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Energy efficiency and thermal comfort upgrades for higher education buildings

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ENERGY EFFICIENCY AND THERMAL COMFORT UPGRADES FOR HIGHER EDUCATION BUILDINGS

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ABSTRACT

Existing higher education buildings have an important role in the minimisation of greenhouse gas emissions from our built environment and in assisting the mitigation and adaptation of our society to climate change. However, operating and managing the building stock of organisations such as universities is complex because their diverse infrastructure and non-uniform building conditions can make it difficult to prioritise the resources needed to upgrade particular buildings and systems.

Thus, the aim of this thesis was to develop a decision support framework to aid the decision making process in terms of assessing the overall building portfolio through optimising retrofit strategies for particular buildings. This work started with an investigation of the current decision making approaches used by different tertiary institutions, followed by the development of Key Performance indicators (KPIs) to map the characteristics of portfolios of higher education buildings. Then a weighting scheme that included subjective and objective weighting factors for these KPIs was presented. Thereafter, a methodology for a particular building of the university portfolio was developed to: a) evaluate the practical performance of existing university buildings in terms of energy and water consumption, indoor environmental quality (IEQ), envelope air-tightness, and overall occupant satisfaction; and b) to identify the optimal retrofit strategy for a particular building in order to minimise total costs (i.e. implementation, operational and maintenance costs whilst preserving satisfactory thermal comfort) through the life of the building. Finally, the effectiveness of the tools developed was tested by analysing the performance of a portfolio of university buildings, and evaluating the theoretical and practical benefits arising from the implementation of various retrofits.

The techniques used included: i) semi-structured, face-to-face and phone interviews conducted with senior staff members and the decision makers of facilities management teams from Australian and New Zealand universities; ii) analysis of building portfolio data gathered from various databases typically used at universities; iii) development of a decision framework that included the normalisation of KPIs and decision makers' preferences through a weighting scheme; iv) a comprehensive sustainability audit undertaken at one of the University of Wollongong (UOW) campus buildings; v) energy modelling to determine the building energy consumption and thermal comfort

conditions; and vi) a sensitivity and retrofit optimisation analysis were conducted to find the best combination of building parameters to minimise total costs.

The results from the semi-structured interviews revealed the following: a) a logical and systematic approach to retrofitting of university building stock was not always pursued, however some commonalities exist, such as evaluation of building condition audits; b) although Key Performance Indicators (KPIs) are critical in assessing the existing building stock prior to refurbishment, there was no consensus on the best KPIs to use; c) existing issues such as missing data or lack of funding were seen as the most common problems in current decision making; d) effective demonstration of the benefits of retrofitting a building to university senior managers is a vital part of seeking funding for the retrofits; and e) the implementation of a given retrofit strategy for a particular building is typically driven by a cost-benefit analysis.

Analysis of these interviews provided the background for determining the most appropriate KPIs for retrofit optimisation in the higher education sector. These KPIs included the characteristics of the building, e.g. energy performance, space utilisation or non-compliance issues. Then the KPIs were normalised through a weighting scheme that prioritised the buildings for retrofitting.

The most significant findings from the comprehensive sustainability audit revealed: a) very poor envelope air-tightness; b) a relatively high occupant dissatisfaction with building indoor thermal comfort conditions; and c) that occupants' perceived health and productivity in the building were below national and international averages.

Thereafter, the sensitivity and retrofit optimisation analysis was applied to a calibrated building energy model. Results showed that: a) the influence of parameters such as internal loads and internal temperature set-points had a significant impact on building performance in terms of energy consumption and thermal comfort; in contrast b) the influence of the quality of the building thermal envelope depended more strongly on the climate, e.g. the building envelope parameters had less impact on energy and comfort in milder climates than in more extreme climates.

This research has provided a framework to better facilitate the assessment of higher education building portfolios so as to reveal the benefits of implementing a particular retrofit strategy. This, in turn, may be used to strengthen the business case for retrofitting, and to assist facilities management (FM) teams to improve their decision

making processes while making potential outcomes clear to the client, i.e. university senior management.

ACKNOWLEDGEMENTS

I want to thank Prof Paul Cooper for his supervision and guidance during my research. I am extremely privileged to have had him by my side in this journey. Thanks for teaching me so many valuable life lessons; you are an example for all of us. I would also like to thank Dr Zhenjun Ma for his key advice and input. I need to thank him for always being willing to help me. Thanks to Dr Georgios Kokogiannakis for always making the time to discuss any issue with me. Despite you joined us in my last stage of the PhD, you were of great help.

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Ledo, L., Ma, Z. & Cooper, P. (2012). "**Improving thermal comfort in naturally ventilated university buildings.**" 12th International Australasian Campuses Towards Sustainability Conference 2012 (pp. 2-12).
My contribution to this paper was mainly all the simulation work, writing, analysis and discussion of the results. This paper has been peer reviewed and it is included in Chapter 7 §7.3.

Ma, Z. J., Daly, D. Cooper, P., Ledo, L. "**Existing building retrofits: Methodology and state-of-the-art.**" *Energy and Buildings* 55 (2012): 889-902.
My contribution to this paper was mainly writing the economic analysis section. This paper has been peer reviewed and one figure is shown in Chapter 2 §2.7.

GLOSSARY

APPA= Association of Physical Plant Administrators

BEMS=Building Energy Management System

BEIMS=Building and Engineering Information Management System

BUS= Building Use Studies

DASH= Data and Analytics Self-service Hub

DM=Decision Maker

DST= Decision Support Tool

ECM=Energy Conservation Measures

EFTS= Equivalent Full Time Students

ESAP=Energy Savings Action Plan

FM= Facilities Management

GBCA=Green Building Council of Australia

HVAC= Heating Ventilation and Air-Conditioning

iC= Innovation Campus

IEQ= Indoor Environmental Quality

IWEC=International Weather for Energy Calculation

KPI= Key Performance Indicator

PIS= Participant Information Sheet

PMV= Predicted Mean Vote

POE= Post Occupancy Evaluation

PPD= Percentage of People Dissatisfied

ROI=Return On Investment

SAMP= Strategic Asset Management Plan

SGHC= Solar Heat Gain Coefficient

TEFMA= Tertiary Education Facilities Management Education

UFA= Usable Floor Area

WHS= Work, Health and Safety

WSAP=Water Savings Action Plan

NOMENCLATURE

$\boldsymbol{\alpha}$ =constant in the EN15251 (2006) defined as 0.8.

$\boldsymbol{\beta_B}$ = best practise benchmark [same units as KPI]

$\boldsymbol{\beta_T}$= typical practice benchmark [same units as KPI]

$\boldsymbol{\delta}$ = declination [°]

$\boldsymbol{\eta}$ = efficiency (or Coefficient of Performance) of the air-conditioning system

$\boldsymbol{\varphi}$= baseline value of KPI [same units as KPI]

$\boldsymbol{\phi_f}$ = heat flux

$\boldsymbol{\Phi}$= normalised value of KPI

$\boldsymbol{\phi}$ =latitude [°]

$\boldsymbol{\psi}$= subjective weighting factor, which represents the relative importance that decision makers give to the KPIs

$\boldsymbol{\rho}$= strength of the Spearman's correlation

$\boldsymbol{\rho_a}$ = the density of air [kg/m^3]

$\boldsymbol{\tau}$ =remaining life of the building

$\boldsymbol{\omega}$= aggregate weighting factor, which incorporates objective and subjective weights

$\boldsymbol{\varpi}$= overall objective weighting factor

$\boldsymbol{\omega_a}$ = hour angle [°]

$\boldsymbol{\partial x/\partial k}$ = sensitivity coefficient

$\boldsymbol{A}$ = area of each exposed surface of the building [m^2]

$\boldsymbol{C_{a,z}}$= annual cost of the retrofit measure for a typical year, including the annual operating, maintenance, and repair costs [$]

$\boldsymbol{C_I}$= initial financial investment cost [$]

$\boldsymbol{C_p}$ = heat capacity of the air [kJ/kg K]

$\boldsymbol{CS}$= cooling slope [W/m^{2}K]

$\boldsymbol{C_{total}}$= overall lifetime cost [$]

$\boldsymbol{E_o}$= heating, ventilation and air-conditioning (HVAC) base load consumption [W/m^2]

$\boldsymbol{G_0}$= extra-terrestrial horizontal radiation [W/m^2]

$\boldsymbol{G_{sc}}$ = solar constant [W/m^2]

$\boldsymbol{H_r}$= relative humidity

$\boldsymbol{I}$ = global horizontal radiation [W/m^2]

$\boldsymbol{I_0}$= hourly extra-terrestrial radiation on a horizontal surface calculated [W/m^2]

$\boldsymbol{I_b}$= beam radiation component of hourly radiation [W/m^2]

$\boldsymbol{k_T}$= hourly clearness index

$\boldsymbol{k}$ = input variable

$\boldsymbol{n_{occ}}$= number of occupants

$\boldsymbol{P}$= productivity

$\boldsymbol{PPF}$= productivity penalty function [$]

$\boldsymbol{R_d}$= discount factor per year

$\boldsymbol{r}$ = real interest rate [%]

$\boldsymbol{S}$ = normalised sensitivity coefficient

$\boldsymbol{\overline{S}_{occ}}$= average hourly salary of an occupant [$/h]

$\boldsymbol{T_{cp}}$= the cooling change-point temperature [°C]

$\boldsymbol{T_{dp}}$= dew-point temperature [°C]

$\boldsymbol{T_{ed-2}}$ = daily mean external temperature for the ith-2[°C]

$\boldsymbol{T_{ed-1}}$ = daily mean external temperature for the ith-1 [°C]

$\boldsymbol{T_{in}}$ =internal temperature of the space [°C]

$\boldsymbol{T_o}$=outdoor air temperature [°C]

$\boldsymbol{T_{rm-1}}$ = running mean temperature for the ith-1 day [°C]

$\boldsymbol{TCPF}$ = thermal comfort penalty function [$]

$\boldsymbol{U_j}$ = overall heat transfer coefficient [W/m^{2}K]

$\boldsymbol{U_w}$ = heat transfer coefficient of the wall [W/m^{2}K]

$\boldsymbol{V}$ =volume flow rate of air entering the building [m^3/s]

$\boldsymbol{V_{\tau}}$ =residual value of a set of retrofit measures [years]

$\boldsymbol{y_j}$ = number of times the retrofit must be renewed in situations where the lifetime of the building component is shorter than the remaining life of building

$\boldsymbol{x}$ = output variable

$\boldsymbol{z}$ = year number

1. Introduction

Existing higher education buildings have an important role in the minimisation of greenhouse gas emissions from our built environment and in assisting the mitigation and adaptation of our society to climate change. However, operating and managing the building stock of organisations such as universities is complex because their diverse infrastructure and non-uniform building conditions can make it difficult to prioritise the resources needed to upgrade particular buildings and systems.

Obtaining a clear understanding of how the precincts of higher education buildings perform will enhance the economic, social, environmental, and operational performance of the Australian university building stock. This research seeks to increase our understanding of the performance of tertiary institution buildings and precincts by mapping their characteristics and developing a decision support framework to better facilitate the assessment of building portfolios. This chapter introduces the research background, the justification, aim and objectives, as well as the research questions, scope, and structure of the thesis.

1.1 Background

One of the most critical challenges facing our society is anthropogenic climate change and its consequences for economies and communities (Parkinson *et al*. 2010). Although the impact of climate change may well prove irreversible according to many authorities, the risks to society may be reduced by embracing adaptation and mitigation strategies; for example, the Intergovernmental Panel on Climate Change (IPCC 2007) urged world leaders to act immediately by reducing greenhouse gas (GHG) emissions.

The uptake of energy efficiency technologies and systems has been identified as one of the most cost-effective ways of reducing GHG emissions (Energy White Paper Task Force 2004), as well as providing energy security, and economic, climate and social benefits (Steuwer 2010). As an example, retrofitting Australia's existing commercial buildings during the next decade could save $1.4 billion a year (ClimateWorks 2010), reduce building emissions by 30% and generate 27,000 jobs (Group ASBEC Climate Change Task 2007; Langdon 2009).

These benefits also apply when the focus is placed on buildings used for higher education because these improvements can play a major role, not only as described

above, but also when the buildings are used as a pedagogical tool to educate and teach students, staff, and the broader community about sustainability (Rohwedder 2004). Rohwedder stated that educational buildings can showcase economic, water and energy savings, reductions in GHG and social responsibility, whilst teaching students that educators care about their future well-being.

Satisfactory and comfortable indoor conditions are essential if we are to improve the health, performance, and learning of university students, and staff (Kats 2006; Corgnati *et al*. 2007). However, most of the existing higher education buildings in Australia were generally designed at a time when the sustainability and comfort of the occupants was not prioritised as highly as at the time of writing (GBCA 2013b). This, in turn, results in inefficient operation and frequently fails to provide acceptable thermal comfort for the occupants throughout the year. Furthermore, universities typically operate a diverse portfolio of buildings with wide-ranging performance issues that affect them to different degrees, which is why a holistic approach is likely to be required when assessing the extent to which university building stock can be made more sustainable and comfortable; this means considering the building stock as a whole portfolio when considering any retrofits and upgrades, rather than in isolation and across a range of attributes. On this basis then, the retrofit decision making process is complex.

1.2 Research Aim and Objectives

The primary aim was to understand current approaches to retrofitting and upgrading existing higher education buildings and develop a decision support framework to evaluate and prioritise retrofitting and upgrades of their portfolios.

To achieve this goal, a number of key objectives were targeted:

i) Carry out a comprehensive literature review.

ii) Determine the views of experts and decision makers from Australian and New Zealand University Facilities Management (FM) teams in order to map their approaches and the factors that influence the retrofitting of higher education buildings in Australia.

iii) Develop a set of Key Performance Indicators (KPIs) to represent the desirable characteristics of portfolios of higher education buildings.

iv) Develop a comprehensive methodology to evaluate the practical performance of existing university buildings in terms of energy and water consumption, Indoor Environmental Quality (IEQ), envelope performance, and overall occupant satisfaction.

v) Develop a methodology to identify the optimal retrofit strategy for a particular building in order to maximise the cost-effectiveness of upgrades in terms of minimising their implementation and energy costs whilst preserving satisfactory thermal comfort through the life time of the building(s).

vi) Test the effectiveness of the tools developed by analysing the performance of a portfolio of university buildings, and evaluating the theoretical and practical benefits arising from the implementation of various retrofits.

1.3 Research Questions

The main research questions to be answered during the course of this research are presented below.

- What are the current perceptions and practices of decision makers and other stakeholders at Australian universities regarding the planning and implementation of refurbishment works, particularly in respect of sustainability outcomes?
- How can optimal upgrade strategies for higher education buildings be developed in order to minimise energy consumption whilst improving or maintaining occupant satisfaction regarding issues such as thermal comfort?
- What are the most efficient audit techniques that will identify the most appropriate retrofit strategy for a given university building?

1.4 Overview of the methodology

This research focussed on understanding the current practices of decision makers at Australian universities and developing a framework to aid decision making around retrofitting higher education facilities, whilst finding an optimal retrofit strategy for one of the buildings in the portfolio. The methodology developed is as follows:

- At a university building portfolio level:

i. Analyse the perceptions, attitudes and current practices of decision makers from Australian higher education facilities management teams via semi structured interviews.
ii. Develop a framework to characterise the building portfolio through KPIs.
iii. Develop a decision framework that includes the normalisation of KPI's and decision makers' preferences through a weighting scheme.

- At a particular building of the university portfolio:
  i. Perform a comprehensive building assessment via:
     - Conducting a sustainability audit to understand the building performance;
     - Analysing the occupants' perceptions and satisfaction with the building through questionnaires.
  ii. Find the optimal retrofit strategy for the building undertaking the following steps:
     - Develop a calibrated building energy model;
     - Perform a sensitivity analysis of the calibrated model;
     - Define a cost function involving the more sensitive parameters;
     - Conduct an optimisation with the defined cost function and the calibrated model.

1.5 Structure of the Thesis

This thesis is structured as follows.

Chapter 1 - Introduction describes the background of the project, and explicates the motivation for conducting this investigation, research objectives, and scope of the work.

Chapter 2 – Literature Review presents a review of retrofitting higher education buildings, types of retrofits, and previous work conducted on the topic. This chapter also indicates the direction of the research.

Chapter 3 –Current Practices, Attitudes and Perceptions of Stakeholders at Higher Institutions explain the methodology used to analyse the interviews conducted to understand stakeholders' attitudes towards current retrofitting practices in higher education institutions. The analysed responses of decision

makers pertaining to different Australian and New Zealander tertiary institutions on the decision making practices used to upgrade and retrofit existing Australian university buildings stock portfolio is also presented.

Chapter 4 –Development of a University Portfolio Characterisation and Decision Support Framework details the methodology used to develop a decision support framework to prioritise university building stocks to be retrofitted.

Chapter 5 – Portfolio Characterisation and Decision Support Framework Case Study exemplifies the methodology developed in Chapter 4 by using UOW as a case study.

Chapter 6 –Development of a Building Retrofit Optimisation Methodology details the methodology developed to find an optimal sustainable retrofit strategy for a university building.

Chapter 7 - Building Performance Assessment: Case Study analyses the performance of the case study building to set the baseline and identify the underperforming areas.

Chapter 8 – Building Retrofit Optimisation: Case Study demonstrates the optimal retrofit strategy used to reduce energy consumption while improving thermal comfort by applying it to a particular case study.

Chapter 9 - Conclusions and Future work brings together the key findings of this research and suggests possible avenues for future work.

The flow chart describing the content of each Chapter and how they are connected is depicted in Figure 1.1.

