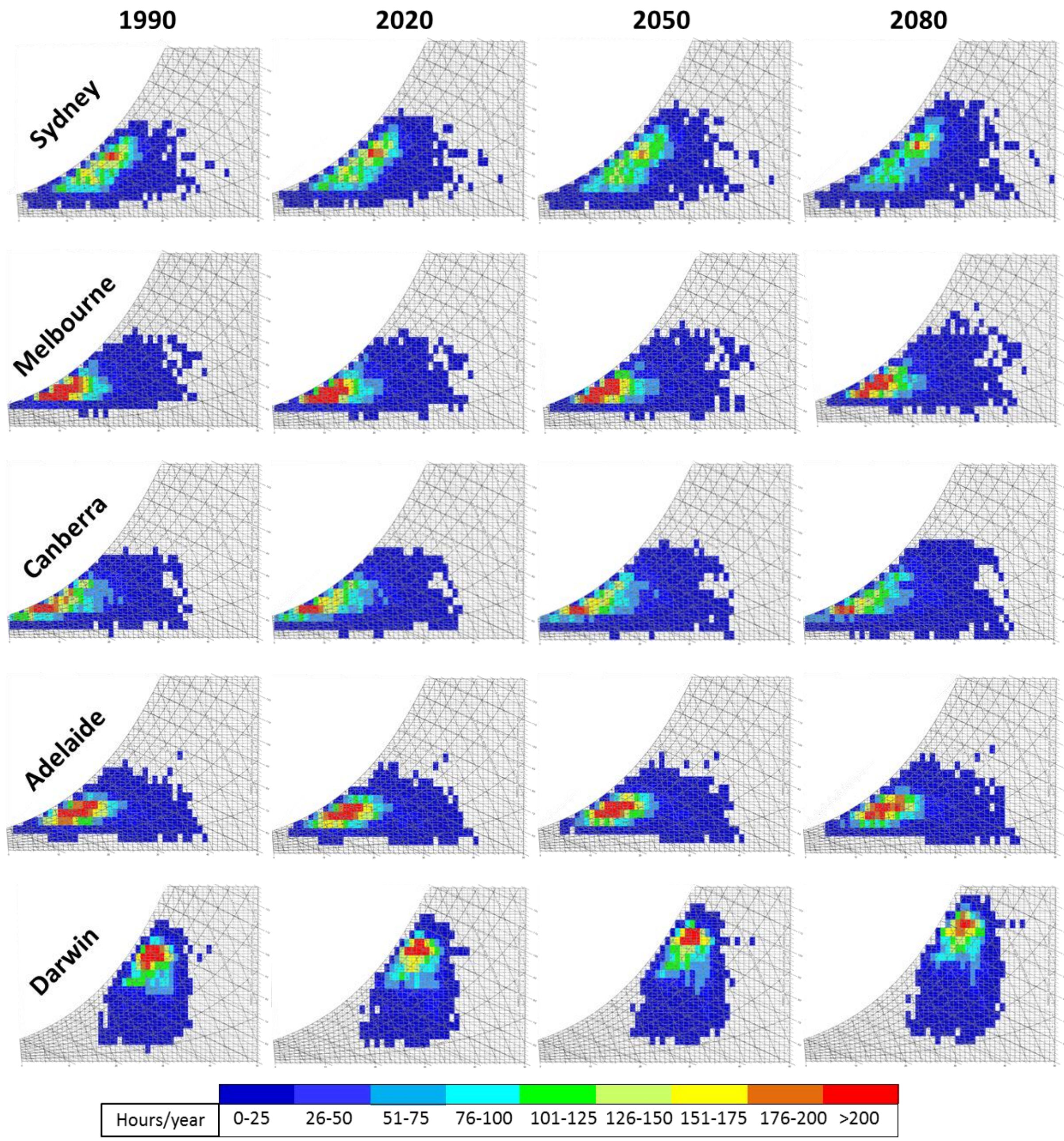


Figure 5-4 Hourly weather data binned on psychometric charts showing projected future changes to humidity and temperature for five Australian capital cities, covering five key climate zones.

5.4.3 Validation of Simulation Method

Validation of the modelling method was undertaken by comparing the present results with those in BRANZ (2007) as a benchmark. As the modelled building was an archetypal building, formal validation against measured consumption data was not possible. However, since the present study

was concerned primarily with the *relative* changes in energy consumption that result from a range of future retrofit options and climate change scenarios, rather than with the *absolute* values of energy consumption, the present author believes that this represents a valid approach.

To validate the modelling method used in the present study, the BRANZ (2007) template building was reproduced, with minor differences identified below. The predicted energy consumption and load distributions from the BRANZ study were then compared to the findings from the present study. One of the key differences between the studies was that envelope construction was considered to be BCA deemed–to-satisfy (DTS) in the BRANZ study. The present study used the same envelope construction for all locations, as it was assumed that buildings in consideration for retrofitting would not be compliant with the current BCA.

A comparison of the results between BRANZ (2007) and the present study with the HVAC definitions from ACADS-BSG (2002) is presented in Figure 5-5. There was no statistically significant difference, at the 95% confidence interval, between the mean predicted result from the present study and the BRANZ study. Figure 5-5 also shows the Australian mean energy intensity for commercial office buildings, taken from Bannister (2004). Whilst the predicted values are lower than the national mean, they are within one standard deviation of the mean. It was expected that the modelled building consumption would be lower than actual consumption data, as numerous minor energy end-uses are ignored.

The total predicted energy consumption varied between the studies by 4.5 to 6.0%, with the present study consistently predicting higher consumption. The simulation predicted similar lighting, ICT equipment, pumps, and heat generation loads in both cases. The present study consistently predicted approximately 5 MJ/m^2 higher DHW and lift loads, a higher chiller load by up to 24% (Canberra) and greater fan energy consumption by up to 25% (Adelaide). It is likely that these differences were primarily due to minor differences in the definition of various system components used between studies, and further evidence-based calibration was not possible without further detailed information. It should be noted that the original BRANZ study used DOE-2 as its simulation engine, and Schwartz and Raslan (2013) has shown that predicted overall energy consumption can vary by up to 35% when simple buildings are simulated in different programs.

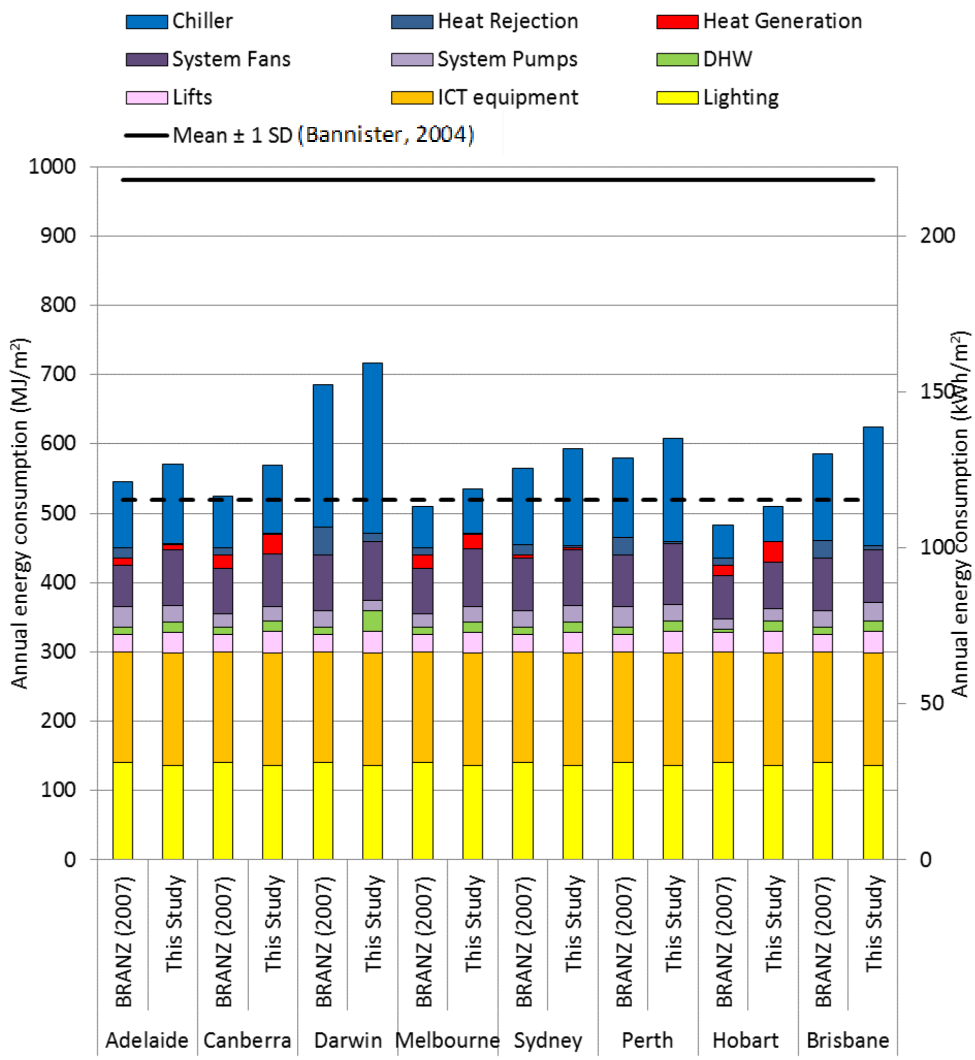


Figure 5-5 Comparison of BRANZ findings with the findings from the present study with HVAC definitions from ACADS.

5.4.4 Predicted Total Energy Consumption

The total energy consumption intensity predicted for the ABCB reference building simulated with predicted future weather conditions for five state capital cities in Australia are shown in Figure 5-6, and summarized in Table 5-5.

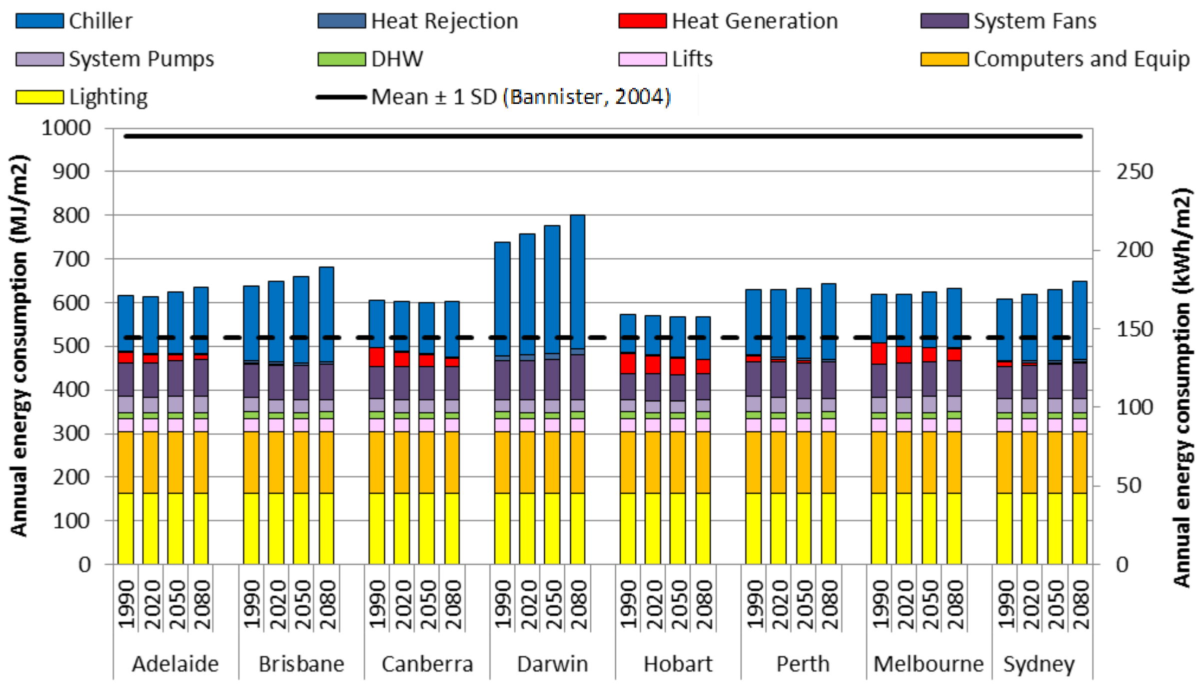


Figure 5-6 Total annual energy consumption and load breakdown as predicted by simulation of the ABCB 'A form' 10 storey building, with modified weather files to represent projected climatic conditions in 2020, 2050 and 2080 for all Australian capital cities.

Table 5-5 Percentage change to total energy consumption, cooling energy consumption, and heating energy consumption due to projected climatic changes in 2020, 2050 and 2080 for five Australian capital cities.

	% change in total energy consumption			% change in heating energy consumption			% change in cooling energy consumption		
	2020	2050	2080	2020	2050	2080	2020	2050	2080
Adelaide	-0.2	1.6	3.3	-27.9	-38	-52	4.9	11.8	19.8
Brisbane	1.5	3.1	6.5	-43.8	-79.4	-100.0	7.0	13.3	24.0
Canberra	-0.7	-0.9	-0.6	-20.4	-34.9	-50.2	4.9	9.3	16.9
Darwin	2.5	4.9	8.3	0	0	0	6.3	11.4	16.9
Hobart	-0.5	-0.9	-0.8	-9.5	-20.5	-30.8	3.2	6.3	11.5
Melbourne	-0.1	0.6	1.8	-22.1	-32.4	-43.9	7.1	13.3	21.5
Perth	0.0	0.6	2.3	-42.8	-64.5	-81.0	4.8	9.7	17.5
Sydney	1.9	3.7	6.9	-32.7	-54.7	-73.1	8.6	16	27.9

It can be seen from Figure 5-6 and Table 5-5 that the predicted impact of climate change on total energy consumption was heavily influenced by local climatic conditions, specifically the presence of a substantial heating demand in 1990. For locations which had a substantial heating demand in 1990 (such as Melbourne), increased cooling load over time was partially balanced by a decreased heating load, which resulted in a relatively small change to the total predicted annual energy

consumption. The total energy consumption for the building in Canberra in 2080 was predicted to decrease by 0.6% as compared to 1990, while the total energy consumption in Melbourne and Adelaide was predicted to increase by 1.8% and 3.3%, respectively. An increase was predicted in the overall energy consumption for cooling load dominated climate zones, i.e. an increase of 6.9% for Sydney and 8.3% for Darwin by 2080. The mean change in total consumption between 1990 and 2080 was statistically significant at the 95% confidence interval; however, changes across smaller time-periods (e.g. 1990-2020) were not necessarily statistically significant. There was a decrease in heating energy in Sydney, but this change in heating consumption was insignificant compared to the increase in cooling consumption.

Compared to the BRANZ study (2007), a lower increase in overall consumption was predicted for all locations, i.e. 6.9% in the present study compared to 14.3% by BRANZ for Sydney, 1.9% versus 9.9% for Melbourne, -0.6% versus 7.7% for Canberra, 3.3% versus 12.0% for Adelaide and 8.3% to 18.8% for Darwin, respectively. The average increase from this study was significantly different to the BRANZ predicted increase at the 95% confidence interval. The predicted change in overall consumption was similar to the predicted changes for the 2070 Low scenario in Guan (2012). It should be noted that the BRANZ climatic predictions are for 2070. In both studies, the increases are solely due to the heating and cooling system energy consumption. The present study predicted a higher heating load in 1990 for the building in all cases other than Darwin, where both studies predict no heating. In the cities which had a significant heating load, the present study predicted a heating load approximately double that predicted by BRANZ (2007). This moderates the predicted increase in overall consumption.

Looking only at the predicted cooling consumption the present study still predicted significantly lower increases in consumption at the 95% confidence interval. The extreme example was in Melbourne; the present study predicted an increase in cooling consumption of 21.5%, while the BRANZ study predicted an increase of 83.3%. Some variation was likely due to the BRANZ assumption that the buildings are BCA compliant and therefore have different construction. The ABCB (2004) found that improving an unregulated building to be BCA compliant would reduce energy consumption for the ABCB Form A building by between 16% and 26%, depending on climate zone. The different HVAC definitions utilised in the present study will also introduce some variations. The view of the present author is that a significant amount of the variation is due to the differences in the predictive weather files used for simulation. This highlights the need for the provision of high quality predictive weather files for building energy researchers and designers, and

a standard agreement for the generation and use of these, as well as the need for further research into this issue.

5.4.5 Influence of Potential Changes in Internal Heat Load Scenarios and Envelope Retrofits on Future Building Energy Consumption

The results presented in Figure 5-6 assumed that energy consumption for items not directly linked with external climatic conditions (i.e. lighting, equipment etc.) remained constant over time. However, the potential change in the internal heat loads from such sources may be significant over the 90-year period of the predictions. When assessing the significance of climate change with respect to selected retrofit selections for a given building and climate zone, changes to these parameter may be significant. Whilst an increase in overall energy consumption of 8.3% against a 1990 baseline may initially appear to be significant, this projection was for 2080, a period of 90 years. Several possible building upgrade and alteration scenarios were simulated to investigate the relative magnitude of this increase. The results of these simulations are presented in Figure 5-7 and Figure 5-8, which show the relative magnitude of climate change effects as compared to potential future changes in internal heat loads.

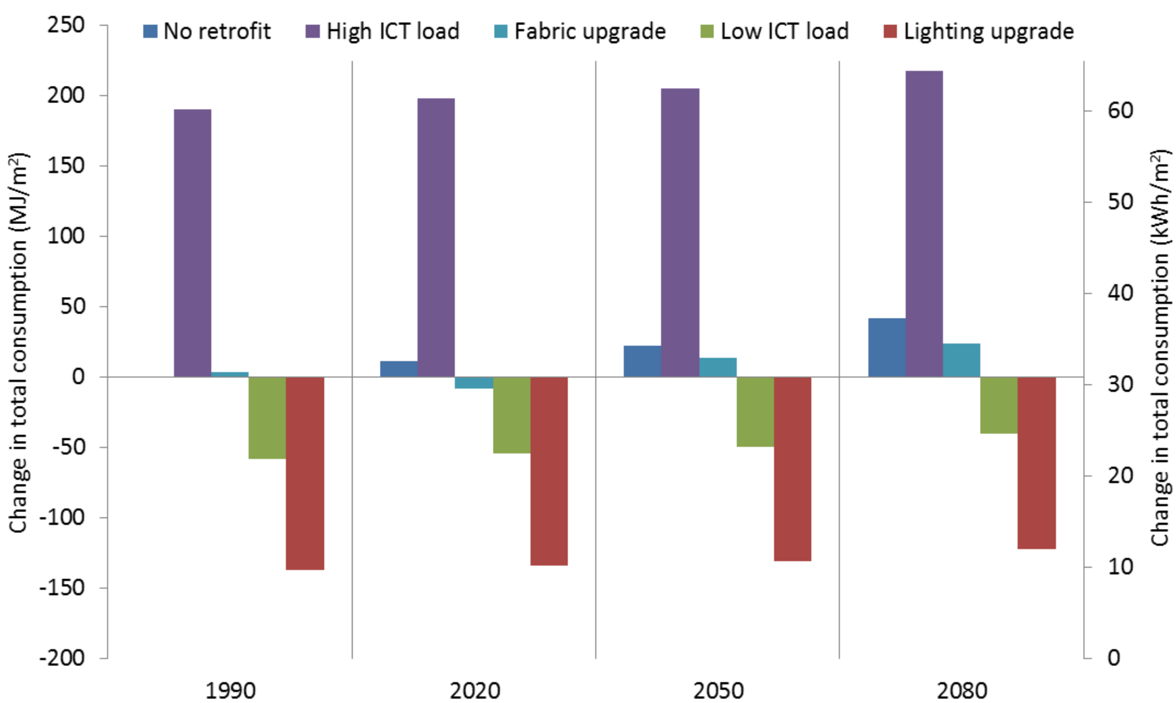


Figure 5-7 Overall change in energy consumption for all modelled scenarios for Sydney from 1990 to 2080, compared against a datum/zero taken to be the 1990 template building consumption.

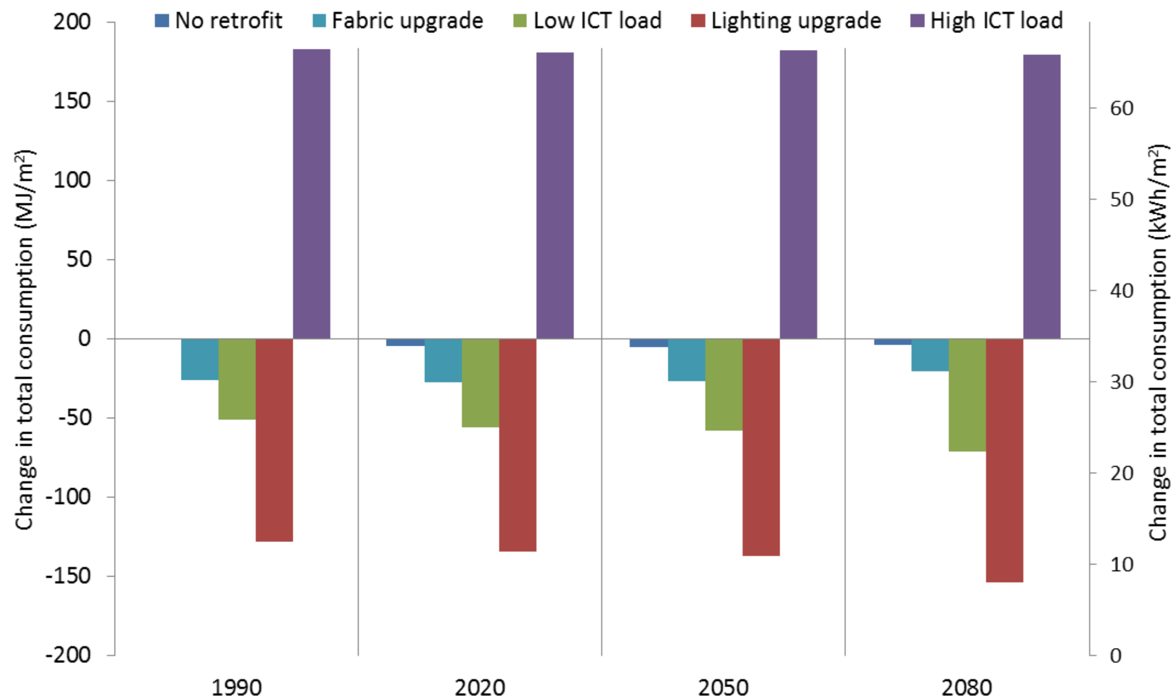


Figure 5-8 Overall change in energy consumption for all modelled scenarios for Canberra from 1990 to 2080, compared against a datum/zero of the 1990 template building consumption.

When compared to other potential changes to building energy consumption due to building services upgrades, the results of the present simulation showed that climate change could be expected to have a smaller relative impact on overall energy consumption. An increase in total energy consumption of 8.3% (for Darwin 1990 vs 2080), the maximum predicted by the present study, was minor compared to the possible trends in ICT energy consumption envisaged by Johnston *et al.* (2011). In 2080 the difference in predicted total energy consumption between the high and low ICT scenarios was 339 MJ/m^2 for Sydney (a 36% increase and a 20% decrease), and 333 MJ/m^2 for Canberra (+29% and -26%). Similarly, relatively simple energy efficiency improvements, such as lighting upgrades, are predicted to have a larger impact on overall energy consumption than climate change over the period 1990 - 2080. All values quoted are significant at the 95% confidence interval. This was to be expected for commercial buildings, as internal loads are typically more significant than envelope loads.

It was also useful to consider the relative impact of climate change on the NABERS energy rating of a building, which is well established in the Australian commercial building sector. The NABERS rating is based on benchmark energy consumption intensities for office buildings, which vary

depending on location. The simulation results of the present study showed that NABERS ratings are insensitive to climate change impacts. There was no change due to climate change between the predicted NABERS Star rating in 1990 and in 2080 at any location in Australia. From the evidence presented above, it is unlikely that climate change will have a significant influence in the selection of optimal retrofit strategies for commercial building retrofits when total annual energy consumption is used as a metric, primarily due to the long time scale. However, the impact of extreme events on other metrics, for instance peak load (and associated future tariffs), will require further investigation. .

5.4.6 Climate Change Influence on Total Design Cooling Requirement

Climate change would also be expected to impact on the design cooling load for HVAC equipment sizing. Building owners considering replacing HVAC systems need to consider changes to the expected maximum cooling load over the whole life of the systems, and a changing climate would be expected to alter design loads. Correctly sized HVAC systems can yield significant capital and operational cost savings compared to standard, over-sized systems (Thomas & Moller, 2007). Figure 5-9 illustrates the design cooling requirement for the archetypal building located in five major cities from 1990 – 2080.

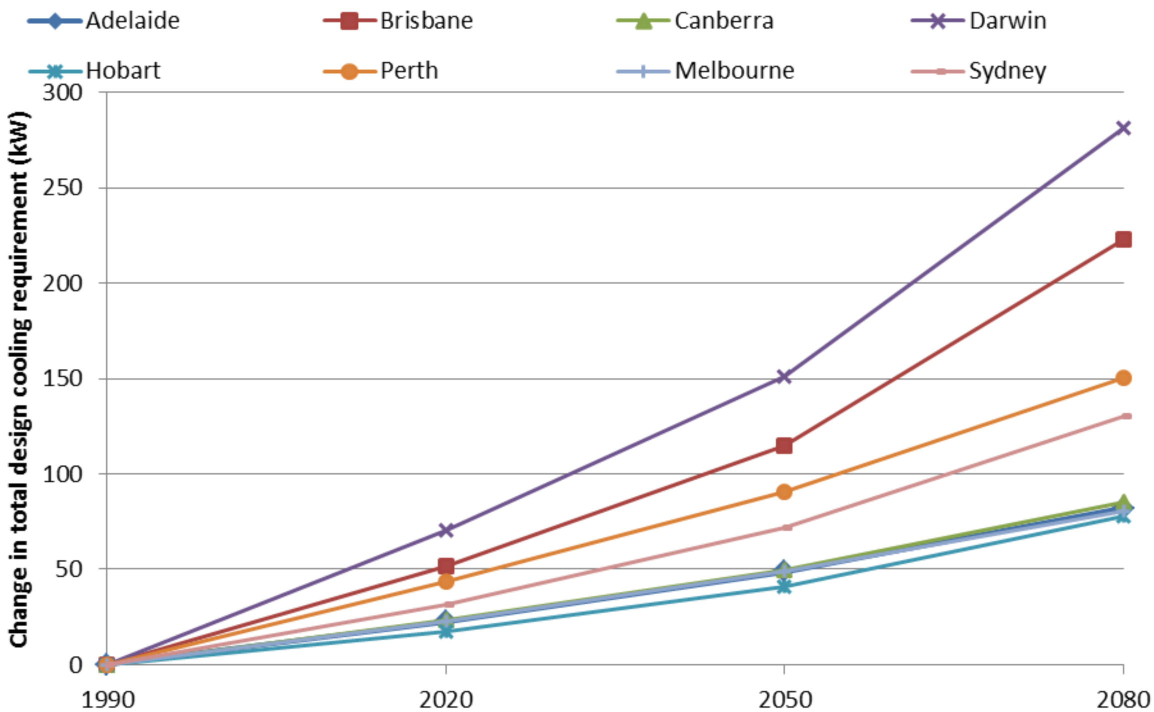


Figure 5-9 Total simulated design cooling requirements for ABCB Form A building for current and possible future climates in 2020, 2050, and 2080 in Australian capital cities

Whilst a substantial increase of between 9.1% and 25.0% was predicted, this was over a period of 90 years. For the 30 year period between 1990 and 2020, the maximum increase in total design cooling requirement was 6.3% occurring in Darwin; while the other simulated cities showed an increase of between 2.5% and 3.6%. All predicted changes were significant at the 95% confidence interval. This 30 year period is the timescale that would have a bearing on the sizing of a HVAC system, and the relatively small impacts predicted are unlikely to be significant in the decision process. The impacts of other future trends shown in Figure 5-7 and Figure 5-8 are of greater concern to HVAC sizing than the changing climate.

5.4.7 Limitations of Modelling

In the actual modelling of the building there was also significant uncertainty. As well as the uncertainty inherent in any building energy modelling project (Guyon, 1997; Neymark *et al.*, 2002; Turner & Frankel, 2008), the use of archetypal buildings and default values meant the results of the present study were indicative of how buildings will behave rather than definitive. In reality, a successful retrofit must be carefully tailored to an individual building. The fact that the results varied so significantly from the findings of the BRANZ (2007) highlights the uncertainty in this

field, and the need for further research to enhance confidence in simulations. The present study also raised reproducibility of results as an important issue in the field of building simulation research. It is generally very difficult to replicate an energy modelling study of a particular building given the limited data on the building provided in the simulation method in most publications. There is a need to generate more examples of well-defined and very well documented benchmark building archetypes that can be used for benchmarking purposes by researchers and energy modelling practitioners.

5.4.8 Chapter summary

Retrofitting of existing buildings is a key strategy to mitigate, and adapt to, future climate change. Moreover, climate change is a factor frequently cited driver by building owners as a reason to undertake retrofits aimed at reducing energy consumption. This chapter has concluded that, when compared to projected changes in energy consumption and cooling load due to basic retrofit strategies and likely scenarios for changes in ICT equipment loads, it would appear that the impact of climate change on building energy consumption is not likely to be a primary factor in the building retrofit decision making process for typical commercial buildings.

6 Risks and Uncertainties Introduced by Common Assumptions in Energy Simulations for Australian Commercial Buildings

To predict a building's energy consumption reliably with Building Performance Simulation (BPS), accurate inputs representing the building's physical characteristics and operation are essential. BPS modellers are often limited by a lack of access to detailed data on specific building construction and operation characteristics. As a result, modellers must rely on assumptions or default values regarding occupant behaviour and hard-to-measure building characteristics, referred to as 'simulation assumptions' in this study, to input to BPS programs. The 'performance gap' identified in Section 2.6 has been attributed to many causes, but one commonly cited cause is the inaccuracy of simulation assumptions (Bordass *et al.*, 2001; Guyon, 1997; Menezes *et al.*, 2011; Simm *et al.*, 2011). Simulation assumptions do not always have an evidential basis for use in Australia; they are often imported from overseas experience, studies and modelling protocols. As construction techniques, building stock compositions, occupant behaviours and usage schedules can vary significantly internationally, simulation assumptions may not represent the Australian situation appropriately. Simulation assumptions can have a significant impact on the simulated energy consumption of a building, and affect the predicted energy savings and payback periods for buildings retrofits.

Insufficiently accurate BPS predictions are likely to become significantly more problematic for industry as new financing schemes relying on predicted quantitative energy savings are introduced locally and internationally. Two recent developments in this area in Australia are Environmental Upgrade Agreements and Energy Performance Contracts, discussed in Section 2.10.5, EUAs have some similarities to 'Property Assessed Clean Energy' legislation operating in parts of America since 2008. A finance provider lends funds to a building owner for water, energy and other environmental upgrades, and this low-risk loan is repaid through a local council charge on the property (OEH, 2013). An EPC is a legal guarantee from a third party that the predicted savings will be realised, or equivalent compensation will be provided. EPCs have been widely implemented internationally (Vine, 2005) and may potentially form a key component of EUA financing (Blundell, 2012). Both of these financing mechanisms tie financial and legal risk to the uncertainty associated with predictions from BPS.

6.1 Review of National and International Simulation Assumptions

Where specific building information is not available, best practice energy simulation assumptions are based on statistically significant studies of a large building stock with similar characteristic to the building in question. As discussed in Section 2.9, Deru *et al.* (2011) utilised the CBECS, along with other sources, to define 16 building archetypes, which were claimed to characterise 70% of the American building stock. The DoE also supports a Buildings Performance Database, containing actual energy use data for 1,472 commercial buildings (U.S. Department of Energy, 2013a). In the United Kingdom the Non-Domestic Energy Efficiency Data Framework, developed from the Non-Domestic Building Stock database (NDBS) (Bruhns, 2000) and other data sources (Liddiard, 2012) provides similar information. The NDBS was built from information contained in the council rates database for four English towns, a general survey and a detailed energy survey. The information collected during the detailed energy survey gives energy modellers the capability to assess the validity of simulation assumptions for the UK building stock.