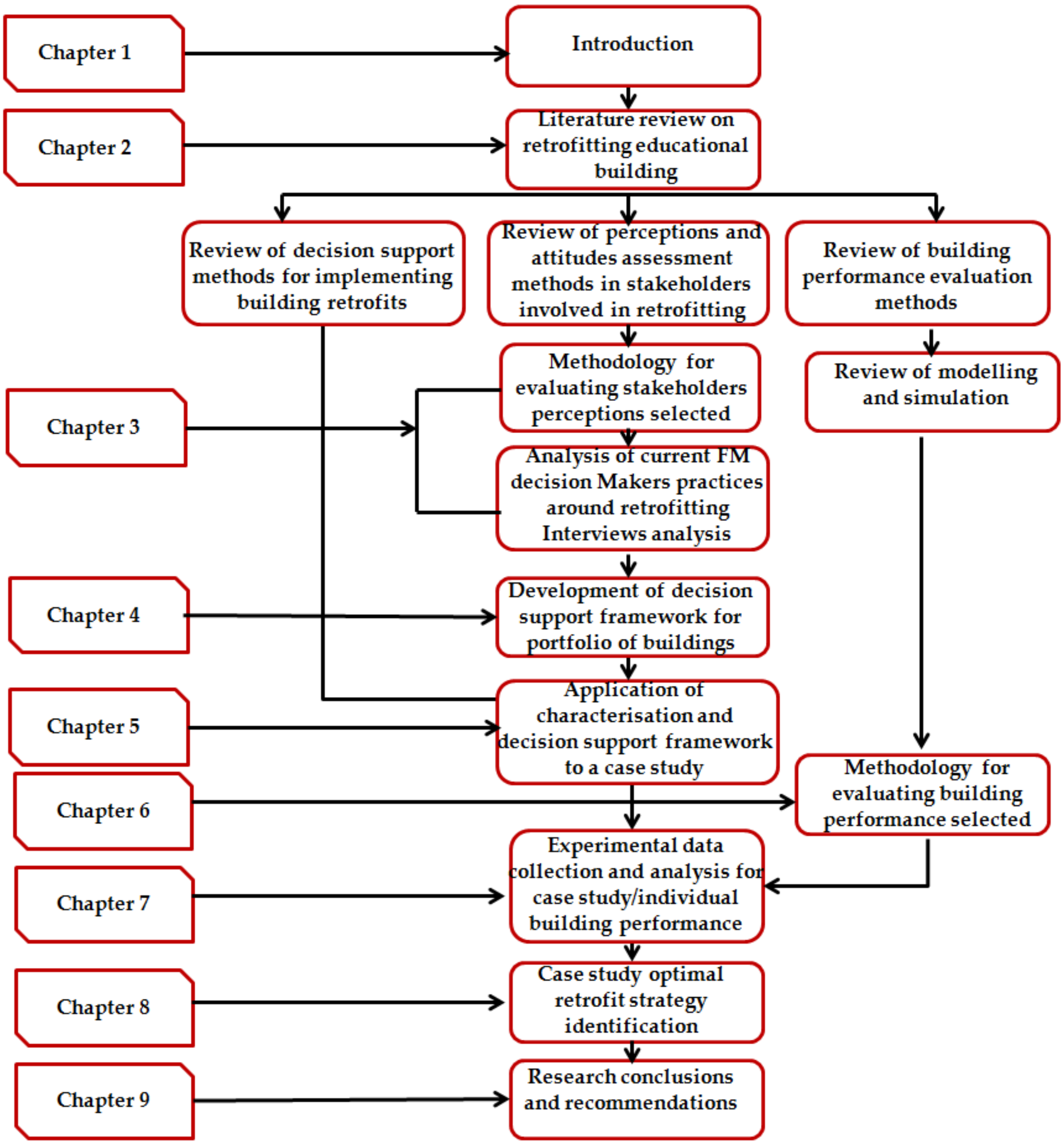

Figure 1.1 Research process flow chart.

2. Literature Review

The Facilities Management budget of an organisation typically requires 30 to 40% of its total expenditure, a figure that corresponds to the second highest cost after the payroll (Amaratunga & Baldry 2000a). At higher education institutions, it is estimated that facilities management represents up to 20% of their operating costs (TEFMA 2009). This chapter reviews the performance of Australian higher education facilities in terms of their energy efficiency and the quality of their indoor environment, as well as the methodologies used to assess this performance. It also examines the retrofitting techniques and facilities management methodologies used for decision making around retrofitting.

2.1 Energy Use of Australian Higher Education Facilities

To be managed efficiently, higher education facilities should maximise their resources while optimising the costs of maintenance and operation (Pukka *et al*. 2012), and since the largest controllable operating expense is energy, understanding their patterns of consumption within the campuses could improve the triple bottom line (Bates 2011).

Australian Universities are one of the fastest growing consumers of energy within the non-domestic building sector (pitt& sherry 2012); they consumed 79% more in energy in 2009 than they consumed in 1999, and by 2020 their total energy consumption is expected to increase by a further 50% compared to the 2009 baseline. Pitt& sherry (2012) investigated energy use in Australian offices, hotels, retail buildings, hospitals, education facilities and public institutions using data collected between 1999 and 2012, and then estimated the energy use for 2020 based on this historical data. The energy intensity, defined as the energy consumption per square metre, of Australian university buildings over time is expected to increase 11% by 2020 compared to the 2009 baseline, while office buildings showed a reduction in energy intensity over time. In 2009, the average annual energy intensity for office buildings was 255 kWh/m^2, whereas university buildings consumed 241 kWh/m^2 annually. These rankings are expected to be reversed by 2020, when office buildings are expected to have a yearly average consumption of 231 kWh/m^2 while university buildings will consume 268 kWh/m^2 annually (pitt& sherry 2012). This recent downward trend in energy intensity is attributed to Australian policy settings such as the impact of the *Building Energy*

Efficiency Disclosure Act 2010. This program required that commercial office space equal or larger to 2000m^2 for sale or lease to provide energy efficiency information in advertising materials. This, in turn, is thought to have contributed to the weak downward trend in commercial building energy intensity since 2010.

Reducing the energy consumed in Australian universities should therefore be of great importance, as should be decreasing their operating costs while improving student learning experiences and demonstrating a commitment to sustainability.

2.2 Potential Energy Reduction of Australian Higher Education Buildings

Uptake in energy efficiency retrofits has been identified as the most cost-effective solution available for reducing energy consumption in buildings (Energy White Paper Task Force 2004); and this could also provide energy security, and economic, climate and social benefits (OECD 2010). As an example, retrofitting Australia's existing commercial buildings over the next decade could save $1.4 billion a year (Abdullah *et al*. 2012), reduce building emissions by 30%, and generate 27,000 jobs (ASBEC 2007; Langdon 2009).

ClimateWorks Australia (2010) investigated the most cost effective ways of reducing Australian GHG emissions to 25% below 2000 levels. It was estimated that the building sector could potentially contribute to an 11% reduction in the total Australian GHG emissions. From this potential abatement, the highest share corresponds to the commercial sector, which represented a possible 77% reduction in GHG emissions. The predicted total percentage of potential reductions in GHG emissions per each sector and type of improvement is shown in Figure 2.1, with the education sector accounting for 11% of this 77% possible reduction. According to ClimateWorks the biggest potential decrease in emissions lies in downsizing and disposing of unnecessary equipment and appliances, whilst upgrading lighting and utilising thermal insulation.

But will this potential abatement be enough to justify retrofitting higher education buildings or does demolishing and rebuilding provide a more cost effective social, economic, and environmental solution?

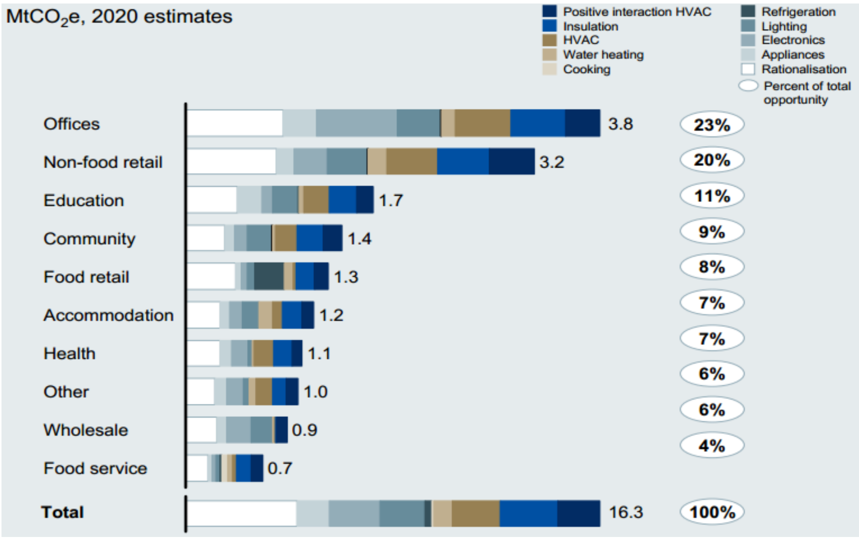

Figure 2.1 2020 emissions reduction opportunity per building sector with different retrofit options (ClimateWorks 2010).

2.3 Demolish and Rebuild or Retrofit Australian Higher Education Buildings

At present two per cent of the total Australian building stock is being built new every year (Department of the Environment Water Heritage and the Arts 2009). Moreover, some of the existing building stock was built without taking sustainability into account (Atkinson *et al*. 2007). Specifically, many Australian tertiary institutions were constructed to meet the minimum building codes at that time which resulted in buildings that are not necessarily comfortable or productive spaces for teaching, researching, and learning (GBCA 2013b). Furthermore, higher education facilities, as with other material resources, are consumable so over time they are decaying and must be replaced or revitalised (Kowalski 1983). Therefore, to improve the value of the buildings in terms of condition, reducing operation emissions, building resilience and improving the internal environmental quality they must be refurbished or replaced, i.e. demolished and rebuilt.

Demolition and rebuilding almost always has a higher impact on the environment than retrofitting (Baker 2009) due to embodied energy, because demolishing the old building and constructing a new one requires energy, and this generates carbon emissions. It has recently been revealed that the embodied energy of buildings is much larger in proportion than was previously considered (Lawson 2006); typically varying from 10 times the annual operating energy for conventional residential buildings to 30 for commercial buildings (Lawson 2006). Furthermore, demolition and waste disposal also

cause emissions, thus demolishing and rebuilding a more energy efficient building will only reduce the overall energy over a longer term rather than immediately, whereas the need to decarbonize the built environment is urgent. The CO_2 emissions for new buildings and the refurbishment of an existing building over time are illustrated in Figure 2.2 (Baker 2009).

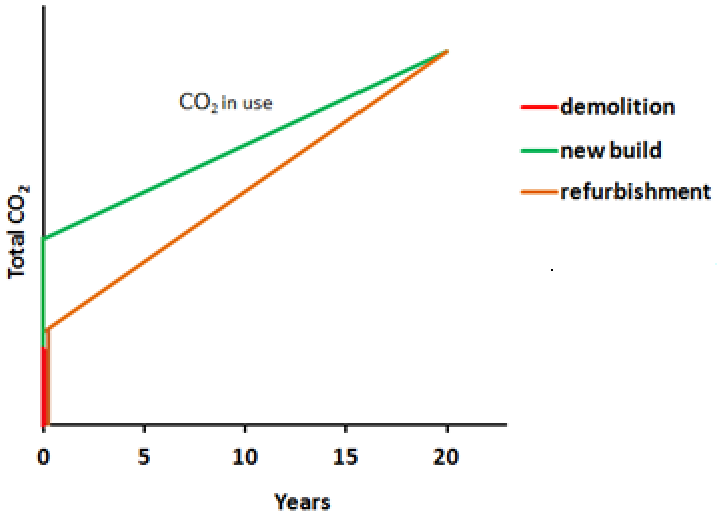

Figure 2.2. CO_2 emissions for newly built and refurbishment over time, adapted from (Baker 2009).

Figure 2.2 shows that during a building's lifetime, the newly built might have less environmental impact, as indicated by a less steep slope, but the refurbished building is the lowest emitter over a long period until it reaches a break point. This break point depends on the building performance, as indicated by the steepness of the slope, so the break point could be extended further by improving the performance of the existing building, depending on the energy conservation measures applied. To this end, and in the short term, the present stock of new and non-refurbished buildings will lead to large energy debts (Power 2008). Additionally, this building stock is replaced, or added to, at only 1-3% per year so to make a significant impact on GHG emissions the existing stock must be improved.

All buildings and institutions, particularly tertiary institutions, have a privileged opportunity of influencing present society and succeeding generations in reducing GHG emissions by embracing energy efficiency measures. Improving the performance of university buildings can play a major role as a pedagogical tool to educate and teach students, staff, and the broader community about sustainability (Rohwedder 2004).

Improving building performance means reducing its energy consumption and enhancing the quality of the internal environment. The importance of reducing the energy consumption has already been explained and now the following section introduces the quality and importance of the indoor environment, particularly in higher education facilities, and then introduces different approaches for measuring building performance.

2.4 Indoor Environmental Quality in Higher Education Facilities

The issues influencing the way we feel in a space are addressed by the Indoor Environmental Quality (IEQ). Having a satisfactory IEQ is crucial for human heath, comfort, and productivity (Spengler *et al*. 2001). At higher education facilities, an adequate indoor environmental quality has significant health and learning benefits for students and staff (GBCA 2013b). Therefore, ensuring an adequate IEQ for newly built or upgrades not only improves pupils' achievements and reduces sick leave from staff and students, it also prevent problems such as the formation of moisture, poor outdoor air quality or insufficient ventilation (GBCA 2013b; Persily 2009).

It is often assumed that an improved IEQ results in rising energy usage, but in reality, improving the IEQ while reducing energy usage is possible by implementing energy efficiency measures (Fisk 2000; Burroughs & Hansen 2011).

The importance of the IEQ in educational spaces was illustrated in Kats' report (2006) where the impact of an adequate IEQ was assessed by reviewing 30 green schools, meaning schools constructed with sustainability awareness. It was noted that educational buildings are typically designed to achieve minimum building code performance, and while this minimises the initial capital costs, it inevitably results in a building that fails to provide a work space that is comfortable and healthy for students and staff. Accordingly, occupant productivity is reduced and absenteeism is increased. The results of 17 independent studies where an overall improvement in health, e.g. colds, respiratory issues or sick building syndrome (SBS) was experienced by improving the IEQ is shown in Figure 2.3.

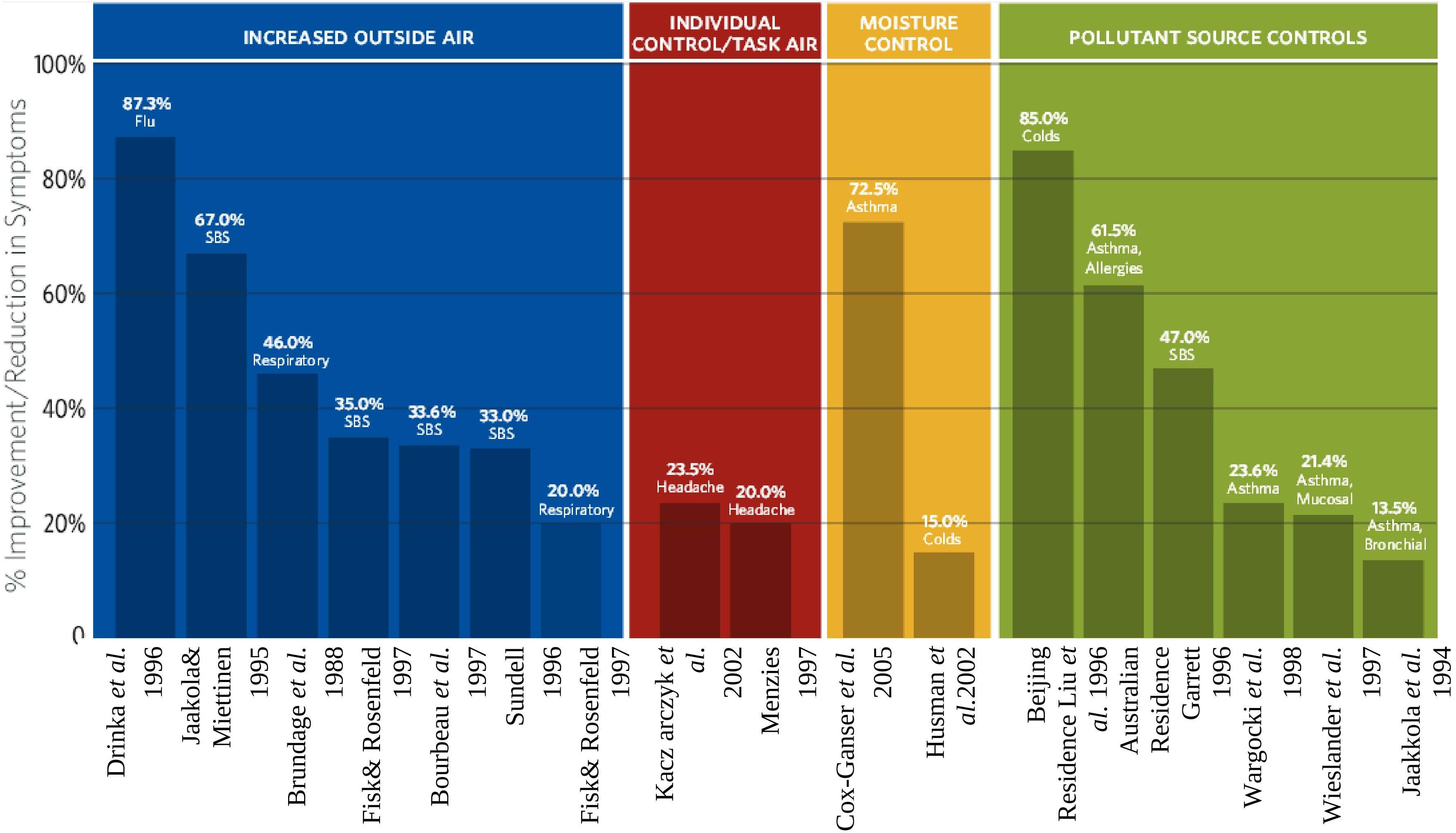

Figure 2.3 Health gains due to an improved indoor air quality (Kats 2006).

All the studies reported improvements in health ranging from 13.5% to 87% reductions in adverse health symptoms due to enhanced quality of indoor air.

Frontczak and Wargocki (2011) conducted a literature review to survey how building indoor environment affected human comfort. The overall impact of environmental indoor variables, including air quality, thermal comfort, visual comfort, and acoustic comfort on Indoor Environmental Quality (IEQ) was revealed by ranking each factor according to their influence on human comfort. Those factors unrelated to the indoor environment such as an occupant's characteristics, i.e. age, gender, country of origin, etc., and building-associated factors such as control over the indoor environment and type of building, and the influence of the outdoor climate on the IEQ were examined. The following conclusions were drawn from Frontczak and Wargocki's literature survey concerning the effect of the aforementioned factors to indoor environmental conditions:

- The type of building and outdoor climate affected the thermal comfort;
- The occupant's ability to control the indoor environment enhanced their thermal and visual comfort, and thereby improved their overall IEQ satisfaction;
- The influence of personal characteristics on comfort could not be strongly supported due to the lack of studies in literature. However, connections such as how the occupant's relationship between superiors and colleagues and their level of education influenced thermal comfort were suggested.

Of all the many environmental factors, having satisfactory thermal comfort was the most important condition for achieving satisfactory IEQ. Acoustic comfort and satisfaction with air quality were not as important, and visual comfort was the least important. Visual comfort and thermal comfort are the IEQ factors that have the strongest influence on energy consumption, and as mentioned previously, thermal comfort is perceived by the building user as the most important parameter influencing their overall comfort. Therefore, thermal comfort is described in detail in the following section.

2.4.1 Thermal Comfort

Thermal comfort is defined as "the conditions of mind that expresses satisfaction with the environment" (ASHRAE Standard 55 2013). A comfortable environment is a subjective state where the individual is neither too hot nor too cold. It occurs when the temperature and humidity of the air immediately adjacent to the body lie in between

narrow ranges, where the air movement is "pleasant" and the air quality provides a sensation of freshness (Race 2006). An adequate comfort zone, with temperatures and humidity where 80% of the occupants do not feel dissatisfied, for summer and winter clothing, where the metabolic rate is between 1 to 1.3 met, i.e. during sedentary activity such as sitting in a lecture room or office, and the average air speed is below 0.2 m/s is shown in Figure 2.4 (ASHRAE Standard 55 2013).

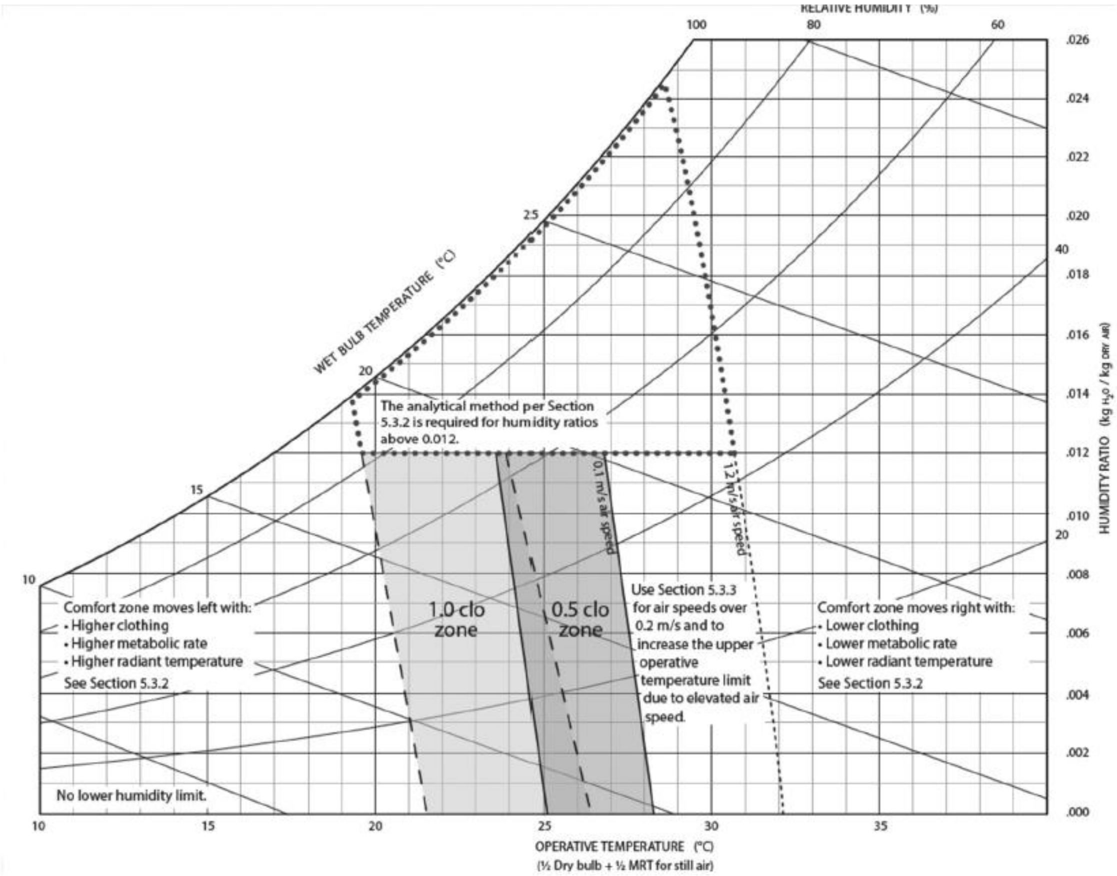

Figure 2.4 ASHRAE graphical representation of the comfort zones for summer and winter, during sedentary activity and air speed below 0.2 m/s (ASHRAE Standard 55 2013).

ASHRAE Standard 55 (2013) was based on the Predicted Mean Vote (PMV) and Percentage People Dissatisfied (PPD), introduced by Fanger (1970). The PMV-PPD model was developed through experiments conducted in a controlled laboratory environment, i.e. a climate chamber where people's responses to their thermal surroundings were investigated. Fanger's thermal comfort experiments did not enable individuals to interact with the environment, thus building occupants were considered as passive receivers of the thermal environment controlled by HVAC systems (de Dear 2004). This in turn limits the practicality of the static model, being adequate in air

conditioned buildings where the climate is kept constant. However, the static model was not thought to be applicable to naturally ventilated buildings (Humphreys 1978).

Furthermore, many authors (Nicol & Humphreys 2002; Brager & De Dear 1998; Yao *et al*. 2009; de Dear 2004) indicated that thermal comfort models should consider human adaptability, where additional factors such as behavioural adaptation, adaptive opportunity, personal acclimatisation, and psychological adaptation must be considered. This thermal comfort model is known as the 'adaptive' thermal model and it was described by Auliciems (1983) as, "When a change occurs causing thermal discomfort, people react in such a way that their thermal comfort is re-established".

Several field studies cited in the ref. (Brager & De Dear 1998) corroborated the unreliability of the PMV model for naturally ventilated buildings by comparing the static model of comfort (PMV-PPD) with the adaptive comfort model. The results showed that the PMV-PPD predictions agreed with the observed thermal sensations for buildings with HVAC systems, but this scenario was completely different in naturally ventilated buildings because the PMV model failed to predict the thermal sensations. In this case the occupants found a wider range of temperatures more comfortable than temperatures suggested by the PMV. This finding was also supported by Brager *et al.* (2004) who studied the effect of personal control on operable windows via surveys and physical monitoring. Their results showed that the greater the adaptive opportunity, i.e. the level of control that the occupant has on their local environment, such as the presence of operable windows, led to a greater tolerance of the temperature range. Wong and Khoo (2003) conducted a study on thermal comfort in Singapore's naturally ventilated classrooms through objective and subjective measurements. Their results indicated that the conventional thermal comfort criteria failed to predict the occupants' thermal comfort because temperatures beyond the conventional thermal comfort range, as stated by ASHRAE Standard 55-92, were indicated as comfortable by the occupants.

Therefore, the adaptive thermal model allows for a more relaxed temperature comfort range in natural ventilated buildings than that established by Standard 55-92 (ASHRAE 55 1992). Hence, to get a more consistent evaluation of thermal comfort, the adaptive comfort theory was included in both American, i.e. ASHRAE Standard 55 (ASHRAE 55 2004), and European, EN15251 (2006), Standards (Figure 2.5).

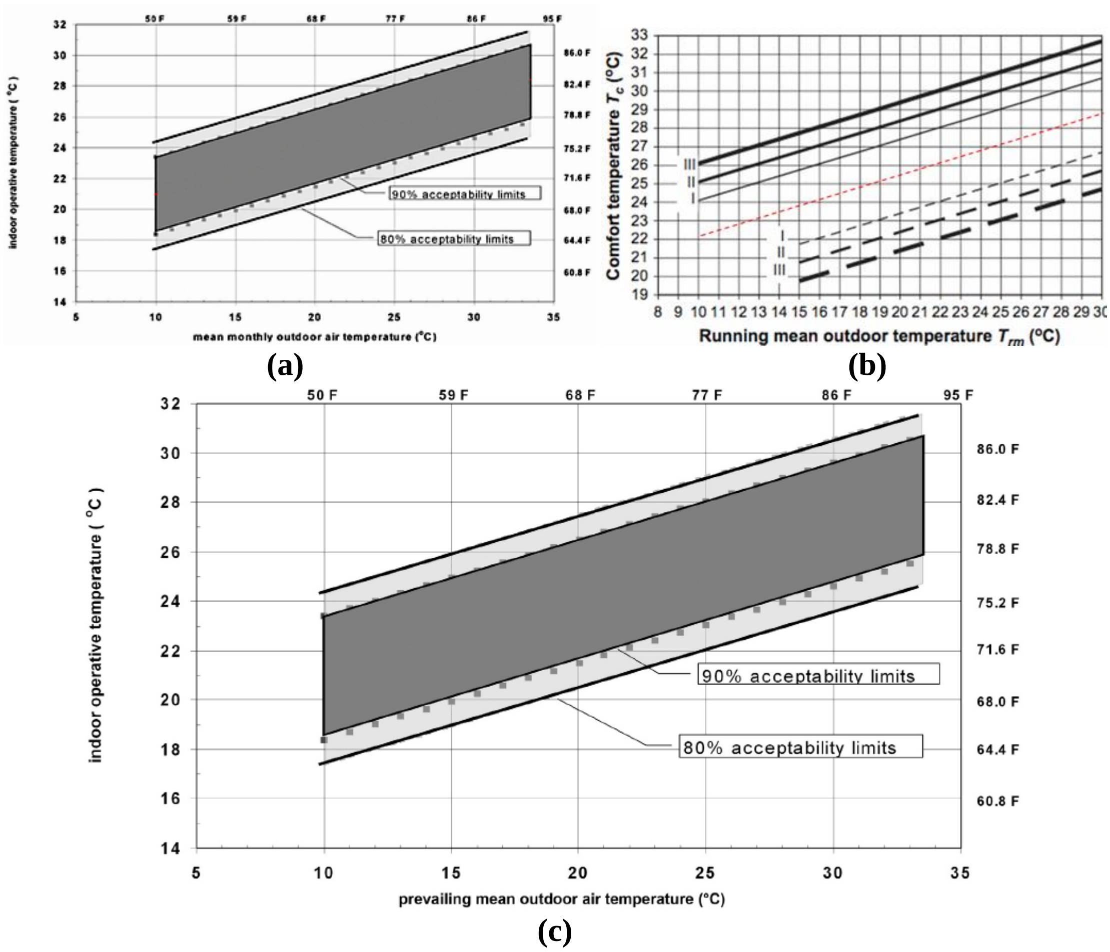

Figure 2.5 Adaptive comfort Standards. (a) ASHRAE 55-2004 (b) EN15251 2007 (c) ASHRAE 55-2013.

The charts for both Standards present a similar concept but with some significant differences, as outlined below (Nicol & Humphreys 2010):

- The comfort temperature is different; thereby each Standard has its own adaptive equation.
- The origin of the ASHRAE data is worldwide whilst the EN15251 data is from Europe.
- The applicability of ASHRAE is limited to naturally ventilated buildings whereas the EN15251 Standard applies for free running buildings where a mixed mode is included in some seasons.
- The outdoor temperature for ASHRAE Standard 55-2004 was represented by the monthly outdoor temperature while the EN15251 adopted an exponential weighted running mean. This enables the European standard to deal with varying weather conditions during days from the same month. However, ASHRAE Standard 55-2013 modified the monthly temperature by the

prevailing mean, which also allows for capturing weather variations within the same month since it is constructed with an average of the outdoor daily mean temperature for previous days.

- To assess the buildings' thermal comfort and condition of the building in general in order to identify potential improvements, the building performance must be investigated. This investigation can be conducted through different methods explained in the following section.

2.5 Building Performance Assessment Methodologies for Higher Education Facilities

Condition of university facilities was found to be a critical factor contributing to satisfaction and dissatisfaction in higher education institutions (Oshagbemi 2006), but since deferred maintenance and worn out campus infrastructure are regular issues for higher education institutions (Kaiser 1993) the performance of existing facilities should be investigated. In addition, the assessment of existing higher education facilities can help facility managers prioritise their tasks, depending on funding availability, and thus minor problems can potentially be resolved before they become major (Lavy 2008).This assessment is basically undertaken through audits.

2.5.1 Auditing

To the best of the author's knowledge, there is no established methodology specifically aimed at energy efficiency auditing of higher education facilities. However, the Association of Physical Plant Administrators (APPA), called APPA: Leadership in Educational Facilities, intended to embed an energy efficiency audit process as part of routine maintenance management for higher education facilities management (Kaiser 1987). The initial approach evolved from a qualitative condition rating for building components and systems, through to a more quantitative approach. This update was captured by Kaiser (1993), who suggested that an audit process should be embedded in maintenance management where specific deficiencies and correction costs could be quantified. However, this proposed audit methodology was limited to the facilities and physical condition and functionality of the equipment.

A standardised auditing procedure for commercial buildings may be found in the Performance Measurement Protocols for Commercial Buildings (PMP) (ASHRAE 2010) that was developed by three leading building industry associations: ASHRAE

(the American society of Heating Refrigeration and Air-Conditioning Engineering), the US Green Building Council, and CIBSE (the Chartered Institute of Building Services Engineers). The PMP provided protocols at three different levels: basic (indicative), intermediate (diagnostic), and advanced (investigative) for consistent performance characterisation; these protocols identify what to measure, how it is to be measured, and the frequency of measurement. Six performance categories were included in the protocols: energy, water use and IEQ, specific thermal comfort, IAQ, lighting and acoustics. These performance categories are explained in the following sections.

Energy Auditing

ASHRAE defines energy auditing as “to identify and develop modifications to reduce energy use and/or cost of operating a building”. The primary purpose for conducting an energy audit is to identify the opportunities for potential energy efficiencies.

The Australian Standard AS/NZS 3598.1:2014 identifies three types of energy auditing:

Type 1: Is a basic energy audit where the overall energy performance of a building is assessed in order to establish the reasonability of the energy consumed. Low cost opportunities that can easily be implemented are identified. It is typically conducted for the initial scoping investigation of a building, or a lower cost study for determining short payback upgrades measures.

Type 2: involves a higher level of detail than a Type 1 Audit, it identifies the building energy sources, the amount of energy consumed, and what the energy was used for; and it requires the historical energy consumption for at least the last year. A site visit is required. Specific energy conservation measures are identified and cost calculations with potential savings are incorporated. The application is typically for identifying energy efficiency measures.

Type 3: is the most comprehensive audit level. A detailed analysis of energy usage with onsite monitoring is undertaken. A typical application involves a detailed study of a process or subsystem through gathered data or a complete energy audit covering two or more systems on site. The potential specific costs and benefits of implementing energy conservation strategies are provided, and whenever possible the ‘non-energy’ gains should be quantified.

Energy audits should be conducted on a regular basis, normally every three to five years, with a view to controlling the energy costs and guarantee an appropriate management of the energy (CIBSE 2004).

Water Auditing

Understanding where and how the water is being used can lead to significant potential water savings. The best way to reduce water consumption is by monitoring water usage and then comparing the current and past water consumption (ASHRAE 2010).

Indoor Environmental Quality Auditing

Indoor Environmental Quality (IEQ), as introduced in *§2.4*, is a key concern for the health and welfare of the building's occupants, and therefore there are specific standards (EN15251 2006; ASHRAE Standard 62.1 2007; ASHRAE Standard 55 2013) that address design values for indoor environments and methods to determine an indoor environment that is deemed to be comfortable. Although there is no formalised methodology to conduct IEQ audits in buildings (Asadi *et al*. 2011), the PMP provides some guidelines on how to approach the measurement protocols.

After reviewing how to objectively assess building performance in terms of energy consumption, water consumption, and indoor environmental quality, the next section introduces an assessment of the performance of buildings from the occupants' perspectives.

2.5.2 Post Occupancy Evaluations (POEs) in Higher Education Facilities

POEs are questionnaires that evaluate to what extent a building meets the needs of its end-users. According to Vischer (2002), after the Second World War most of the housing in North America and Western Europe was constructed without considering people's needs, behaviour, or lifestyle, and better decisions could have been made if information from users had been considered. The logic of assessing user needs and perspectives to improve the performance of buildings led to the development of POE in the late 1960s (Vischer 2002).

POE has generally focussed on residential and commercial buildings whereas performance of higher education institutions has not been investigated to the same extent (Riley *et al*. 2010). Nevertheless, POE can help to reduce the buildings' operational and environmental costs as well as to improve the overall quality of life,

productivity, and comfort of the users (Nicol & Roaf 2005). POEs typically consist of questionnaires on the occupants' satisfaction, and the energy consumption and operational management. They can be used for benchmarking, assessing a building design or refurbishment approach or/and investigating a problem (Cohen *et al*. 2001).

The multiple benefits from conducting POE in higher education facilities are summarised in Table 2.1 (HEFCE & AUDE 2006).

Table 2.1 Benefits of conducting a POE (HEFCE & AUDE 2006).

Short term benefits	**Medium term benefits**	**Longer term benefits**
Problem identification and solution-finding for these issues.	Built-in capacity for building adaptation to organisational change and growth.	Long-term improvements in building performance.
Tackle user needs. Educated decision making.	Finding new utilisation for buildings.	Enhancement in quality of the building.
Improve space use based on feedback from use.	Better understanding of the building.	Strategic analysis.

Although there are no standardised methods for conducting building occupant questionnaires, Peretti & Schiavon (2011) stated that it is advisable to have a clear plan and a defined goal prior to conducting a POE. Two approaches can be followed to carry out a POE: develop one's own personalised methodology or use an existing one. The circumstances typically determine which approach to choose, but generally, the level of expertise required for inferring your own methodology is higher than the existing method. The most frequently used approaches for a POE are shown in Table 2.2 (HEFCE & AUDE 2006).

Conducting a POE could enlighten the actual use and operation of university buildings, while closing the gap between theory and practical energy consumption (Menezes *et al*. 2012). A small number of POE survey results are available in the literature for university buildings to inform the retrofit process (University of Nottingham 2013) or to assess occupant satisfaction after a retrofit has been conducted (Morrison 2008).

Table 2.2 Frequent methods to conduct a POE adapted from HEFCE & AUDE (2006).