6.1.1 Data Sources and Simulation Protocols in Australia

Databases similar to those used in international studies to inform building simulation assumptions are not available in Australia; an issue identified by Aherne (2013). The most comprehensive energy consumption database analysis to date in Australia was the pitt&sherry (2012a) report, in which 4,308 energy consumption records (base, tenancy or whole building yearly energy consumption) for 1,715 unique buildings across Australia were complied. However, this project did not attempt to address the lack of data on building attributes and occupant behaviours that impact building energy consumption in Australia. Work is currently being undertaken by a number of groups and individuals with the aim of 'harmonising' the simulation assumptions used in three key modelling protocols in use in Australia. This was discussed in more detail in Section 2.6.4 and Chapter 7. One aspect of this effort is to identify the necessary source data in Australia to base simulation assumptions and default values (Aherne, 2011; Exergy Australia, 2011; Swain *et al.*, 2013).

6.1.2 Simulation Assumptions

As noted above, for many parameters affecting energy use in commercial buildings no large-scale studies with actual field measurements have been undertaken in Australia. Moreover, there are a

number of previous studies that demonstrate the wide range of values found in operational buildings.

A desktop analysis by Reilly (2002) used minimum lighting standards in Australia, and common luminaires to identify an average lighting power density of 13.5 and 17.15 W/m^2 for offices larger and smaller than 36 m^2 respectively. ABCB (2006a) suggested the lighting power density in office buildings may be as low as 9.3 W/m^2. Donnelly (2002) identified typical lighting power density input ranges for BCA Class 5 buildings (offices) for energy simulation as 9-20 W/m^2. Camilleri and Babylon (2011) found an average lighting power density of 21.1 W/m^2 after undertaking detailed monitoring of 60 commercial premises in New Zealand. Jenkins *et al.* (2011) assumed a lighting power density of 9.4 W/m^2 for offices in the UK in their investigation of methods to achieve a 50% reduction in carbon emissions by 2030. Deru *et al.* (2011) used a lighting power density of 10.8 to 16.9 W/m^2 in their commercial reference buildings for the U.S, depending on age. The analysis of the BEER conducted in Chapter 4 found and average LPD of 13.51 W/m^2 (SD = 6.00). It was also found that 73.1% of the spaces assessed were outside the current LPD assumptions recommended by Australian modelling protocols, of between 7 to 12 W/m^2 (Aherne, 2011).

Aherne (2011) showed the recommended value for ICT power in the three energy modelling protocols in use in Australia, identified in Section 2.6.4, varying from 11-15 W/m^2. Donnelly (2002) identified ICT density ranges office buildings for energy simulation as 0-20 W/m^2. Deru *et al.* (2011) used a power density of 7.5 W/m^2 in their representative offices. Chidiac *et al.* (2011b) assumed an ICT power density of 30 W/m^2 for post 1975 constructions in Canada. BSRIA (2003) has a recommended rule of thumb value of 15 W/m^2. Menezes *et al.* (2013) found benchmark values for ICT equipment power in the UK varied between 10 and 18 $W/m^{2.}$ The author quoted research by the British Council for Offices, which showed an ICT power density range from 3 to 61 W/m^2, with more than a third of monitored buildings having a density greater than 15 W/m^2.

Egan (2011) examined the simulation assumptions used for air-tightness and occupancy density of Australian office buildings, and the energy implications of these inputs. The infiltration rates for six office buildings in Canberra were measured; the average infiltration rate was found to be 0.46 ACH (Air changes per hour), with a range from 0.26 to 0.81 ACH. Simulations were conducted for six buildings, with input infiltration ranging from 0.25 to 1.5 ACH with an increment of 0.25 ACH. The predicted energy consumption was found to vary by up to 15% at 0.25 ACH, and by up to 30% at 1.5 ACH, against a datum of 1 ACH, across all modelled buildings and climates.

Egan (2012) measured the occupant density in three office buildings in Canberra; the reported results ranged from 21.6 to 47.3 m^2/person, with an average of 28.6 m^2/person. Simulations were also conducted with peak occupant density ranging from 12.5 to 75 m^2/person. Across all modelled buildings and climates, energy consumption varied by up to 15% at 75 m^2/person, up to 13% at 12.5 m^2/person, against a datum of 15 m^2/person. Warren (2003) conducted a survey of office use in Australia with 258 respondents. The author found that the average occupant density in Australian office buildings was 20.6 m^2/person, with an interquartile range from 14 to 53 m^2/person. GREG (2004) reported the occupant density targets for government offices in Australia, which ranged from 15 to 18 m^2/person, with an average achieved density of 18.3 m^2/person. Donnelly (2002) found assumed occupant density BCA Class 5 buildings (offices) ranged from 2 to 20 m^2/person.

It is difficult to comment meaningfully on the validity of current common simulation assumptions without substantial data resources specific to Australia, however in light of these studies it is clear that the range of values found in real buildings will heavily influence energy consumption, and may be a significant source of inaccuracy in energy simulation.

The preceding targeted review of relevant publications has shown that there is a wide range of simulation assumptions currently being employed in literature for simulation of buildings in the Australian context, and that actual conditions in the existing stock may be significantly different from the assumed value. It has also further emphasised that the use of assumptions and heuristics is an accepted feature of building simulations for certain building attributes. The range of simulation assumptions and default values for key parameters identified through the literature review is summarised in Table 6-1.

Table 6-1 Range of simulation assumptions used in previous publications for modelling Australian Building Codes Board (ABCB) Form A and Form B archetypal buildings.

Parameter	Form A	Form B	Input range for other building archetypes in international literature[1]
Lighting power density (W/m²)	9.3 – 15	9.3 – 15	9.3 – 26
ICT power density (W/m²)	11 – 15	11 – 15	7.5 – 30
Ventilation requirements (Litres/second/person)	7.5 – 10	10	7.5 - 12.5
Occupancy (m²/person)	10	10	5 – 53
Window U-value (W/m²)	1.52 - 5.89	2.7 - 5.89	1.37 - 6.42
Infiltration (ACH)	0.5 - 1.5	1 - 1.5	0.44 - 1.5

1 – Key studies consulted in sourcing values (Chidiac et al., 2011b; Deru et al., 2011; Jenkins et al., 2011; Lam & Hui, 1996; Stocki et al., 2007)

6.2 Research Method

In the absence of statistically significant real-world data on energy consumption and occupant behaviour in commercial buildings, the present study tested the sensitivity of energy simulation outputs to the quantitative values of assumed input parameters for the ABCB Form A and Form B template buildings. DesignBuilder, a user interface for the EnergyPlus dynamic thermal simulation engine, was employed for this analysis. Form A and Form B buildings were simulated in all Australian capital cities with the relevant IWEC EnergyPlus weather files. A RMY file was used for Hobart (Tasmania) since an IWEC file was not available. A more detailed discussion of these features was included in Chapter 3

6.2.1 Base Building and System Description

The ABCB Reference buildings used in this sensitivity analysis have been discussed in detail in Section 3.5. The geometries of the buildings were sourced from ABCB (2001) and were outlined in Table 3-2, along with the base case model inputs used for the buildings from ACADS-BSG (2002). The total building energy consumption was compared to national and state averages determined from real world data from Australian office buildings (Bannister, 2004; pitt&sherry, 2012a) to validate that the predicted energy consumption was realistic.

6.2.2 Sensitivity Analysis

In this study, a Differential Sensitivity Analysis (DSA) was conducted following the procedure outlined in Section 3.6. The minimum and maximum values for each parameter of interest are shown in Table 6-2. DSA was appropriate for this study as the aim was to test the sensitivity of building energy use to the value of user assumptions, rather than a probability distribution of an uncertain input. DSA provides information about the sensitivity of a parameter at a single point in the parametric space, and does not provide insight into areas outside the parametric range of a given set of simulations, unless the data can be linearly extrapolated (Bertagnolio, 2012). Again, this was appropriate, as this study tested the uncertainty of predicted building energy use to the known range of commonly assumed values for various inputs.

The sensitivity of each variable was expressed as the non-dimensional influence coefficient, introduced in Section 3.6. Several limitations were considered when making comparison across parameters based on a calculated influence coefficient. The influence coefficient was calculated with an assumption that the output will vary approximately linearly (Simm *et al.*, 2011) in response to a change in input, and any deviation from linearity will cause errors. The coefficient of determination (R^2) value can be calculated as a check for linearity for each input parameter. It is vital to remember that for simulation of building performance, every parameter has a limited range of realistic values, so the percentage change to the input parameter will be constrained uniquely for each input. Some parameters, notably temperature, are sensitive to the selection of a datum and scale. This is discussed further below.

Table 6-2 displays the high, low, and base case values of the input variables; the output parameter was the total building energy consumption. In some situations more than three values were simulated, to represent simulation assumptions from previous studies. The input parametric range was determined based on the following data sources: statistically significant real-world Australia data; statistically significant real-world international data; field measurements from Australia; default values included in standards and modelling protocols; and previously published input values from Australian studies. The envelope upgrade scenarios represent an improvement to best practice for windows, and a doubling of installed insulation for walls and roofs.

Table 6-2 High and low scenarios for sensitivity analysis

Parameter of interest	Base inputs	Low Scenario	High Scenario	ZCA Scenario (ZCA, 2013)
Lighting power density (W/m^2)[1]	15	9.3	21	12
ICT power density (W/m^2)[2]	15	7.5	20	11
Ventilation requirements (Litres/second/person)[3]	10	7.5	12.5	7.5
Occupant Density (m^2/person)[4]	10	5	50	10
Infiltration (ACH)[5]	1	0.25	1.5	1
Cooling set-point (^oC)[6]	24	28	22	24
ICT usage schedule (hrs/wk)[7]	103.1	60.9	136.3	103.1
Occupancy Schedule (hrs/wk)[8]	48.2	37.9	58.2	48.2
Window U-Value (W/m^2-K)[9]	5.89	1.70	3.16	5.7
Wall U-Value (W/m^2-K)[10]	0.522	0.264	1.322	0.522
Roof U-Value (W/m^2-K)[10]	0.28	0.17	0.85	0.28

***1.** Low scenario from ABCB (2006a), high from Camilleri and Babylon (2011);*
***2.** Low scenario from Deru et al. (2011), high from Donnelly (2002);*
***3.** Low scenario from minimum required rate in AS1668.2 (Standards Australia, 2012), high from Stocki et al. (2007);*
***4.** Low scenario from ABCB (2006a), high from Warren (2003);*
***5.** Low and high scenarios from Egan (2011);*
***6.** Low scenario from Schiller et al. (1988), high from Samarakoon and Soebarto (2011);*
***7.** Low scenario assume 5% of equipment was left on outside hours, high assumes 75% of load was left on 24 hours;*
***8.** Low scenario assumes 85% occupancy during business hours, 50% during lunch, high assumes 100% until 6 pm, 50% 7-8 am and 6-7 pm;*
***9.** High scenario was double glazing with an air gap, and low scenario was low-e double glazing with an argon gap;*
***10.** Low value represents the ABCB template construction with the insulation removed, and the high scenario was a doubling of the thickness of the insulation layer.*

The input values were selected to create a wide parametric space, covering expected conditions, occupant behaviour, and building constructions of a majority of Australian commercial office conditions. The values were taken from a wide range of sources as identified in the footnotes to Table 6-2, inputs related to HVAC specific attributes (e.g. chiller COP) or attributes unlikely to change due to a retrofit (e.g. window-to-wall ratio) were not considered in this analysis. The simulation assumptions used for the Zero Carbon Australia (ZCA) Buildings Plan (2013) were also

simulated. The ZCA values were thought to be to be most representative of the Australian commercial building stock by ‘experts from academia and industry’; as discussed in Section 2.9.3.

The buildings were first simulated with the base inputs, and then the parameters of interest were varied one at a time while holding all the other parameters constant. The total building energy consumption was calculated for each case, and the average influence coefficient across each parameter range was calculated. The coefficient of determination (R^2) was also calculated to test the assumption of linearity. Cases with a value of R^2 less than 0.8 were taken to indicate that the assumption of linear response may not hold, and that further investigation would be required to understanding the interaction.

6.3 Results

6.3.1 Model Validation

The predicted whole building annual energy intensities for the ABCB Form A and Form B buildings modelled with the base case simulation assumptions for all Australian capital cities are shown in Figure 6-1. The predicted energy intensities were all within one standard deviation of the average Australian energy intensity for office buildings for all locations calculated by Bannister (2004). pitt&sherry (2012a) identified the average energy end use breakdown for Australian office buildings from a dataset of 1,150 buildings. The breakdown indicated that electricity was primarily used for HVAC (43%), lighting (26%), and ICT (20%). Domestic hot water (DHW) and other electrical processes make up the balance. The simulations of the present study indicated that the building archetypes had an average energy breakdown of 49.6% HVAC, 28.5% ICT, 29.6% lighting, 1.4% DHW and 1% other electrical processes, which provided some confidence in the validity of the modelling (noting that a number of second order ancillary electrical processes were not modelled).

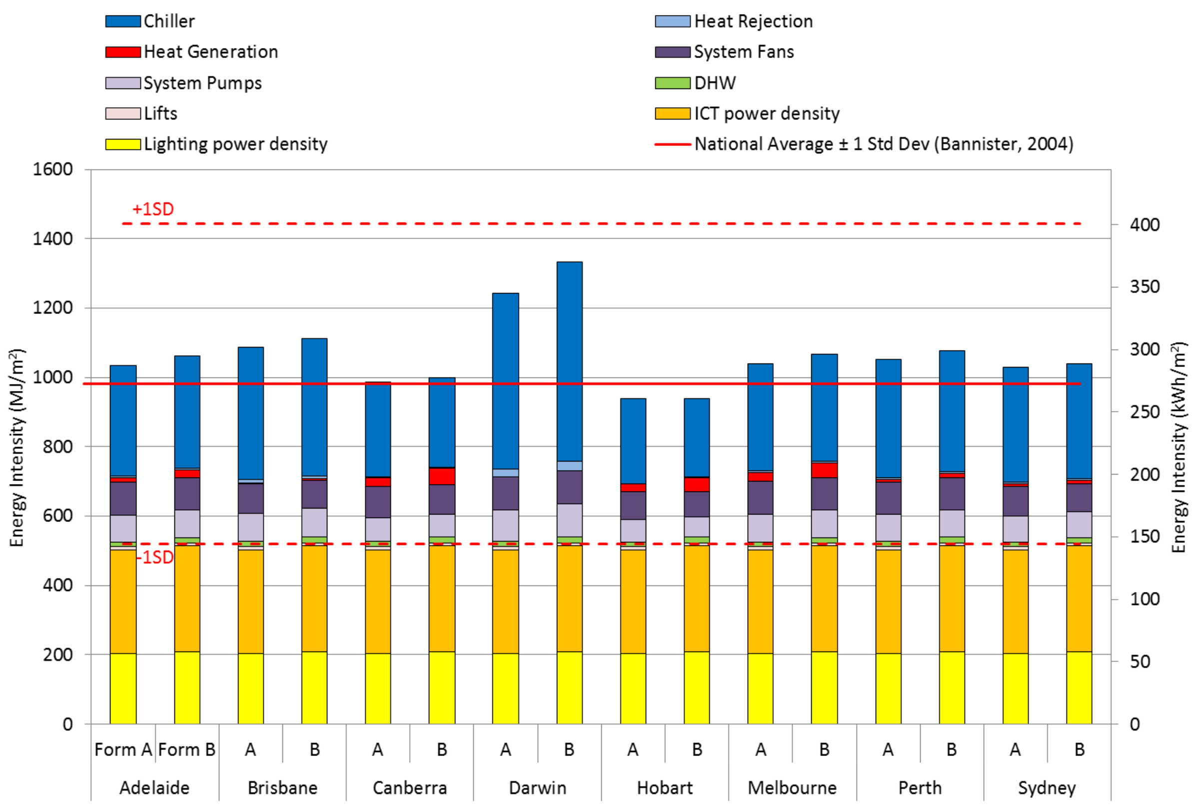


Figure 6-1 Predicted energy intensity from simulation of ABCB Form A and Form B archetypal buildings, including load breakdown, compared to average national energy intensity for office buildings reported by Bannister (2004).

The predicted annual energy intensities were found to be within one standard deviation of the relevant state average for all locations, except Perth and Darwin, as shown in Figure 6-2. Bannister (2004) did not provide a state average energy intensity for New South Wales (NSW) or the Australian Capital Territory (ACT), and an extensive literature review by the present author could locate no other reliable source. The average energy intensity for each location calculated from the BEER was used (see Section 4.2.1). There were insufficient records in the database to calculate an average for the ACT or the Northern Territory (NT). The calculated averages and the averages from Bannister (2004) agreed within one standard deviation with the Australian, Sydney, and Melbourne values published in pitt&sherry (2012a). The values for Adelaide and Hobart had noticeably larger standard deviation than other locations; this was most likely due to the small sample size for these cities in the initial study (Bannister, 2004).

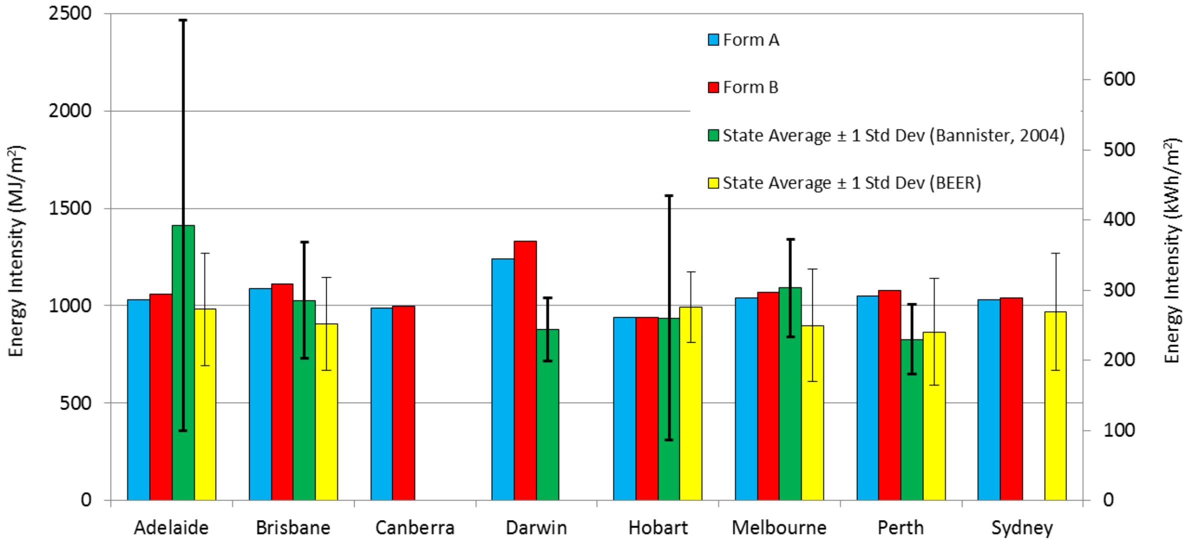


Figure 6-2 Predicted annual energy intensity for ABCB Form A and Form B buildings modelled with base case simulation assumptions for all Australian capital cities. Also displayed is the average state energy intensity for commercial office buildings published by Bannister (2004).

The predicted energy intensity was more than one standard deviation above the state average calculated by Bannister (2004) for both Darwin (NT) and Perth (WA), although Perth was within one standard deviation of the BEER average for WA. There were several possible causes for the disparity, including: building construction not being representative of the building stock in those locations; the modelled cooling set point being higher than the actual set-point in those climates (although Adelaide is in the same climate zone as Perth); or differences in occupant behaviour. pitt&sherry (2012a) found that Perth had the lowest base building energy consumption of any studied locations, but had insufficient data to estimate tenancy consumption in Perth, and base or tenancy consumption in Darwin. pitt&sherry (2012b) also noted that in the authors' experience, energy consumption between two climate extremes (hottest and coolest) in Australia should be no more than 6-8%. This suggests that the high prediction for Perth and Darwin may have been due to incorrect simulation assumptions.

The buildings modelled with the base case inputs would have been rated 0 to 3 Stars under NABERS, depending upon locations (see Table 6-3) and would be characterised as poor to average in energy performance. This was not an unexpected result, as some of the inputs to the model had their source as a worst-case assumption. For instance, the NABERS schedules and occupancy defaults are conservative values to be used when no other information is available, and would be expected to predict high energy consumption.

Table 6-3 NABERS star rating for modelled buildings in all locations with the base case assumed values for input parameters.

	Adelaide	Brisbane	Canberra	Darwin	Hobart	Melbourne	Perth	Sydney
Form A	2	1.5	2.5	0	3	3	0	2
Form B	2	1	2.5	0	3	3	0	2
Average consumption from CBD (2013)	2	2.5	NA	NA	2.5	3.5	2	2.5
Average consumption from Bannister (2004)	0	1.5	NA	NA	3	3	2	NA

That the building simulated in the Perth climate would have been rated 0 Stars by NABERS was further evidence that the building forms and simulation assumptions were not representative of the actual situation in this location, as the average NABERS rating for commercial buildings in Perth was 2 Stars. Without a detailed understanding of the building stock of those locations it was difficult to identify the source of the difference, from the evidence of the present study the ABCB archetype buildings with the base case simulation assumptions may not be representative of commercial buildings in Perth or Darwin.

6.3.2 Total Energy Sensitivity to Building Inputs

The predicted annual energy consumptions for a number of input variable scenarios are shown in Figure 6-3 and Figure 6-4: the base case; an 'all-high' scenario and an 'all-low' scenario, with the maximum and minimum predicted consumption in the parameter space; and a scenario with the simulation assumptions developed by ZCA (2013).

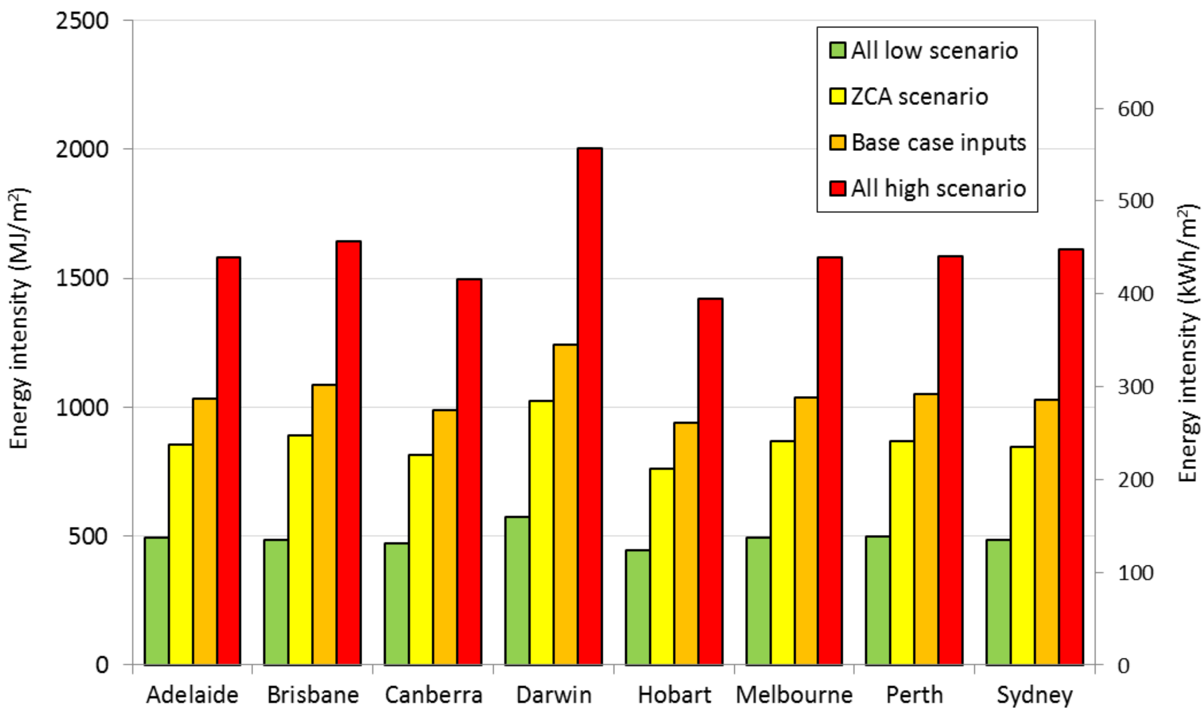


Figure 6-3 Total predicted energy intensity of ABCB Form A building. Base case scenario refers to base case simulation assumptions taken from ACADS-BSG (2002), high and low scenarios are maximum and minimum EUI scenarios simulated with the values listed in Table 6-2, and ZCA refers to a scenario with simulation assumptions from ZCA (2013).

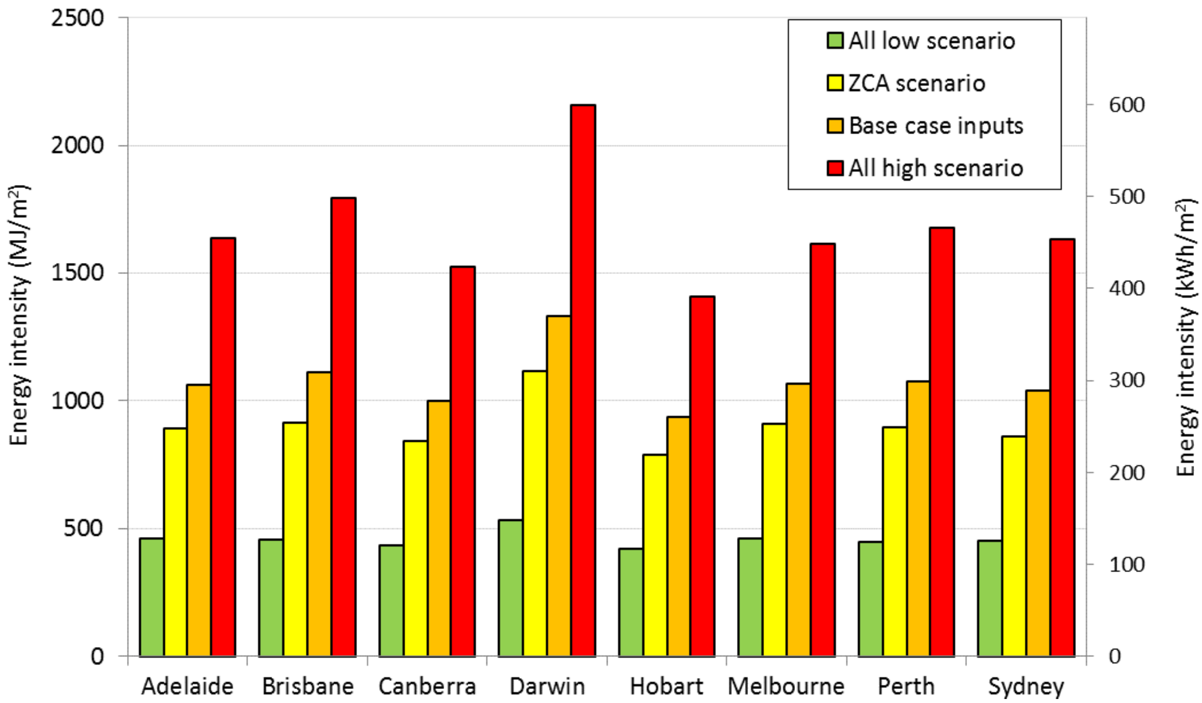


Figure 6-4 Total predicted energy intensity of ABCB Form B building. Base case scenario refers to base case simulation assumptions taken from ACADS-BSG (2002), high and low scenarios are maximum and minimum EUI scenarios simulated with the values listed in Table 3, and ZCA refers to a scenario with simulation assumptions from ZCA (2013).

Energy consumption in the all-high scenario was consistently more than double the all-low scenario. The all-high and all-low inputs were selected to be extreme values, however, they were extreme values that could have been expected in the Australian commercial building stock, and indeed had been used in previous studies. The predicted building energy consumption from simulations with the ZCA inputs was consistently lower than the base-case inputs from ACADS-BSG (2002), i.e. 17 to 25% lower for Form A (Perth and Darwin, respectively) and 15 to 18% lower for Form B (Melbourne and Brisbane, respectively). ZCA also used the NABERS schedules for occupancy, equipment and HVAC. Given the magnitude of predicted savings generally expected for energy efficient retrofits, this was considered a significant difference.

6.3.3 Sensitivity Analysis

Table 6-4 and Table 6-5 present the Type 2 influence coefficients; the highlighted values with R^2 less than 0.8 indicate that the total energy consumption had a complex response to changes to the input parameter; and further examination would be required to characterise the influence of that input variable on energy consumption. Figure 6-5, Figure 6-5 and Figure 6-6 demonstrate the relative magnitude of the calculated influence coefficients.

Table 6-4 Absoulte value of Influence Coefficients of input parameters for Form A buildings in capital cities in Australia.

	Adelaide	Brisbane	Canberra	Darwin	Hobart	Melbourne	Perth	Sydney
Cooling set-point	-0.82	-0.79	-0.97	-0.74	-1.02	-0.85	-0.82	-0.79
ICT Power Density	0.39	0.40	0.42	0.36	0.45	0.38	0.40	0.41
Lighting Power Density	0.29	0.28	0.30	0.26	0.30	0.28	0.29	0.29
ICT Usage Schedule	0.27	0.27	0.29	0.25	0.30	0.34	0.37	0.31
Occupant Density	0.07	0.13	0.05	0.15	0.04	0.07	0.09	0.10
Ventilation Requirement	0.04	0.08	0.00	0.10	-0.01	0.02	0.04	0.04
Wall U-Value	0.02	0.01	0.01	0.12	0.01	-0.02	0.01	0.01
Window U-Value	-0.01	-0.03	-0.02	-0.02	-0.04	0.00	-0.02	0.18
Occupancy Schedule	0.01	0.03	0.02	0.03	0.02	-0.05	0.03	0.03
Infiltration	0.01	0.01	0.01	0.01	-0.02	0.01	0.01	0.00
Roof U-Value	0.00	0.00	0.00	0.00	0.00	-0.02	0.00	0.00

Table 6-5 Absoulte value of Influence Coefficients of input parameters for Form B buildings in capital cities in Australia.

	Adelaide	Brisbane	Canberra	Darwin	Hobart	Melbourne	Perth	Sydney
Cooling set-point	-0.96	-1.00	-1.05	-0.98	-1.14	-1.02	-0.98	-0.97
ICT Power Density	0.36	0.39	0.38	0.35	0.40	0.35	0.38	0.40
Lighting Power Density	0.26	0.28	0.28	0.25	0.29	0.25	0.27	0.29
ICT Usage Schedule	0.25	0.25	0.35	0.23	0.28	0.25	0.25	0.26
Infiltration	0.11	0.08	0.10	0.14	0.07	0.12	0.09	0.07
Occupant Density	0.08	0.12	0.05	0.13	0.04	0.07	0.10	0.10
Ventilation Requirement	0.05	0.07	0.01	0.08	-0.01	0.03	0.05	0.05
Wall U-Value	0.01	-0.01	0.01	0.00	0.01	0.01	0.00	0.01
Occupancy Schedule	0.01	0.03	0.00	0.03	0.01	0.01	0.02	0.02
Roof U-Value	0.00	-0.01	0.00	0.00	0.00	0.01	0.01	0.01
Window U-Value	0.00	-0.03	0.00	-0.02	-0.01	0.01	0.01	-0.01

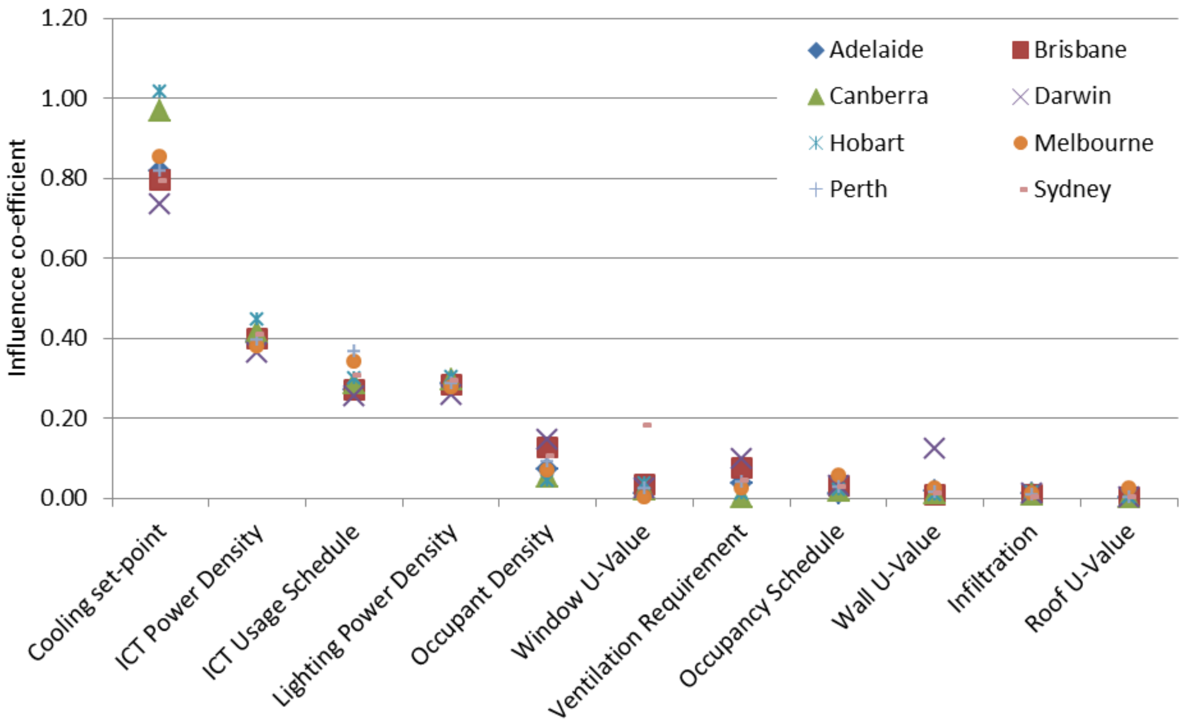


Figure 6-5 Type 2 Influence Coefficient of variables calculated with predicted total energy consumption of the ABCB Form A building, showing all tested variables in all capital cities in Australia.

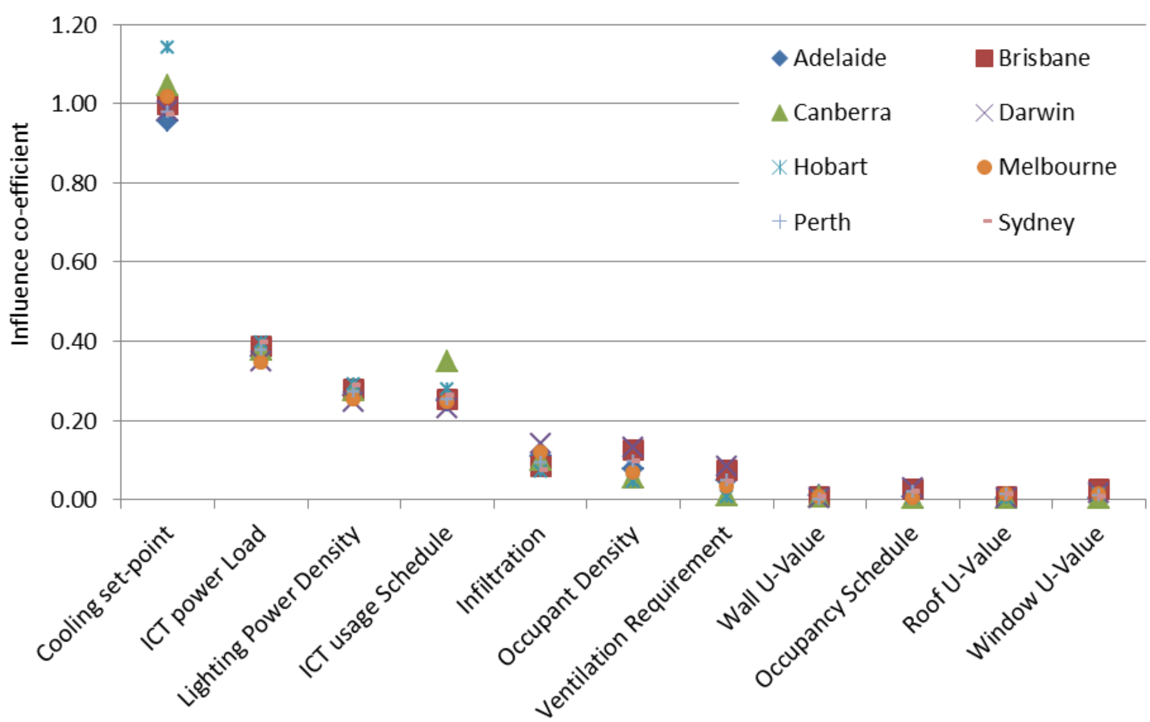


Figure 6-6 Type 2 IC of variables on predicted total energy consumption of the ABCB Form B building, showing all tested variables in all capital cities in Australia.

For all locations, the four most influential parameters were found to be; cooling set-point temperature, ICT power density, ICT usage schedules, and lighting power density. Cooling set-point and equipment load were the most influential for all locations; ICT usage schedules, and lighting power density varied in relative importance by location. There was a marked decrease in the influence coefficient for the rest of the input parameters. The four most influential parameters directly influenced the energy consumption of a specific system, while the remaining inputs had a second-order effect on the HVAC system. This result can be expected, as internal loads are known to be of greater importance than the envelope loads in commercial buildings.

Considering only the influence on heating and cooling demand, the relative scale of the calculated IC's are similar to the whole building consumption, as shown in Figure 6-7 and Figure 6-8. Cooling set-point temperature, ICT power density, ICT usage schedules, and lighting power density were again the most influential inputs, although the relative importance of the internal gains was somewhat diminished, and location had a more significant influence.

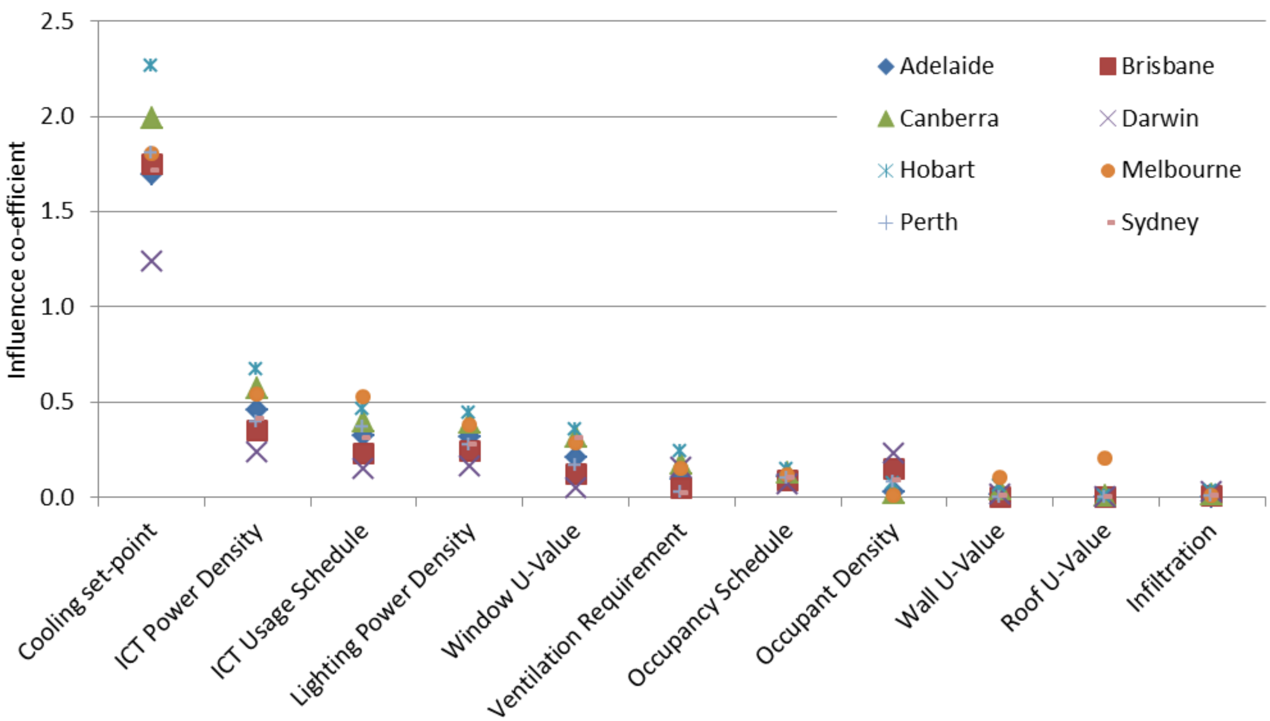


Figure 6-7 Type 2 IC for variables on predicted heating and cooling energy consumption of the ABCB Form A building, showing all tested variables in all Australian capital cities.

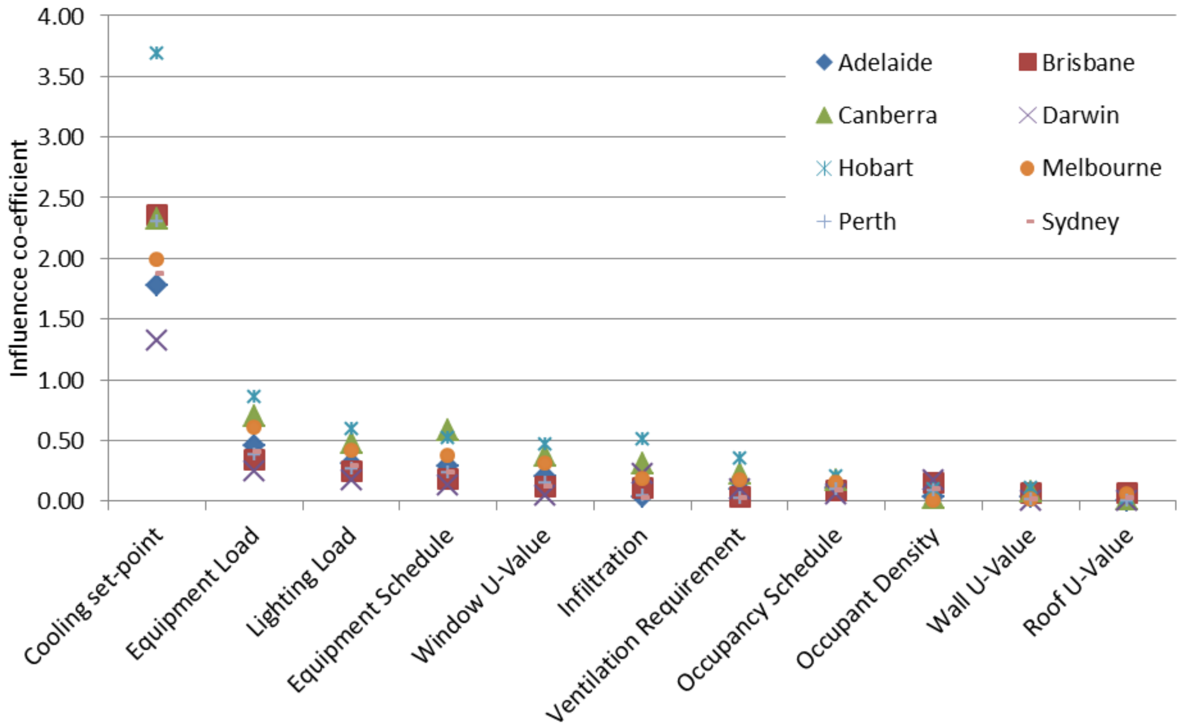


Figure 6-8 Type 2 Influence Coefficient for variables on predicted heating and cooling energy consumption of the ABCB Form B building, showing all tested variables in all capital cities in Australia.

6.4 Discussion

Although non-dimensional influence coefficients have been previously identified as the most useful output from a DSA, consideration must be given to several potential concerns. The selection of the datum and measurement scale for some parameters can heavily influence results. Some parameters have physical or mathematical constraints on the scale and datum that can be used. Usage schedules are limited by the number of hours in the week, and the laws of thermodynamics limit U-values. The influence coefficient calculated for cooling set-point temperature was heavily dependent on the selection of scale and zero. For the Form A building simulated in Sydney, the calculated influence coefficient was -0.79, -9.79, and -1.37 for the Celsius, Kelvin, and Fahrenheit scales respectively. For this study, Celsius was used as it the unit most commonly used in connection with HVAC set points, and a datum of zero chosen. It is important to be aware of the issue and not treat the influence coefficient as an absolute value, however it was identified as the most useful comparison measure for use in building energy sensitivity analysis (Bertagnolio, 2012; Simm *et al.*, 2011).

To further illustrate the significance of simulation assumptions, a simple lighting retrofit of the Form A template building in the Sydney CBD, a prime candidate for an EUA, was analysed. The case study examined the energy and financial savings for a commonly implemented lighting upgrade, reducing lighting power density to 5 W/m^2 (Blundell, 2012; Geest & Erp, 2011; OEH & Parramatta City Council, 2012; Built Environment Supplier Advocate, 2013).

Table 6-6 Predicted energy and financial savings of a simple lighting retrofit for the Form A office building in Sydney CBD. Electricity cost = 16.2c/kWh

	Base LPD (W/m^2)	Retrofit LPD (W/m^2)	Predicted Lighting Energy Saving (kWh/yr.)	Predicted Lighting Energy Saving (%)	Predicted Total Energy Saving (kWh/yr.)	Predicted Total Energy Saving (%)	Predicted HVAC Energy Saving (%)	Simple Payback – Lighting savings (years)	Simple Payback – total energy savings (years)
'All low' scenario	9.3	5	166,347	44.4	227,208	15.8	7.2	14.1	10.3
Base case	15	5	415,869	66.7	615,083	19.5	12.5	5.6	3.8
'All high scenario'	21	5	665,390	76.2	973,276	20.5	13.1	3.5	2.4

As can be seen in Table 6-6, pre-retrofit simulation assumptions can significantly affect the financial attractiveness of a building upgrade. Considering the total predicted energy savings, including increased HVAC efficiency, the payback period calculated varied from 2.4 to 10.3 years. An industry survey of 253 executive decision makers suggested that the average allowable payback period for energy efficiency projects in Australia was 3.0 years (compared to global average of 3.4 years) (Institute for Building Efficiency, 2012). It is clear that incorrect pre-retrofit simulation assumptions could be preventing financially attractive retrofits from being implemented.

The issue of accuracy and uncertainty in energy modelling is becoming increasingly important in Australian policy and industry. There are currently few repercussions for a modeller who produces an erroneous or insufficiently accurate model, as raised during the panel discussion at the recent Australian Institute of Refrigeration, Air-conditioning and Heating Building Simulation Workshop (Melbourne, 2013), and this can foster a lack of confidence in simulation in the building industry. The move, discussed in Section 4.3, to establish an accreditation scheme for retrofit consultants is in part a reaction to a perceived lack of confidence in industry.

Despite this, predictions of energy consumption and savings from BPS are being relied upon to justify investment in building energy efficiency upgrades, retrofitting and refurbishments. There may soon be significant financial and legal implications attached to simulation predictions, with the introduction of EUA legislation, and potential increased use of EPC's, introduced in Section 2.5. Both EUAs and EPCs present interesting cases when considered from the perspective of building simulation, particularly the uncertainty associated with making predictions of the energy savings potential of a building retrofit. In an EPC any risk is clearly apportioned to energy service company (ESCO), who is responsible for providing the rating predictions (see Section 4.3).

For an EUA without an EPC, there is an amount of risk and uncertainty in the wording that a tenant's contribution must not exceed a 'reasonable estimate' of cost savings to tenants (OEH, 2013). The decision of whether it is attractive to enter into an EUA must be made on energy and financial savings predicted by BPS, which has a proven 'performance gap' between predicted and actual savings. As Williamson (2010) states 'claims about simulation can lead to a spurious impression of accuracy and therefore legitimacy. Likewise, inappropriate applications of simulation may result in wrong decisions and an erroneous allocation of resources." Mills *et al.* (2006) provided a visual representation of the "spurious impression of accuracy", shown in Figure 6-9

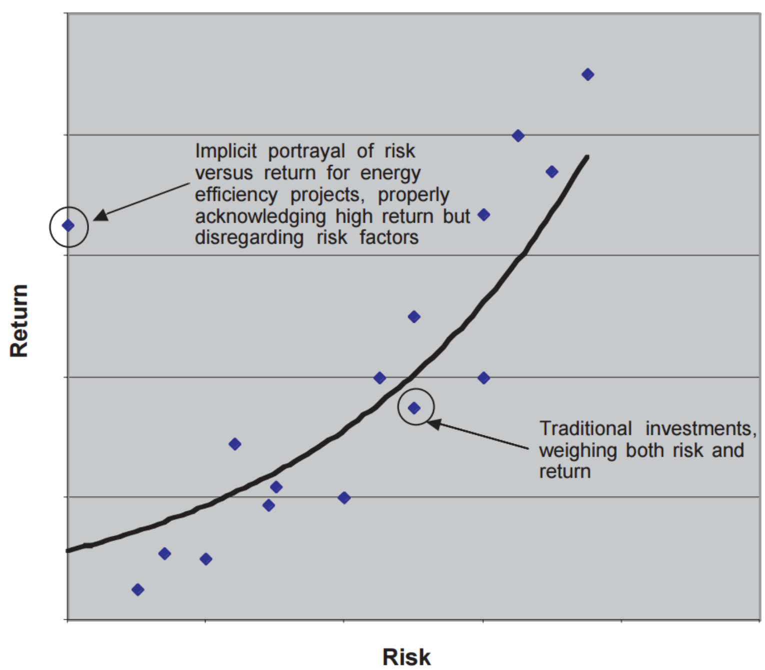


Figure 6-9 Schematic portrayal of the risk-return scenarios in building energy model reports, where 'risks are typically relegated to qualitative descriptions or anecdotal footnotes, at best' (Mills et al., 2006).

In reality, there is often a significant financial risk tied to the prediction of energy savings from a technical retrofit from thermal simulation. For certain technologies, e.g. lighting upgrades, there is a record of achieved savings to allow confidence in estimations from techniques other than detailed simulation. However, for deep or complex retrofits involving changes to building fabric, HVAC and controls, it is more difficult to have confidence in predictions from thermal simulation. Incorrect assumptions regarding occupant behaviour and building operation, or poor quality installation or commissioning of new technologies can all render predictions from a simulation inaccurate. The use of simulation protocols is one attempt to standardise these assumption, which will be examined in the following chapter.

7 Quantitative Impact of Default Assumptions in Simulation Protocols

The differential sensitivity analysis conducted in the previous chapter identified cooling set-point, ICT power density and usage schedule, and lighting power density as inputs which most strongly influenced the predicted energy consumption of a reference commercial office building in Australia. These inputs are generally determined by the tenancy fit-out and occupant energy-related behaviour. The representation of occupancy behaviour in commercial buildings is complex, and accurate information regarding these inputs is often unavailable at the time of simulation, as discussed in Section 2.6.3.

BPS users thus often rely on assumption, heuristics, and default values to inform these inputs to the model. The variation in the assumed values used in previous studies for these uncertain parameters was highlighted in the previous chapter. To minimise the influence of modeller interpretation and assumption on predictions from BPS, a number of simulation protocols have been developed to guide the BPS process for different schemes. These protocols standardise many aspects of the modelling process for a particular scheme, including the assumptions used for uncertain values. They are widely used in industry, as discussed in Chapter 4.

7.1 Introduction

Three simulation protocols are commonly used in Australia, namely: i) the BCA JV3 Verification using a reference building (ABCB, 2013), ii) 'NABERS Energy – Guide to building energy estimation' (NABERS, 2011), and iii) Green Star 'Greenhouse Gas emissions calculator guide' (GBCA, 2013b). ASHRAE 90.1 In addition, the 'Energy Standard for Buildings Except Low-Rise Residential Buildings' (ASHRAE, 2013) is an internationally recognized simulation protocol, which is used by some consultants in Australia. These protocols were discussed in detail in Section 2.6.4; and a brief summary is provided here for the benefit of the reader.

These protocols set out specific simulation methods and rationales, which must be followed for each corresponding scheme. Each protocol has a slightly different goal, and therefore a slightly different method. It is important to note that the NABERS protocol is the only protocol to have 'simulation of actual performance [of a building] as its primary target' (Bannister, 2005). The other protocols rely on comparison of a design against a defined reference building. The *default values*

and schedules specified in these protocols are often used in other simulation studies (outside of the programs for which they are mandated) as being representative of commercial buildings in Australia (ABCB, 2006a; BRANZ, 2007; Judkoff *et al.*, 2008; ZCA, 2013).

i) Clause JV3 in the BCA provides detailed instructions as to the inputs to be used for building simulations to determine whether or not the annual energy consumption of a proposed building (including services) is more than that of a benchmark building that is known to comply with the energy efficiency requirements of Section J. The intent of this protocol is to ensure compliance with a minimum standard of energy efficiency.

ii) The 'NABERS energy: guide to building energy estimation' provides a guide for the use of BPS to estimate base-building or whole-building energy use for a NABERS Commitment Agreement, which is a commitment from a developer of a new or refurbished building to achieve a specific NABERS star rating.

iii) The Green Star greenhouse gas emissions calculator guide is based on the JV3 verification method. The predicted energy consumption of the proposed building is compared to the predicted consumption of a 'standard practice building'. Green Star 'points' are awarded for every 5% reduction in predicted GHG emissions relative to the standard practice building.

iv) ASHRAE standard 90.1 Appendix G, from the U.S., serves a similar purpose to the JV3 alternative solution verification, allowing the energy efficiency provision to be flexible to new designs and technologies that can be shown through BPS to improve building performance.

The three protocols for the Australian context have been developed by different organisations and for different purposes. Therefore, their recommended default values do not necessarily align. The differences in the protocols is causing 'frustration, confusion and additional expense' (Aherne, 2011) in the simulation industry, due to the need to re-work models for compliance with multiple schemes, and there is a push to align the protocols (Exergy Australia, 2011). The attempt to harmonise inputs across the three protocols is concerned firstly with standardisation of the assumptions, and then with quality improvement of the inputs to ensure they are representative of actual conditions. The need to understand the implications of the selection of the default values on predicted energy consumption was recognised by Aherne (2011).

This chapter therefore presents an uncertainty analysis of the predicted energy consumption of two buildings as a function of the default assumptions and diversity profiles taken from the four simulation protocols. Table 7-1 lists the key occupancy-dependent BPS assumption from each protocol. The corresponding diversity profiles are displayed in Figures 7-1 to 7-3.

Table 7-1 Occupancy assumptions and default values for office towers from four simulation protocols.

Parameter	JV3	NABERS	Green Star	ASHRAE
Maximum Occupancy (m^2/p)	10	15	10	5[a]
Temperature Bands (^oC)	18-26	N/S	18-26	21 – 24[b]
Ventilation rate (L/s/p)	10	N/S	10	9.45
Lighting Loads (W/m^2)	9	12	9	8.8
Equipment Loads(W/m^2)	15	11	11	7.5[c]

N/S means the protocol does not specify a value. In these cases the JV3 input was used.
a- ASHRAE 62.1: Ventilation for acceptable indoor air quality (ASHRAE, 2007a)
b - 90.1 - 2007 (ASHRAE, 2007b)
c -90.1 - 2010 (ASHRAE, 2010a)

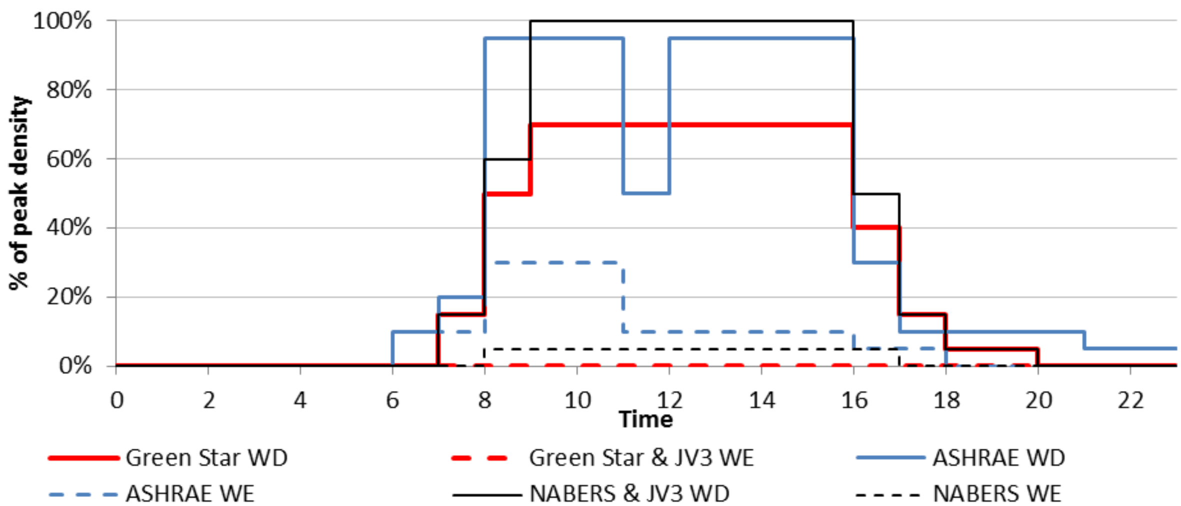


Figure 7-1 Default occupancy diversity profiles recommended for use by the four simulation protocols.

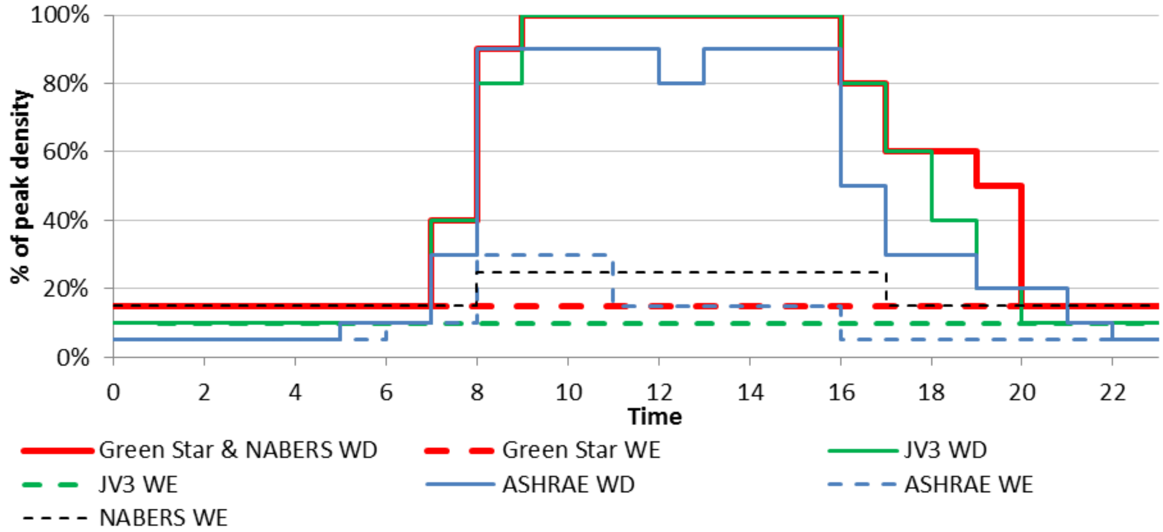


Figure 7-2 Default lighting diversity profiles recommended for use by the four simulation protocols.

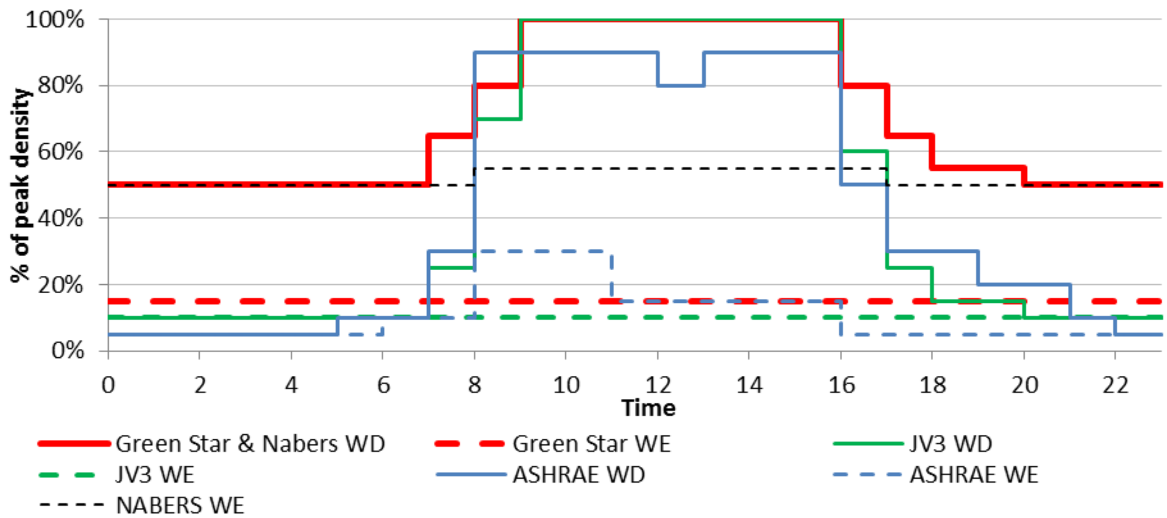


Figure 7-3 Default equipment diversity profiles recommended for use by the four simulation protocols.

7.2 Method

An uncertainty analysis was conducted to determine the impact of variation in default assumptions recommended for use by four simulation protocols on total office building energy consumption in Australia. Two buildings were simulated, a reference building and a case study building.

7.2.1 Building and System Description

Building 1, the 'Reference Building', was the ABCB Form A building, discussed in detail in Section 3.5, and used in Chapters 5 and 6. Building 1 was simulated in Sydney (BCA Climate Zone 5 – warm temperate) and Melbourne (BCA Climate Zone 6 – mild temperate). Building 2 was a Secondary Grade fringe CBD five-storey office building in the early stages of an energy retrofit, located in Northern Sydney. Table 7-2 summarises the characteristics of the two buildings simulated in this study.

As identified previously, Building 1 has been widely used in Australian BPS studies. Inputs for the base case for Building 1 were as in Chapter 6. For Building 1 the HVAC system was modelled to be consistent with the baseline HVAC System 7 from Table G3.1.1-4 from ASHRAE 90.1 for both locations. Building 2 was a Secondary Grade building, with poor energy performance, which was scheduled for upgrade works. The HVAC system of Building 2 was modelled from design documentation, and updated to reflect as-built conditions based on site visits, site notes and a third-party mechanical services evaluation. Nine months of measured base building energy data was accessible for Building 2. However, during the recorded period only two floors of the building were tenanted. The occupancy was reflected in the simulation for validation. Further detailed information regarding Building 2 is presented in Chapter 8.

Table 7-2 Summary characteristics of the modelled buildings

Parameter	Building 1	Building 2
NLA (m^2)	9,000	7,500
Floor plate configuration (m)	31.6 x 31.6	60 x 39.25
Number of floors	10	5
Floor to floor height (m)	3.6	3.6
Basement/carpark	1 storey carpark	4 storey carpark
Glazing fraction	0.38	0.2
Construction	HW concrete	HW concrete
Windows	Sgl Glazing	Sgl & Dbl Glazing
HVAC system types	VAV, WC chiller, hot water reheat	VAV, AC chiller, elec reheat

7.2.2 Simulation Approach

This study did not follow the entire simulation process outlined in the protocols explicitly; rather default values and diversity profiles recommended for occupant-influenced loads were extracted from the protocols and applied to the building models. For example, The ASHRAE 90.1 protocol

required different HVAC systems to be modelled depending on the US climate zone specified; however, in this study one HVAC system was modelled for both locations for simplicity. The four simulation protocols were examined and recommended BPS inputs were identified, as summarised in Table 7-1.