Method	Format/techniques used	Focus	How long does it take?	When is/can it be used?
De Montfort method	Forum, walk-through buildings	Broadly covers the process review and functional performance	1 day	A year after occupation
Design Quality Indicators	Questionnaire	Covers functionality, building quality and impact	Questionnaire completion is online. It takes about 20-30 minutes. The analysis is immediate	At design stage and after completion
Overall Linking Score	Questionnaire in hard copy or web based. 7 point scale	Occupant survey sector include educational diagnosis tool	10 minutes for each occupant	About 12 month after occupation
CBE survey- Centre for the Built Environment	Web based questionnaire	Occupant satisfaction with Indoor Environmental Quality and building design, optional areas available	10 minutes to complete questionnaire	No specifications
BUS occupant survey	Building walk through and questionnaires	Occupant satisfaction and productivity	10-15 minutes to complete questionnaire	On its own or in conjunction with other methods. Anytime but after 12 months
BOSSA- Building Occupants Survey System for Australia	Questionnaire, right-here-right-now questionnaires with IEQ measurements	User satisfaction, productivity, systems performance	Overall process varies time needed	No specifications
Energy Assessment and reporting methodology	Energy use survey, data collection, e.g. from energy bills	Energy use and potential savings	Full assessment up to one person per week	Once the building its completed. On its own or in conjunction with other methods, e.g. BUS
Learning from Experience	Facilitated group discussions or interviews	Team learning from its experience	Ranges from single seminar to continuous evaluation	Can be used before, during and after project

2.5.3 Established Sustainability Assessment Methodologies for Higher Education Facilities

One of the primary aims of evaluating building performance is to determine a baseline that can be compared against a benchmark. Benchmarking not only permits underperforming areas to be identified, but also facilitates quantification of the value of any underperformance. Most University buildings currently benchmark their performance against past performance, i.e. an internal benchmark, or with other universities, i.e. an external benchmark (HEFCW 2007).

Internal benchmark: The first step for most universities is to evaluate the development of their own performance and the reasons for this performance. An internal benchmark normally entails a detailed study of the occupancy, building schedules, and weather conditions. According to Higher Education Estates Manual - Energy Section (2007), the benchmarks relating to historical performance such as those showing consumption over a period of time, are possibly the most significant benchmarks for universities.

External benchmark: This is more complex than an internal benchmark, so it should be carried out after determining the internal benchmark and the factors influencing the parameter investigated. An external benchmark compares the university performance against other universities under equivalent conditions. Benchmarking external buildings can also be conducted through a well-established sustainability assessment method that provides a target level for the environmental performance of an existing building for typical and best practice. Established methods for assessing sustainability are reviewed below, and those specifically tailored to existing higher institutions are highlighted in Table 2.3.

Sustainability assessments target collecting and reporting information for decision making through different building phases, i.e. design, construction, and use of the building (Bragança *et al*. 2008). Over the last twenty years the approach to assessing the sustainability of buildings has advanced with the development of sustainability and environmental assessment tools for buildings (Mateus & Bragança 2011). The first commercially available sustainability assessment tool for buildings is claimed to be the Building Research Establishment Assessment Method (BREAM), created in 1990 in the UK, but since then, many other environmental assessment tools have been developed.

Table 2.3 Building sustainability rating systems and main indicators of evaluation for existing builds.

System	Main indicators of assessment	Developer- Reference
BREEAM	Energy, water, materials, transport, waste, pollution, health& well being, management, land use& ecology and innovation. Based on BREEAM UK refurbishment and fit out 2014.	Building Research Establishment (BRE), UK BREEAM, IEA Annex 31 (2001).
LEED	Sustainable site, water efficiency, energy& atmosphere, materials& resources, indoor environmental quality and innovation. Based on LEEDv4 for building operation and maintenance.	U.S. Green Building Council, USA- Leadership in Energy & Environmental Design, LEED
Passivhaus	Controlled ventilation, window maximum U-value of 0.85 $W/(m^2K)$, airtightness limits, thermal comfort requirements, maximum cooling demand, heating demand and primary energy. Passive house requirements for schools.	Passive House Institute
HK-BEAM	Site aspects, energy use, water use, indoor environmental quality, materials, innovations and additions. Hong Kong BEAM for existing Buildings.	Hong Kong Building Environmental Assessment Method (BEAM) Society (Chan & Chu 1996)
CASBEE	Energy Efficiency, resource efficiency, local environment, indoor environment, services performance. Tailors schools.	Comprehensive Assessment System for Building Environment Efficiency through Japan GreenBuild Council (JaGBC)& Japan Sustainable Building Consortium (JSBC)
GREEN STAR	Management, Indoor Environmental Quality, Energy, Transport, Water, Materials, Land Use and Ecology, Emissions. Green star Education v1	Green Building Council of Australia – Green Star (2003)

These environmental assessment tools generally evaluate building indicators such as the energy, water, or indoor environmental quality via a scoring method where the score is based on a comparison between the current indicator baseline and a benchmark. The results indicate how sustainable the building's performance is, however, a comparison between tools and their results is extremely difficult (Haapio & Viitaniemi 2008), because the tools were designed for different types of buildings and used different databases, guidelines, questionnaires and benchmarks adapted to their cultural and climatic priorities, and therefore it is difficult to use these established tools for a different building type or region than the ones they were designed for. Furthermore, while Haapio and Viiraniemi (2008) recommended that the results of an assessment tool and the tool itself should be able to demonstrate how it affects decision making, they found that generally there is no connection between the aforementioned tools and the decision making process.

After the building performance has been benchmarked, those areas of a building needing improvement, i.e. performing below the benchmark, can be identified. To improve the energy efficiency and indoor environmental quality, many available retrofit options can be implemented. These are reviewed below.

2.6 Sustainability Refurbishment Technologies and Systems

Retrofit options can be categorised into two types according to their potential savings, financial risk, and overall impact on building performance and sustainability: 'standard' and 'deep' retrofit measures. A standard retrofit provides a low-risk investment and can usually achieve a 15-30% reduction in energy consumption (Fluhrer *et al*. 2010), while a deep retrofit involves a larger upfront investment, usually has longer payback periods, and therefore has higher risks, but the energy savings are typically over 50%, optimising costs and GHG reductions (Bendewald *et al*. 2014; Fluhrer *et al*. 2010). There are many refurbishment strategies available with different benefits, constraints, and costs. For instance the Arup Existing Buildings//Survival Strategies (2008) presented approximately 200 different retrofits/solutions to improve building performance. Improvements made by retrofit strategies can be classified into technical, organisational, or behavioural (Thomas *et al*. 2007).

2.6.1 Technical Improvements

Technical improvements include upgrades to the envelope, such as fabric insulation or window shading, building services such air conditioners, duct insulation, boilers, lighting upgrades, building services and Information and Technology (IT) systems, office equipment and water. Table 2.4 presents examples of technical improvements that address different issues, e.g. energy, water or IEQ, from low cost to considerable cost, meaning costs under an annual project budget; they are divided by the potential improvements provided, and the level of intervention required for the upgrade, i.e. Level 1 indicates a minor refurbishment or tune up, Level 2 is for an intermediate refurbishment such as lighting upgrades, Level 3 is for a major refurbishment such as the replacement of plant services or floor finishes, and Level 4 designates a complete refurbishment such as a structural change and alterations to the façade.

Table 2.4 Technical improvements and their qualitative assessment of their costs, intervention levels and potential benefits (ARUP 2008).

Type	Intervention	Cost Level	Intervention Level	Potential Benefits
Lighting	Lighting upgrades	1	2	Reduced energy consumption, longer lifespan and reduced flicker if LED is installed.
	Dimming sensors according to available light	2	2	Reduced energy consumption and visual comfort improvements
	Occupancy sensors for lighting	2	2	Reduced energy consumption as the lighting is controlled based on the detection of an occupant.
Electrical	Upgrade all motors to high efficiency	2	2	Performance of equipment is improved
	Occupant controlled isolation switch	2	2	Reduced standby power
	Power factor correction	3	2	Power factors corrections units can increase the energy efficiency and reduce operating costs. However, the capital costs are substantial.
HVAC	Modify set-point	0	1	Reduced energy consumption.
	More efficient air-conditioning	3	3	Reduced energy consumption and improve thermal comfort.
	Switch controlled HVAC	2	1	Ensuring Air-conditioning does not operate unnecessarily. Reduced energy consumption and costs.
Building Fabric	Paint roof with reflective paint	1	1	Reduced solar transmitted through the roof. Reduced energy consumption.
	Add solar control film	1	1	Reduced solar heat gains, improved thermal comfort.
	Upgrade ceiling insulation	2	3	Reduce conduction through roofs. Improved thermal comfort.
Fit out	Internal blinds	1	1	Reduced solar gains, improved thermal comfort.
	Use thin client technology	1	1	The actual processing of the computer is done on a central server, less energy than a traditional system and reduces the heating load in the space.
	Select energy efficiency appliances	1	2	Reduced energy consumption.
IEQ	External shading	2	2	Solar gains can be reduced, thermal comfort and visual comfort can be increased.
	Personal control of thermal conditions	3	3	Increased thermal comfort by providing occupants with control over their thermal environment.
Water	Water efficient fixtures	2	2	Reduce bathroom, kitchen and laboratories water usage by changing taps and shower caps.
	Rainwater storage tank	3	2	Underground rainwater tank can be used to store water for outside use. Reducing the water consumption.

2.6.2 Organisational Improvement

Organisational measures refer to promoting some modifications in the structure of the organisation that involve senior management to achieve better energy efficiency and sustainability in existing buildings. Some measures might include positioning the organisation in the energy market, a tactical reaction to climate change concerns, improved capital investment decision making, and communication to improve organisational culture, for example (Pears 2004).

The Australian Research Institute for Environment and Sustainability (ARIES) (2009), which is a not-for-profit research and consultancy centre that aims to promote improvements in sustainability through the sectors of education, business, community and government, discussed how organisations can make a successful change towards sustainability. The organisation and stakeholders should engage with energy efficiency and inculcate certain components into their education. These components can be summarised as:

- Building up a clear and shared vision of the future by looking ahead;
- Using critical thinking and reflection;
- Participating in the decision making process, and changes that can engage people across the organisation;
- Building connections with the stakeholders outside your area to share experiences via partnership;
- Systematic thinking where an organisation considers the 'big picture' rather than focussing on specific issues.

Australian educational buildings are particularly active in taking up programs for sustainability. Approximately 25% of Australian schools have embedded sustainability programs through the "Australian Sustainable School Initiative". This initiative provided a framework for Education and Sustainability activities via specific actions and activities (ARIES 2009). Australian universities have also been active in adopting changes in their operational processes and introducing sustainability courses in their curriculums. Australasian Campuses Towards Sustainability (ACTS) is an organisation that facilitates the exchange of information across the tertiary sector in Australia between environmental officers and managers aiming to support change towards best practice sustainability within the operations, curriculum, and research of the tertiary education sector.

2.6.3 Behavioural Improvement

Two buildings with identical characteristics and systems but different occupants can vary their energy use up to a factor of 4 ascribed to their occupants behaviour (EeB 2010). Furthermore, a variety of occupancy factors was found to have equal or higher repercussions on energy use than the building characteristics had on energy use (Frankel *et al*. 2012)

Therefore, modifying building user behaviour can have a large impact on energy savings, but his is a challenging task because their behaviour is influenced by economic, social, psychological, cultural, and educational factors. In addition, the way occupants use buildings is not understood very well (CIBSE 2004).

As mentioned in §2.4.1 on adaptive thermal comfort, occupants might take some actions to restore their comfort by wearing more clothes, drinking a hot beverage, or closing the window if they are cold. Thus, the amount of control that an occupant has over their environment, i.e. adaptive opportunity, impacts the building's energy consumption and IEQ. One study showed that incorporating these adaptive measures can potentially vary the perception of a comfortable temperature by up to 2.5°C (HEFCE & AUDE 2006). However, building managers should be cautious on how much control is left to the occupant because some behaviour might lead to a waste of energy.

To compare predicted and actual energy consumption, the Royal Institute of British Architects (RIBA) and the Chartered Institution of Building Services Engineers (CIBSE) launched 'CarbonBuzz' in 2008. Figure 2.6 shows the median of both the predicted and actual energy consumption for schools, general offices, and university campus buildings from the CarbonBuzz database and it points to the existence of a 'performance gap' between the predicted and real energy consumption. The differences ranged from 60-70% for schools and general offices, while universities had the highest performance difference, with an 85% discrepancy between actual and predicted energy consumption.

The results from studies from the Post Occupancy Review of Buildings and their Engineering (PROBE) project attributed these discrepancies to deficiencies in the modelling programs. However, Menezes *et al.* (2012) ascribed the overall differences to the inability of current modelling methods to represent realistic occupants and the operation of buildings due to inadequate assumptions. This could be linked to the

considerable lack of occupants' feedback concerning the real use and operation of buildings.

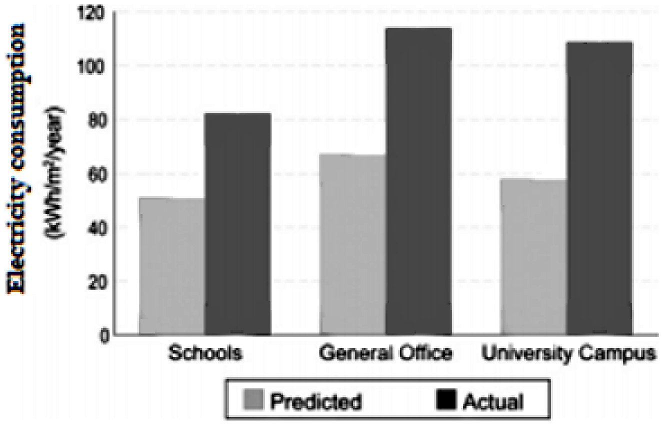

Figure 2.6 Predicted and actual energy consumption by sector (Menezes *et al*. 2012).

Lenoir *et al.* (2011) concluded that an occupant's behaviour is one of the most significant parameters affecting building performance. The performance of educational and commercial buildings was assessed at the design stage without occupants and during real operation with occupants. A comparison between a building's performance with and without occupants revealed a 50% divergence between both phases, and therefore it was seen as imperative that the effect that occupants have on building performance must be assessed accurately.

In order to examine the different upgrades to be implemented, a decision on the options should be made, but despite the benefits stemming from implementing energy efficiency opportunities, the uptake of building retrofits is still slow.

2.6.4 Barriers for Implementing Sustainable Retrofits at Higher Education Facilities

In Australia, the uptake of energy efficiency measures is very slow; from 1973 to 1998, Australia's energy efficiency was only augmented by 0.7 per cent a year whereas that in other developed countries increased by 1.6 per cent a year (Energy Efficiency Council 2010). To understand why energy efficiency measures are not widely implemented in Australian buildings, the key barriers need to be highlighted. They can be classified under four major categories (Weber 2007): a) institutional barriers where barriers are caused by political institutions such as government, b) market barriers where the obstacles are due to the market, c) organisational barriers where the difficulty comes from within the organisation, and d) behavioural barriers coming from individuals. The major barrier hindering the uptake of retrofits for university buildings is a lack of knowledge by the Decision Maker on the quantity of investment required and the

efficacy of the prospective energy savings measures (IEA 2007). This might result in incorrect or inappropriate selection of retrofit measures or not being able to demonstrate the benefits of the retrofit selected.

Possible tools to overcome these barriers are as follows (Weber 2007):

- Education: The knowledge of energy efficiency opportunities could be provided via education.
- Information to assist option: An expert could provide the required technical knowledge needed to choose a suitable opportunity. This information could also be supplied through a decision- support tool.
- Funding: Closing the gap between initial investment and return might be possible with financial support or by subsidising investment in energy efficiency.
- Penalties: The energy inefficient might be penalised by a fee.
- Regulatory reform: Amendments should be made to avoid unintended results.
- Prohibition and minimum standard: A ban on undesirable practises can avoid its use, while setting minimum standards can ensure that the performance will be at least higher than this limit.

After examining different refurbishment technologies, identifying possible barriers hindering the retrofit uptake and potential tools to overcome them, the methods and tools available for implementing retrofit strategies are reviewed in the following section.

2.7 Approaches and Tools for Retrofit Decision making

Ma *et al.* (2012) presented a systematic methodology for identifying, determining, and implementing retrofit measures for existing buildings (Figure 2.7). This approach has two parts: a) strategic planning and models/tools selection, and b) major retrofit activities involved in the retrofitting process. On one hand the strategic planning and models intend to provide information and resources supporting retrofitting, and on the other, the major retrofit activity is divided into activities during pre- retrofit, retrofit, and post retrofit. Fundamentally, a pre-retrofit decides whether a retrofit should be carried out, and then the retrofits are implemented, while in the post retrofit phase, measurements and verifications are undertaken to ensure the retrofit performs as specified.

Another retrofit methodology is detailed in CIBSE Guide F - Energy Efficiency, where the approach focusses on retrofitting energy efficiency measures. The steps involved in

retrofitting cost–effective energy conservation measures in existing buildings are as follows: i) discover the focus of high energy consumption, ii) determine the potential for energy savings through measurement, audits, or benchmarking, iii) identify practical measures to achieve these savings, iv) allocate funds for these measures, v) decide on equipment on the basis of certified or verified products, vi) determine further benefits, e.g. environmental, and comfort, etc., vii) find financial support for the planned measures based on the benefits, viii) implement the measures in a planned way with the least disruption to the building, and ix) monitor the savings to verify their achievement and guarantee the savings.

The United Nations environment programme (UNEP) developed the Greening Universities Toolkit v2.0 (UNEP 2014). It is a framework to encourage universities worldwide to develop their own strategies for greening their campuses, i.e. make them resource efficient and low carbon emissions. Although the framework not only focusses on buildings, it provides a set of actions to promote sustainability in campus infrastructure. These measures include building energy efficiency actions, such as periodic recommissioning and building tunning, building water efficiency actions, e.g. sub-metering major water uses, occupant behaviour measures, e.g. staff training or awareness campaigns, an minimise waste to landfill, as an example it is suggested to do a campus based exchange and reuse program. In order to enable systematic campus transformation, it was highlighted to develop a business case that includes the savings achieved with the programs versus the costs.