DesignBuilder was employed for this analysis, and IWEC EnergyPlus weather files were used for all locations. Building 2 was simulated using a Real-time Year (RTY) weather file for the same period as metered energy data was available for validation. For calibration of the detailed model, a modified version of the data hierarchy from Raftery *et al.* (2009) was utilised, with inputs being modified only by data from parameters rated higher in the list below;

1. Direct observation (site surveys);
2. Operation documents and commissioning documents;
3. Simulation protocols;
4. Benchmark studies and best practice guides;
5. Standards, specifications and guidelines;
6. BPS program default values.

The buildings were first simulated in the base case configuration. The default assumptions recommended for use by each protocol were then applied to the base case building, holding all other parameters constant at their base case value. The total energy consumption and energy use breakdown were extracted from the model, and the results were analysed. This was repeated for the four protocols. Only the inputs listed in Table 7-1 or shown in Figures 7-1 to 7-3 and climatic data were altered; all other inputs to the simulation were kept constant for each building. Predicted base building energy consumption was compared to measured consumption for Building 2.

7.3 Results

This section presents the results of the uncertainty analysis conducted on two buildings, a Reference Building and a case study building. The analysis considered the impact of default assumptions recommended for use by four simulation protocols on total building energy consumption

7.3.1 Building 1 – Australian Building Codes Board Form A Building

The predicted whole building energy consumption is shown in Figure 7-4 for the four studied simulation protocols for Sydney and Melbourne. The predicted energy consumption from the

various protocols was sensitive to building location; however, NABERS predicted the highest consumption for all locations.

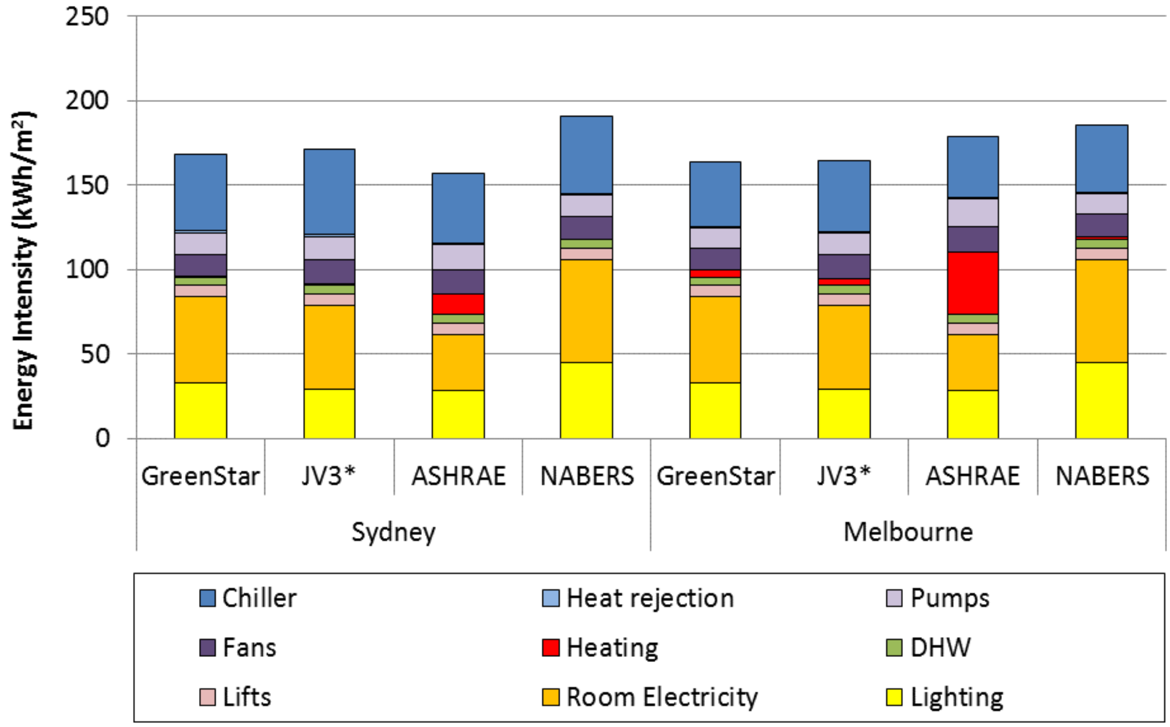


Figure 7-4 Predicted energy consumption for Building 1, a reference office tower, for Sydney and Melbourne simulated with inputs from four simulation protocols.

Compared to the outputs predicted using the Green Star protocol for Sydney, the predicted whole-building consumption was: 1.4% higher for the JV3 protocol; 13.4% higher for the NABERS protocol; and 6.7% lower for the ASHRAE 90.1 protocol. In Melbourne, the differences were: 0.6% higher for the JV3 protocol, 13.5% higher for the NABERS protocol, and 9.2% for the ASHRAE 90.1 protocol. The ASHRAE protocol predicted proportionally higher HVAC and base building loads, and lower plug and process loads (including lighting) compared to the other protocols. The average HVAC-to-Plug-load ratios were 1.0, 1.1, and 0.8 for Green Star, JV3 and NABERS, respectively. However, this ratio was 1.7 for the ASHRAE protocol because of the low internal gains recommended by ASHRAE, as shown in Figure 7-5, and the tighter thermal comfort temperature bands. For Sydney, simulation using the ASHRAE defaults, but with a widening of the temperature bands to those recommended by Green Star, resulted in a 14.9% decrease in predicted energy consumption.

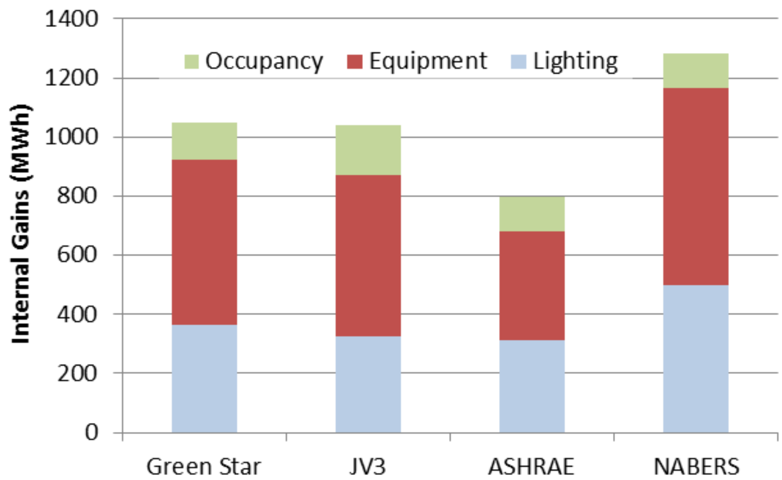


Figure 7-5 Predicted internal gains due to occupancy, lighting and equipment usage as specified by four simulation protocols for the ABCB Form A building for Sydney.

In both locations, the use of the ASHRAE default figures resulted in a significantly higher predicted heating load. In Sydney, the ASHRAE protocol predicted a heating energy consumption of 5.5% of total consumption compared to 0.4% for Green Star and JV3, and 0.1% for NABERS. In Melbourne ASHRAE predicted heating as 17.5% of total energy compared to 2.5% for Green Star, 2.2% for JV3, and 0.9% for NABERS. The primary reason for this discrepancy was the tighter comfort temperature band; relaxing the temperature bands to those recommended by JV3 decreased the predicted heating required for Sydney to 0.5% of total consumption. Similarly, for Melbourne the use of the JV3 set points reduces heating to 3.4% of total consumption.

The daily usage profiles for a three-day period in a cooling period in Sydney (January) are shown in Figure 7-6. This figure illustrates the effect that the diversity profiles recommended by the protocols had on predicted baseline and peak loads. It can be seen that simulations conducted with the diversity profiles from the NABERS and JV3 protocols result in similar peak demand, but have substantially different after-hours loads. Similarly, ASHRAE and Green Star predict similar weekend load profiles, but vary significantly for weekdays.

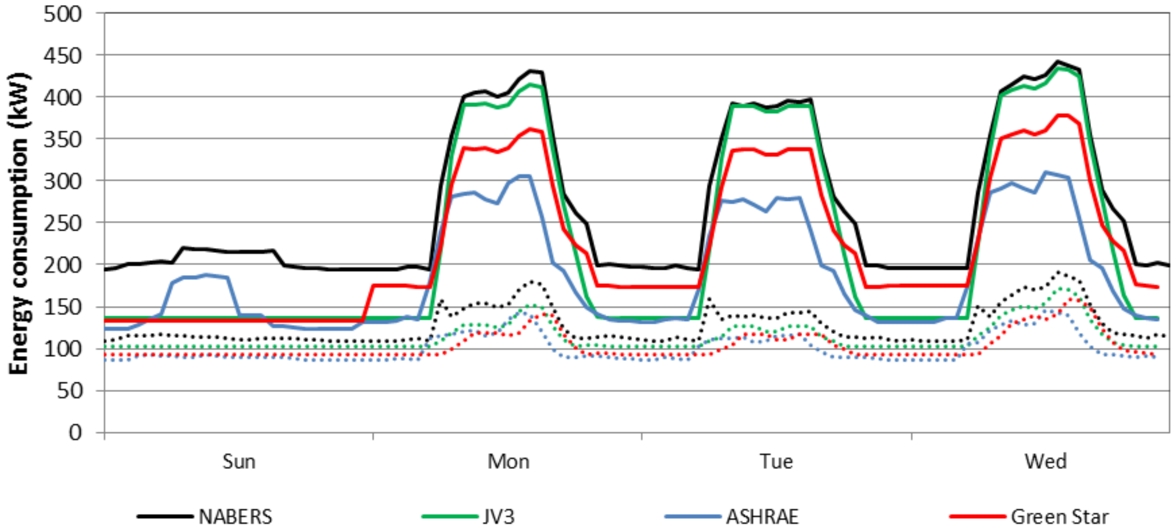


Figure 7-6 Daily whole building energy demand profile for Building 1, simulated with four alternate input protocols, for four days in January. Solid lines represent whole building consumption, and the dashed lines represent the HVAC and base building services component of the consumption.

As expected, the demand profiles closely reflect the input schedules. The NABERS protocol assumes 50% of equipment was left on over the weekend, compared to the Green Star assumption of 15%. On average, this assumption accounts for almost half (46.2%) of the difference in total predicted energy consumption between NABERS and Green Star.

7.3.2 Building 2

Validation of the base building model was conducted with nine months of consumption data taken from utility bills from 2013. Historical climate data was used from a weather station located approximately 5 km from the site, with records covering the period for which utility data was accessible. During the validation period, the building was only partially tenanted, when the bottom three floors were unoccupied. This was modelled in the simulations. An acceptable level of accuracy was defined in accordance with ASHRAE (2012), as a model having a CV (RMSE) of less than 15%, and a NMBE of less than 5%. It should be noted that ASHRAE (2012) stipulates the use of 12 months of baseline data to ensure a model is calibrated, which was not accessible for this particular building.

The monthly base building energy consumption for the calibrated model is shown in Figure 7-7, along with the base building consumption from utility bills. Following the calibration process

outlined in Section 7.2.2, the calibrated model produced a CV (RMSE) of 9.1% and a NMBE of -0.2% compared to the utility data, and can therefore be considered calibrated according to ASHRAE (2012).

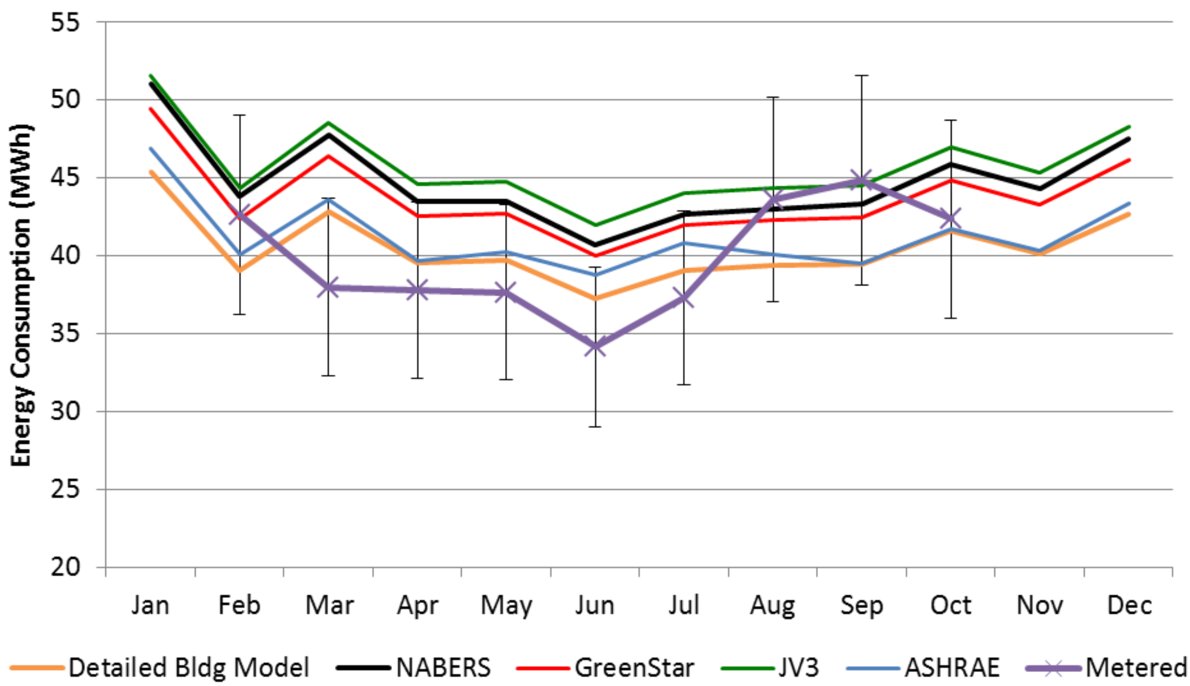


Figure 7-7 Monthly measured and predicted energy consumption for Building 2 calibrated model. Error bars show ±15% of base building consumption. Base building predictions made using the four modelling protocols are also shown.

The predicted monthly consumption for the case study building simulated with the default assumptions from the four protocols tested was also displayed in Figure 7-7. All four protocols predicted annual base building energy consumption greater than the measured data. The JV3 protocol predicted the highest energy consumption (12.8% greater than measured) followed by NABERS (10.0%), and Green Star (7.6%). ASHRAE predicted consumption 1.76% greater than measured. It should be remembered that these values are for partial occupancy. If applied to a fully occupied building, it is likely that the influence of the default values would have been more substantial. This is discussed further in Chapter 8. It was expected that the ASHRAE protocol would result in a higher predicted consumption, given the tighter assumed comfort bands, and the relative importance of cooling set-point demonstrated in Chapter 6. Reasons for why this did not occur can be postulated through an examination of the predicted energy end-use breakdown.

The annual whole building energy end-use breakdown of the building, as predicted by simulations with the four simulation protocols is shown in Figure 7-8. It can be seen that the NABERS protocol results in the highest predicted whole building consumption, 20.4% greater than the ASHRAE protocol, which gives the lowest predicted consumption. The results for the ASHRAE protocol show the lowest lighting and ICT consumption, as was the case for Building 1. The reason for this can be clearly seen in Figure 7-9, where the equipment and lighting power density diversity profiles are shown. The equipment and lighting power density default value has been combined with the recommended diversity profile, to illustrate the changing internal gains assumed by each protocol. The ASHRAE protocol predicted a peak internal gain of 14.7 W/m^2, compared to 24.0 W/m^2 predicted by the JV3 protocol. This substantially greater internal heat load, at a time of maximum cooling demand, had a significant influence on the predicted base building energy consumption of the case study building.

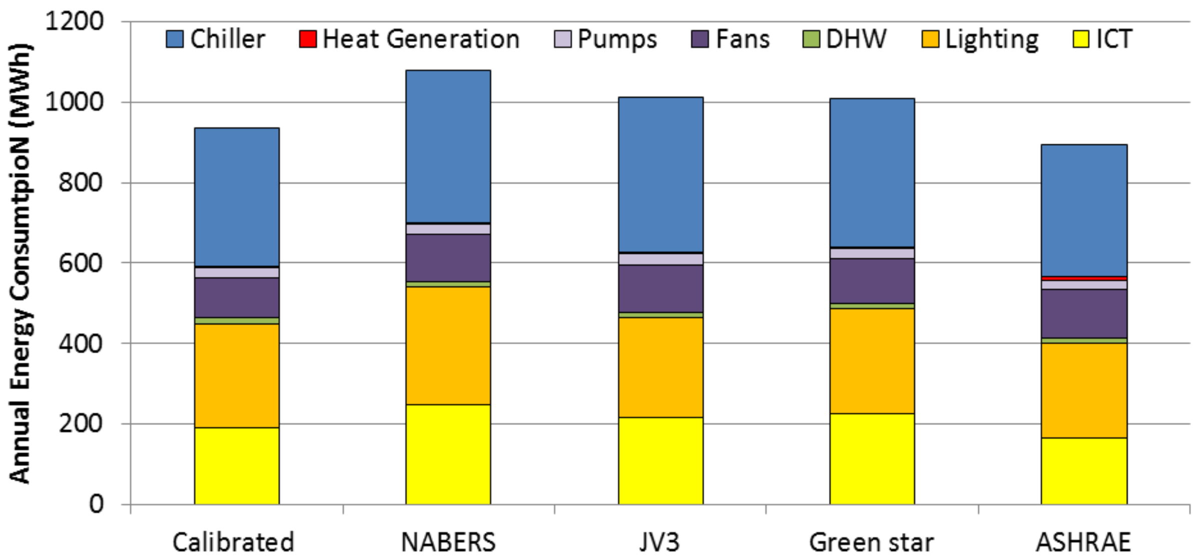


Figure 7-8 Predicted annual energy end use breakdown for Building 2 simulated with the use of four simulation protocols and compared with a simulation 'calibrated' against actual performance data.

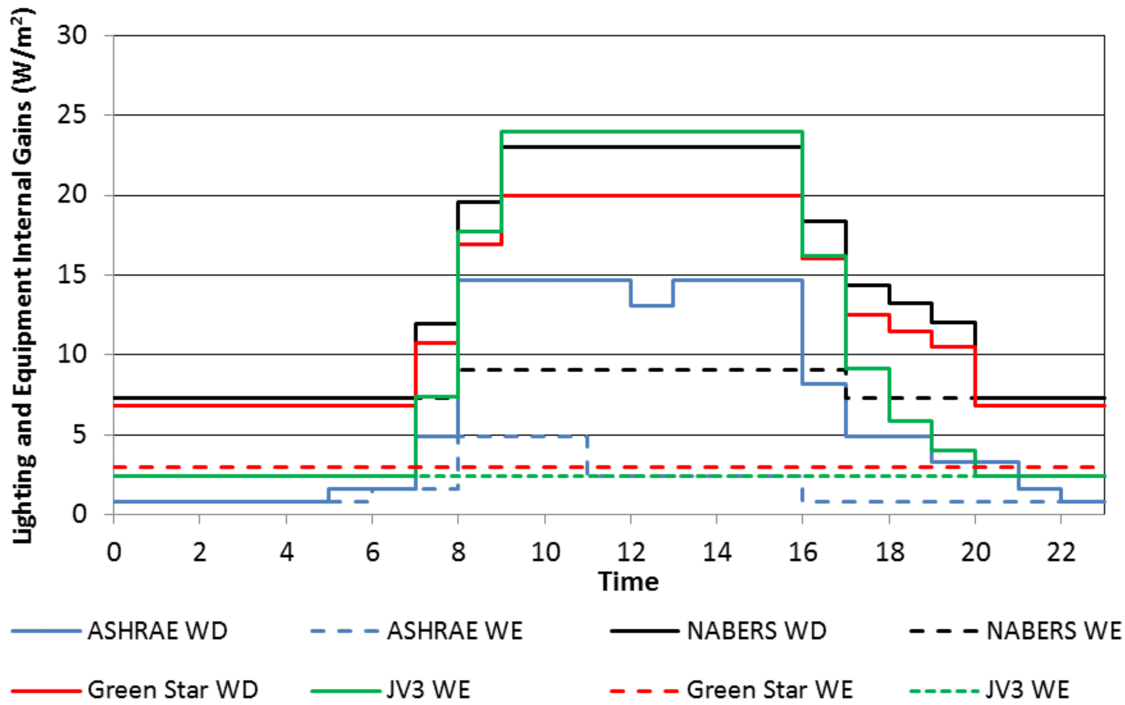


Figure 7-9 Lighting and equipment internal gains profile for the four tested protocols.

The calibration metrics calculated for the base building predictions from each protocol are shown in Table 7-3. The NABERS, Green Star, and ASHRAE assumptions resulted in acceptable CV (RMSE) values, but only the ASHRAE assumptions also produce an output with an acceptable NMBE value.

Table 7-3 Monthly discrepancy between measured and predicted base building energy consumption with the use of four simulation protocols to represent Building 2.

	JV3	NABERS	Green Star	ASHRAE	Calibrated
CV (RMSE)	16.4%	14.1%	12.2%	9.9%	9.1%
NMBE	14%	11%	9%	2.0%	-0.2%

As was expected, the protocols did not result in predictions of the energy consumption of the building that corresponded closely to the metered data, for a number of reasons including the following. Only the NABERS protocol was designed to be used for absolute predictions; the other protocols were designed for comparison against a benchmark building with similar characteristics. NABERS was by design a conservative protocol. However, for the case study building, there was poor information regarding expected occupant density and schedule, lighting schedule, and tenancy equipment fit-out. It was likely that for a building such as this, with poor documentation, these protocols would be relied upon by a typical modeller for BPS inputs. The results from this study

show that the default value selected for these parameters can influence the prediction of the base and whole building performance, and has the potential to influence optimal retrofit strategies.

7.4 Discussion

Analysis of the ABCB reference building showed that the selection of simulation protocol can significantly affect predicted energy consumption, and load breakdown for office buildings in Australia. Investigative simulation identified the following as significant features of the simulation protocols:

- NABERS usage schedules assumed that 50% of equipment is left on after –hours, including weekends. The weekend load was significantly higher than predictions from other protocols, and this accounts for almost half of the difference between NABERS and Green Star protocols. NABERS also assumed a low occupant density, which impacted on internal gains and therefore HVAC loads.
- ASHRAE 90.1 required tighter temperature/comfort bands than the other protocols, and this increased energy consumption by almost 15%. This, combined with low occupant density, gave a proportionally higher base building prediction. This was balanced somewhat by lower specified equipment and lighting power densities, however, the load breakdown differed significantly from that predicted by the other protocols.
- JV3 and Green Star predicted similar performances for both locations, and significantly lower than NABERS. JV3 specified a higher peak equipment power density, but this was balanced by low after-hours usage.

For Building 2, the case study building, there was limited information available regarding expected occupant density and schedule, lighting schedule, and tenancy equipment fit-out. It was therefore necessary for the present author to make an engineering judgment as to an appropriate value. The tested protocols were reasonable sources upon which to base assumptions of the uncertain inputs. The uncertain parameters can all influence the performance of the HVAC system substantially, and potentially influence optimal retrofit strategies. A 12.8% difference between the highest and lowest prediction was found for base building consumption, and a 20.4% variation for whole building consumption.

It was difficult to provide meaningful comment on how representative of the Australian building stock the assumptions embedded in the simulation protocols were, without access to large databases of building attributes. The average Lighting Power Density from the Building Energy Efficiency Register was shown in Section 4.2.1 to be 13.5 W/m^2 (SD = 6.00), which suggests that values specified in all protocols may have been low, although reasonable. It was also shown that 73.1% of the functional spaces assessed under BEEC had an NLPD outside of the range of assumptions used in the Australian protocols; with 57% of spaces having a NLPD higher than 12 W/m^2. Warren (2003) found an average occupancy in Australian office buildings of 20.6 m^2/person, with an interquartile range from 14 to 53 m^2/person. This suggests the occupancy assumptions of the Australian protocols may have been too high. However, that study had a limited sample size, and relied on self-reported occupant density. In Australian offices, HVAC set-points are generally 20 – 24 ^{o}C on an annual basis, 22.5 ± 1.5 ^{o}C in summer, and 21.5 ± 1.5 ^{o}C in winter (Roussac *et al.*, 2011). This suggests the temperature bands recommended by Green Star and JV3 may be somewhat less stringent than operating practice.

An extensive literature search revealed no large-scale study that had undertaken actual field measurements of ICT power density, or ICT usage schedules in Australia. This makes it difficult to determine the validity of the simulation assumptions for these three inputs, which were shown in Chapter 6 to strongly affect predicted consumption. All three inputs have some level of occupant or organisational influence, and it is therefore difficult to estimate actual values during an energy audit. The results of this study suggest that it would be useful to devote some effort to improving the accuracy of the simulation assumptions for these particular inputs. It was shown in Chapter 6 that whilst the most significant inputs were related to a buildings' tenancy energy consumption, they were also the most influential parameters when just the heating and cooling load was considered. Therefore, accurate representation of these parameters is essential when considering upgrades to the base building services. The forthcoming results of detailed monitoring in New Zealand as part of the Building Energy-End Use Study (BEES) may provide further information on these inputs with some relevance to the Australian stock.

The results from the present study have highlighted the importance of including uncertainty and sensitivity analyses as a routine part of BPS, particularly when BPS is used in the retrofit optimisation problem. Results from additional case studies would enhance transparency in this area.

8 Calibrated Reference Buildings for Simplified Building Performance Simulation: Case Studies

Previous chapters have explored several sources of quantitative uncertainty in BPS. The issue of uncertainties around internal heat loads within a building was highlighted as being at least as important as local climate and building construction details. Common protocols used in Australia to standardise assumptions regarding internal loads and schedules were shown to reduce the variability in predictions. However, it was also shown that even using values embedded in protocols, there is still significant uncertainty in both base and whole building consumption. These results have underlined the limitations of the use of single figure deterministic values to represent energy consumption in existing buildings.

Secondary Grade building owners are particularly affected by capital availability and access to information, two barriers which have implications for retrofit optimisations. As identified in Chapter 4, the cost of a BPS engagement is a significant barrier to owners. Many retrofit decision for Secondary Grade buildings are thus made on the basis of a Type 2 energy audit, which effectively limits the recommended upgrades to technology with a proven payback (e.g. lighting, variable speed drives, replacing obsolete items – see Section 4.1.3). BPS is a valuable tool for the consideration of integrated retrofits that will achieve deep cuts to energy consumption. This chapter examines the feasibility of a simplification to the BPS process to represent existing Secondary Grade commercial office buildings for retrofit decision-making. Three detailed building case studies have been used to study the practical implementation and efficacy of the use of 'Calibrated Reference Buildings', as well as the additional uncertainty introduced.

8.1 Introduction

To contribute to Australia's recommended emission reduction targets of 40 – 60% below 2000 levels by 2030 (Climate Change Authority, 2014), the commercial building sector must achieve substantial efficiency improvements in the next upgrade cycle. Whilst efficiency improvements of 15 – 30 % are considered typical for an energy upgrade, meaningful contributions to the reduction targets will require deeper cuts. 'Deep' retrofits, defined variously as retrofits reducing energy consumption by greater than 45 % (Moser *et al.*, 2012) to 60% (RMI, 2010), require 'integrated, whole-building energy efficiency measures that [are] coordinated with planned equipment replacement and … optimize cost and GHG reductions' (Fluhrer *et al.*, 2010).

BPS is an important tool in delivering deep retrofits, permitting the consideration of complex system upgrades and changes to the building fabric. However, development of a detailed BPS model represents a significant cost to a building owner, in addition to the cost of an energy audit. The issue of 'high transaction costs to … obtain relevant information or expertise' was highlighted by the Low Energy High Rise study (Kempener, 2007) as a key market failure in the commercial office retrofitting sector. In Section 4.1 the cost barrier of conducting an energy audit was identified as a significant hurdle to building owners engaging in a retrofit process. For Prime Grade commercial buildings, with large project budgets, this is a less significant barrier. For Secondary Grade buildings, the issue of high upfront costs is particularly challenging. As discussed previously, such buildings are more likely to be smaller and in private ownership, often with less access to capital and expertise, and with less potential for large cost savings; although the potential for energy savings on a per m^2 basis may be high. There are some recent examples of significant investment in this sector (Yu, 2015), which highlight the potential.

The use of simplified energy simulation methods could improve access to life cycle cost information, which may persuade Secondary Grade building owners to consider integrated retrofit scenarios. Reducing the cost barrier to the use of BPS would allow a building owner to consider more holistic retrofit initiatives that would not be considered in a standard 'Type 2' energy auditing engagement. The benefits of increased access to simplified insights from BPS are well documented (Cerezo *et al.*, 2014; Hand *et al.*, 2008; Leal *et al.*, 2013; Sansregret & Millette, 2009). Tools such as the 'Deep Retrofit Scoping Tool' (NBI & The Weidt Group, 2014) in the U.S. provide simple insights, but have limited customisability. In the residential sector there are a number of tools designed to promulgate BPS to a broader user base by reducing the modelling effort required, e.g. (LBNL, 2015; Ecologic, 2015),

One simplification is the use of reference or archetypal building simulations. Conceptually this is similar to the use of early 'concept design' models of new buildings. The latter are used to facilitate estimates of energy performance at a point where the details of the building design have not emerged, but design decisions have a major impact on the final building performance. Whilst the use of reference buildings will introduce additional uncertainties into predictions, they can significantly reduce the modelling effort and cost. That is, whilst reference building models may not be as accurate as detailed building models, they may provide useful insights at a significantly lower cost. It must be noted here that the simulation or benchmarking of individual buildings is not the intended purpose of reference buildings (Deru *et al.*, 2011).

In Chapter 4 Consultant F identified that their company utilised BPS of simplistic reference buildings to give indicative savings for retrofits when detailed performance simulation was not included in the consultancy fee; to test the energy savings from widening the HVAC set-point temperatures in a Sydney office, for example. Cory *et al.* (2011) discussed the use of 'template' or reference buildings as a method to simplify the modelling of existing buildings. The authors concluded that there is potential for calibrated template buildings to be 'just as accurate as calibrated detailed models.' They also suggested reference buildings models can reduce modelling errors, and decrease inter-user variability in modelling predictions. However, the authors were simply testing geometric forms; the template buildings did not include construction, occupancy or HVAC information.

Three detailed building case studies are presented in this chapter and have been used to study the practical implementation and efficacy of using reference buildings to represent existing Secondary Grade commercial office buildings for retrofit decision-making. Six stages of model calibration were simulated for three reference buildings and the predicted energy consumption was compared with a validated Baseline Model. An uncertainty analysis of the influence on whole building energy consumption of the geometry, construction, and occupancy macro-parameters from the reference buildings was undertaken.

8.2 Research Method

A multi-stage simulation study was undertaken on the three case study buildings. This consisted of several stages, shown schematically in Figure 8-1:

i) An extensive search for suitable case study buildings was carried out over 3.5 years. The search used professional associations and networks to identify building owners, modellers, who may have appropriate buildings and detailed construction/performance information available, and were willing to make the data accessible to the current author;

ii) A final list of case study buildings was selected after initial review of the detailed information available for all buildings. Several buildings were discarded at this this stage due to poor documentation and data accessibility issues;

iii) Detailed building energy models were created for each case study building, and validated against metered consumption data. Details of the inputs to the case study

Baseline Models are given in Appendix C. The validated models were then simulated with typical weather data and typical occupancy inputs to create the 'Baseline Models'.

iv) Simulations were carried out to explore the usefulness of using reference buildings to represent actual buildings. Reference building models were simulated at six stages of calibration, and the resulting energy consumption compared with the detailed building energy model outputs.

v) The relative importance of different input macro-parameters on the residual uncertainty of building energy consumption was determined.

The case study buildings were selected based on the availability and accessibility of data. To qualify for inclusion in this study the building was required to be a Secondary Grade building (determined by expert opinion), and sufficient information was required for the development and validation of a BPS model. This effectively limited potential case studies to buildings that had recently undertaken, or were in the process of, a building energy efficiency upgrade. As an upgrade strategy had been designed, all the information required for a typical retrofit optimisation process was assumed to be available.

The identification of the buildings was a significant research task, due to the small proportion of Secondary Grade buildings for which energy retrofits have been undertaken. A formal request for case study buildings was circulated through industry mailing lists, sent to appropriate research groups, and shared with key contacts in industry and government. As part of the qualitative investigations, participants were asked to identify any suitable case study buildings, or contacts to follow up. A total of ten potential case study buildings were identified; site visits were undertaken at five of these. Three buildings were excluded as they were not commercial office buildings, three buildings were excluded due to poor documentation and data gaps, and one building was excluded due to privacy issues which resulted from changing ownership and management.

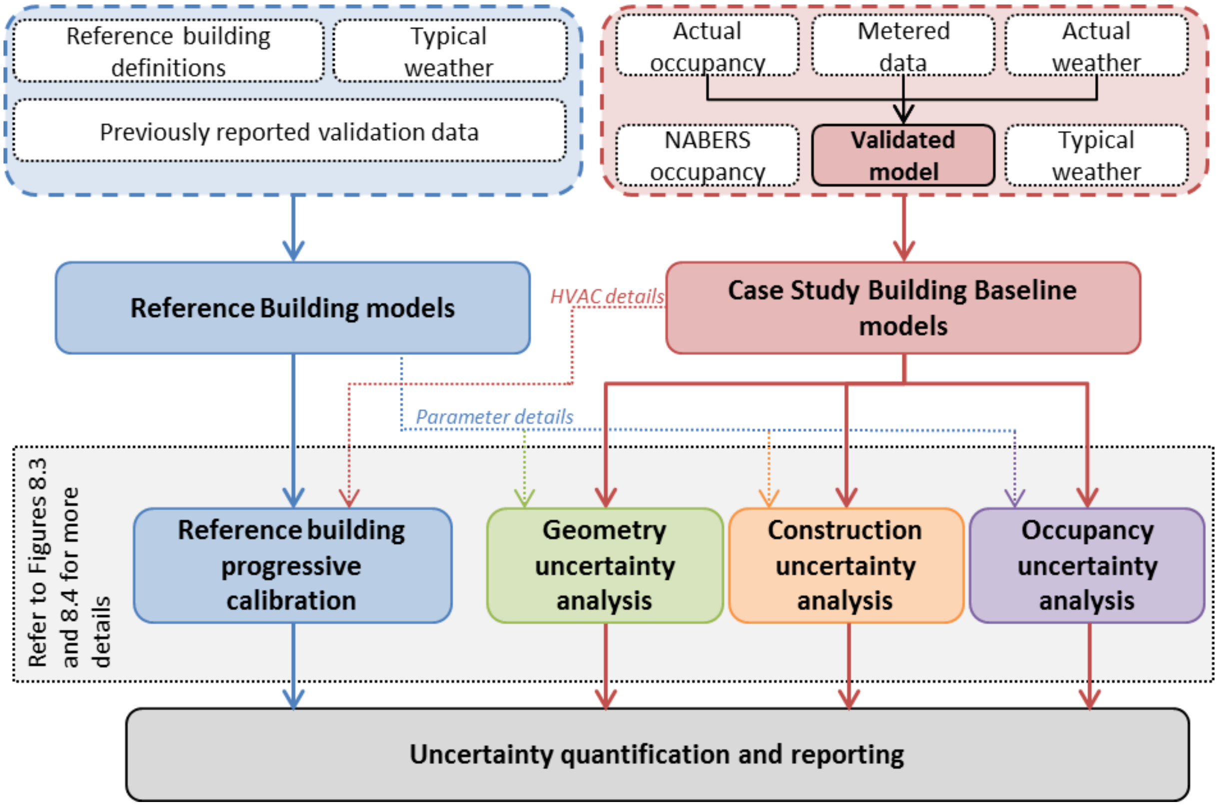
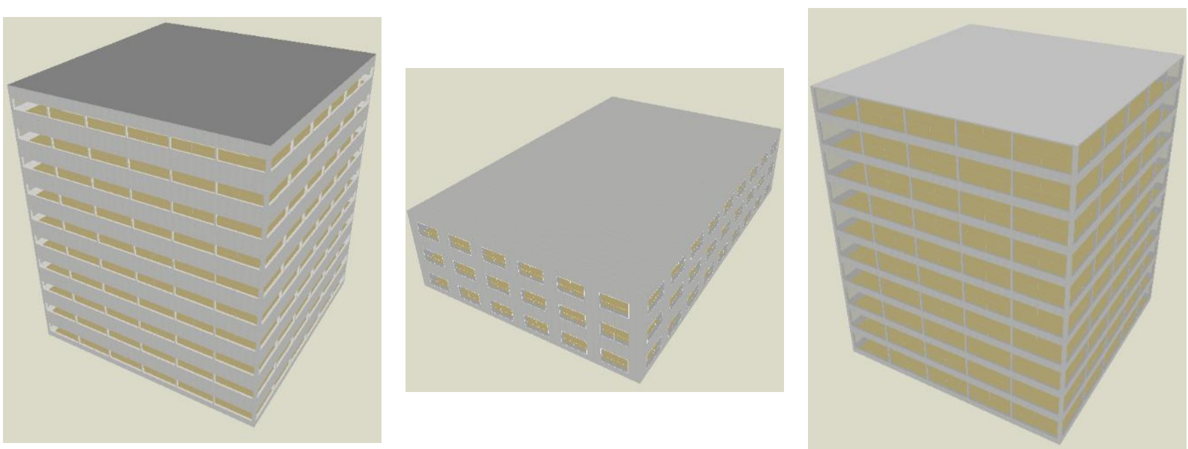


Figure 8-1 Schematic of the research method, including validation of reference and case study buildings, the reference building progressive calibration, and the macro-parameter Uncertainty Analyses (UAs). Further detail regarding the method for the reference building progressive calibration is provided in Figure 8-3, and for the macro-parameter UAs in Figure 8-5.

The specific reference buildings considered in this study are referred to as the 'Reference Buildings'. The three Reference Buildings from which the macro-parameter definitions were extracted were developed by: i) the Australian Buildings Codes Board (ABCB); ii) Zero Carbon Australia (ZCA); and iii) the US Department of Energy (DOE). These Reference Building models were progressively calibrated to match the case study building Baseline Model. An Uncertainty Analysis (UA) was then undertaken to explore the residual uncertainty between the predictions of the Reference Building models with a calibrated HVAC system, and the predicted energy consumption of a detailed, validated energy model of the case study building (the 'Baseline Model'). The UA tested the uncertainty introduced through standardised inputs for three macro-parameters, namely: geometry, construction, and occupancy. The inputs tested were entitled 'macro-parameters' as they were made up of groups of individual parameters that each had an associated uncertainty. For instance, the 'construction macro-parameter' incorporated the properties of each material used in the buildings, which may themselves have had an uncertain value.

8.2.1 Reference Building Descriptions

The ABCB and ZCA Reference Buildings have previously been employed by others to represent the energy consumption of Australia's existing office stock (BRANZ, 2007; ZCA, 2013). The DOE Reference Buildings were based upon a significant data collection and analysis exercise in America (Deru *et al.*, 2011), and were created in accordance with the EnergyPlus model available for download. The Reference Buildings were discussed in Section 2.9. Specific details of the models are shown in Table 8-1 and visualisations from DesignBuilder are shown in Figure 8-2. The models were validated using the total energy consumption and load disaggregation presented in previous studies.



ABCB Form A DOE Med Office ZCA Office

Figure 8-2 Reference Building visualisations from the DesignBuilder modelling program

Table 8-1 Building geometry and systems inputs for Australian Building Codes Board, U.S. Department of Energy, and Zero Carbon Australia Reference Buildings

Macro-parameter	Parameter	Australian Building Codes Board Form A	US DoE Medium Office Post 1980 [1]	Zero Carbon Australia Office 1980-2000
	Total floor area (m^2)	9,985.6	4,982	9,985.6
Geometry	**Number of floors**	10	3	10
	Aspect Ratio	1:1	1.5:1	1:1
	Flr to flr height (m)	3.6	3.96	3.6
	Internal zones	3.6 m perimeter and core	3.6 m perimeter and core	3.6 m perimeter and core
	Glazing fraction	0.38	0.33	0.73
Construction	**Infiltration**	0.5 ACH when plant operating (otherwise 1.5 ACH)	4 m^3/m^2-hr	1 ACH
	Exterior walls	Insulated HW concrete ($R_{overall}$ = 1.8 m^2K/W)	Steel framed ($R_{overall}$ = 0.83 m^2K/W)	Insulated HW concrete ($R_{overall}$ = 1.8 m^2K/W)
	Roof	Insulated HW concrete (R = 3.6 m^2K/W)	Insulation above metal deck (R = 1.71 m^2K/W)	Insulated metal deck (R = 1.5 m^2K/W)
	Floors	175 mm concrete with carpet (R = 0.8 m^2K/W)	200 mm concrete with carpet (R = 0.47 m^2K/W)	150 mm concrete with carpet (R = 0.43 m^2K/W)
	Windows	Single clear 6 mm (U = 5.89 W/m^2K, SHGC = 0.5)	Single clear 6 mm (U = 5.89 W/m^2K, SHGC = 0.44)	Single clear 6 mm (U = 5.6 W/m^2K, SHGC = 0.6)
Occupancy	**Lighting density (W/m^2)**	15	16.89	13
	Equipment density (W/m^2)	15	10.76	11
	Occupant density (p/m^2)	10	18.58	10
	Min vent rate (L/s/p)	10	10	7.5
HVAC	**HVAC system types** [2]	VAV, water-cooled AC, gas boiler	VAV with PACU and gas furnace	CAV AHU with Air-cooled chiller, gas boiler

1 - Location specific details (e.g. insulation levels) taken from Los Angeles, California (Horne *et al.*, 2005).
2 – VAV is Variable Air Volume, CAV is Constant Air Volume, PACU is Packaged Air Conditioning Unit, and AHU is Air Handling Unit.

8.2.2 Baseline Model Creation

Validation of the detailed energy models for each of the three case study buildings was undertaken via comparison with monthly utility data. Each building was simulated with historical weather data from the nearest BOM station during the period for which utility consumption data was available. Calibrated models were defined in accordance with ASHRAE (2012), as a model with a predicted CV (RMSE) < 15%, and NMBE < 5%, based on monthly utility data. There were issues of data accessibility for model validation, discussed below in Section 8.3.1, which imposed limitations on the validation process for the detailed building models. However, this study was concerned primarily with the *relative* difference in energy consumption predicted by the different modelling approaches, rather than with the *absolute* values of energy consumption. Thus, the results of the simplified model were considered relative to the predicted performance of the detailed energy model for each case study building.

Each detailed model represented a 'best attempt' to model the building accurately, using all the data that was available for a retrofit design engagement. The model was taken as the benchmark for the following comparative simulations. After the detailed model was validated, it was simulated with the relevant TMY weather file, and full occupancy. Occupancy was defined in accordance with the NABERS energy modelling protocol, with implications explored in Chapter 7. The NABERS protocol was used as retrofits are often scheduled to coincide with changes in tenancy (see Chapter 4), and therefore existing conditions are unlikely to be maintained. Information regarding probable future tenancy fit-out or behaviour was not available to the present author.

8.2.3 Progressive Calibration of Reference Building Models

An Uncertainty Analysis was undertaken to investigate the impact that increasing levels of calibration had on the accuracy of predicted energy consumption for the three Reference Building models. Six levels of progressive calibration were identified, primarily relating to the HVAC inputs, as shown in Figure 8-3. Figure 8-5 provides further detail on the UA into residual differences between the final stage calibration and the detailed model.

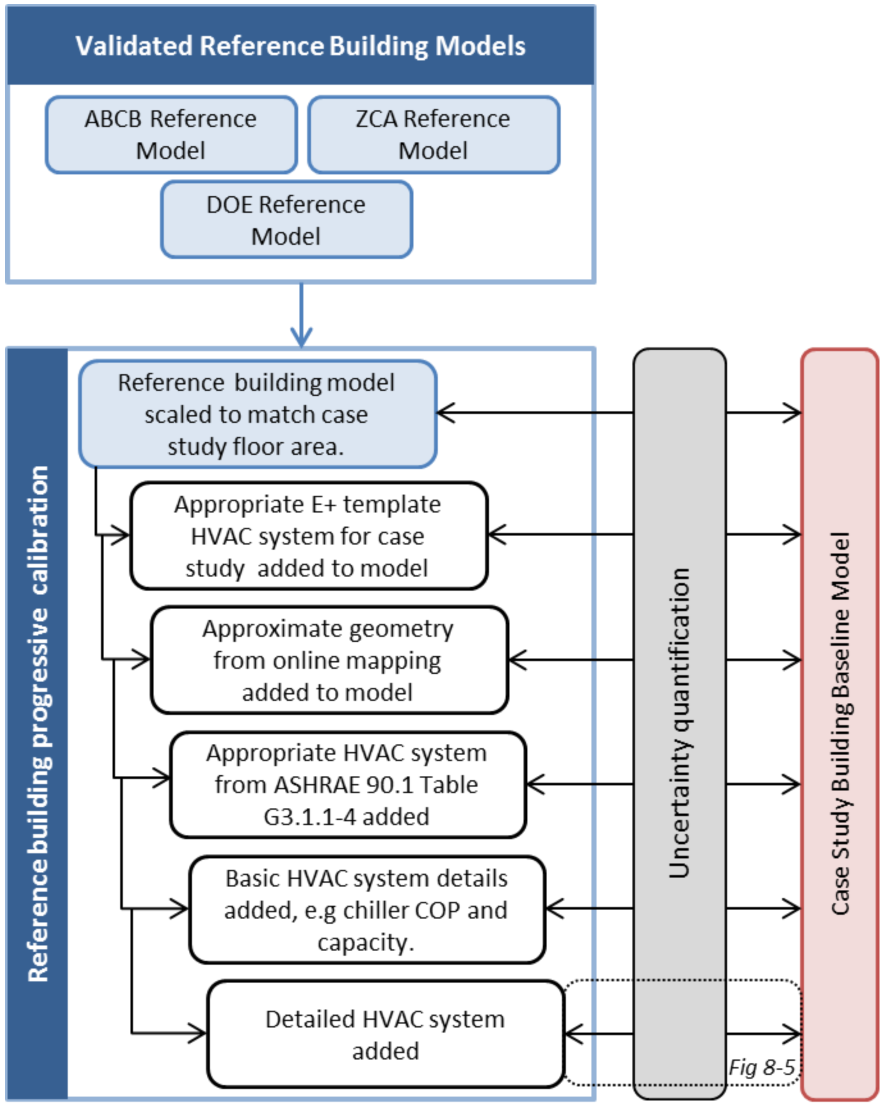


Figure 8-3 Schematic of the process followed for progressive calibration of the Reference Building models, incorporating increasingly detailed information from each case study.

The starting point for the progressive refinement was the validated Reference Building model, described above. The reference model was then geometrically scaled to match the number of stories and the gross floor area of the case study building; all other inputs remained unchanged.

The first calibration was to change the Reference Building HVAC system for an EnergyPlus HVAC template system that matched the case study building system, for instance a VAV system with a central chiller. At this stage, all detailed inputs to the HVAC system were left as for the Reference Building, or if inappropriate for the new system type, were changed to the EnergyPlus default values, i.e. plant component sizes were determine by the auto-size routine.

The next stage in the calibration was the alteration of the Reference Building geometry to approximate that of the case study building. The approximated form had an estimate of the floor area and aspect ratio for each floor of the case study building, an estimated window-to-wall ratio, and any major architectural, shading or glazing features. Data for this stage was taken only from online mapping, as this simplification would avoid the need for a site visit. An example is given in Figure 8-4.

Figure 8-4 An example of the method for geometry approximation using online mapping.

The third calibration stage was to alter the HVAC system model to the baseline system defined in ASHRAE 90.1 Table G3.1.1-4 (ASHRAE, 2013) which most closely matched the case study building. Table G3.1.1-4 provides a small number of well-defined HVAC systems based on building size and climate, and is often used as a basis for assumptions regarding uncertain systems. All Reference Building data for the HVAC system was replaced at this stage with values from either ASHRAE 90.1 or EnergyPlus defaults (if not defined in the standard).

At the next stage, the further detail regarding the case study HVAC system was added to the model. Important characteristics of the major HVAC components were incorporated in the model, e.g.: number and capacity of chillers and cooling towers, chiller COP, boiler efficiencies, pump powers, and fan sizes. HVAC system information that was based on detailed zoning, such as VAV and terminal heater capacities and auxiliary systems, was not included.

The final stage of calibration was to import the entire HVAC system definition from the validated Baseline Model into the Reference Building model (i.e. all the actual as-built information from

drawings, third party reviews, suite inspections etc..). At this stage the difference between the Detailed Model and the Reference Model are limited to the occupancy and construction definitions, and the geometric approximations.

This process was repeated for the three Reference Buildings, for each case study, which resulted in nine progressive calibration runs. The process is summarised in Table 8-2.

Table 8-2 Stages of the progressive calibration of simulations/models.

Reference Building scaled model	The Reference Building model was scaled to match the case study building floor area and number of stories and simulated with the typical weather data for that location. All other inputs as for the Reference Building model.
Calibration Stage 1	An appropriate simple HVAC system was applied to the model. Any defaults not explicitly defined by Reference Building remained as EnergyPlus defaults. All plant capacities were auto-sized.
Calibration Stage 2	Model altered to match the case study building geometry approximately, based on information from online mapping sources.
Calibration Stage 3	The HVAC was replaced with the most representative system from ASHRAE 90.1 Table G3.1.1-4. Any values not specified in the Reference Building model were left as ASHRAE defaults, or EnergyPlus defaults if not specified by ASHRAE 90.1. This calibration stage involved re-modelling the HVAC system using the DesignBuilder detailed HVAC interface, which allowed much greater flexibility in the input detail, and was essential to allow further calibration.
Calibration Stage 4	The HVAC system was updated with basic HVAC information from the case study building, sourced from a brief site visit. Information included number of chiller, Chiller COP and capacity, cooling tower, capacity, pump sizing, etc.
Calibration Stage 5	All HVAC data used in the creation of the case study Baseline Model was input to the model at this stage. Any difference between the model at this calibration stage and the Baseline Model is due to the geometry, occupancy, and construction macro-parameters, analysed in 8.3.3
Case study Baseline Model	The validated model, simulated with typical weather data and NABERS occupancy defaults.

8.2.4 Macro-parameter Uncertainty Analysis

At the final stage of calibration, any residual inaccuracy in the model was considered to be the result of uncertainties in the occupancy, construction, and geometry definitions of the Reference

Buildings, which had been carried through the progressive calibration. To understand this uncertainty quantitatively, uncertainty analyses were undertaken on the three Reference Building definitions of these three macro-parameters. Geometry, construction, and occupancy were therefore tested. The simulation procedure is summarised schematically in Figure 8-5. This was conducted as a one-at-a-time differential analysis, although the tested factor in each case was a macro-parameter, i.e. a parameter consisting of numerous individual parameters. The parameters contained within each macro-parameter are shown in Table 8-1.

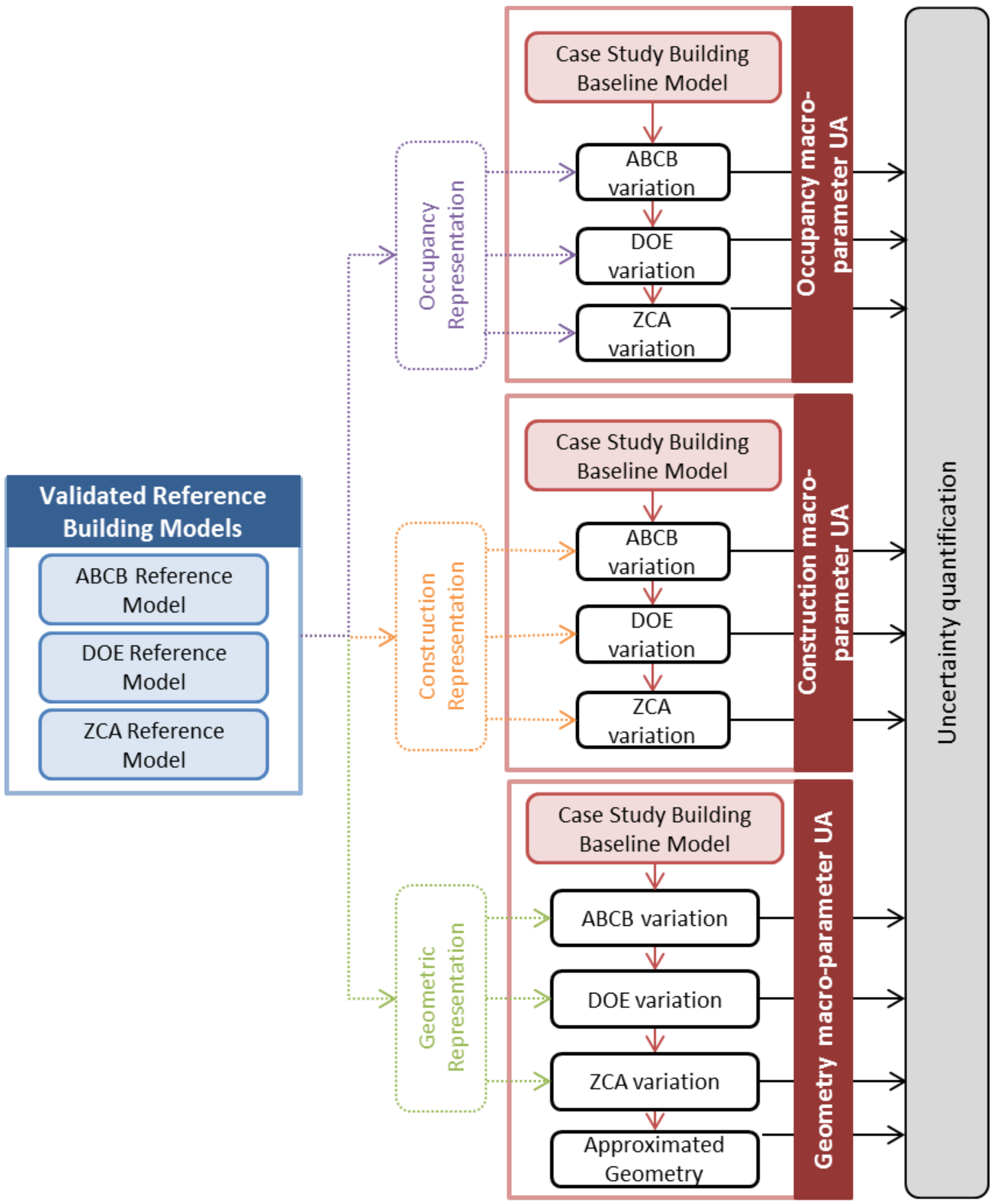


Figure 8-5 Reference Building macro-parameter sensitivity analysis methodology followed for each case study. Each solid box represents one model run. Colours correspond to macro-parameter detail defined in Table 8-1.

8.3 Results

This section presents an introduction to the case study buildings, and the results of the validation of the case study detailed models. The results of the progressive calibration of each Reference Building is then presented, along with an analysis of the residual uncertainty associated with three key macro-parameters at the final calibration stage.

8.3.1 Case Study Building Description and Model Validation

One B Grade, and two C Grade buildings were identified for case study analysis. All three buildings were located in Sydney, primarily due to the researchers' networks of contacts/actors in that region. Specific details that would allow identification of Building 1 and Building 2 were omitted from this thesis, as the information was commercially sensitive at the time of writing. Some identifiable information regarding the third case study is included here, however, the descriptor 'Building 3' was retained for consistency. Images of the building and model are shown for Building 3 only. The level of detail in the representation was consistent across all three buildings.

Model validation for all three buildings was undertaken against the accessible metered utility data. For Building 1, only nine months of consumption data from 2013 utility bills was accessible. For Building 2, the utility data accessible was an aggregation of three adjacent buildings' consumption (two offices and a warehouse), which were measured through a single meter. Disaggregation was completed according to building floor areas, the average annual electricity consumption of the adjacent office (from a public NABERS record), and the average energy intensity of a warehouse (from (U.S. Department of Energy, 2013a)). Whilst disaggregation following this method introduced uncertainty into the validation process, no further sub-metered data was accessible, and this study was primarily concerned with inter-modal comparisons.

The buildings were simulated with a Real-Time Year (RTY) weather file, formed from twelve months of observations (sourced from the nearest BOM weather station and including interpolated radiation data) arranged to form a calendar year which covered the period for which utility data was accessible. During the period for which utility data was accessible, both Building 1 and Building 3 were partially tenanted; Building 1 was approximately 40% occupied, and Building 3 was 57% occupied. High vacancy rates are a key driver for retrofit activity (see Section 2.10.5), therefore poor information with regard to post retrofit occupancy is likely to be common during retrofit

optimisation. In both cases, the vacancies were represented in the model for the purpose of validation.

Case Study Building 1

Case Study Building 1 (B1) was a Secondary Grade five-storey commercial office building located in Northern Sydney. At the time of the site inspection by the current author (Oct 2013), the building was in the early stages of an upgrade; the initial design had been completed, but works were yet to begin. B1 was nine storeys in total, with four levels of below-ground parking and five levels of office space. The office space was leased to multiple tenants. Building construction was heavyweight, with concrete floors, concrete wall panels, and a flat concrete roof. The building fabric was mostly uninsulated. There was double-glazing on the southern façade, and single glazing on all other facades. All windows had an external or internal film to reduce light and heat transfers; however, the film was in poor condition, and in many areas appeared to be ineffective at preventing solar gains. Blower door testing was undertaken, with a measured permeability of 3.2 $m^3/m^2/hr$ @ 50 Pa.

A mechanical services review had previously been undertaken by a third party for the building. This review provided detailed information with regard to the installed HVAC system. There were significant discrepancies between the installed system and the building documentation, e.g. two York air-cooled chillers on the roof provided the primary cooling, whilst the design documentation showed five chillers on the roof. Air-Handling Units (AHU's) at each level supplied air to Variable-Air-Volume (VAV) boxes, and onwards to electric duct heaters and fan terminal units. There were two smaller heat exchange units located on the roof, which served the southern perimeter of level one and level two. The car park levels were served by a mechanical ventilation system, consisting of constant speed supply and exhaust fans. The HVAC plant servicing this building was quite old, and no provision was made for economy cycles or night purging. Expected upgrades included lighting replacement and controls upgrade, chiller replacement, Variable-Speed-Drives to the AHU's, and replacement of major pumps. Details of the modelling inputs for the building are given in Appendix C.

The measured and predicted monthly base building energy consumption for Building 1, simulated with actual occupancy and weather, is shown in Figure 8-6. The period shown included nine months of measured data starting from February 2013. Calculated from the nine data points, the detailed

building model had a CV (RMSE) of 12.8%, and NMBE of -1.6%, which was within ASHRAE's acceptable range based on the Guideline for the Measurement of Energy and Demand Savings (ASHRAE, 2012) (as noted, the ASHRAE guidelines specify a minimum of 12 data points for validation).

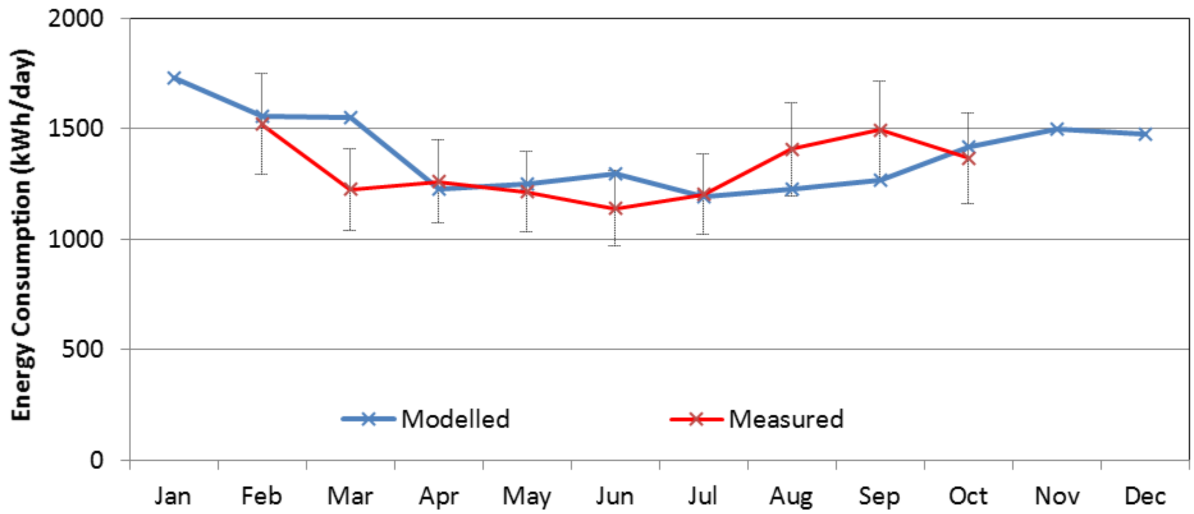


Figure 8-6 Comparison of the predicted base building energy consumption from the detailed Case Study Building 1 model to the accessible monthly base building energy consumption records. Bars show ± 15% at each metered data point.

Case Study Building 2

Case Study Building 2 (B2) was a B/C Grade two-storey commercial office building located in Northern Sydney. At the time of writing, the building was in the early stages of an upgrade. The office space was leased to a single tenant. Building construction was heavyweight, with concrete slab floor, concrete blockwork walls, and a metal clad roof. There was insulation and sarking to the roof, and some insulation in sections of the external wall, with no insulation below the slab. Windows were all single glazed with aluminium frames, and no films applied. Air tightness testing was not undertaken. Although B2 was considered B/C Grade, the building was operating at a high standard of energy performance prior to the upgrade, estimated to be at the equivalent of 4.5 Star NABERS.

The HVAC system was characterised from as-built drawings from the last building upgrade, in 1999, and a third party building condition audit. Generally, the plant was in good condition. The HVAC system was comprised of three central cooling towers, which provided chilled water to fifteen water sourced packaged heat pumps (cooling only) throughout the building. Heating was

supplied from VAV units with electric reheat to the perimeter spaces, and electric duct heaters to core areas. Each water-cooled package unit had capability for an economy cycle, which was utilised. Overall, the plant was in good condition, and operated efficiently. The building was in the early stages of a retrofit. Planned works include lighting replacement with LEDs, an upgrade of the cooling towers, and replacement of the individual packaged units with a centralised AHU and condenser. Details of the modelling inputs for the building are given in Appendix C.

Building 2 was modelled using as-built documentation, site notes and a third party energy modelling report. Twelve months of measured building energy data was accessible. However, the metering configuration during the recorded period also recorded power delivered to three adjacent buildings, and did not differentiate between base building and tenancy. Energy consumption for B2 was obtained by subtracting the estimated energy consumption for the adjacent buildings. Energy consumption was accessible for one of the adjacent buildings from a publicly accessible NABERS rating. The consumption of the other building was estimated from building floor area and average energy intensity for the building use (warehouse). Validation of the detailed model was made against 12 months of consumption data taken from utility bills from January 2013, disaggregated from two neighbouring buildings. The measured and predicted monthly base building energy consumption for the building is shown in Figure 8-7. The detailed building model had a calculated CV (RMSE) of 12.1%, and NMBE of 1.5%, which was within ASHRAE's acceptable range (ASHRAE, 2012).