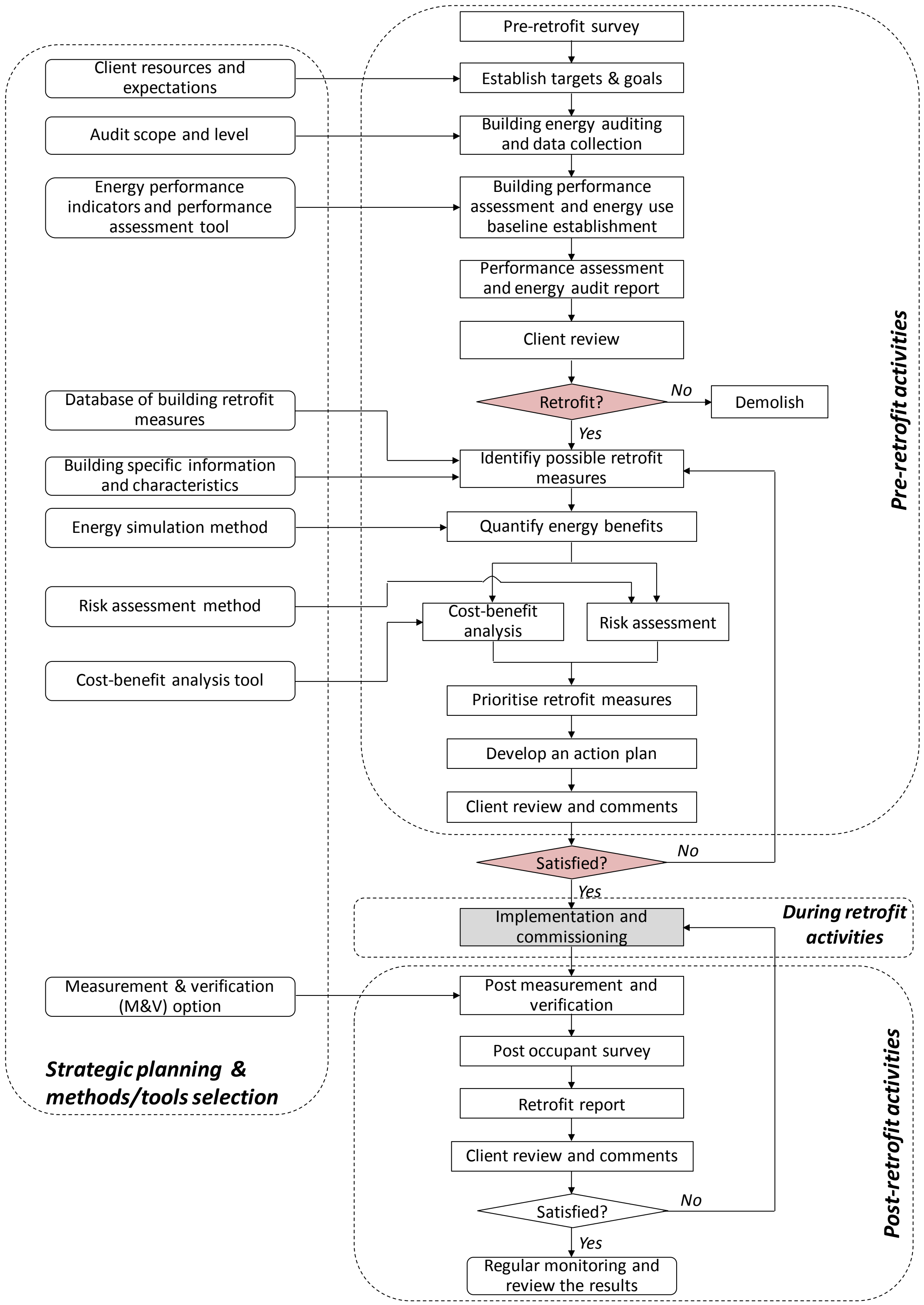

Figure 2.7 Method for retrofitting, with the key activities and tools in a building retrofit process, from Ma *et al.* (2012).

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2.7.1 Approaches of Higher Education Facilities Manager Teams to Retrofitting Decision making

A research conducted by APPA (Christensen *et al.* 2006) investigated building asset investment strategies on American higher education buildings. The state of the art in the field revealed that despite the increasing need of investment for renovation and replacement of ageing campus infrastructures, there was no standard practice for managing the physical assets, integrated decision making was unusual, and the decision concerning facilities investment were frequently made independently and without enough or consistent data. As a consequence, a conceptual framework to support comprehensive decision making of facilities investment was developed. This was in form of a strategic investment pyramid (Figure 2.8).

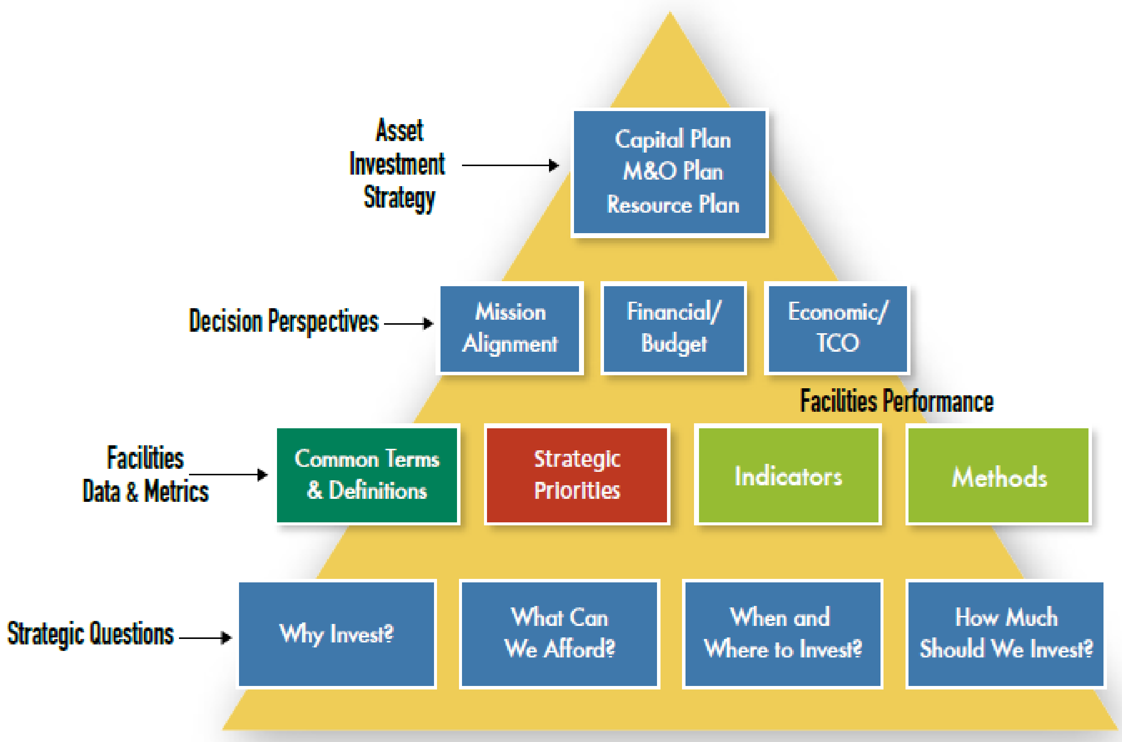


Figure 2.8 Strategic investment pyramid from APPA (2006).

APPA (2006) divided the strategic investment pyramid into four principal stages. The foundation basically entails strategic questions that must be answered for any asset investment. The second layer includes the information and metrics that help to answer the strategic questions. Data on facilities performance is crucial to identify the existing condition of the facilities, setting the project goals, and understanding the impact of different investment options, and thereby aiding in justifying the expenditure. Next, the decision perspectives are the institution's long term objectives that are the lenses through which the strategic questions, metrics, and data are seen. Finally this leads to

the creation of an asset investment strategy. The development of an asset investment strategy for a portfolio of buildings provides a strong basis for planning and maintaining existing facilities.

One of the most widely used approaches for retrofitting evaluation is building energy performance simulation (Santamouris & Dascalaki 2002; Koinakis & Sakelaris 2008), an approach that includes simulating the building performance only, or building assessment via both auditing and building performance simulation. In the following section building performance simulation is explained.

2.7.2 Building Performance Simulation

Building simulation programmes were developed in the 80s to forecast building performance during design by using historical weather data (Bluyseen 2014). Energy modelling software can help to quantify the effect of implementing energy conservation measures on a building's internal temperatures, humidity and light levels and hence energy consumption. The estimation of energy savings derived from the modelled energy consumption are needed to determine the feasibility of implementing certain conservation measures (Yalcintas 2008), and therefore modelling assists in making informed decisions about up taking an upgrade. The resulting energy savings estimated from a simulation model for existing buildings requires validation and/or calibration because the operation of existing buildings are often difficult to represent accurately (Heo *et al*. 2012). This issue promoted the launching of best practice techniques by the International Performance Measurement and Verification Protocol (IPMVP) in 2002 to validate the predicted energy savings and distribute the associated risks via the correct quantification of uncertainties.

A building simulation normally uses weather files such as a typical meteorological year (TMY) (in Australia TMY are called Reference Meteorological Year, RMY), Test Reference Year (TRY) or International Weather for Energy Calculation (IWEC). These files were created by assembling 12 average months. The weather data file for a city is generally applied for nearby locations, although some variables such as solar irradiance could be estimated more precisely from the exact location instead of using nearby data, if the two places are more than 20 km away from each other (Muneer 1997). As an example, Chow *et al.* (2006) reviewed the development of TMY and TRY files for two regions on the southern coast of China across from Hong Kong, and concluded that customising the weather file by creating a typical year with local weather data enabled to obtain more accurate results. Therefore, to obtain the correct accuracy, a simulation

of their own weather file must be carried out by mounting a weather station in the specific location of interest, and then monitoring the weather data and using the monitored variables to create a weather file.

Energy simulation programs are an important way of investigating the effect of implementing multiple retrofit strategies measures on the building performance. Nevertheless, searching for the best retrofits via energy simulations is time consuming and obtaining the optimum retrofit strategy is highly improbable because of the huge decision space and endless combinations (Asadi *et al*. 2012). Alternatively, decision making tools such as a cost-benefit analysis, a multi-criteria analysis, and energy rating systems can be used because they are all typically in conjunction with energy simulation in order to reach the optimum retrofit strategy to be implemented. The main difficulty is that there are still several competing objectives that must be evaluated to find the best potential solution (Asadi *et al*. 2011), albeit a unique optimum does not exist because the objectives are competing. Therefore, a tool to support the decision maker (DM) is needed to reach the best feasible solution by considering the trade-offs between the DM preferences (Diakaki *et al*. 2008).

2.7.3 Optimisation Techniques

After spending time creating a simulation model, the user typically does not identify the input parameters values leading to an optimal system performance (Wetter 2001) because this process is tedious; it entails changing the inputs, running the simulation, interpreting the new results and guessing how to vary the parameters for the next run. This is an extremely complex process whereby the user cannot understand the non-linear interactions of the different parameters. The solution is to dramatically reduce the effort via mathematical programming where the optimal solution can be searched automatically by specifying an objective function.

Optimisation algorithms can typically be categorised as either conventional gradient-based methods or gradient-free methods (Magnier & Haghighat 2010), but since buildings commonly exhibit non-linear behaviour, only gradient-free methods are normally applicable.

The most extensive optimisation techniques in this group are Genetic Algorithm (GA) and Particle Swarm Optimisation (PSO) techniques. GAs are based on Darwin’s theory of evolution and merge these evolutionary principles with problem solving algorithms. The evolutionary method provides more opportunities for the better elements in the

population to have descendants, so the elements in the population gradually improve over time (Krarti 2012). GA has been used effectively in many building optimisation strategies (Caldas & Norford 2003; W. Wang *et al*. 2005; Hamdy *et al*. 2011). For instance, GA was used by Caldas and Nordford (2003) to optimise the design and operational design of a building envelope as well as the heating and air-conditioning system. Wang *et al.* (2005) used GAs to optimise the performance of energy efficient building envelopes during the design stages. Hamdy *et al.* (2011) conducted a study on the minimum energy required to improve thermal comfort in a Finnish fully air conditioned office via a simulated optimisation. Despite being successfully implemented in some instances, the major shortcoming of GAs is the very significant computational time required due to the many iterative calculations that GA necessitates. If this is added to the typically high computing resource requirements for building simulations, the resultant time investment is claimed as making GAs non-viable (Magnier & Haghighat 2010).

Another optimisation algorithm type is the Particle Swarm Optimisation (PSO) approach, which is based on an analogy to the behaviour of a flock birds or a school of fish (Wang *et al*. 2012). The fitness of an objective function is assessed for each individual particle such that, in each iteration, the particle's movement is affected by three factors: it has an existing momentum and seeks to carry on its current course, its own best position from the first iteration to the current one acts as a draw to pull it back to a better state, and it is also guided towards the best position in the swarm. These three components are added vectorally to produce movement to the next location in the solution space where the objective function is recalculated.

The PSO and GA results and computational time were compared by determining the optimal design of a building's cooling heating and power system (Wang *et al*. 2010). It was found that PSO was faster and provided more reliable and accurate results than GA.

Despite the aforementioned retrofit methodologies (auditing, energy modelling, and optimisation), in most case studies the experimental data or results reached on-field were missing (Aste & Del Pero 2013). This is a key issue, because reporting successful results achieved by implementing the methodology results into being able to replicate it in similar projects with a guarantee of success.

Another methodology to help the retrofitting process corresponds to decision support tools. Assessing a portfolio of existing buildings to improve its economic, social, and

environmental performance via retrofitting is a complex process that might depend on various interacting factors (Ward & Choudhary 2014). To aid in the decision making process for selecting an optimal retrofit strategy, a number of Decision Support Tools (DST) have been developed.

2.7.4 Decision Support Tools

The most relevant DSTs identified in the literature, i.e. in this thesis only those DST that permit a building assessment to be made were considered, are summarised below. These reviews helped to shape the proposed decision support framework developed in this thesis.

EPIQR (Flourentzos *et al*. 2000) is a DST for domestic dwellings, but it is reviewed here because it influences other DSTs in the non-domestic sector (Strachan & Banfill 2012). This assessment of building conditions considered more than 50 elements where users needed to allocate a deterioration code. An Indoor Environmental Quality (IEQ) was also assessed via a questionnaire for occupants. Another DST, which is similar to the EPIQR assessment but is orientated to non-domestic buildings, is TOBUS DST (Flourentzou *et al*. 2002), which includes an extra assessment on lighting and day lighting evaluation. While both tools evaluate the building elements and occupants' IEQ satisfaction, other aspects such as water, objective IEQ through acquired objective data, maintenance expenditure, and compliance issues are not included.

A slightly broader assessment of building performance is encountered in XENIOS (Dascalaki & Balaras 2004), a GA (Genetic Algorithm) DST (Juan *et al*. 2009) and Hybrid Decision Support System (Juan *et al*. 2010). XENIOS is intended for hotels; not only it assesses the condition of the facility elements, it also helps in an environmental impact evaluation. This includes estimating the levels of different air pollutants based on the energy consumed by the hotel. Water is also assessed. A GA based DST is intended for domestic buildings where it aims to improve the quality and performance of dwellings via six main aspects that are then divided into sub criterion. The main aspects evaluated are safety, usage, convenience, comfort, utility, and comfort. Then, an assessment score is obtained from evaluating the main aspects through a questionnaire, and if that score is lower than a suggested minimum threshold, refurbishment is then recommended. The refurbishment options are selected based on whether the users' preference is a quality or budget priority. This hybrid DST (Juan *et al*. 2010) enables the sustainability levels of non-domestic property to be assessed via different criteria, i.e.

site, energy and water efficiency, materials and resources, and IEQ. The refurbishment strategy is provided based on a trade-off between the user's selected budget and the quality of the refurbishment.

The DST that prioritised retrofits, also incorporated building energy management system (BEMS) data (Doukas *et al*. 2009). This system prioritises building upgrades based on a comparison between current building energy performance data acquired from the BEMS and a benchmark. This means that the operation with the highest difference from the benchmark is the first that needs to be addressed. While being an intelligent method, as in all of the aforementioned DSTs, its scope is restricted due not only because the building performance assessment is exclusively energy driven but also because subjective aspects coming from the decision maker are absent in this tool.

All the aforementioned DSTs were reviewed by Strachan and Banfill (2012). Essentially, the limitations commonly found in all those DSTs were:

- Not considering the occupant's views in the whole process. That includes the whole process, from building assessment to the building post-refurbished.
- The usefulness of the DSTs. A data update in the DST should be included with new data recorded as per Doukas *et al.* (2009).
- Data quality. The sources of the data were not provided.
- Inclusion of externalities. External factors such as legislation or an organisation's strategic views which might affect the suitability of some interventions were omitted.

Strachan and Banfill (2012) also developed their own DST that seems to be capable of taking more than one building into account. It also allows for a comprehensive energy performance building assessment that considers the occupant's views. However, its scope is limited to energy efficiency and therefore the refurbishment only focussed on improving energy savings. Hence, in their current assessment of building condition only the energy performance and associated carbon emissions were considered. Finally their building assessment module, in the author of this thesis opinion, also has the two drawbacks described below:

- Despite stating that it can evaluate more than one building it appears to be unable to accomplish an energy assessment for a whole building portfolio. For instance, audits of all buildings must determine the internal heat gains, the efficiency of equipment, IT, and small lighting. These inspections are desirable

but will probably not occur, particularly in institutions such as universities where only a limited budget is available. Therefore, before requesting that all buildings be audited, the available data should have been investigated. Furthermore, the occupant's views per building are being asked for, and while this perspective of the building is a crucial part of building assessment and refurbishment, it is extremely demanding of time and resources, so consulting the occupants' in-situ while assessing a whole building portfolio was considered to be impractical. There are other tools that account for the occupants' dissatisfaction and knowledge of the building without requiring a great deal of time.

- The reason for conducting the refurbishment is asked, but the reason for a refurbishment might not always be known beforehand. The data analysis might help in deciding which feature is underperforming.

2.7.5 Decision Support Tools for Educational Buildings

The International Energy Agency (IEA) found that energy conservation measures were rarely implemented while retrofitting education buildings because the decision maker had insufficient knowledge of the potential savings and amount of investment required (IEA 2007). Hence, Annex 36 developed the Energy Concept Advisor (ECA) computer tool to help in the decision making process for any uptakes of different energy conservation measures. The ECA allows for different options such as analysing building performance, benchmarking it via a comparison against and national database and providing a list with the most energy efficient and economic technical retrofit measures to be implemented in an education building upgrades. The tool guides the user through the process of retrofitting and provides a technical and economic assessment. However, many of the drawbacks mentioned beforehand, and cited by Strachan and Banfill (2012) were presented in this decision support model.