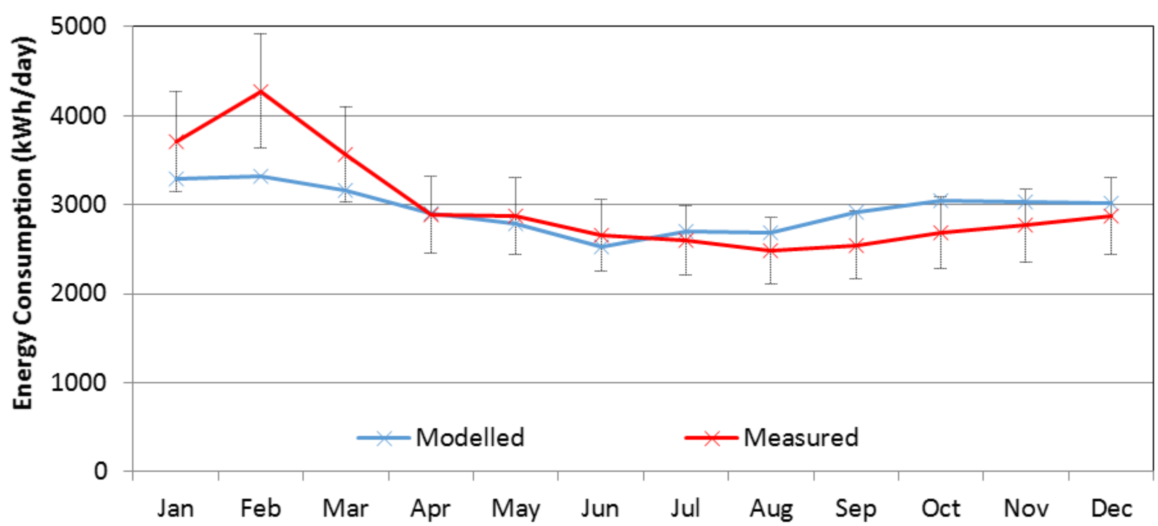


Figure 8-7 Comparison of the predicted base building energy consumption from the detailed Case Study Building 2 model and the accessible monthly base building energy consumption records. Bars show ± 15% at each metered data point.

Case Study Building Three

Case Study Building 3 (B3) was a C Grade seven-storey commercial office building located in Parramatta, in Western Sydney. The building is shown in Figure 8-8 and the detailed model geometry is shown in Figure 8-9. Building construction was heavyweight, with concrete slab floors, a mix of concrete and masonry walls, and a metal clad roof. There was minimal insulation throughout. Windows were all single-glazed with aluminium frames, and no films applied. Air tightness had not been previously tested, however, a site visit (Dec 2014) identified the building as likely to have poor air tightness. The windows in the building were nominally operable, although the facilities manager noted that they were not used in practice. The seals around these operable windows were relatively poor, and were expected to result in poor air-tightness.

Figure 8-8 Case Study Building 3, a seven-storey, C Grade commercial building located in Parramatta, Western Sydney.

The HVAC system was characterised from as-built drawings and a third party energy audit. The HVAC system was comprised of two central cooling towers that provided water to a central chiller plant (which served floors 1-6) and a packaged unit (which served the ground floor). Heating was supplied by a central boiler plant. All components other than the boiler appeared original to the building, and were identified as approaching, or having exceeded, service life. At the time of the present analysis (Feb 2015), the building was in the later stages of a major retrofit. Works included an upgrade of the cooling towers, installation of a high-efficiency chilled water system, including variable refrigerant flow and heat recovery, lighting replacement with LEDs and a controls upgrade to occupancy sensors, and replacement of the lifts, which were a significant energy end-use. The

works were partially funded through an Environmental Upgrade Agreement. Details of the modelling inputs for the building are given in Appendix C.

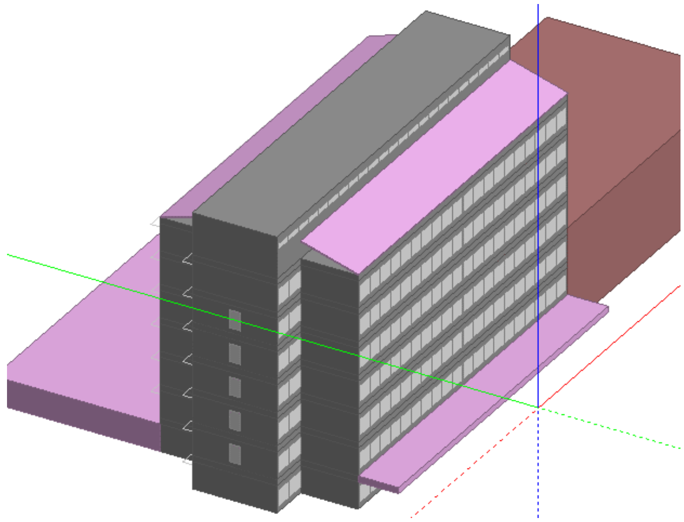


Figure 8-9 DesignBuilder geometric representation of Building 3 for model validation.

The detailed model of Building 3 was developed using as-built documentation, site inspection notes and a third party energy audit report. Monthly building energy utility data was accessible, for the period from June 2012 to Aug 2013. The building was simulated with a Real-Time Year (RTY) weather file for the period for which utility data was accessible. Figure 8-10 shows the measured and predicted monthly base building energy consumption for the building. The detailed building model had a CV (RMSE) of 6.8%, and NMBE of 2.1%, which was within ASHRAE's acceptable range (ASHRAE, 2012).

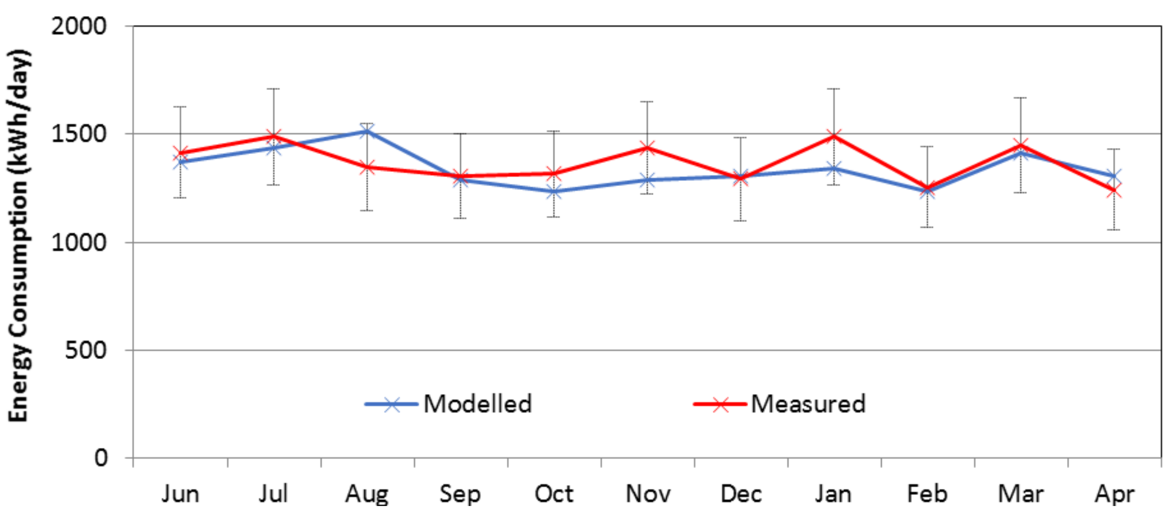


Figure 8-10 Comparison of the predicted base building energy consumption from the detailed Case Study Building 3 model and the accessible monthly base building energy consumption records. Bars show ± 15% at each metered data point.

8.3.2 Progressive Calibration of Reference Building Models

Once the case study building detailed models were validated against metered data, they were simulated with typical weather conditions using TMY files (Liley *et al.*, 2013), and full occupancy in accordance with the default values from the NABERS protocol (NABERS, 2011). A test was then conducted to explore the uncertainty and error that result from the simplifications and assumptions that were embedded in the Reference Building definitions. A model was created for each Reference Building, and then additional model details with regard to the building HVAC and geometry were progressively added, to identify any relationship between model detail and accuracy. For each progressive calibration, energy consumption information was normalised for gross floor area, as minor variations in floor area occurred as a result of different geometric representations. The residual uncertainty, which resulted from the Reference Building definitions for the geometry, construction and occupancy macro-parameters, was analysed and is presented in Section 8.3.3. The results of the progressive calibration of the Reference Buildings to each case study building are given in Figures 8-11 to 8-13, and a description of the calibration stages has already been provided in Table 8-2. Discussion of the results and potential implications is included in Section 8.4.

Case Study Building 1

The results of the progressive calibration of the three Reference Building models to represent Case Study Building 1 is presented in Figure 8-11 and Table 8-6 present measures of annual and monthly accuracy, in comparison with the Case Study Baseline model. All three Reference Buildings were predicted to have greater energy use intensity than the Baseline Buildings in their initial form, i.e. when scaled to match the Case Study floor area and number of storeys.

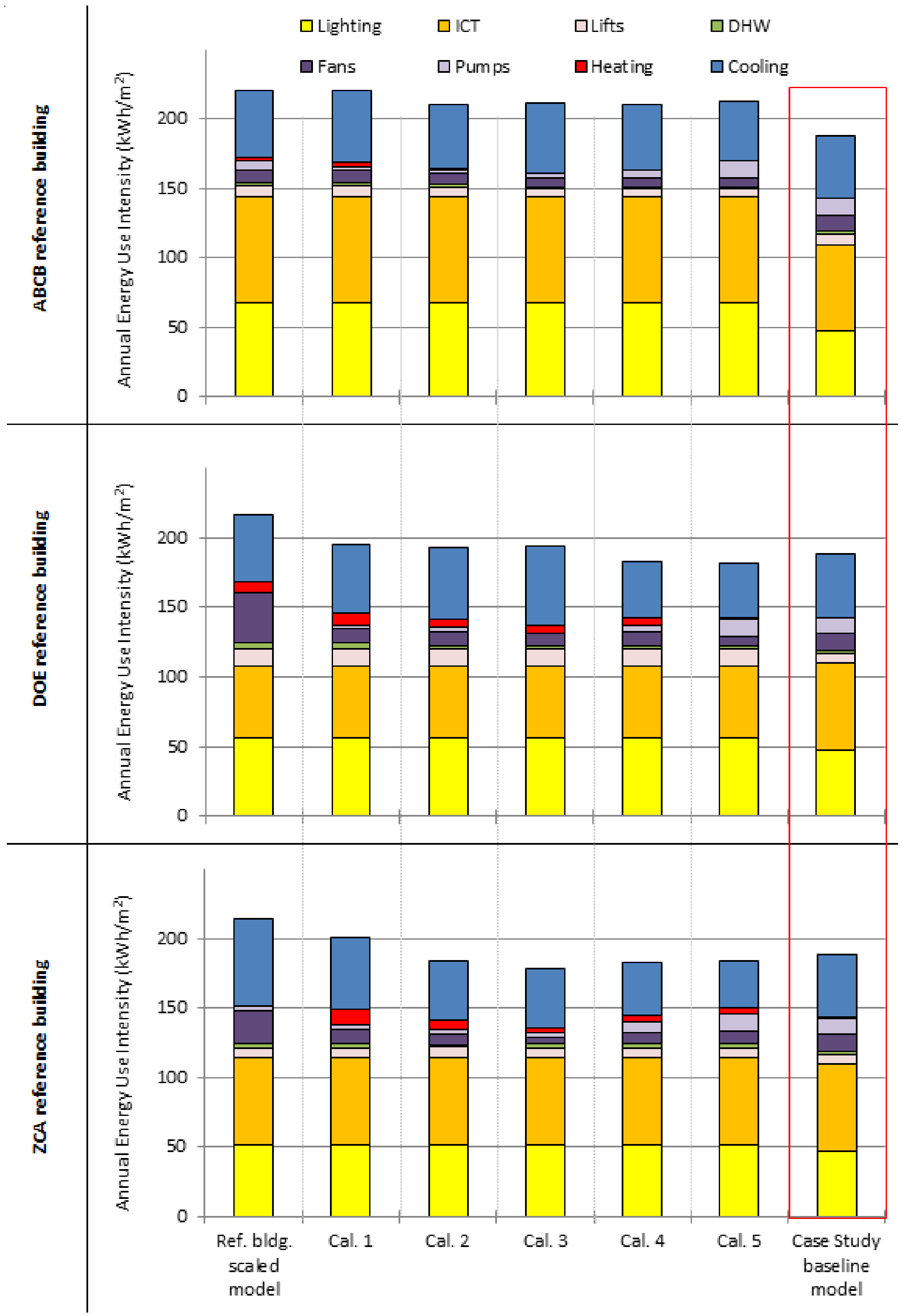


Figure 8-11 Progressive calibration of the three tested Reference Buildings to represent Case Study Building 1.

Reference Building Model The ABCB Reference Building model predicted the highest consumption, 17.9% greater than the baseline, whilst the ZCA and DOE both predicted consumption to be 13.8% greater than the Baseline Model. The assumed high internal gains were the primary cause of the high prediction for the ABCB, whilst the modelled HVAC systems for the other two Reference Buildings caused the high predictions; specifically the constant air volume system in the ZCA Reference Building and the high fan pressure rise and longer operating hours specified in the DOE Reference Building.

Calibration Stage 1 As a consequence of the initial model inputs, both the DOE and ZCA model predictions improved substantially when an appropriate HVAC system was applied to the models, to within 2.5% and 6.3% (greater) of the baseline, respectively. The ABCB building still predicted 16.9% greater consumption after the first calibration stage.

Calibration Stage 2 The application of an approximation of the Case Study building geometry slightly improved the prediction for the ABCB and ZCA Reference Buildings, to a difference of +11.8% and -2.2%, respectively. The DOE model prediction was 2.6% greater than the baseline, slightly worse than the previous calibration stage. This calibration stage also improved the alignment of the monthly predictions of three models with the Baseline Model to below ± 15%. At this stage, both the DOE and ZCA models were calibrated with the Baseline Model to an acceptable level using the ASHRAE criteria.

Calibration Stage 3 The next calibration stage, which involved remodelling the HVAC system using the DesignBuilder detailed input interface and the appropriate system and defaults from ASHRAE 90.1 Table G3.1.1-4, did not substantially alter the predicted EUI for any of the models.

Calibration Stage 4 Calibration Stage 4 was to input basic system specific information regarding the major HVAC components. For Building 1, a brief site visit had determined the presence of two air-cooled chillers, and the chiller nominal COP, manufacturer, model and capacities. Calibration Stage 4 slightly decreased the model alignment for the ABCB and DOE models, to +11.8%, -2.3% and -3.1% for the ABCB, DOE, and ZCA models respectively.

Calibration Stage 5 The final calibration stage, in which the detailed representation of the building HVAC from the Baseline Model was applied to the reference models, resulted in a minor predicted decrease in accuracy for both the ABCB and DOE models; the ZCA model at the final calibration stage predicted -2.4% less consumption than the Baseline Model. The major difference at this stage

for Case Study Building 1 was the presence of an air-handling unit serving each floor, whereas the previous stage modelled a centralised AHU. Significant increases in fan and pump consumption can be seen at this stage of the calibration, in line with the Baseline Model prediction.

The absolute average difference between the three Reference Buildings and the Baseline Model was calculated at each calibration stage, and is shown in Table 8-3. It can be seen that there was a slight decrease in model alignment with the Baseline Model from Calibration Stage 2 to Calibration Stage 5, however the change was minimal. Significant improvements in model alignment were seen at Calibration Stage 1 and Calibration Stage 2, where an appropriate HVAC system was input, and the geometry approximately matched to the Case Study building.

Table 8-3 Difference in predicted building energy consumption for the Progressive Calibration of the three tested Reference Buildings to represent Case Study Building 1.

Calibration stage	**ABCB**		**DOE**		**ZCA**		**Absolute average (|x|)**
	Annual	CV (RMSE)	Annual	CV (RMSE)	Annual	CV (RMSE)	Annual
Ref. Bldg Scaled floor area	17.9%	18.9%	13.8%	14.7%	13.8%	14.5%	15.2%
Cal. 1 EnergyPlus defaults: VAV with AC Chiller	16.9%	17.9%	2.5%	7.7%	6.3%	10.5%	8.6%
Cal. 2 Approximate geometry	11.8%	12.5%	2.6%	5.9%	-2.2%	8.2%	5.5%
Cal. 3 ASHRAE 90.1 System	12.2%	12.8%	3.1%	5.5%	-2.2%	5.7%	5.8%
Cal. 4 HVAC plant basic details	12.3%	13.5%	-2.3%	3.1%	-3.1%	4.2%	5.9%
Cal. 5 HVAC as Baseline Model	13.2%	13.8%	-3.8%	4.5%	-2.4%	3.8%	6.5%

Case Study Building 2

The results of the progressive calibration of the three Reference Buildings to represent Case Study Building 2 are presented in Figure 8-11, and Table 8-6 presents measures of annual and monthly accuracy. As for Case Study Building 1, all three Reference Buildings predicted a greater energy use intensity than the baseline building in their initial form, when scaled to match the Case Study floor area and number of storeys.

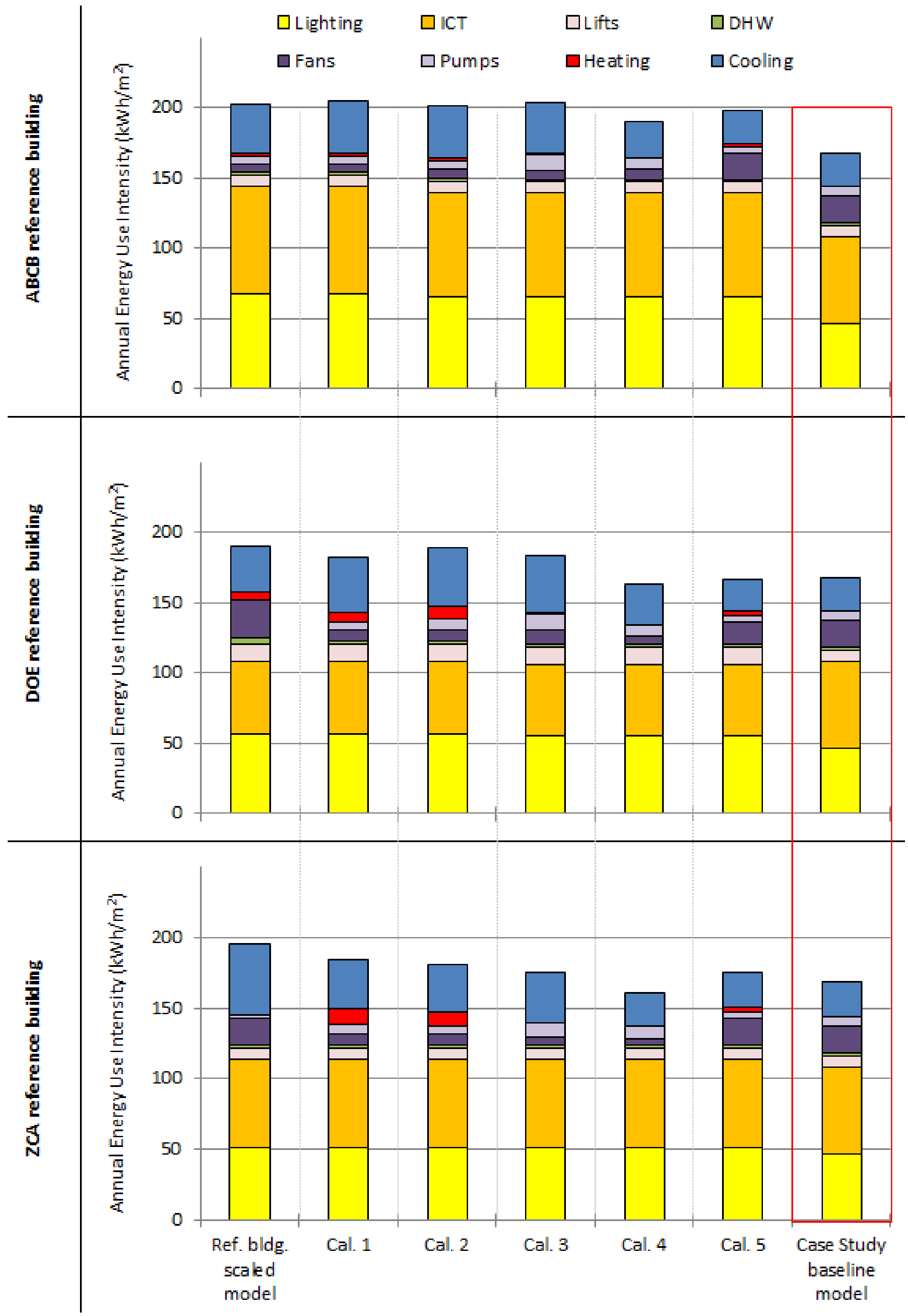


Figure 8-12 Progressive calibration of the three tested Reference Buildings to represent Case Study Building 2.

Reference Building Model The ABCB reference model predicted the highest consumption due to the high internal loads defined by the Reference Building, i.e. 20.3% greater than the Baseline Model. The ZCA led to a predicted consumption 15.9% greater than the baseline, and the DOE model predicted consumption to be 11.7% greater. The HVAC definitions, discussed in relation to Case Study Building 1, were again the primary source of the discrepancy for these models.

Calibration Stage 1 The ABCB Reference Building HVAC, a VAV system with water-cooled chiller, was retained at the first calibration stage, which resulted in no predicted change in consumption for that building. Both the DOE and ZCA model predictions improved substantially when an appropriate VAV ventilation system was applied to the models, to a prediction 8.5% and 9.6% greater than the baseline, respectively.

Calibration Stage 2 The application of an approximation of the Case Study building geometry slightly improved the prediction for the ABCB and ZCA buildings, and resulted in a slight decrease in alignment for the DOE building. The Case Study building was a deep-plan office building with a relatively simple geometric form, and thus minor changes to the building geometry were not anticipated to have a strong influence on consumption.

Calibration Stage 3 The next calibration stage, with the HVAC system defined in accordance with a system from ASHRAE 90.1 Appendix G, improved the alignment of the DOE and ZCA model, to a prediction 8.8% and 6.3% greater than the baseline, respectively. The ABCB model prediction increased slightly, to 21.6% greater than the baseline. This was due to a slight increase in predicted fan and pump power for the three models, which was offset by the removal of much of the predicted heating power consumption for the DOE and ZCA buildings. The high internal gains specified by the ABCB building meant that minimal heating load was predicted, whilst both the DOE and ZCA buildings predicted small but significant heating for all previous simulations.

Calibration Stage 4 Calibration 4, in which the basic detail regarding major HVAC plant components were input, increased model alignment to 19.4%, 3.8% and -3.4% for the ABCB, DOE, and ZCA models respectively. Chiller COP and cooling tower details were input at this stage, and economy cycle capability was added. These combined to predict a reduction in cooling and fan power consumption.

Calibration Stage 5 The final calibration stage, in which the detailed representation of the building HVAC from the Baseline Model was applied to the reference models, resulted in good alignment between the predictions for both the DOE (-1.3%) and ZCA (4.4%) models; the ABCB model at the

final calibration stage predicted 18.9% greater consumption than the Baseline Model. The HVAC system of Case Study Building 2 consisted of eight water-cooled packaged units, with individual supply and return fans. Significant increases in fan power consumption can be seen at this stage of the calibration, in line with the Baseline Model prediction. This was due to the appropriate fan power, from the third party mechanical report, being applied to the individual packaged units at this stage.

The absolute average difference between the three Reference Buildings and the Baseline Model was calculated at each calibration stage, and is shown in Table 8-4. For Case Study 2, model alignment with the Baseline Model improved at each calibration stage. The ABCB model consistently predicted higher consumption, and was relatively unaffected by the calibration process, due to the high internal gains assumed by this Reference Building.

Table 8-4 Difference in predicted building energy consumption for the Progressive calibration of the three tested Reference Buildings to represent Case Study Building 2.

Calibration stage	**ABCB**		**DOE**		**ZCA**		**Absolute average (|x|)**
	Annual	CV (RMSE)	Annual	CV (RMSE)	Annual	CV (RMSE)	Annual
Ref. Bldg Scaled floor area	20.3%	21.5%	11.7%	13.1%	15.9%	17.0%	16.0%
Cal. 1 EnergyPlus defaults: VAV with WC Chiller	20.3%	21.5%	8.5%	11.5%	9.6%	15.5%	12.8%
Cal. 2 Approximate geometry	20.1%	21.4%	11.1%	14.4%	7.2%	13.8%	12.8%
Cal. 3 ASHRAE 90.1 System	21.6%	22.6%	8.8%	9.6%	6.3%	9.0%	12.2%
Cal. 4 HVAC plant basic details	19.4%	20.4%	3.8%	4.2%	-3.4%	4.7%	8.8%
Cal. 5 HVAC as Baseline Model	18.9%	19.7%	-1.3%	1.8%	4.4%	4.7%	8.2%

Case Study Building 3

The results of the progressive calibration of the three Reference Building models to represent Case Study Building 3 is presented in Figure 8-13 and Table 8-5 presents measures of annual and monthly alignment of each calibration with the Case Study Baseline Model.

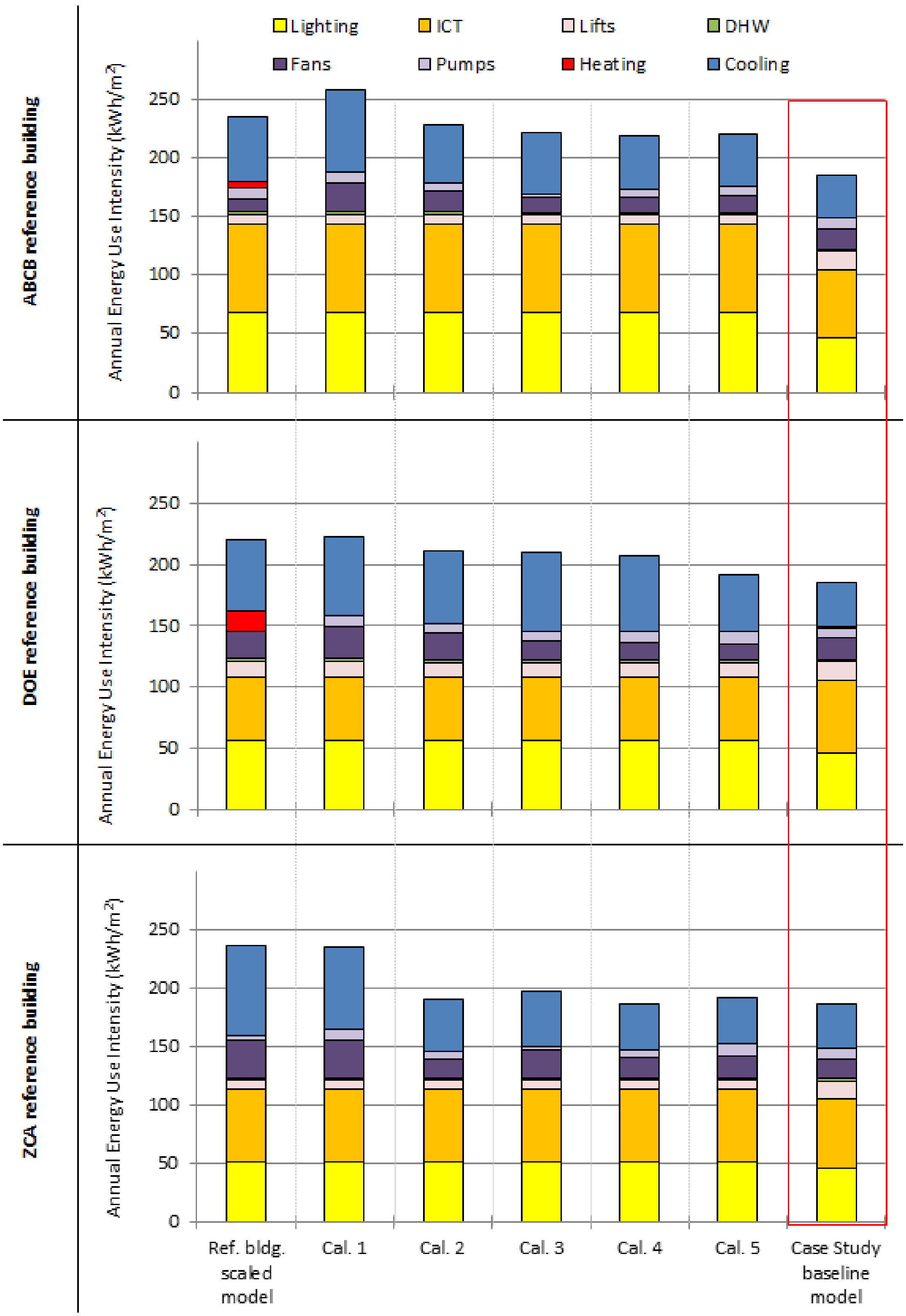


Figure 8-13 Progressive calibration of the three tested Reference Buildings to represent Case Study Building 3

Reference Building Model All three Reference Buildings predicted a greater energy use intensity than the baseline building when scaled to match the Case Study floor area and number of storeys, by an average of 24%. The ZCA reference model predicted the highest consumption, 27.4% greater than the Baseline Model. The ABCB predicted consumption to be 26.3% greater than the baseline, and the DOE model predicted consumption to be 18.4% greater.

Calibration Stage 1 Only the ZCA model prediction improved in alignment when an appropriate HVAC system was applied, and only by 0.7%. The Case Study building had a Constant-Air Volume (CAV) HVAC system, which was a similar system to that defined in the ZCA Reference Building. Modelling the ABCB and DOE buildings with a CAV system increased the predicted EUI for both models, to be 38.9% and 20.0% greater than the Baseline Model, respectively.

Calibration Stage 2 Calibration of the geometric representation of each model, to an approximation based on online sources, substantially improved the alignment of the model with the Case Study Baseline Model. The ABCB building prediction improved to 23% greater than the baseline, DOE improved to be 13.5% greater, and ZCA to be 2.8% greater. The improvement at this calibration stage was due primarily to the removal of glazing on the eastern and western facades from the Reference Building models. Case Study Building 3 had minimal glazing on these facades; an investigation into the influence of this is presented in the macro-parameter analysis, in Section 8.2.4 The remaining difference at this stage in the calibration of the ABCB model was primarily due to the assumed high internal loads; for the DOE building, it was related to long hours of HVAC operation, which will be discussed below.

Calibration Stage 3 The next calibration stage, which was to define the HVAC system in accordance with a baseline system from ASHRAE 90.1 Appendix G, had a relatively minor influence on the model alignment. The ABCB (19.2%) and DOE (13.1%) predictions were slightly improved, whilst the ZCA prediction (5.2%) was slightly further from the Baseline Model.

Calibration Stage 4 Calibration 4 also had a minor impact on the model predictions. Chiller capacity, boiler efficiency, cooling tower capacity, and major pump details were input. This increased model alignment to 18.2%, 11.9%% and 0.3% for the ABCB, DOE, and ZCA models respectively.

Calibration Stage 5 The final calibration stage, in which the detailed representation of the building HVAC from the Baseline Model was applied to the reference models, resulted in good alignment

between the predictions for both the DOE (5.2%) and ZCA (3.1%) models. The ABCB model at the final calibration stage predicted 18.7% greater consumption than the Baseline Model, due overwhelmingly to the high internal loads.

The absolute average difference between the three Reference Buildings and the Baseline Model was calculated at each calibration stage, and is shown in Table 8-5. For Case Study Building 3, model alignment with the Baseline Model improved at each calibration stage, after the appropriate HVAC system was input at the first calibration stage. The absolute average alignment was strongly affected by the assumed high internal loads of the ABCB at each calibration stage, and the long HVAC hours of operation from the DOE Reference Building, until the final calibration.

Table 8-5 Difference in predicted building energy consumption for the Progressive calibration of the three tested Reference Buildings to represent Case Study Building 3.

Calibration stage	**ABCB**		**DOE**		**ZCA**		**Absolute average (|x|)**
	Annual	CV (RMSE)	Annual	CV (RMSE)	Annual	CV (RMSE)	Annual
Ref. Bldg Scaled floor area	26.7%	29.3%	18.4%	22.7%	27.4%	29.1%	24.2%
Cal. 1 EnergyPlus defaults: CAV with WC Chiller	38.9%	40.8%	20.0%	21.5%	26.7%	28.2%	28.8%
Cal. 2 Approximate geometry	23.0%	24.4%	13.5%	14.8%	2.8%	5.6%	13.1%
Cal. 3 ASHRAE 90.1 System	19.2%	20.5%	13.1%	14.2%	5.2%	7.3%	12.5%
Cal. 4 HVAC plant basic details	18.2%	19.8%	11.9%	12.6%	0.3%	2.1%	10.1%
Cal. 5 HVAC as Baseline Model	18.7%	20.9%	5.2%	8.6%	3.1%	3.7%	9.0%

8.3.3 Macro-parameter Uncertainty Analyses

This section presents the results of the uncertainty analyses undertaken to investigate the residual uncertainty remaining at the final stage of the progressive calibration of the Reference Building models. The error and uncertainty associated with the simplifications in the Reference Building models was tested for three macro-parameters, namely geometry, construction and occupancy. In each case, the simplification from the reference model was applied to the validated Baseline Model

to understand the change to predicted energy consumption, with all other parameters remaining unchanged. There were numerous complex interaction between individual parameters contained in each macro-parameter, and between the macro-parameters. This is discussed below, however it should be noted that the simple addition of the individual uncertainties would not necessarily correspond to the total uncertainty. It should also be noted in any comparisons between the results below that each of the three case study buildings had a significantly different HVAC systems.