2.8 Concluding remarks

Energy use at Australian universities has been estimated to increase 11% by 2020 compared to the 2009 baseline value (ClimateWorks 2010). The link between improved IEQ and occupants' health and productivity benefits has been shown in various studies (Spengler *et al*. 2001; Kats 2006; GBCA 2013b), nevertheless, conventional higher education buildings in Australia are generally only designed to comply with a minimum

standard in building codes. This leads to buildings that are not always energy efficient or provide spaces with the required level of comfort for the occupants (GBCA 2013b).

Assessing a portfolio of existing buildings to improve economic, social, and environmental performance via retrofitting is a complex process that might depend on various interacting factors (Ward & Choudhary 2014). In order to improve the performance of Australian higher education facilities in terms of energy efficiency and indoor environmental quality (IEQ), the usual performance of the building needs to be investigated. This process can be conducted through an audit and Post Occupancy Evaluation to meet established sustainability assessment methodologies that could be used to improve building performance. The effect of implementing multiple refurbishment technologies can be investigated via energy simulation, but searching for the best retrofit strategy is a tedious process and obtaining the optimum retrofit strategy using energy simulation alone is highly improbable due to the huge making decision space and endless combinations (Asadi *et al*. 2011). Therefore, mathematical programming can automatically search for the optimal solution by specifying an objective function (Wetter 2001).

To aid in the whole decision making process for assessing building performance and selecting a retrofit strategy, a number of decision support tools (DST) have been developed (Strachan & Banfill 2012). This review identified some areas worthy of further research. Firstly, the overview of sustainable building assessment methodologies revealed that the assessment tool itself, and its subsequent results should be able to demonstrate how it affects decision making. However, a connection between the tools examined and how the decision making process was informed by its results seems to be missing. The different retrofit methodologies reviewed, particularly auditing, energy modelling and optimisation indicated that in most case study applications, the experimental data or results reached on-field are missing (Aste & Del Pero 2013). This is a key issue because reporting successful outcomes achieved by implementing the methodology means being able to replicate it in similar projects with a guarantee of success.

Decision Support Tools are able to provide a comprehensive assessment of a building to identify any deterioration of various elements. Most DSTs have focussed on the energy performance of the building(s) or on a limited assessment scope; there was no demonstration of applicability for the whole building portfolio in the DSTs reviewed.

In most cases, information was acquired by inspecting the utility bills, but that does not always result in the level of accuracy required, so metering or BEMS (Building Energy Management System) data should be utilised instead. It is appreciated that costs are normally considered while identifying refurbishments, but which aspects of an assessment are more important for the Decision Makers was not typically included in this process. In case they are accounted for, it is just to choose between budget and quality. This point is generally relevant in institutions with strategic objectives, where a specific field needs to be improved, or some aspects of a building is to be promoted for branding purposes, or there are some precise organisational goals.

3. Practices and Perceptions of Higher Education Facilities Retrofit Decision Makers and Stakeholders

3.1 Introduction

This chapter describes the methods used and results obtained from the present study in understanding and evaluating practices, attitudes, and perceptions of different stakeholders involved in retrofitting of Australian higher education buildings. This assessment was based on the views elucidated from Facilities Management (FM) teams from eight Australian Universities and one New Zealand University. These particular stakeholders were engaged in order to gain a high-level picture of how Australian higher education FM teams have developed and implemented their decision making processes for the refurbishment of their building stock.

This chapter is structured as follows: i) preparation for and execution of the interviews, ii) the method used to analyse the qualitative data, iii) discussion of the interviews results and iv) a summary of the current approaches to implementing energy efficiency upgrades at a particular Australian university.

3.2 Project Plan and Ethics

In this part of the study two separate project plans and associated human ethics applications were developed and submitted for approval prior to commencing the research. The participants came from two distinct stakeholders groups: i) decision makers, and ii) occupants of a case study building.

The knowledge and perceptions of the first group were evaluated through semi-structured interviews of higher education Australian facilities management team decision makers. The perceptions of the second group were evaluated via Post Occupancy Evaluation questionaries. In addition permissions were gained to install temperature and humidity sensors in the offices and permission to conduct a permeability test, CO_2 concentrations and other Indoor Environmental Quality measurements in the occupants' offices. The ethics applications were approved by the University of Wollongong/Illawarra Shoalhaven Local Health District Human Research Ethics Committee. The decision makers and occupants of the building provided written consent to participate in the study.

3.3 Interviews

Interviews and focus groups are methods commonly used in qualitative research projects (Gill *et al*. 2008). The task of bringing together different decision makers at the same time proved to be difficult due to their tight time constraints and poor availability, so interviews were the preferred method for this target group. Semi-structured interviews were adopted because they provided the interviewer and/or interviewee the flexibility to deviate from set questions if a detailed reply was needed (Gill *et al*. 2008). The participants' roles and home university characteristics in terms of climate zone (ABCB 2013; Level 2015) and equivalent full time students (EFTS) are outlined in Table 3.1.

Before conducting the interviews, a Participant Information Sheet (PIS) with a comprehensive explanation of the project and a Consent Form were provided through email or in person to the participants (see Appendix A). All the consent forms were signed before conducting the interview.

Most interviews took between 15 to 40 minutes, depending on the position and interests of the participant. In one case, the interviewee preferred to answer by email. The interview data analysis was carried out via a qualitative study outlined in the next section.

Table 3.1 Participants roles, recruitment and characteristics of university were they are employed.

Participant	Interview date	Recruitment	University Characteristics	Characteristics
Participant *A*	5th Nov 2014	In person a conference	Climate zone 4, 18000 Equivalent Full Time Students (EFTS)	Energy Officer
Participant *B*	6th Nov 2014	In person at a conference	Climate zone 2, 16000 EFTS	Environmental Manager
Participant *C*	6th Nov 2014	In person at a conference	Climate zone 2, 4500 EFTS	Facilities Management Director
Participant *D*	16th Nov 2014	Through phone	Climate zone 7, 14500 EFTS	Engineering Services Manager
Participant *E*	26th Nov 2014	In person at a conference	Climate zone 5, 28500 EFTS	Director of Property, Facilities and Development
Participant *F*	8th Dec 2014	Responded via email the questions	Climate zone 6, 22500 EFTS	Director of Planning& Development, Infrastructure and operations Group
Participant *G*	24th Mar 2015	In person at a meeting	Climate zone 5, 17500 EFTS	Sustainable Projects Engineer
Participant *H*	10th Apr 2015	Through phone	Climate zone 3, 12000 EFTS	Deputy director, Planning& Development
Participant *I*	16th Apr 2015	Through phone	Climate zone 5, 23000 EFTS	Manager Sustainability

3.4 Qualitative analysis methods

The procedure for analysing the interviews and the qualitative feedback obtained from the POE is detailed in Table 3.2.

Table 3.2 Procedure used for analysing the interviews

Step	Action to undertake
1	Review transcripts against audio for the recorded interviews. Highlight the text describing obviously emerging themes.
2	Find patterns and themes in the reviewed transcripts, and sort the data involved: • Deductive approach, i.e. using predetermined groups to categorise the data • Inductive approach; where the categories originated from, by analysing the data.
3	Reflection to re-review the transcripts and recode other potential missed themes.
4	Identify relationships between themes.

The analysis involved examining the data to identify common themes or patterns, following the steps listed in Table 3.2. First, all the transcriptions were read and compared with the original audio recordings of the interviews, and the apparent themes were identified. The transcriptions were read again, in detail, and emergent themes were identified and coded. A third review of the data enabled recoding with a more nuanced perspective, sometimes some unusual or conceptually interesting themes then emerged. QSR International's NVivo 10 qualitative data analysis software package (QSR International 2002) was used to implement this coding process. For a detailed discussion of the considerations in qualitative research and analysis refer to Creswell (2003) and Saldeña(2012), for example.

3.5 Positionality Statement

Since qualitative research is subjective, it is imperative to interpret and present the data objectively. However, some bias is unavoidable because all research is influenced by the researcher, so the researcher should have a reflexive approach to the data collected to prevent allowing their personal beliefs and values to influence the analyses (Ritchie & Lewis 2003). I have always been concerned about how our way of living might damage the planet. One avenue for reducing human impact on the planet is by decreasing our greenhouse gas emissions. My previous studies showed that greenhouse gas emissions can be reduced by building onsite generation

through renewable energy, whereas my current research suggests that retrofitting existing buildings can improve their energy efficiency and thus reduce our CO_2 emissions. I was particularly interested in researching university buildings because they can also influence succeeding generations, as well as the broader community. This interest brought me to my topic, whilst also hoping to understand the decision making process surrounding retrofitting universities. I had no interaction with university Facilities Management teams prior to this research and no previous experience on how decisions around retrofitting works are conducted within these institutions; these facts helped my neutrality as an observer. As a downside, that also meant that I was also learning how to obtain useful information from FM staff through the interview process and during the early interviews I could have focussed more on some particular aspects of the topic.

3.6 Current Practices of Facilities Management Staff and Decisions Makers in Retrofitting Higher Education Building Portfolios

One objective of this research was to understand how Australian universities can improve the economic, social, and environmental performance of their buildings, an objective that will be achieved via a qualitative characterisation of the current higher education Facilities Management (FM) staff practices around retrofitting their building portfolio. The method key stakeholders use when deciding on the refurbishment works at university, including their practices and attitudes, is not understood very well because there is very little information in the existing literature.

This section presents the results of the decision maker interviews and provides information on the strategies that higher degree institutions pursue when retrofitting their building stock portfolio, including whether any particular key performance indicators (KPI) are used in the building assessment to assist in their final decisions. The key themes which emerged from the interviewees are presented in the following sub-sections. The interviews were transcribed and coded as stated in §*3.4*.

3.6.1 Australian Higher Education Buildings Upgrades Processes

Interviewees were asked to describe how decisions on buildings upgrades were made at their institution, particularly those made to improve energy efficiency, thermal comfort, functionality, and the environmental sustainability of the buildings.

The interviewees were in relatively good agreement regarding the typical decision making process for building upgrades, the differences raised were mainly due to: a) different strategic and organisational goals, i.e. type and scope of a university's strategic asset management plan, and whether it included design guidelines, space master planning, backlog maintenance planning, and environmental management; and b) the interviewee's background where discipline-specific insights into the building upgrade process were given depending on their department. For example, the interviewee from a sustainability team provided a detailed view of the process, while the planning and development interviewees presented the big picture of the overall upgrade process without describing the steps within the process.

The key features of a typical retrofit process for higher education buildings developed from the interviews responses is illustrated in Figure 3.1, although not all universities will have the full strategy shown in the diagram. For instance, the Strategic Management Plan differs for each university and therefore it might contain more or less information. All the respondents could describe their institution's typical approach to buildings upgrades, but it was pointed out that a university is a complex business and 'typical' methods for retrofitting higher education buildings might not exist. FM Participant *E* stated:

> *At the moment, the [university] business is always changing, so there is no formula [for building upgrades]. If someone says they've got a formula, they're lying! I can tell you that now! And the business changes all the time, so all you can do is to keep your finger on the pulse and understand how the business is changing year by year.*

But with regards to the key stakeholders involved in the retrofitting decision making process, several communalities were identified. Some respondents mentioned the senior team together with the executive director of the facilities management as the key people engaged in the process as stated by Participant *A* and *E*:

> *Capital Works Group will make some decisions – well, guided by the executive director – based on which buildings will be refurbished, based on strategic priority.*

and

We don't necessarily make the decision for the university, so what we do is, we take the business case that the faculty's prepared; we give it some rational context. And we do actually say whether we support it or not, and we say that because, you know, it's a good spend, we can achieve X, Y or Z in addition to that, or we might even say, "Look, it's a good idea, but if you waited three years, we're going to renovate that building anyway, so don't spend money now. Do it later." So that does happen, but we give that decision to the Vice-Chancellor and his senior team, basically, and then they all make a decision based on the university's objectives.

Only one respondent referred to the occupants as a crucial stakeholder. Participant *G* stated that *"The occupants are always involved in the decision making [...] some of the refits are occupant driven".*

A representative retrofit methodology, shown in Figure 3.1, was created based on the inputs from all interviewees. Essentially, the decision to upgrade a particular building within the university portfolio is guided by strategic needs, growth requirements, campus development and space rationalisation. This is informed by both the Strategic Asset Management Plan (SAMP) and the senior executive stakeholders, e.g. the executive director of the Facilities Management Team and the senior executive. The SAMP framework considers the space master plan, backlog maintenance issues, environmental management plan requirements, and the capital available. Then, to determine which of the portfolio of buildings need to be retrofitted, two factors were often raised as key considerations, i.e. an assessment of the building's condition and its functionality. This idea of was illustrated by Participant *B*:

…. the end users of the space requirements have changed, so that then drives the refurbishment to remodel the space ... Or it's [the driver] around the condition assessment of the buildings.

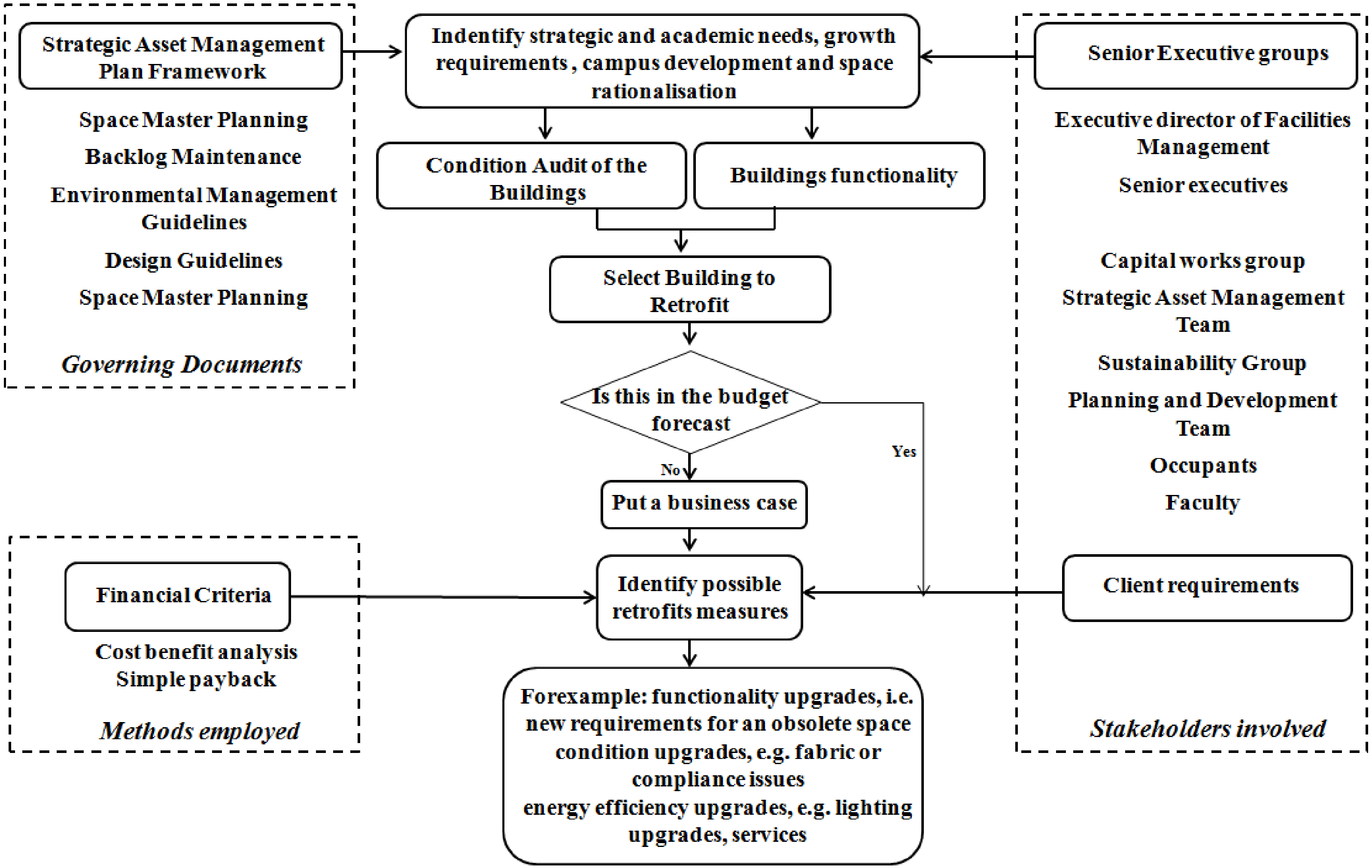


Figure 3.1 Schematic of the common themes, stakeholders and strategies identified by retrofit decision maker interviewees.

A condition audit rates the deterioration and physical condition of the elements of each building, including the criticality of various elements and the building's expected remaining lifetime. While the functionality of the building refers to whether a building housing a faculty or research centre is fit for purpose, e.g. the need for expansion of a research centre after obtaining a grant may trigger the functionality issue. After analysing the functionality of the building together with its criticality versus its lifetime; a business case for retrofitting is generally put forward. The business case is heavily dependent on whether the retrofit was anticipated in the budget. This might be initiated by the capital works group, the planning and development group, the faculty and/or the sustainability team.

The prioritisation of key factors as to whether a building is to be refurbished was found to be extremely dependant on the institution. In some instances just one criterion was considered. The factor that was highlighted more often by the interviewees as the highest driver was space functionality. As an example, FM Participant *D* stated:

> *Unfortunately, we haven't got any prioritisation based on those criteria [the criteria used to take the decisions]… Nobody wants to pay and upgrade the poor buildings. They'd rather do everything based on functionality.*

Interviewees *I* and *H* highlighted their view that determining which building to prioritise for retrofit is typically based on functionality:

> *It is totally based on need [the prioritisation]. If a faculty has an imminent need to expand, I guess they would be prioritised first.*

and,

> *Space utilisation and the need for space are probably driving which buildings to refurbish first.*

It was shown that prioritising a building for retrofitting also has an emotional aspect. This implies that sometimes, if a building has been neglected for a while, regardless of its success as a faculty, it is prioritised against other buildings as a first option. Participant *E* stated that:

> *Rightly or wrongly, and whether the business is doing well is not playing a factor at the moment, so there are some emotional things at play […] Very senior executives are saying, "Well, Humanities, we've left them alone for*

so long…They need a new facility!" So that does play a role. That's not a business decision. Sometimes it's emotional. It seems to be fair, you know…and then, on the other hand, we get situations where, "Well, we're not going to upgrade your building, because your business is not doing as well as it could!"[…]So there is a rational approach, but that doesn't mean the university doesn't make the emotional decision to go.