Geometry

The predicted HVAC Energy Use Intensity (EUI) of the three case study buildings, as simulated with the geometry macro-parameter taken from the three Reference Buildings is presented in Figure 8-14. The EUI of the HVAC equipment was considered, as the geometric changes did not influence other end-uses (daylight control was not employed).

Table 8-6 Summary of error introduced into the calibrated model by simulating the simplified geometry forms of the Reference Building models.

	Building 1	Building 2	Building 3	Absolute average ($\lvert\bar{x}\rvert$)
ABCB (1:1, WWR 38%)	1.8%	-1.7%	17.5%	7.0%
DOE (2:1, WWR 33%)	0.9%	-2.4%	14.2%	5.8%
ZCA (1:1, WWR 73%)	5.7%	0.8%	15.1%	7.2%
Approximated geometry	2.9%	-2.2%	4.1%	3.1%

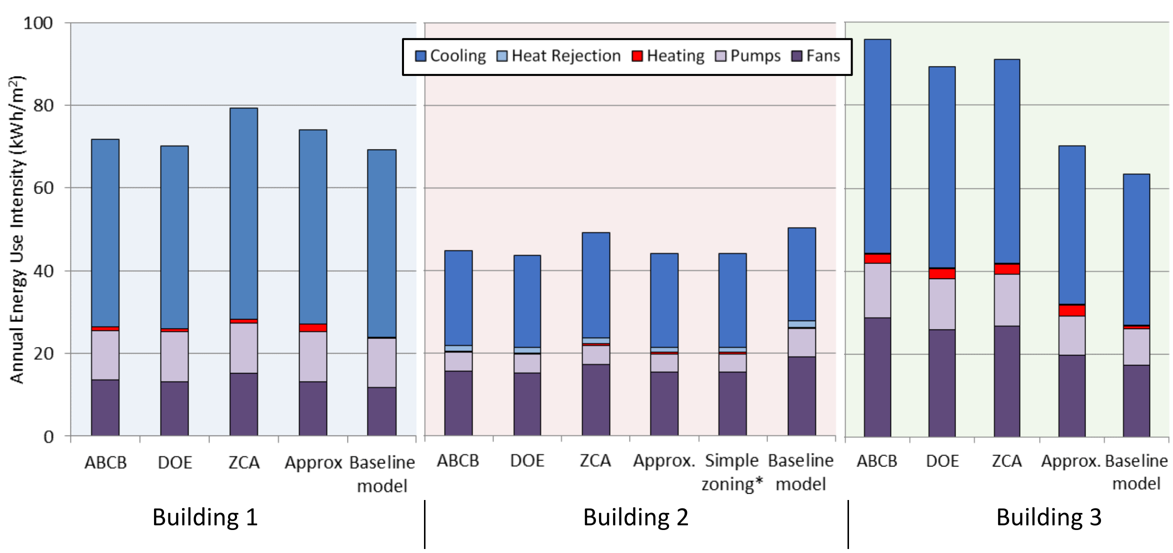


Figure 8-14 Predicted annual HVAC energy use intensity for a range of geometric representations of the three case study buildings. ABCB, DOE, and ZCA refer to the case study buildings simulated with the geometry macro-parameter inputs from the three Reference Buildings, defined in Table 8-1. For Building 2, simple zoning refers to a model run of the Baseline Model, with the HVAC zoning altered to match that used in the other four simulations for that building.

For Building 1, the three reference geometric forms all slightly over predicted the HVAC consumption, by an average of 2.8%. The magnitude of the predicted EUI displayed a direct relationship with the WWR of the Reference Building. The ZCA Reference Building predicted the highest consumption; 5.7% greater than the baseline. The ZCA building assumed a high glazing faction (73%), which was the primary cause of the high predicted EUI. The approximate geometry assumed from online mapping sources used a WWR of 40%, with an aspect ratio varying from 1.4:1 to 0.8:1, dependant on the particular storey. The case study simulated with the approximate WWR and aspect ratio resulted in a HVAC EUI that was 2.9% higher than the model simulated with detailed geometry.

The simplified geometric representations of Building 2 resulted in an absolute average difference in predicted whole building EUI of 1.6%, and an absolute average difference in HVAC EUI of 6.6%. As for Building 1, the predicted magnitude of HVAC EUI varied directly with the WWR of the Reference Building form. The HVAC system of Building 2 was comprised of multiple packaged units, which served individual zones. Simplification of the building geometry to match the Reference Buildings necessitated a simplification of how the HVAC zones were represented. Therefore a further model representing Building 2 was created (simple zoning in Figure 8-14), which was the Baseline Model altered to reflect the simplification of the HVAC zones in the Reference Building models. This necessitated a slightly less accurate definition of the HVAC system (e.g. actual data for electric duct heaters which served a specific zone could not be used). The differences between the Reference Buildings geometric macro-parameter prediction and the Baseline Model with simplified HVAC zones were much less pronounced. The absolute average consumption of the simplified geometry models was 1.2% different to the baseline with simple zoning, and the HVAC EUI differed by an average of 3.6%. This suggested that an important limitation of geometric simplification for some systems may be information of the HVAC zones.

For Building 3, the geometric macro-parameter representations predicted an average 15.6% greater HVAC Energy Use Intensity (EUI), compared with the Baseline Model. The approximated geometry, which had a WWR of 63% and an aspect ratio of 1.8:1, led to a HVAC EUI 4.1% greater than the baseline. The discrepancy between the Reference Building geometries and the approximated model was largely due to glazing detail, particularly the glazing on the western wall. The building, and the model with approximated geometry, had no glazing to the western or eastern facades, and shading (1 m overhang) to the northern façade. This had a significant influence on the predicted consumption. The ABCB geometric form, which initially predicted a 17.5% greater EUI,

predicted a 4.2% greater EUI when the glazing on the east and west façade, and the shading to the north was added. The glazing on the western façade was responsible for 55% of the difference for this geometric form; the glazing on the eastern façade for 18%.

Construction

The results of the uncertainty analysis into the impact of the use of construction macro-parameter details from the three Reference Buildings, for the three case study buildings, is shown in Figure 8-15, and summarised in Table 8-7. Again, the EUI of the HVAC components is shown, as changes to the construction representation did not affect the predicted consumption of other systems.

Table 8-7 Differences between predicted whole building EUI for the case study buildings simulated with the Reference Building construction templates and that for the case study constructions.

	Building 1	Building 2	Building 3	Absolute average (|x|)
ABCB	-7.7%	4.0%	-1.2%	4.3%
DOE	-4.1%	1.4%	0.8%	2.1%
ZCA	-7.1%	5.2%	2.1%	4.8%

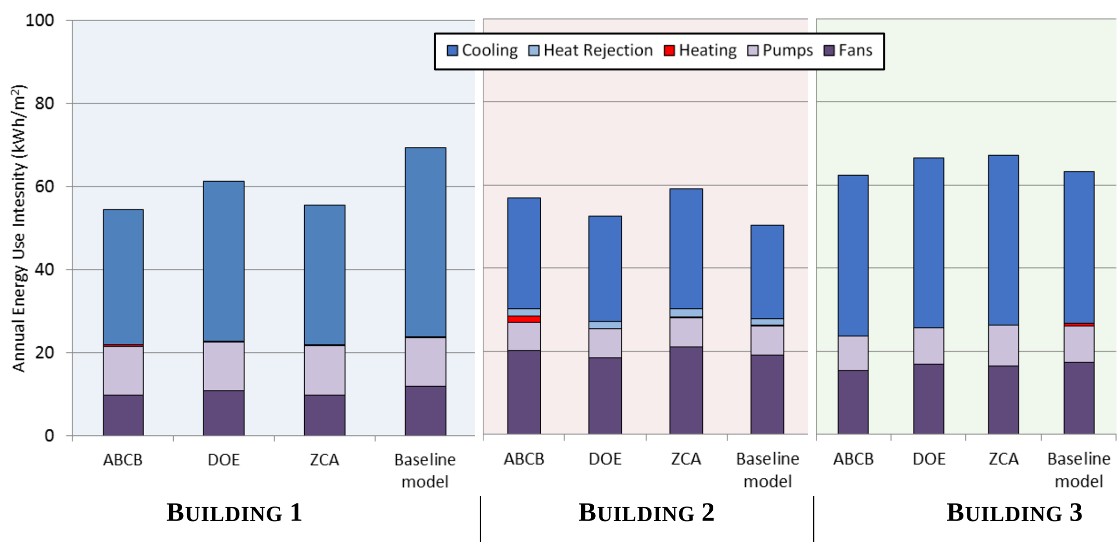


Figure 8-15 Predicted annual HVAC energy use intensity for three case study buildings simulated with the construction inputs from three Reference Buildings. ABCB, DOE, and ZCA refer to the case study buildings simulated with the construction macro-parameter inputs from the three Reference Buildings, defined in Table 8-1.

For Building 1, the Baseline Model simulated with the construction macro-parameter inputs from the three Reference Buildings predicted an absolute average EUI 6.3% lower than the Baseline Model. The ABCB construction inputs predicted the lowest EUI (-7.7%), ZCA the next lowest (-7.1%), and the DOE the highest, at 4.1% lower than the baseline. The Baseline Model had a very

low value for infiltration, based on results from air-tightness testing from a third party. The building test found an air permeability of 3.2 $m^3/m^2/hr$ @ 50 Pa, approximately equal to 0.015 ACH at natural conditions. It was hypothesised that the tested value may have been erroneous, due to the large floor plate tested, the exceedingly low result, and site inspections that identified gaps in the envelope. The low infiltration rate in the calibrated model was considered a likely factor in the predicted differences. Parametric analysis was undertaken in the range from 0 and 2 ACH. This test showed that HVAC EUI varied by 18% across the parametric range, which was significantly greater than the error seen in the sensitivity analysis. The construction macro-parameter also encompassed differences in building insulation, thermal mass, and glazing properties. Building 1 was mostly uninsulated, whilst a moderate level of insulation was assumed for all Reference Buildings.

The results for Building 2 follow a similar trend to those for Building 1, although the average difference between the three reference models and the calibrated model was smaller, at +3.5 %. Again, the predicted EUI had a direct relationship to the infiltration rate in each case. A parametric test of infiltration on consumption confirmed a direct relationship between infiltration rate and both whole building and base building energy consumption. Across the range from 0 - 2 ACH, predicted whole building energy consumption varied by 7.1%.

For Building 3, the absolute average difference between the Baseline Model and the construction test was 4.1%. A high infiltration rate (2 ACH) was assumed for Building 3, based on a site inspection and third party report. The predicted consumption of the Baseline Model was tested for relationship to infiltration, across the range 0 - 2 ACH. This revealed predicted variation of 21.3%, with higher infiltration corresponding with lower consumption for fans and cooling. The results of the sensitivity analysis in Chapter 6 showed that infiltration had a complex relationship to energy consumption in the Sydney climate. The results from this present study provide further evidence for this.

Occupancy

The predicted whole-building EUI for the three Reference Building occupancy representations, and the Baseline Model simulated with the occupancy default figures from the NABERS simulation protocol (NABERS, 2011) is presented in Figure 8-16. The differences between predictions for each Reference Building and case study are summarised in Table 8-8. When considering the occupancy macro-parameter it is important to note that the Baseline Model was simulated with the

NABERS default values, which are generally considered a conservative representation of occupancy (see Chapter 4). The assumed values for all occupancy parameters in the Reference Buildings were, as expected, in the middle of the range of 'typical' values identified in Chapter 6; which moderated the observed variation. Individual assumptions within the occupancy macro-parameter also combined to moderate the influence, e.g. the DOE building assumed a higher lighting power density, but lower hours of operation, in relative terms.

Table 8-8 Summary of difference between predicted whole building EUI for the case study buildings simulated with the Reference Building occupancy inputs compared to the default values from the NABERS protocol.

	Building 1	Building 2	Building 3	Absolute average (|x|)
ABCB	23.8%	16.5%	14.2%	18.2%
DOE	3.5%	2.3%	-5.3%	3.1%
ZCA	2.6%	4.9%	-2.9%	3.5%

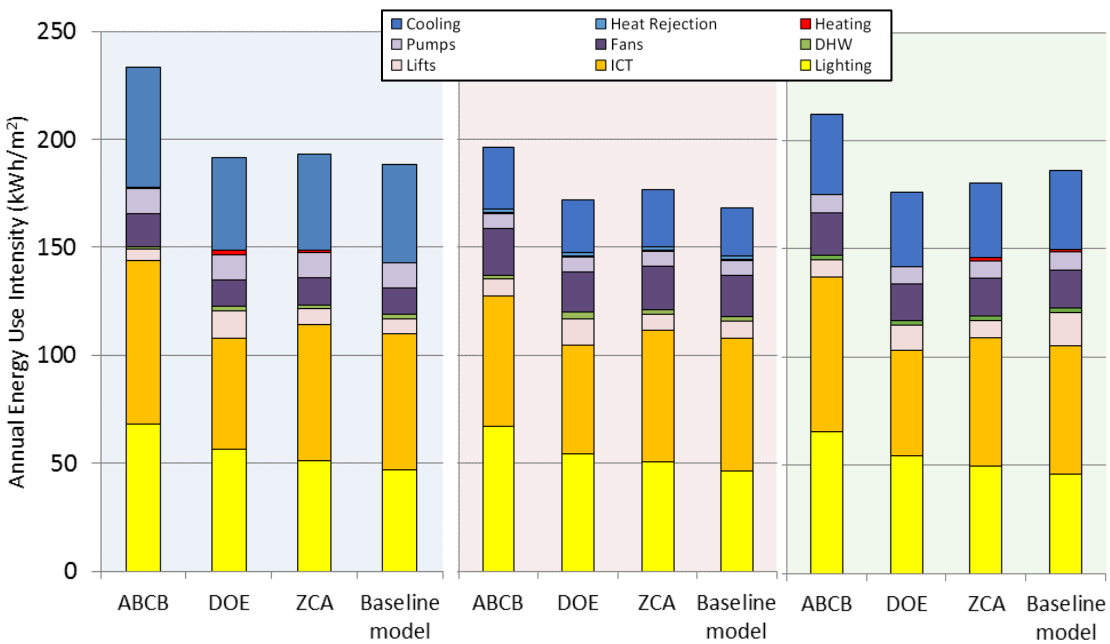


Figure 8-16 Predicted whole building annual energy use intensity for three case study buildings simulated with the occupancy inputs from three Reference Buildings. ABCB, DOE, and ZCA refer to the case study buildings simulated with the construction macro-parameter inputs from the three Reference Buildings, defined in Table 8-1.

The occupancy inputs had a relatively large influence on both whole-building and base-building predicted consumption for Building 1. The absolute average difference for the three reference occupancy inputs was 9.9%. The occupancy input from the ABCB Reference Building, which have relatively high internal lighting and equipment gains, and diversity schedules with high out of hours

equipment consumption, predicted a 23.8% greater whole building EUI, and 19.7% greater HVAC EUI, compared to the Baseline Model. The DOE occupancy inputs resulted in a predicted whole building EUI 3.5% greater than the baseline, and the ZCA inputs predicted a 2.6% greater EUI. The occupancy macro-parameter also had a substantial influence on both whole-building and base-building predicted consumption for Building 2. The three variations predicted an absolute average 7.9% greater whole building EUI, and 11.4% greater base building EUI. Again, the ABCB values resulted in a significantly higher prediction. The results for Building 3 followed the trend of those for Building 1 and Building 2. The absolute average variation was 7.5%, with the inputs from ABCB providing the largest error, of 14.2%.

8.4 Discussion

Overall, increasing the model detail led to increased accuracy of the model predictions. The absolute average accuracy of all Reference Building predictions to all case study building Baseline Models at each calibration stage is given in Table 8-9, along with an estimate of the modelling effort required. The initial calibration stages, which were to select an appropriate HVAC system for the buildings, and model an approximation of the geometric form, significantly improved the accuracy of the Reference Buildings, with minimal modelling effort. Gates *et al.* (2012) identified the use of detailed geometry with default HVAC settings as the most 'effective and efficient detail level to model'. This would roughly correspond to Calibration Stage 2 in this study, which resulted in a prediction with an absolute average difference of 10.7% for the three case study buildings.

The final model calibration, using the detailed HVAC representation, an approximate geometric representation, and the reference occupancy and construction representations, predicted whole-building consumption to within an absolute average difference of 7.9%, and 4.0% for the base-building. However, creating the detailed representation of the HVAC system for input at this calibration was a substantial task, which dominated the majority of modelling effort. The collection of appropriate data to allow a building model with such detail to be created is also a significant task, which for this study was completed by others.

Table 8-9 Average accuracy of models at each calibration stage, compared to Baseline Model

	Average accuracy compared to Baseline Model		Information required	Modelling effort
	Whole Building	Base Building		
Ref. Bldg Scaled floor area	18.5%	27.0%	Reference Building definition	Very minimal, << 1 hr. once reference model was constructed
Stage 1 EnergyPlus defaults:	16.7%	21.7%	Verbal description of HVAC system type	Very minimal, <<1 hr more than previous calibration.
Stage 2 Approximate geometry	10.7%	12.2%	Online mapping, or building photographs	Minimal ≈ 1 hr more than previous calibration.
Stage 3 ASHRAE 90.1 System	10.3%	12.6%	Verbal description of HVAC system type	Moderate ≈ 1 hr more than previous calibration.
Stage 4 HVAC plant basic details	8.3%	9.7%	Site visit or HVAC plant documentation	Moderate - Variable depending on level of detail. May require rezoning to ensure plant is serving correct spaces.
Stage 5 HVAC as Baseline Model	7.9%	4.0%	Detailed building energy and condition audit.	Significant ~ 5 to 20 days modelling, following significant data collection

The assumptions embedded in the Reference Building models had a considerable effect on the accuracy of each stage in the calibration process. Figure 8-17 presents a summary of the average, minimum and maximum difference at each calibration stage for each Reference Building.

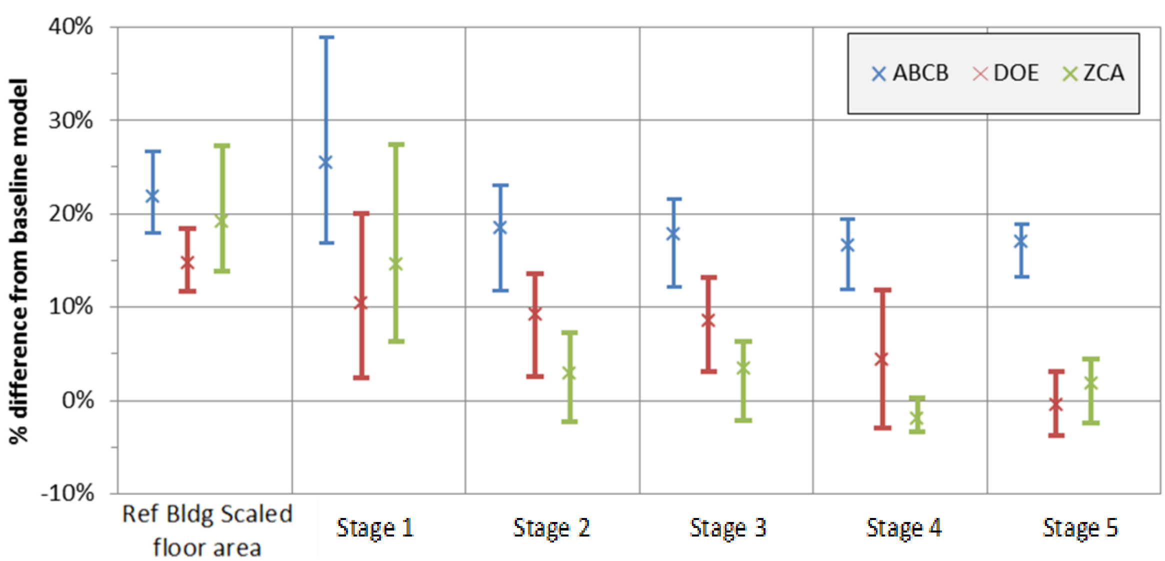


Figure 8-17 Maximum, average and minimum difference between each Reference Building model and the Baseline Model at each calibration stage.

It can be seen that the accuracy of the prediction at each calibration stage was strongly affected by which Reference Building was selected. All simulations with the ABCB Reference Building produced more than 10% discrepancy compared to the baseline. The ZCA building produced good alignment with the baseline building at Calibration Stage 2 and onwards. Many of the assumptions for the ZCA Reference Building were sourced from the NABERS protocol. As the Baseline Model was simulated with NABERS defaults, this skews the comparison towards the ZCA building somewhat.

A summary of the results from the macro-parameter uncertainty analysis is displayed in Figure 8-18. The absolute average variation from the Baseline Model, for all Reference Buildings and case studies, for the geometry macro-parameter was 6.7% (SD = 7.3%), 3.7% (SD = 2.4%) for construction, and 8.2% (SD = 9.1%) for the occupancy macro-parameter.

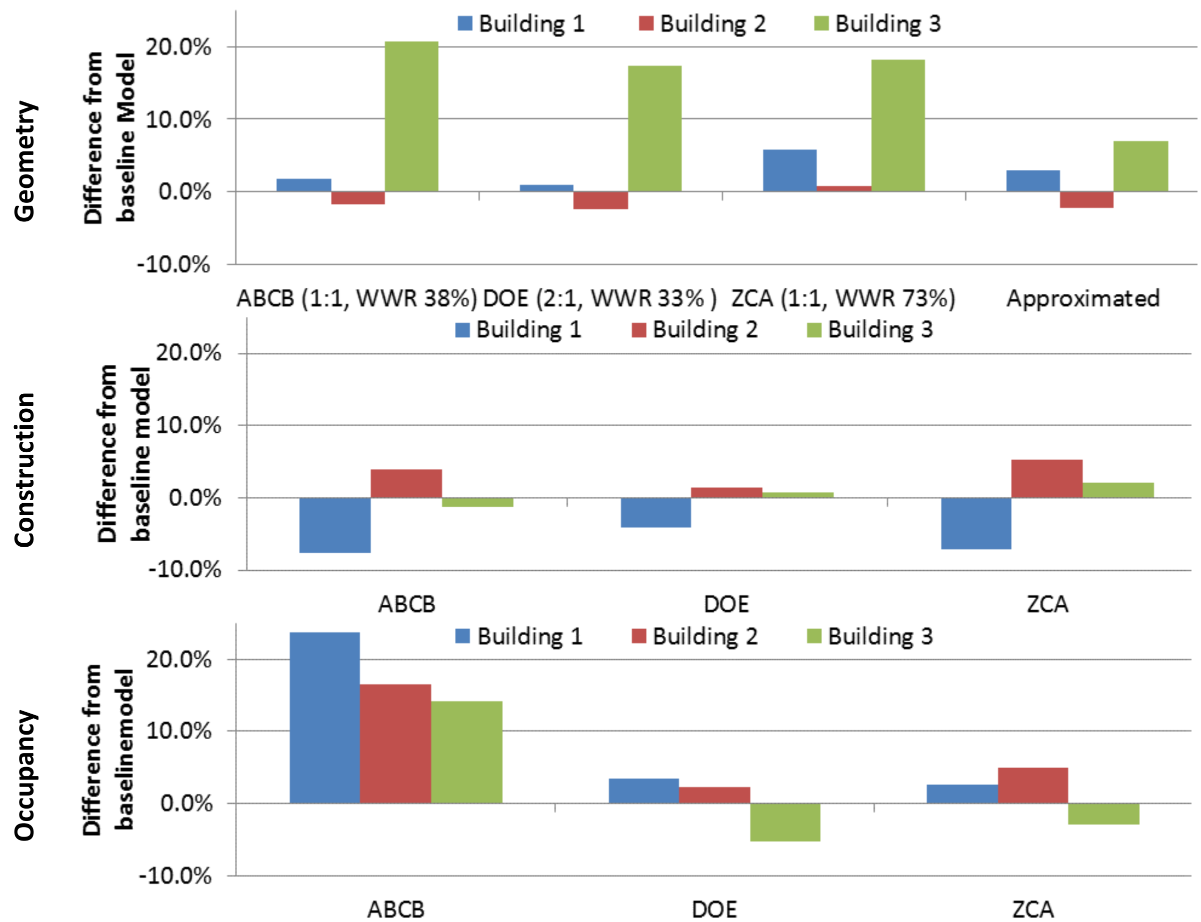


Figure 8-18 Summary of difference in predicted whole-building EUI between the three case study building Baseline Models, and the models perturbed with the geometric, construction and occupancy macro-parameters from the Reference Buildings.

As for preceding chapters, the occupancy inputs had a relatively large influence on both whole-building and base-building predicted consumption for all the case study buildings. The ABCB inputs, which specify high internal gains, predicted over twice the absolute average, an average of 18.2% greater than the calibrated model for the three case study buildings. The occupancy inputs were tested against the Baseline Model simulated with the relatively conservative NABERS default inputs. Thus, the fact that the occupancy macro-parameter resulted in a large variation serves to reinforce the relative importance of accurately representing the occupancy of a building.

The geometric macro-parameter absolute average was heavily affected by the high predictions for Building 3 for all Reference Building models. Case Study Building 3 had no glazing to the west or east, and had shading to the northern windows, which were not accounted for in the reference models. The approximated geometry significantly improved the model alignment for Building 3; this calibration stage had an absolute average error of 3.1%. The WWR was found to influence the predicted consumption significantly, and the Reference Building form that had the closest proportion of north facing glazing to the case study building was found to be most accurate, although the effect was slight.

The construction macro-parameter was found to have the smallest uncertainty. It is likely that this is due to similarities in construction materials between the case study office buildings and the Reference Buildings. The parametric range for construction material properties is constrained by physical considerations, for instance maintaining structural integrity, which is a much tighter constraint than geometric form, for example. There was therefore a smaller range of input variation for this macro-parameter. The importance and complex influence of building air tightness on predicted EUI was highlighted. In office buildings, which generally have high internal loads, in a cooling-dominated climate such as Sydney, increasing air-tightness beyond a certain point can often increasing cooling consumption.

This study had a number of limitations, which deserve consideration. It is inadvisable to draw strong conclusions from the results of the three case study investigations. This is particularly so for commercial building energy simulations. It has been noted previously that the eccentricities of individual buildings can significantly influence energy consumption. It is possible that if the approach was applied to another three Secondary Grade case studies, significantly different findings would emerge. Uncertainty Analysis conducted at the macro-parameter resolution does not allow for Influence Coefficients to be calculated, as a simple determination of the percentage change in

input values cannot be calculated. Therefore, it was difficult to compare quantitatively the relative significance of a change in two macro-parameters, for instance a change to a building's geometry versus a change in a wall construction type. Further, superposability of individual parameters may mean that large changes to a number of parameters will not result in a correspondent change in the macro-parameter.

Many of the systemic issues identified in Chapter 4 may be addressed to some extent through the use of reference buildings to simplify the BPS process. This method has additional advantages beyond reducing modelling cost, Firstly, in contrast to other simplifications; a reference building model can be further calibrated as more information becomes available. New modelling software packages capable of leveraging cloud computing to complete hundreds of model runs in parallel for Uncertainty and Sensitivity Analysis (e.g. the Parametric Analysis Tool for OpenStudio), make this capability extremely beneficial. Sensitivity Analysis of a reference building model calibrated with approximate geometry and template HVAC system (i.e. to stage 2) can be used to identify key parameters to investigate during a site visit or energy audit (Zirnhelt *et al.*, 2014). Likewise, analysis of potential retrofit strategies in a simplified model can be used to inform targeted investigations of the key parameters for promising retrofits. For instance, if a retrofit under consideration is a lighting upgrade, the efficiency of existing lighting systems must be well understood. The use of cloud computing in this way can also provide an improved representation of risk and uncertainty, rather than a single figure deterministic value.

Standardisation of uncertain inputs, which can reduce inter-user variability of results, increase reproducibility of results, and improve model documentation is a further advantage of calibrated reference models (Gates *et al.*, 2012). The development of a fully specified BPS model, particularly for a Secondary Grade building, involves the use of many assumptions and heuristics. Evidence based calibration and rigorous validation against metered data can improve confidence in the model, however calibration in accordance with ASHRAE Guideline 14 is no guarantee of model accuracy, nor of accurate savings predictions from retrofit analysis (Im & Bhandari, 2014; Karpman *et al.*, 2014; Raftery *et al.*, 2011). The use of reference buildings as a starting point for progressive calibration of an energy model would ensure a consistent starting point for all simulation users, and allow a third party to more effectively scrutinise model inputs with reference to default values. Any calibration of the reference building definition could be recorded, to provide a log of changes that would aid model interrogation an enhance reproducibility of results by others. However, the use of

reference buildings in this way is dependent upon appropriate reference building definitions being available for the Australian context.

The present study has shown that reference buildings calibrated with simple building information have the potential to represent actual office buildings in Sydney for BPS with an acceptable level of uncertainty, compared to a fully specified and validated Baseline Model. The accuracy of the prediction was dependant on the assumed HVAC system, geometry and occupancy of the reference building. Calibration of the Reference Buildings with an approximation of the HVAC and geometry of the case study building was shown to improve the model prediction substantially, without significant additional modelling or data collection effort. Further calibration of the HVAC system improved the model alignment with the Baseline Model, and to increase the relative importance of the occupancy, construction and geometry simplifications embedded in the Reference Building definitions. Occupancy was found to be particularly influential, whilst geometry was shown to be potentially important, dependent upon the case study building form.

9 Conclusions

The aim of this project was to enhance the understanding of the impacts of uncertainties associated with Building Performance Simulation (BPS) of the energy consumption of lower quality commercial office buildings in Australia. This study was one of very few conducted with a focus on Australian conditions and was unique in that it employed both qualitative and quantitative analyses to investigate the uncertainty of BPS when used in practice.

The review of existing literature elucidated the context of and motivation for this study, and identified significant knowledge gaps. In general, only limited existing data sets were found to be accessible to address these knowledge gaps on the commercial building stock in Australia. Nevertheless, three databases with specific building and energy information related to the Secondary Grade building stock were identified and accessed. The databases were analysed for insights into the Australian existing buildings stock, and the building retrofitting industry more broadly.

The analysis of the Building Energy-Efficiency Register found that the average whole building energy intensity of office buildings in the database was 1063.3 MJ/m^2, which aligned closely with previous studies. It was also found that the spaces within the database had an area-weighted average lighting power density of 12.2 W/m^2, and that 73.1% of the zones assessed had lighting power densities outside of the range of common assumption used in Building Performance Simulations.

The Building Attribute Database for Melbourne, from Wilkinson (2011a), provided further evidence to support anecdotal claims related to the energy savings potential of Secondary Grade buildings. Secondary Grade buildings in the database were found to be smaller, older, more likely to be in private ownership, and with a higher Energy Use Intensity than Prime Grade buildings. In addition, the present analysis of the Energy Saver Scheme Database found that lighting was the most commonly recommended building upgrade (across numerous commercial building types), followed by installation of variable speed drives, hot water system upgrades, and then HVAC upgrades. This triangulated with the results of the qualitative study, which found that consultants were confident to recommend these proven technology without extensive BPS.

The qualitative investigation was designed to investigate the research gaps for which data was not accessible, and to support methodological triangulation with the quantitative studies to enhance

confidence in the findings. A revised systematic approach to building energy retrofitting was proposed, refined from Ma *et al. (2012)* to incorporate the need for building and system condition evaluations, regular client collaboration, and to highlight the importance of expert knowledge. Commercial pressure was found to be interrelated with BPS accuracy, and often to result in increased uncertainty in BPS predictions. The use of heuristics and assumptions to determine variable and uncertain inputs was identified as a shortcoming which was driven strongly by commercial pressures acting on practicing modellers in industry. The Environmental Upgrade Agreement financing model was discussed, and the potentially significant financial risk due to uncertainty in BPS savings predictions was highlighted through comparison with EPC procedures.