Finally, once a prioritised list of buildings to refurbish was determined, the retrofit measures to be implemented in the building were identified based on a combination of: a) client requirements, b) building condition reports, and c) a cost-benefit analysis of different upgrade measures. Normally, this cost-benefit analysis included a simple payback period that was generally between 4 to 6 years maximum, and may depend upon other metrics such as capital costs, energy savings, and greenhouse emissions savings. The measures that provided the biggest benefit for the least cost were prioritised. Occasionally, research and teaching benefits were also taken into account.

In some instances, despite following the aforementioned criteria, only one or two factors were used. As highlighted by FM Participant *D* and *C*:

[…]Basically, all of our upgrades currently are based on functional changes or needs.

and

What we're doing now is looking at our condition audits that we do about every five years, and then we call on our university renewal finance to actually go back in and re-work the buildings […] mainly [we based our decisions on] the condition audit reports.

The specific retrofit strategy to implement was typically informed by building-specific information based on reaching a particular target. As Participant I stated:

A big cost benefit analysis was undertaken […] and they prioritised the measures that gave us the biggest benefit for the least cost […]. Well, we probably base that on the metrics [capital costs, energy savings, greenhouse gas savings]. […] I guess it's looking at each building's performance as it is, and prioritising the measures that will make the greatest difference to energy consumption.

Despite the requirement that certain targets be achieved, financial considerations were found to be the major constraint and driver when implementing sustainable retrofits, as repeated by the majority of respondents. This idea was exemplified by Participant *E*, *A*, *G* and *B*, respectively:

> *[…]They [the building upgrades] are always driven by cost.*

and,

> *I think that the budget, probably to some extent, dictates what we can and can't do in that space. At a higher level, I mean, we have our corporate sustainability targets, […] we've got energy reduction, carbon reduction, so ultimately our executive director is responsible for achieving those, so he will be, I guess, working with the head of planning, design and construction, and driving the targets, so while you might have a limited budget, you need to consider working with strategic management and the green team (regarding) how you can also make some savings in this space.*

and,

> *Probably by again prioritising the problems of the building [using the condition report] and then looking at the budget to see how many problems we can fix*

and,

> *...Our forecast of what's going to be involved [in retrofitting a building] is probably not a hundred percent accurate. And then, you know, whilst we're doing it, "Oh, it'd be good to kind of squeeze that in as well!" So there are budget issues.*

> Linked to the budget, another driver cited to implement a certain retrofit measure was the "bang for a buck" approach. This was illustrated by Participant *G*, *B*, *A* and *H*: *We look at the budget to see how many of the [building] issues we can fix. Then, the one [issue] that gives the most bang for buck is the issue that would be addressed.*

and

> *But generally, it [the implementation of sustainability initiatives] is payback-driven, and so we've got a mandate to go out to a ten year payback period, but generally the projects, at the most I'd go to would be about six.*

and

> *our guiding light is probably the quantum of the savings that we can achieve from the effort that we put in, so probably taking a, I guess, "bang for a buck" approach.*

and

> *We are looking at ROI [Return On Investment] with each of those initiatives [the upgrades].*

The sustainability teams were also referred to as being in command of implementing sustainability initiatives as part of their own budget without following the aforementioned procedure as mentioned by Participant *B* and *A* respectively: "*So, me as an environmental manager, I have a budget to go out and implement sustainability initiatives, so the work around continuous commissioning around mechanical systems, and things like that. And so I just do that, regardless, on my own*" and "*in regards to energy efficiency there's our group, the sustainability team, and I guess we're…we're currently looking at how we can best implement energy efficiency projects in a range of buildings across the university".* The approach to implement sustainability upgrades at University of Wollongong is detailed in *§3.7.*

3.6.2 Proposed Changes to Improve the Decision making Process

One particular objective of this study was to identify how current decision making practices for retrofitting higher education buildings in Australia could be better informed. Two themes emerged from the responses; the need to understand the business, and consistent communication between the stakeholders involved in the retrofitting process.

Business knowledge was mentioned by *F*, *E*, and *H* as a key resource in improving decision making:

> *The decision making process could be better informed and improved through internal stakeholders understanding the imperative for them to develop their own business unit strategies, to address business growth,*

commercial activities and community engagement initiatives, which underpin the identification of service delivery requirements.

and,

Understanding what that building is, and how it contributes, and what we need to do. So I mean, whilst forty million dollars is a big spend, if we plan in advance and we say, "In five years' time, we'll spend sixty-five and get a better outcome," then that's the decision we need to make.

and,

… The hard thing for us is that to do the job properly you've got to understand the business. You can have the external parties coming and understand[ing] the business of maintenance or refurbishing buildings but not necessarily note the future directions of academic needs which will determine which buildings to prioritise. […] The most information that you've got and the best understanding of your buildings that you've got, the better planning you can do of course.

Whilst Participant *B* and *A* perceived better collaboration as a step towards improving their retrofitting methodology,

… when the projects guys are planning their stuff, there's probably room for improvement in the kind of information-sharing collaboration between the two teams to say, "I've got this new project, here are all the lessons learned from the past." And we're getting better at that. So a big piece of work is the relationship, you know, flows smoothly; because there's a whole lot of information that you've got to capture.

and,

So, I'm a bit torn about whether or not you do it that way [implementing a retrofit under an energy performance contract], or if it would be better for us to maybe team with the backlog maintenance group and try to work with them as they do a project, or if we just commission them ourselves and run them as our own projects.[...] ultimately our executive director is responsible for achieving our corporate sustainability targets, so he will be, I guess, working with the head of planning, design and construction, and

driving the targets, so while you might have a limited budget, you need to consider working with strategic management and the green team (regarding) how you can also make some savings in this space.

Lack of sharing and communication was an issue raised by Participant *E*:

Some universities are famous for doing that [not communicating with different departments], because they're complex businesses.

Another problem faced by FM decision makers was gaps in the information. MS stated that the retrofitting process could be improved by some of the data being more freely available. The acquisition of extra information before conducting any upgrade would embed the requirements for the upgrade into the 'scope of works', and thereby in the budget. This in turn would permit the upgrade to be conducted. Although the level of missing information differed depending on the university, all the respondents agreed there are always gaps in information. However, in some instances basic information (e.g. as-built documentation) might not exist for some old buildings or might not have been updated if the buildings have already undergone previous renovations. Also, more specific information about the building would aid the process, as highlighted by Participant *A*:

…even something as simple as drawings can be a challenge to collate and – well, latest drawings, anyway. We've got a few buildings that have been renovated four times in the last twenty years, and it's hard to know exactly what the true state of the building is.

Moreover, Participant *D* raised the issue of current benchmarks being unavailable at a building level rather than the whole institution. Therefore, making a benchmark available would facilitate the retrofitting process:

It'd be interesting to see what it [the benchmark] was like on a building basis rather than as a whole institution [..] It'd be interesting to see it broken down into "per building", which is a point we'd like to get to. [...] We'd like to get to a point where we could look at each building separately.

3.6.3 Systematic Decision Making Frameworks and Tools

The interviewees discussed whether they followed a systematic framework through the decision making process and whether they had considered developing some tools to improve the process.

The most common systematic approach framework cited by the respondents involved putting a business case together to outline the retrofit expenditures and returns that the university would expect to receive for its money. This was illustrated by Participant *B*:

> *The university has to prioritise how they spend money, so what we've done now is […] developed a business case template or tool which outlines to the faculty, "OK, you've got a great idea, but what you have to do is, you have to put in process, develop a business case to allow the university to understand what strategic benefits that money will bring to the university. So if you're going to spend a million dollars, what does the university get out of making that investment?".*

Several interviewees indicated they used a strategic asset management plan and campus development frameworks as systematic tools, i.e. documents, to guide any renewals.

Two respondents stated they did not follow any systematic strategy, including Participant *H*:

"*No [we do not follow any systematic framework] but we are about to start aligning the 'life index' with the building proposals [for retrofitting]".*

Two interviewees indicated they used the Green Star frameworks to assess university building stock, but that these could be used in different ways. The "Green Star-Communities" is a rating tool that treats university buildings as a precinct in order to obtain an average Green Star rating for the whole campus, while another approach was the use of the "Green Star-Education v1" tool to rate a particular new building. Another two interviewees stated that using Green Star could help to embed sustainability in the retrofitting process in a more rigorous way, but they also agreed that a Green Star application is an expensive process and the money could be better invested elsewhere in the project. In the New Zealand case, the interviewee alluded to the fact that a decision was taken within New Zealand Universities not to use Green Star due to its associated costs.

Two university representatives claimed to have developed their own software tools to aid the decision making process. In one case, strategic asset management software that brings together different databases such as Archibus (Archibus 2015) was implemented to aid the data management. However, the downside of this software, as underlined by an interviewee *D*, was its inability to analyse building performance "*I think that if there were other items of software, maybe to help us with the analysis and the performance of the building, then you could actually look to see whether you could defer a refit, or you needed to bring a refit on quickly"*. At another university, a cost calculator had recently been developed. By understanding the cost of running the facilities via metering and dashboards, a more accurate costing system can be achieved. The remainder of the interviewees agreed that a tool to help decision making would be very helpful. To illustrate this idea Participant *A* and *D* raised the following:

> *if there were some sort of guide or decision making tool that could help us focus on where we might best achieve energy reductions, energy savings in these particular types of spaces that could really help us target our efforts.*

and,

> *Definitely, the key thing that would probably help would be [...] actual replacement cost estimates against these [buildings'] deficient elements. So basically, when you do come to set your budget, you can go, "Right, well, we've got this old fire system, and to bring it up to standard is going to cost $300,000." So suddenly you can try and pick up that cost in your initial factoring, rather than pay it off.*

3.6.4 Key Performance Indicators Used

Most respondents agreed that, Key Performance Indicators (KPIs) should be used in the decision making process to assess the viability of retrofitting the building stock. As Participant *F* stated:

> *The use of KPIs is not only appropriate and useful but very important in assessing the feasibility and to assess existing building stock for refurbishment and/or adaptively use. [...] KPIs are valuable metrics to reduce the subjective element of the decision making process, particularly where there are complex high-value, high-risk projects competing for limited resources to be considered. KPIs are also a good checklist to*

minimise the risk of important issues being overlooked during the decision making process.

However, there was no consensus on using universal KPIs for higher education institutions because some universities mentioned different building performance metrics as KPIs, while other institutions provide KPIs around compliance, space utilisation, or a mixture of them. The first idea was illustrated through Participant *C* and *D* respectively:

They [The KPIs] are all around building performance.

and,

We have got that condition report which, in theory, provides you with KPI's around it, that will help you decide which building to retrofit, but that data is essentially ignored in favour of, purely, functionality

Whilst the latter idea was raised by FMD team members *G* and *B*:

There would be BCA [Building Code of Australia] approvals or regulations at the top of the list [...], space utilisation comes in too. We tend to try to make sure that we use the space effectively.

and

I collect metrics to measure how we're going around energy use and waste and travel, carbon emissions [...]And the KPIs around the condition assessment.[...] We now have a KPI to say that we want all of our buildings to be at least 67% of new building standard.

The reason why KPIs differed between institutions might best be answered by one respondent who stated, "*all KPIs should either be clearly understood or defined and tailored for specific projects".* However, the rest of the interviewees did not suggest that the KPIs varied depending on the project. Indeed the interviewer gained the impression that the subjective weighting given to KPIs might vary depending on the nature of the project and the strategic goals of the institution. This idea was mentioned by Participant *F*: "*Ranking KPIs generically is not possible in the absence of a specific project or class of asset".*

The following section describes the method used to implement energy efficiency upgrades at a specific university, i.e. University of Wollongong (UOW). The

information was acquired from several meetings in 2014 with the Sustainability Engineer from the UOW FM team. A financial summary was also obtained.

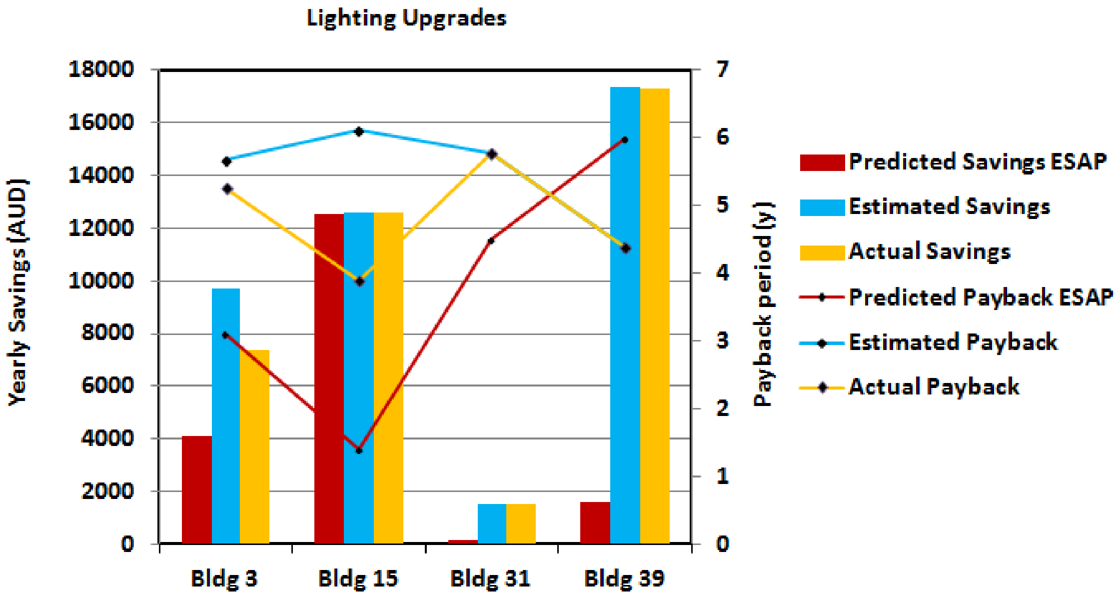
3.7 Current Practices to Implement Energy Efficient Upgrades at UOW

In order to improve the operations of UOW buildings, the Facilities Management Division (FMD) at UOW established an energy management policy and set-up energy procurement procedures and an Energy Savings Action Plan (ESAP) to guide the implementation of energy efficiency measures on UOW building stock.

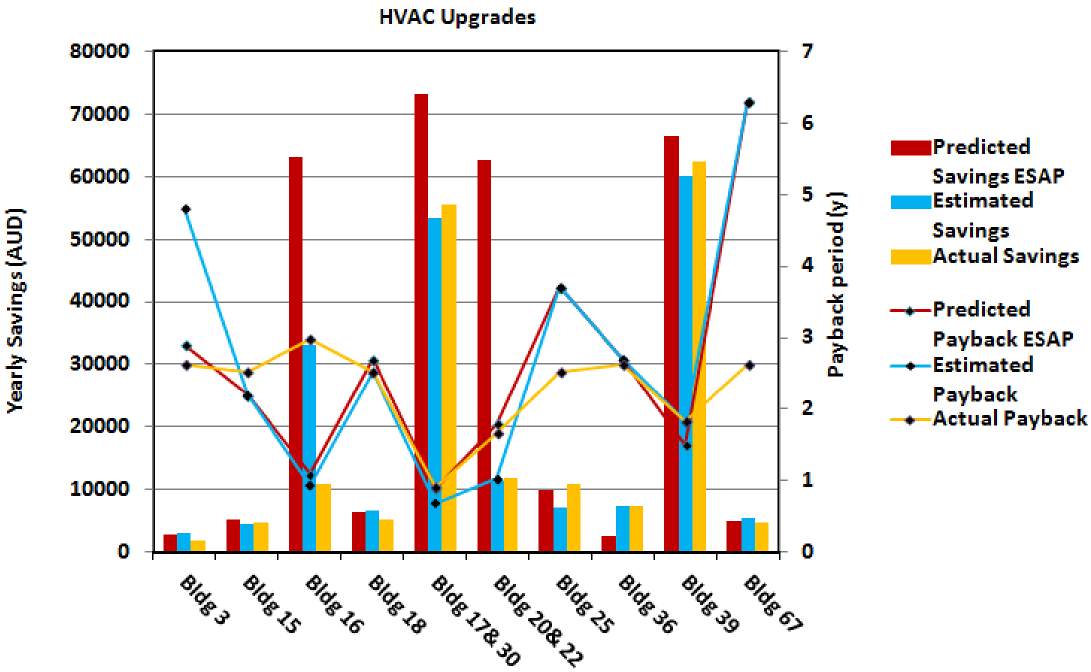
The ESAP was first developed in 2006 and entailed a review of lighting and mechanical services across the campus to understand performance and recommend upgrades whenever relevant via subcontracting of a consultant company who conducted Type 2 energy audits in the buildings. The audits identified energy efficiency opportunities that included preliminary estimated implementation costs, savings, and simple payback. Subsequently, the FMD sustainability team was responsible for reviewing the suggestions and deciding which upgrades were to be carried out. In practice, the sustainability team relied on overall commercial decision drivers to decide on the uptake of an upgrade option; these drivers were the estimated payback time, current requirement for item replacement, and maintenance savings. This meant that even though a payback period might not have been very attractive, i.e. > 4 years, if the assets were due for replacement, the expenditure should still have been made.

As case study examples, Building 3 was using T12 fluorescents and Building 15 had T8 fluorescents. Both lighting bulbs were due for replacement, and a decision had to be made on which type of fluorescent to use. If T8 was to be replaced, very little energy savings would result, so even though a T5 lighting upgrade had a payback time of more than 5.5 years, it was decided to upgrade to T5 fluorescents to achieve some energy savings because the replacement costs had to be spent anyway.

Figure 3.2a and Figure 3.2b presents annual energy cost savings estimated: i) from the 2006 ESAP, ii) by the Sustainability Team, iii) and the measured annual savings together with simple payback times for different upgrades, namely the lighting and HVAC systems at UOW building stock from 2009 to 2011. The data was sourced from a financial summary by the UOW FM Sustainability Team and post-processed by the present author.



(a)



(b)

Figure 3.2 Estimated and actual energy savings and payback for a) lighting upgrades and b) HVAC upgrades.

The ESAP predicted savings and payback were calculated by a consultant while estimated savings and payback were calculated before the upgrades were implemented by the university sustainability team. The actual savings and actual payback were calculated based on a one year period energy consumption logging for HVAC upgrades, whereas the theoretical calculation for lighting upgrades was based on consumption by the nameplate power. According to the sustainability team, this method provided an accurate estimate of energy consumption.