An Uncertainty Analysis of the quantitative importance of climatic representation on the selection and performance of particular retrofits and refurbishments of commercial office buildings in Australia was carried out. It was found that the predicted energy consumption of the reference building simulated in this study was relatively insensitive to the selection of the source for Typical Meteorological Year files.

Predictive weather files were created to provide hourly data for future climatic conditions for five major population centres in Australia up until 2080. The weather files were generated assuming mid-to-high range global emissions continuing in the future. The weather files generated revealed a relatively small increase in dry bulb temperature for Australia (mean 3.1 ^{o}C). The projected weather conditions were found to affect energy consumption and cooling load in the studied reference building. Predicted building energy consumption was found to vary by between -0.6% and +8.3% depending on climate zone, and an increase in the total design cooling equipment capacity of 9.1% to 25.0% was predicted.

When compared to projected changes in energy consumption and cooling load due to basic retrofit strategies and likely scenarios for changes in ICT equipment loads, it was concluded that the impact of climate change on building energy consumption is not likely to be a primary factor in the building retrofit decision making process for typical commercial buildings.

The sensitivity and uncertainty of predictions of whole building energy consumption from BPS to a range of simulation assumptions and default values for unknown or variable building and occupancy inputs was then tested. Predicted energy consumption of two reference buildings was found to vary by more than 50% from the baseline consumption when simulated with high and low

simulation assumptions sourced from previous research projects or real world measurements. Up to 25% difference in total energy consumption was predicted between the simulation assumptions from two previous studies, which aimed to represent a typical Australian office building. It was also found that the simple payback period of a simple retrofit could vary by 300% depending upon the source for base case input assumptions.

The influence coefficient was also calculated for the eleven tested variables. The inputs that most strongly influenced the predicted energy consumption for the modelled buildings were found to be: i) cooling set-point, ii) ICT power density, iii) ICT usage schedule, and iv) lighting power density. The sources of common assumptions were examined, and the validity was discussed.

A further investigation then tested the uncertainty impacts of the use and selection of a modelling protocol on the predicted energy consumption from BPS. Three Australian simulation protocols, and one influential protocol from the U.S. were reviewed. It was found that simulations which used default values embedded in the NABERS modelling protocol predicted the highest average energy consumption, 13.5% greater than the lowest prediction for Sydney. This study suggested that the use of default values for occupant-controlled loads recommended by simulation protocol can still result in substantial variation in building energy use predictions and end-use load breakdowns.

The final chapter considered the feasibility of the use of Calibrated Reference Buildings to reduce the modelling cost of representing Secondary Grade buildings for retrofit analysis. Three Secondary Grade case buildings were identified for this study. Three commercial office Reference Buildings were calibrated to align with the validated Baseline Models. The uncertainty at each calibration stage was quantitatively determined, and the residual uncertainty at the final calibration stage was further examined. A strong trend was found with models which had undergone the most calibration produced results that aligned most closely with the Baseline Model. The final model calibration resulted in a predicted absolute average difference of 7.9% in whole building consumption, and 4.0% in base building. The selection of an appropriate HVAC system for the buildings, and the use of an approximation of the geometric form, significantly improved the accuracy of the reference buildings, with minimal increased modelling effort.

The residual uncertainty which remained at the final stage of calibration was further tested. As a result, the relative influence of simplifications to the geometry, construction, and occupancy macro-parameters used by three Reference Buildings was presented. The absolute average error for the

geometric simplifications was 6.7%. Estimating the geometry based on the information accessible from online mapping sources was able to reduce this to 3.1%. The absolute average error introduced through the use of template construction details was found to be 3.7%. Infiltration was determined to be a key parameter. The assumed occupancy inputs from the Reference Buildings were found to increase predicted EUI by an average of 7.8%. The use of Calibrated Reference Buildings was found to be a promising technique to reduce the modelling cost of representing Secondary Grade office buildings in Sydney, whilst retaining the primary utility of a fully specified and validated Baseline Model.

This study has contributed to an enhanced understanding of the importance of uncertainty in prediction of energy consumption from BPS for commercial office buildings in Australia. The use of multimethod research techniques has provided a more nuanced insights into the commercial building stock and retrofitting industry in Australia. This study was one of few conducted with a focus on uncertainty in predictions of energy use for Australian commercial office buildings, and was unique in its focus on Secondary Grade commercial buildings. It was further distinctive in that it employed both qualitative and quantitative analyses to investigate the uncertainty of BPS in practice.

9.1 Recommendations for further research

Numerous research questions were identified through the course of this research, which were beyond the scope of this study. The research questions are concerned with to two related objectives; to improve the understanding and representation of uncertainty in BPS of commercial office building, and to reduce the uncertainty of predictions from BPS through improved understandings of the existing building stock and improved simulation practices. Both goals fundamentally relate to the need to improve access to and confidence in predictions from BPS to encourage the implementation of deep retrofit solutions. Suggested future research activities include:

- Development of a national building energy and energy related attributes survey and database. The short-lived effort by the CSIRO to create an Australian Building Energy Repository was an activity that could yield significant benefits for the energy modelling and building retrofitting industries. In the US, the CBECS provided essential data for the development of evidence based reference buildings. The US Department of Energy also maintain a building performance database (U.S. Department of Energy, 2013a), which contains information of the energy performance of over 72 000 commercial buildings in the

US, categorised according to building use, location, construction, occupancy attributes, and installed systems. Similar initiatives have been completed in the U.K. This is a significant research activity, but one that would yield greatly enhanced understanding of the Australian building stock.

- An obvious extension of the previous recommendation is the development of fully specified commercial reference building based on the database results. Numerous international studies have utilised statistical data to identify and define reference buildings to characterise a stock to a sufficient degree, and with an acceptable level of uncertainty. Reference buildings for a segment of the national building stock have been developed based on this technique in the U.S (Deru *et al.*, 2011), Japan (Yamaguchi *et al.*, 2007), Ireland (Famuyibo *et al.*, 2012), Scotland (Clarke *et al.*, 2004), Canada (Parekh, 2005), and England (Choudhary, 2012). As discussed in Chapter 8, the use of reference buildings to simplify simulation of Secondary Grade buildings is dependent on the reference building having appropriate inputs. A typical reference building, created with reference to an extensive database of building attributes unique to the Australian commercial building stock is likely to be more appropriate than the reference buildings currently available.

- Since the present investigation of the impact of projected climate change on building energy use was undertaken, a major research effort, the NSW / ACT Regional Climate Modelling (NARCLIM) project, has reached completion. This research project undertook downscaling of four Global Climate Models, at a grid resolution of 10 km. This means that regionally specific projections of future weather conditions are now available. It would be a worthwhile exercise to investigate the implications of these improved projections on commercial buildings. As noted, the morphing technique used in this project limited the evaluation of the impact of extreme events. The use of eXtreme Meteorological Years (XMY) or similar may allow insights into the impact of extreme events. Of particular interest may be a comparison of the resilience of heavyweight vs curtain-wall construction to extreme heat events.

- An obvious area for future research, highlighted by others, is obtaining actual measurements of conditions and behaviours in existing buildings. Information was found to be lacking in the Australian context for air-tightness, occupant density and schedules, equipment power density and usage schedules, and achieved thermal conditions. Air-tightness testing is a large unknown in energy simulations, and is often used as a method of

tuning simulation results to match metered consumption (ASHRAE, 2012), in the absence of tested data.

- With regard to Secondary Grade building, the key hurdle to characterisation of this segment of the building stock has been engagement with the building owners, and the identification of case study buildings. The recent announcement (Yu, 2015) of a partnership between the Clean Energy Finance Company, and a major real estate investment group to acquire and upgrade twelve non-prime commercial buildings represents a significant research opportunity. It is likely that involvement in this project would provide crucial insights into characteristics of the Secondary Grade stock, and potential energy savings, challenges and opportunities for retrofitting.

- The results of Chapter 8 reinforce the importance of adequately representing the HVAC system in a commercial office building to obtain accurate results. A beneficial exercise would be to extend the uncertainty and sensitivity analyses undertaken in Chapter 6, to reference buildings simulated with a range of common HVAC systems. The increasing utility of cloud computing would significantly reduce the modelling load of this exercise. Information on commonly installed HVAC systems for the Australian context may be able to be gained from The Calculating Cool program managers (Sustainability Victoria, 2014). The results of this could further inform targeted energy audits, to focus on the key parameters for different installed systems.

- Finally, investigation of variability in energy predictions which result from modeller decisions is an area which has not previously been examined in Australia. Several overseas studies have highlighted this as an important consideration (Berkeley, 2013; Guyon, 1997). It is likely that contextual factors, particularly the use and prevalence of simulation protocols, would strongly influence this variability. A study which compared the relative variability in results from three groups of modellers who: created a model from scratch, created a model from scratch with the aid of a simulation protocol, and who modified a reference building to match an actual building, would be intriguing.

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Appendix A

National Construction Code Classification of Buildings and Structures

Principles of classification

The classification of a building or part of a building is determined by the purpose for which it is designed, constructed or adapted to be used.

Classifications

Buildings are classified as follows:

Class 1: one or more buildings which in association constitute—

(a) Class 1a — a single dwelling being—

(i) a detached house; or

(ii) one of a group of two or more attached dwellings, each being a building, separated by a fire-resisting wall, including a row house, terrace house, town house or villa unit; or

(b) Class 1b —

(i) a boarding house, guest house, hostel or the like—

(A) with a total area of all floors not exceeding 300 m2 measured over the enclosing walls of the Class 1b; and

(B) in which not more than 12 persons would ordinarily be resident; or

(ii) 4 or more single dwellings located on one allotment and used for short-term holiday accommodation, which are not located above or below another dwelling or another Class of building other than a private garage.

Class 2: a building containing 2 or more sole-occupancy units each being a separate dwelling.

Class 3: a residential building, other than a building of Class 1 or 2, which is a common place of long term or transient living for a number of unrelated persons, including—

(a) a boarding house, guest house, hostel, lodging house or backpackers accommodation; or

(b) a residential part of a hotel or motel; or

(c) a residential part of a school; or

(d) accommodation for the aged, children or people with disabilities; or

(e) a residential part of a health-care building which accommodates members of staff; or

(f) a residential part of a detention centre.

Class 4: a dwelling in a building that is Class 5, 6, 7, 8 or 9 if it is the only dwelling in the building.

Class 5: an office building used for professional or commercial purposes, excluding buildings of Class 6, 7, 8 or 9.

Class 6: a shop or other building for the sale of goods by retail or the supply of services direct to the public, including—

(a) an eating room, café restaurant, milk or soft-drink bar; or

(b) a dining room, bar area that is not an assembly building, shop or kiosk part of a hotel or motel; or

(c) a hairdresser's or barber's shop, public laundry, or undertaker's establishment; or

(d) market or sale room, showroom, or service station.

Class 7: a building which is—

(a) Class 7a — a carpark; or

(b) Class 7b — for storage, or display of goods or produce for sale by wholesale.

Class 8: a laboratory, or a building in which a handicraft or process for the production, assembling, altering, repairing, packing, finishing, or cleaning of goods or produce is carried on for trade, sale, or gain.

Class 9: a building of a public nature—

(a) Class 9a — a health-care building, including those parts of the building set aside as a laboratory; or

(b) Class 9b — an assembly building, including a trade workshop, laboratory or the like in a primary or secondary school, but excluding any other parts of the building that are of another Class; or

(c) Class 9c — an aged care building.

Class 10: a non-habitable building or structure—

(a) Class 10a — a non-habitable building being a private garage, carport, shed, or the like; or

(b) Class 10b — a structure being a fence, mast, antenna, retaining or free-standing wall, swimming pool, or the like; or

(c) Class 10c — a private bushfire shelter.

Appendix B

PARTICIPANT INFORMATION SHEET FOR EXPERT INTERVIEWS

TITLE: *A survey of expert opinion on attitudes and practices relating to the use of building thermal simulation in determining optimal energy-efficiency retrofit strategies for low PCA grade commercial buildings.*

PURPOSE OF THE RESEARCH

This is an invitation to participate in a study conducted by researchers at the University of Wollongong. The purpose of the research is to survey expert opinions on attitudes and practices relating to the decision-making process involved in determining optimal energy-efficiency retrofit strategies for commercial buildings.

INVESTIGATORS

Prof Paul Cooper	Daniel Daly	Dr Zhenjun Ma
Sustainable Building Research Centre	SBRC	SBRC
02 4221 3355	0403 491 374	02 4221 4143
pcooper@uow.edu.au	dhd316@uow.edu.au	zhenjun@uow.edu.au

METHOD AND DEMANDS ON PARTICIPANTS

If you choose to be included, you will be asked to participate in semi-structured interview, with an expected duration of 30-60 minutes, which will have the audio recorded. The interviewer will ask your opinions and practices relating to the decision-making process involved in determining optimal energy-efficiency retrofit strategies for commercial buildings. Typical questions in the interview include: What do you see as the major challenges facing building retrofitting, and building energy research in Australia in the coming years? Why do you think the potential saving from building retrofitting are not being realised on a broad scale? The research, possibly including some direct quotes, may appear in my PhD thesis, and academic journals, subject to your consent.

POSSIBLE RISKS, INCONVENIENCES AND DISCOMFORTS

Apart from the 30-60 minutes of your time for the interview, we can foresee no risks for you. Your involvement in the study is voluntary and you may withdraw your participation from the study at any time and withdraw any data that you have provided to that point. Data will be securely stored according to the University of Wollongongs' archiving policy. Refusal to participate in the study will not affect your relationship with the University of Wollongong.

ETHICS REVIEW AND COMPLAINTS

This study has been reviewed by the Social Sciences Human Research Ethics Committee of the University of Wollongong. If you have any concerns or complaints regarding the way this research has been conducted you can contact the UOW Ethics Officer on (02) 4221 3386 or email rso-ethics@uow.edu.au.

Thank you for your interest in this study.

CONSENT TO PARTICIPATE IN INTERVIEW

THE ROLE OF BUILDING SIMULATION IN DETERMINING OPTIMAL RETROFIT STRATEGIES FOR LOW PCA GRADE COMMERCIAL BUILDINGS.

Daniel Daly, Paul Cooper, Zhenjun Ma, Sustainable Building Research Centre

You have been asked to participate in a PhD research study conducted by PhD candidate Daniel Daly from the Sustainable Building Research Centre (SBRC) at the University of Wollongong. The purpose of the study is to survey expert opinions on attitudes and practices relating to the decision-making process involved in determining optimal energy-efficiency retrofit strategies for commercial buildings. You were selected as a possible participant in this study as an industry leader in the field of building simulation or building retrofitting. Please read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

- This interview is voluntary. You have the right not to answer any question, and to stop the interview at any time or for any reason. The interview should take about 30 minutes.
- Unless you give us permission to use your name, title, and/or quote you in any publications that may result from this research, the information you tell us will be confidential.
- This interview may be recorded for use as a reference while proceeding with this study. If you do grant permission this conversation will not be recorded. You have the right to revoke recording permission and/or end the interview at any time.
- I understand that my participation in this research is voluntary; I am free to withdraw from the research at any time. My withdrawal from participation will not impact my relationship with the University of Wollongong.
- I understand the procedures described above. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

(Please check all that apply)

☐ I give permission for this interview to be recorded.

☐ I give permission for the following information to be included in publications resulting from this study:

☐ my name ☐ my title ☐ direct quotes from this interview

..../........./...........

Signed Date

....

Name (please print)

Please contact Daniel Daly (0403 491 374, dhd316@uow.edu.au) or Paul Cooper (02 4221 3355; pcooper@uow.edu.au) with any questions or concerns. If you have any concerns or complaints regarding the way the research is or has been conducted, you can contact the Ethics Officer, Human Research Ethics Committee, Office of Research, University of Wollongong on 4221 3386 or email rso-ethics@uow.edu.au.

RELEVANT EXTRACTS FROM APPLICATION FOR APPROVAL TO UNDERTAKE RESEARCH INVOLVING HUMAN PARTICIPANTS

A. GENERAL INFORMATION

1. Descriptive Title of Project:

A survey of expert opinion on attitudes and practices relating to the use of building thermal simulation in determining optimal energy-efficiency retrofit strategies for low PCA grade commercial buildings.

2. 7 line summary of project aims:

Characterise the current state of the existing building retrofitting industry, including; government agencies', academic institutes', and professional associations' activity in the field, and identify key challenges facing the industry in the future. Understand the decision-making process used to assess building retrofit strategies, including economic, technical, and attitudinal barriers and incentives to the implementation of energy efficiency retrofits for low PCA grade buildings.

3. Participating Researchers

Principal Investigator/Supervisor		
Title	First Name	Family Name
Professor	Paul	Cooper
Qualifications	PhD, MSc, BSc(Eng)Hons	
Position	Director, Sustainable Buildings Research Centre, Faculty of Engineering	
Role in project, relevant research experie	Supervisor, with over 25 years of experimental research experience in the measurements and modelling.	
Second Investigator (in absence of PI)		
Title	First Name	Family Name
Dr	Zhenjun	Ma
Qualifications	PhD, MSc, BEng Hons	
Position	Lecturer, Sustainable Buildings Research Centre (SBRC), Faculty of Engineering	
Role in project, relevant research experie	Supervisor, with experimental research experience in thermal measureme and modelling.	
Second Investigator (in absence of PI)		
Title	First Name	Family Name
Mr	Daniel	Daly
Qualifications	BEng (Hons)	
Position	PhD student, Sustainable Buildings Research Centre, Faculty of Engineerin	
Role in project, relevant research experie	Interviewing, and research analysis of interview data. Experience in developing, collecting, and analysis of survey data obtained during Honours thesis in Engineering (HE10/299). Further experience will be obtained through supervision by experienced researchers.	

5. Expected duration of Research (Please specify as near as possible 'start' and 'finish' dates for the conduct of research):

FROM: Sept 2013 TO: Sept 2014

6. Purpose of Project

Indicate whether the research is one or more of the following:

☒ Student Research - specify:

Course undertaken: Doctor of Philosophy

Unit/Faculty/Department: Sustainable Buildings Research Centre, Faculty of Engineering

Supervisor/s: Prof Paul Cooper, Dr Zhenjun Ma

C. RESEARCH METHODS

9. Research Categories

A Research procedures used

☒ Interviews (structured or unstructured)

☒ Telephone interviews

B Research areas

☒ Qualitative research

11. Research design and justification

Participants will be asked to participate in a semi-structured interview, in person or via Skype, with an expected duration of 30-60 minutes. In the interview participants, experts in the field of building simulation or retrofitting, will be asked specific questions about how they view current trends and practices, and general questions on what they see as important challenges for the industry going forward. A semi-structured approach is appropriate, as it will allow the participant to direct the interview towards areas they view as important, rather than the interviewer setting the agenda.

After the interview, participants may be asked to clarify or provide further information about certain responses. This request will be via email.

D. ETHICAL CONSIDERATIONS

13. What are the ethical considerations relevant to the proposed research, specifically in relation to the participants' welfare, rights, beliefs, perceptions, customs and cultural heritage? How has the research design addressed these considerations? Consideration should be at both individual and collective level.

The greatest burden associated with this research is expenditure of time.
Thought has been given to minimising this burden. Inconvenience due to expenditure of time may be alleviated to some extent by conducting interviews at the most appropriate time and location for the participant, with the researcher conducting the travel. Participants will be advised and assured that they may choose to refuse to participate at any time should participation become inconvenient.

E. RISKS AND BENEFITS

16. Detail the expected benefits of the study to the participants and/or the wider community.

This study will identify future challenges facing the building simulation and retrofitting industry in Australia. The wider community will benefit from publications helping to identify research priorities in this area, and providing a starting point for further discussions about the role of simulation in building retrofitting and decision making. There has been little previous qualitative research in this area collating expert opinions on challenges and pitfalls in this area.

F. PARTICIPANTS

17. Mark the categories relevant to this proposal.

☒ Healthy members of the community

☒ Employees of a specific company/organisation

18. Expected age(s) of participants – please mark one or more

☒ Adults (> 18)

19. What is the rationale for selecting participants from this/these group/s?

The participants invited to participate in this research project are experts in the field of building retrofitting or building simulation, with experience in commercial building retrofitting. They will be identified via networks established already by staff/students of the Sustainable Buildings Research Centre (SBRC). The judgement for inclusion as experts will be made by the research team, with experience in this field.

G. RECRUITMENT

20. How will potential participants be approached initially and informed about the project?

Initial approach to potential participants will be via email to their professional email account.

21. Where will potential participants be approached by the researchers to seek their participation in the research, and where will research activities involving participants be conducted?

Potential participant will be approached via email to their professional email account. Research activities will be conducted at the most convenient location for the participant, either in their office, at UOW, or via Skype.

22. How many participants in total do you anticipate will be involved in the project? If the research has several stages and/or groups of participants, please provide the total number of participants expected as well as the number and participant group involved in each stage.

Of order 20 experts will be invited to participate.

H. CONSENT PROCESS

24. How will consent for participation be obtained?

☒ **in writing**

Please explain why the method chosen is the most appropriate and ethical.

Potential participants will be contacted via email, with an invitation to volunteer for the study. The participant is free to reply to the invitation and arrange an interview, indicating consent to be involved, or ignore the invitation.

A formal consent form (attached) will be included covering publication of material resulting from the study. Obtaining consent in writing provides unambiguous consent and indicates that the participant has been provided with specific information about the project. If the interview is to be conducted by phone or Skype, the consent form will be provided to the participant via email in advance.

26. For participants who have the capacity to consent, how does the process ensure that informed consent is freely obtained from the participant?

Potential participants will be free to choose whether to reply to the researchers initial approach for an interview. A consent form (attached) will be provided to potential participants prior to the interview, ensuring that the participant are free to decline to participate at any stage.

28. How does the project address the participants' freedom to discontinue participation? Will there be any adverse effects on participants if they withdraw their consent and will they be able to withdraw data concerning themselves if they withdraw their consent?

There will not be any adverse effects on participants if they withdraw their consent. If participants withdraw their consent during the project, they will be able to withdraw data concerning themselves.

I. CONFIDENTIALITY AND PRIVACY

31. How will the privacy of individual subjects be protected when recording and analysing the data?

Participants will be asked to give written consent if they are willing to be directly quoted in publication, using either their real name or a pseudonym. A contact list with participants' real names, contact and address details, and pseudonyms, will be kept separate to other recordings and data.

32. Will information collected from data or interview be published or reported?

YES ☒ **NO** ☐

The information will form a part of the student's PhD dissertation, and may appear as part of a journal article, book chapter, report, and media articles.

33. Will any part of the research activities be placed on a visual or audio recording (eg audiotape, photograph or video-tape)?

YES ☒ **NO** ☐

33.a What will the recording be used for?

Recordings of semi-structured interviews will be made to aid in transcription, and analysis. Excerpts may also be used for illustrative purposes in the follow-up analysis and final publications/reports.

33.b Who will see/hear the recording?

Members of the research team will have access to the recordings. If any excerpts a published in the dissertation of journal articles the audience would have access to these segments.

34. Data (including questionnaires, surveys, computer data, tapes, transcripts and specimens) must be securely stored at all times. Where will the data be held and who will have access to it:

a. during the project?

Soft copy data will be securely stored on the SBRC computer system.

Hard copy data and portable storage devices, such as audio recorder disks or USB drives, will be stored securely in a UOW locked cabinet.

There will necessarily be times when the researcher is carrying data with them (such as between and after interviews). The researcher would ensure that they kept this data on their person. Also, there may be times when researchers collect data from participants and are unable to return the data to UOW immediately (e.g. if interviews occur after hours). If this occurs, the researchers will either keep the data on their person or store it securely in their home until they are able to deliver it to the UOW workplace.

Members of the research team will have access to the data.

b. on completion of the project?

Data will be stored securely and archived according to UOW archiving policies. Data will be stored at the Sustainable Building Research Centre in a locked cabinet.

35. Data should be held securely for a minimum of 5 years (15 years for clinical research) after completion of the research. How long will the data be stored for? If it is not being stored, please provide an ethical justification for this.

Data will be stored securely and archived according to UOW archiving policies.

Example interview topic guide – Consultant with BPS experience

- Could you please talk me through the major stages of a typical retrofitting project from your perspective, from the first contact to last contact;
  - Prompt: Could you also identify who the major stakeholders are, and which parts of the process they influence the decision;
  - Prompt: What do you think brings a client to you with a particular building? What starts that process from a client's point? [JV3, NABERS, Other BCA compliance issues]. Why do you think they come to you, rather than another company?
  - Prompt: Do you carry out any post-occupancy evaluation of retrofits? Do you revisit retrofits to see whether predicted savings are achieved?
- Do you use any decision support tools, software or rules of thumb for identifying possible retrofits strategies for a building?
  - [Prompt if no] Are suggested retrofits based on an engineer's previous experience of successful strategies?
- How do innovative solutions enter thinking? What evidence do you require before suggesting a new retrofit to a client?
- What are the most common building retrofits you see implemented for commercial buildings?
- Are there any common issues in the retrofit decision making process?
- How confident are you that your predicted savings will be achieved through retrofitting?
- What initiatives/programs do you see as particularly effective, or is there any you would like to see established in the building energy retrofitting field?
  - [Prompt] EUA's?
- What do you see as the major challenges or major opportunities facing the building energy retrofitting industry in Australia in the coming years?
- What experience do you have using BPS?
- Which tools do you use?
  - [Prompt] Do you have in-house tools, e.g. spreadsheets. If so, for which aspects of a buildings energy use are they used?
- Have you had formal training in the use and limitations of the software package you use? Did you find it valuable?

- What is the most common driver for simulating a buildings energy performance?
    - [Prompt] NABERS, JV3, GreenStar
    - Are you ever/often asked to use BPS outside of the schemes for which it is required (e.g. to determine optimal retrofit strategies?)
- When simulating a building outside of a protocol where do you source your assumptions?
    - [follow up] In these cases do you follow a modelling protocol? If so which one?
- Do you disclose/discuss the input assumptions used in BPS with clients? Do clients ever question you about inputs etc… Are they knowledgeable?
- Do you think there is a need for a more evidence base BPS protocol specifically aimed at the Australian context?
- Do you have a way of factoring in the performance gap to predictions from BPS?
- Do you think it is an issue for clients to distinguish between high- and low-quality consultants with regard to BPS?

Appendix C

Case Study Detailed Model Inputs

Table C-1 Summary of building energy model input data for detailed building model of case study Building 1.

Input	Building 1
Climate Data	Historical weather data from the Macquarie Park station, approximately 5 km from site used for validation. TMYC weather files for Sydney Observatory Hill (BoM station 66062) approximately 15 km south used for comparative simulations.
Building Geometry	Geometry from original architectural drawings was reproduced by tracing the floorplan imported into DesignBuilder. Modelled wall were set at the edge of the plan walls (DesignBuilder convention). NLA = 7,436 m^2, floor plate configuration = 60 m x 39.25 m, floor-to-floor = 3.6 m
Material properties	Construction material properties were estimated based on site inspection, construction documentation, and a third party condition report. Assumed construction was generally uninsulated heavyweight construction; U-values were Wall = 1.8 W/m^2-K, Floor = 2.5 W/m^2-K, Roof = 3.9 W/m^2-K.
Glazing	Glazing located by dimensions and spacing of windows on architectural drawings and from on-site inspection. Majority glazing modelled as single glazing (U = 5.78 W/m^2-K, SHGC=0.82), double glazing modelled on southern facades.
Car parks	Lower four levels of building are car parks, during tenanted period only 2 levels were utilised. Modelled but excluded from floor area for comparison of energy intensity.
Lighting Power Density	11.9 $W/m^{2,}$ derived from original electrical plans
Lighting Diversity Profile	From NABERS
Equipment Density	11 ± 10% W/m^2(NABERS, 2011)
Equipment Diversity Profile	From NABERS
Occupant density	20 m^2/person (Warren, 2003)
HVAC system type	Variable Air Volume with Air-Cooled Chiller, Central AHU for each floor, auxiliary packaged units for south side of Level 1 and Level 2. Detailed information incorporated from site inspection and third party mechanical review. Chiller reference COP = 2.6.
HVAC Operation profile	From NABERS
HVAC Control	Cooling set point = 24 ^oC, heating set point = 20 ^oC, No economy cycle.
HVAC Zoning	Core and perimeter, based on original mechanical drawings.

Table C-2 Summary of building energy model input data for detailed building model of case study Building 2.

Input	Building 1
Climate Data	Historical weather data from the Macquarie Park station used for validation, approximately 1 km from site. TMYC weather files for Sydney Observatory Hill (BoM station 66062) approximately 15 km southwest was used for comparative simulations.
Building Geometry	Geometry from original architectural drawings was reproduced by tracing the floorplan imported into DesignBuilder. Modelled wall were set at the edge of the plan walls (DesignBuilder convention). NLA = 7,374 m^2, floor plate configuration 75 m x 50 m, floor-to-floor = 3.6 m
Material properties	Construction material properties were estimated based on site inspection, construction documentation, and a third party condition report. Assumed construction was generally blockwork walls, concrete SOG, and insulated metal clad roof; U-values were Wall = 1.1 W/m^2-K, Floor = 1.7 W/m^2-K, Roof = 0.4 W/m^2-K.
Glazing	Glazing located by dimensions and spacing of windows on architectural drawings and from on-site inspection. Glazing modelled as single glazing (U = 5.0 W/m^2-K, SHGC=0.4)
Lighting Power Density	6.7 W/m^2 derived from original electrical plans, and in accordance with third party values.
Lighting Diversity Profile	From NABERS
Equipment Density	11 ± 10% W/m^2 (NABERS, 2011)
Equipment Diversity Profile	From NABERS
Occupant density	10 m^2/person (NABERS, 2011)
HVAC system type	Central chilled water planted, Water Cooled Packaged Units serving individual zones, VAV with electric reheat to perimeter zones, Electric duct heating to core. Chiller reference COP = 3.0.
HVAC Operation profile	From NABERS
HVAC Control	Cooling set point = 24 ^oC, heating set point = 21 ^oC, Economy cycle available.
HVAC Zoning	Detailed zoning from original mechanical drawings.

Table C-3 Summary of building energy model input data for detailed building model of case study Building 3.

Input	Building 1
Climate Data	Actual weather data from the Parramatta North BOM station (066124), approximately 4 km from site used for validation. TMYC weather files for Mascot (BoM station 66037) approximately 20 km southeast used for comparative simulations.
Building Geometry	Geometry from original architectural drawings was reproduced by tracing the floorplan imported into DesignBuilder. Modelled wall were set at the edge of the plan walls (DesignBuilder convention). NLA = 3307 m^2, floor plate configuration = 18 m x 33 m, floor-to-floor = 3.27 m.
Material properties	Construction material properties were estimated based on site inspection, construction documentation, a third party energy audit. Assumed construction was generally uninsulated concrete; U-values were Wall = 2.9 W/m^2-K, Floor = 1.6 W/m^2-K, Roof = 2.9 W/m^2-K.
Glazing	Glazing located by dimensions and spacing of windows on architectural drawings and from on-site inspection. Glazing modelled as single glazing (U = 5.0 W/m^2-K, SHGC=0.82). Window to Wall Ratio (WWR) = 63%. No windows on western or eastern façade.
Lighting Power Density	13 W/m^2 based on electrical drawings, and third party energy audit
Lighting Diversity Profile	From NABERS
Equipment Density	11 ±10% W/m^2 (NABERS, 2011)
Equipment Diversity Profile	From NABERS
Occupant density	15 m^2/person from NABERS, 43% unoccupied.
HVAC system type	Central chilled water plant, Central CAV AHU, central gas boiler. Chiller reference COP = 3.0, boiler efficiency = 80%.
HVAC Operation profile	From NABERS
HVAC Control	Cooling set point = 24 ^oC, heating set point = 20 ^oC, No economy cycle.
HVAC Zoning	Detailed zoning from original mechanical drawings.