The lighting upgrades presented in Figure 3.2a show lower saving by ESAP than the actual. Both actual and estimated payback periods were always higher than predicted in the ESAP, and the savings predicted by ESAP were lower than the actual; most likely because of a conservative approach adopted by the consultant. For instance, the implementation costs were overestimated and the energy cost for calculating the estimated savings was higher than the real cost used for real savings. The same reason can be used to justify the discrepancies between estimated payback and savings from the sustainability team and real savings.

However, the financial summary for the HVAC system upgrades showed the opposite trend (Figure 3.2b), where typically the ESAP predicted savings were higher than the real savings. The estimated simple payback was found to be either lower or higher than the actual simple payback, depending on the building. This was attributed to the difficulty of calculating the real HVAC system upgrades savings without any sub-monitoring emplaced. To illustrate this effect, during the HVAC systems upgrades, Information Technology Services (IT) implemented a new phone system throughout the campus that increased power consumption, so it was difficult to know whether the real savings ascribed to HVAC upgrades were just from the building level power consumption.

Simple payback periods for lighting and HVAC upgrades are often the key drivers of retrofit uptake, but the actual and predicted payback and savings by ESAP and the sustainability team differed from 0 to 300%. The highest disagreement was in the HVAC because predicting its utilisation is difficult. In order to implement retrofits that might be discarded due to a higher payback or to better understand the actual benefits of retrofit in terms of energy savings, measures such as sub-monitoring or modelling are suggested.

3.8 Summary

A qualitative characterisation of current practices in Australia around retrofitting higher education buildings was conducted via nine semi-structured interviews with different stakeholders involved in the decision making processes. The key features of a typical approach to retrofitting university buildings were proposed based on the interviewees' responses. A discussion on building refurbishment prioritisation through decisions on the strategy followed for implementing retrofits was also undertaken. Proposed changes

in current practices to make better informed decision were outlined, and the use of existing systematic frameworks was investigated. The inclusion of Key Performance Indicators (KPIs) in decision making was also discussed. Finally, the current approach to implement energy efficiency upgrades at a specific university was summarised. The investigation of the current practices to implement energy efficiency measures showed that the actual and predicted payback of HVAC upgrades could differ up to 300%. As simple payback is often one of the key drivers for retrofit implementation, it is extremely complex to make an informed decision with this information.

An analysis of interviews results provided the background for some of the following chapters. The interview responses led to the creation of the KPIs to be introduced in Chapter 4. The possibility of creating a framework to aid in the decision making process was identified as being very useful by most of the interviewees. Development of a framework to support decision making for retrofitting higher education buildings was a goal of this project.

The framework described below sets out a method to understand the building portfolio and find an optimal retrofit strategy that minimises energy consumption while improving thermal comfort. This, in turn, facilitates the business case, a response repeatedly mentioned as one procedure to follow to get funding for retrofitting because then the benefits to the client (e.g. university or faculty) become tangible.

4. Development of a Characterisation and Decision Framework for University Building Portfolios

4.1 Introduction

The physical environment in which an organization operates has an important impact on its successful operation and efficiency, and upgrades/modifications to facilities could significantly improve the institution's efficiency (Amaratunga & Baldry 2000b). To estimate the effectiveness of proposed modifications to infrastructure by facilities managers and other stakeholders, one needs to understand whether current facilities are meeting their intended purpose (Lavy *et al*. 2010).

This chapter outlines the development of a framework to characterise a portfolio of university buildings and an associated decision support framework. This framework was designed to help decision makers understand their building stock in terms of the overall building portfolio and by optimising retrofit strategies for particular buildings. This chapter details how the key issues relating to the technical, economic, social and environmental factors of higher education buildings were identified and then used to develop a set of Key Performance Indicators (KPIs). This is followed by a description of a weighting scheme that includes subjective and objective weighting factors for the KPIs.

4.2 Decision Support Framework

Decision Support is a widely used term referring to rational decision making processes. Bohanec (2003) defined decision support as helping people organise their data and thoughts in order to make decisions. In this work the Decision Support Framework (DSF) methodology is intended to enable decision makers to make an informed decision on their building portfolio assessment and decide which retrofit measures should be implemented.

Typically, these decision making tools are focussed on selecting the best retrofit strategy for a particular building. Although the economic and/or environmental needs are normally considered, the organisational and strategic institutional requirements are often ignored (e.g. *§2.7.4*). However, the decision making process for rational upgrading/retrofitting of institutions such as Universities, should consider the building

stock as a complete portfolio rather than buildings in isolation. Therefore, the Decision Support Framework developed in this work proposes:

i. that a broader range of Key Performance Indicators (KPIs) including environmental, economic and social factors be included to evaluate the building portfolio,
ii. the university building portfolio be assessed as a whole, not buildings in isolation, and
iii. the tangible and intangible (institutional strategic needs) objectives be integrated to account for building performance and the priorities of decision makers and stakeholders.

Before introducing the university buildings stock characterisation and the decision support framework, a description of how concept was developed is presented in the next section.

4.3 Framework Conception Process

Developing the DSF methodology was an iterative and lengthy process typically composed of four major avenues, as shown in Figure 4.1, i.e. current Facilities Management (FM) staff practices, evaluation of typical data existing at higher education FM groups, evaluation of particular upgrades for different buildings, and senior consultant expertise.

The process began by surveying the databases already existing at universities, particularly Australian universities.

This information provided an understanding of how to judge the best approach in terms of usability and accessibility of the datasets, in order to characterise tertiary institution buildings. This analysis suggested that their features can be characterised on the basis of quantitative data such as energy consumption, operational costs, or water consumption because they are easily available. Thus, a baseline performance for those characteristics can be determined and used for benchmarking.

This was the basis for developing the key KPIs approach to characterise a building portfolio. According to Alwaer and Clements-Croome (2010) KPIs are essential for implementing refurbishment strategies because they enable the performance of current buildings to be quantified. Once the current performance of different building

characteristics has been obtained, levels of performance between different buildings can then be compared for a particular characteristic/KPI. This process enabled the development of a more holistic way of understanding the university building stock performance, i.e. a way to shift from the perception of high-level building performance (building portfolio characterisation via KPIs) to a more specific view. First, the concept to assess a portfolio of buildings was defined and then transitioned to a particular building.

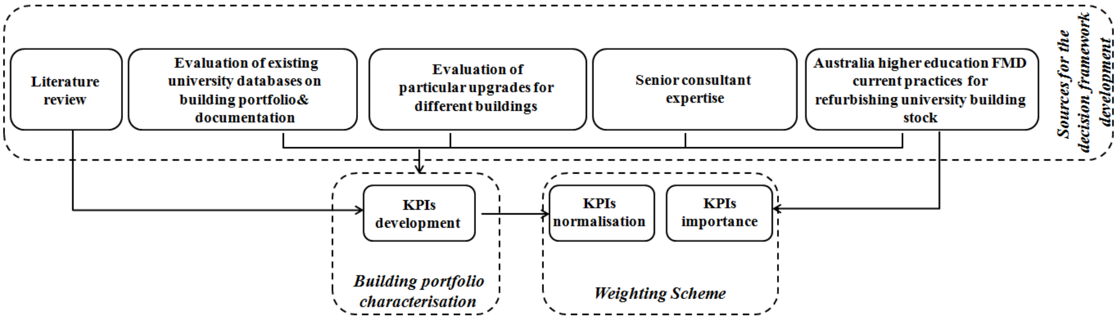


Figure 4.1 Schematic of the process used to develop the Decision Support Framework.

As a key part of the development of the methodology, interviews were conducted with members of higher education Facilities Management (FM) teams in Australia and New Zealand to understand how they currently assess the education portfolio of buildings (as described in the previous chapter). This in turn generated a substantial qualitative output that enabled:

i. their decision making process for building retrofitting to be understood,
ii. their business case for selecting a particular building to be upgraded to be understood,
iii. indirect feedback of the methodology to be received, and
iv. direct constructive criticism and the importance of the proposed KPIs to be received by the author.

The information provided by the Australian FM teams was used to improve the draft methodology, so that university strategic goals and planning were incorporated, for example. Moreover, informal discussions with senior managers from property, university facilities, and development and campus planners from different higher education FM teams also helped to refine the methodology.

Development of the final part of the method, which was focussed on the individual building level, was assisted through the expertise of a senior consultant with

international experience in refurbishment and discussions with the sustainability officer at UOW, and the knowledge gained from assessing upgrades previously implemented at UOW.

To this end, acquiring sound knowledge from those sources allowed for different iterations in the methodology that resulted in the final framework that is explained in the next section.

4.4 Decision Support Framework

The framework developed in this study is shown schematically in Figure 4.2. The methodology moves from the assessment of the whole portfolio of buildings through to individual building assessment, and is structured as follows.

1) Characterisation of the building portfolio. Here a set of KPIs is developed through a high-level audit of the entire building portfolio and existing building stock records and databases are examined. The availability of data and records will vary depending on the tertiary institution, and although some data is likely to be available for all universities, its granularity might be different. For instance, these records would include energy and water consumption, but the level of detail could differ from metered half hourly consumption through to monthly consumption from the utility bills. Similarly, a Building and Information Maintenance System (BIMS) may, or may not, be available, where temperatures are recorded for space in buildings being controlled/monitored. A database aiding facilities asset management, such as ARCHIBUS (Archibus 2015), might also be available including a space and occupancy survey data as well as tracking and managing the physical assets, or building floor plans detailing usable floor area (UFA), materials and spaces. Once the available data accessible in the high level audit is analysed, the operational and conditional KPIs can be created for each building.

2) KPI Weighting Scheme. After identifying the KPIs, the baseline value and reliability of the data for each KPI and building is determined. Then individual KPIs may be compared across buildings. However, to compare across all KPIs and all buildings, means that a weighting scheme is needed; incorporating both objective and subjective weights. The whole building portfolio can then be ranked to provide a prioritised list of buildings for refurbishment. Objective

weighting factors are obtained by normalising performance KPIs (as detailed in §4.4.3). Subjective weightings are decided by decision makers and their priorities.

3) Individual Building Retrofit Assessments. Individual building-level assessments involve comprehensive audits to gain an in-depth understanding of the building performance (which will be discussed in depth in Chapter 6). Knowing how a building performs helps prioritisation of the retrofit options and identification of a feasible retrofit strategy that will reduce the energy consumption and improve indoor environmental quality.

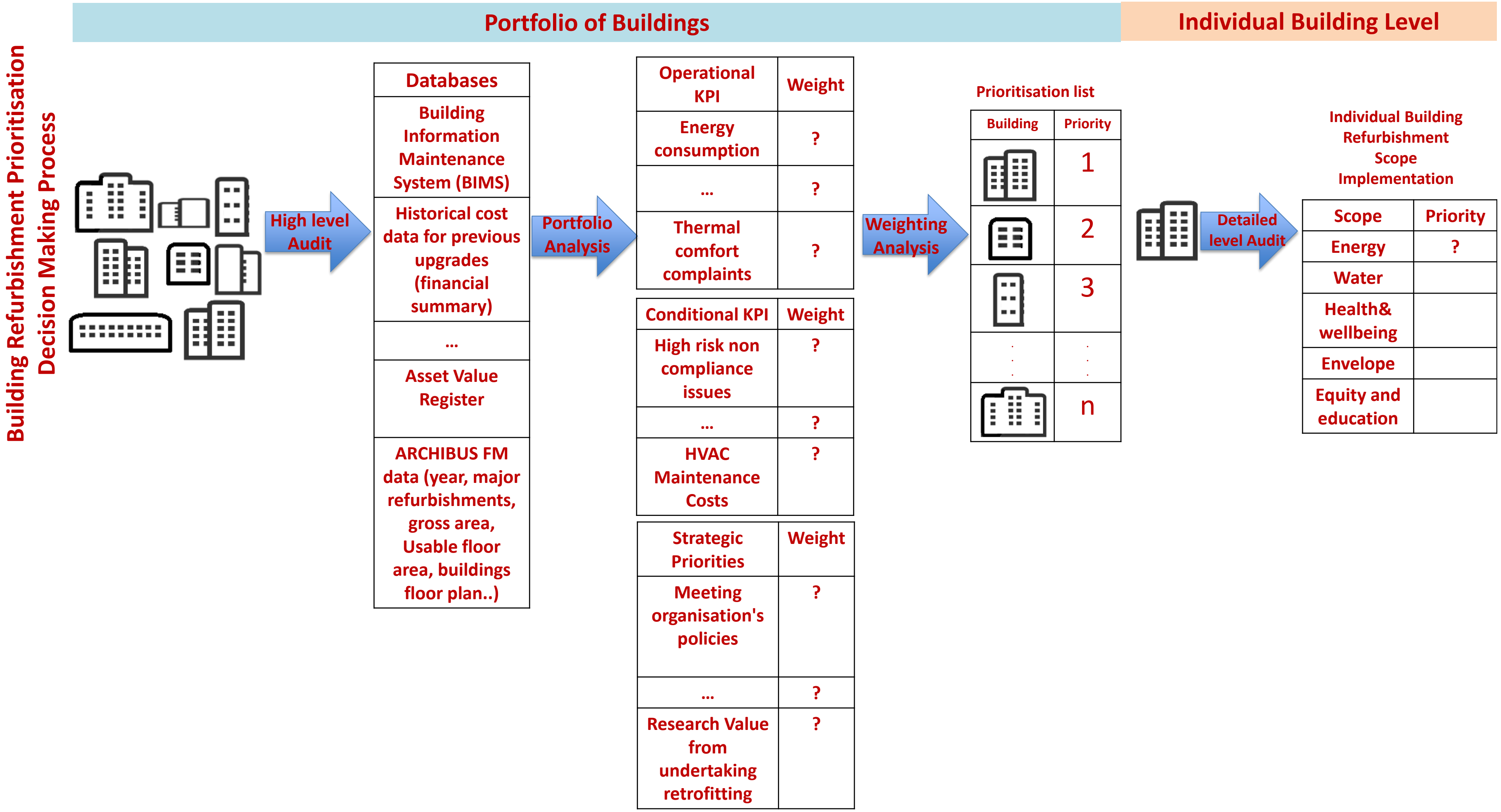


Figure 4.2 Schematic of the Decision Support Framework methodology.

The following sections describe each of the building portfolio assessment stages, including:

i) a characterisation of the university building portfolio, including the development of KPIs and the acquisition of the data, and
ii) a weighting scheme that underpins the decision support tool.

4.4.1 Characterisation of University Building Portfolios

This section describes how the KPIs used to characterise university precincts were developed.

Development of Key Performance Indicators (KPIs)

A performance indicator was defined by Becker (2004) as "a representation of a measure of some characteristics that are determined relevant to indicate a condition". Being able to identify KPIs to assess the performance of buildings is a crucial and challenging task (ALwaer and Clements-Croome 2010). According to Bakens (2003), there is no clear approach to determining the performance indicators needed to assess sustainable buildings, even though KPIs are needed to characterise the building stock in terms of benchmarking for current performance, helping to set targets, and evaluating progress towards reaching them (Becker 2004; Lavy 2008). Moreover, utilising KPIs for building assessment can help the management team make important decisions (Lavy *et al*. 2010).

In this thesis the method used to select KPIs was a combination of a: comprehensive literature review that focussed on previous KPI studies and building assessment systems; university quantitative data and resources; and a review of current practices through interviewing senior staff and facilities managers involved in upgrading buildings.

The KPIs were first drafted based on an extensive literature review (e.g. Becker 2004; Lavy *et al*. 2010; ALwaer & Clements-Croome 2010; Yang *et al*. 2010; Lourenço *et al*. 2014) as summarised below.

Becker (2004) investigated the most important elements needed to develop a sustainable assessment framework, and then stated that the indicators were utilised in all assessment methods, so their selection depends on the data, time, and resources available, and the specific needs of the group selecting the features of concern. According to Becker

(2004), any indicator should be representative and simple, which means being usable and easy to use; permit a comparison against each other; be sensitive to change; be usable at different stages; be capable of representing a specific issue (relevant); be quantifiable; provide value but at the same time be cost effective; and finally, be easily obtainable, i.e. ease of access to the data. Those characteristics were applied by two of the few existing studies on developing KPIs for building assessment studies (ALwaer & Clements-Croome 2010; Yang *et al*. 2010). Alwaer and Clements-Croome (2010) investigated how to select a set of KPIs to assess intelligent buildings. Their KPIs were based on a thorough literature review, and then stakeholders tested the selected KPIs. Architects, engineers, assessors, and building users evaluated the KPIs, and they provided a diverse perspective on what KPIs were suitable for assessing building performance.

Yang *et al*. (2010) explained a method to identify and weight indicators for assessing Chinese residential buildings and, like Becker, their KPIs were identified through a literature review and surveys of experts. Despite using a consistent method, the final list of indicators was, in my opinion, not ideal because two of the most valuable indicators related to building operation, i.e. overall energy consumption and indoor temperature, were not considered. However, variables such as the outdoor environment were incorporated as a performance indicator for assessing energy efficiency.

An identification and categorisation of KPIs was carried out by Lavy *et al.* (2010) to help assess facility performance; their final indicators were very comprehensive and ranged through physical, financial, and functional KPIs. However, a more concise list of indicators for decision making was stated as being needed for future research, while the extensive list of indicators such as survey-based categories limited its practicality and feasibility at a building portfolio level.

Another study focussed on improving the energy performance of schools (Lourenço *et al.* 2014) by choosing some strategies derived from the KPIs. In this case two KPIs were selected, i.e. energy use and CO_2 emissions. According to the authors, these KPIs covered the stakeholders' primary concern for the performance and sustainability of the schools, but in this instance although the KPIs helped to characterise the energy performance, the scope was limited to energy, so the overall assessment was incomplete.

The second phase of this work involved consulting stakeholders about the selection of KPIs. The stakeholder group was limited to decision makers from higher education facilities management teams, which ensured that the specific needs of this group were accounted for and any skewness in the KPIs selection was reduced.

The KPIs were used for the high-level assessment of building portfolios, so there was a trade-off between the effort required to acquire the data to construct a given KPI, assign its value, and its relevance. While some of the indicators from the established sustainable buildings assessment and peer reviewed literature were considered, several were ruled out because their application in the analysis of a portfolio of buildings was impractical. For instance, information on air tightness, waste management or detailed indoor environmental quality for each building requires significant time and effort to acquire. So viable alternatives that provided similar information in a concise manner were examined, e.g. unsolicited complaints on a broad range of issues were used as an indicator to rate building performance from the occupants' perspective. Unsolicited complaints about commercial buildings are an indicator of occupant dissatisfaction with the environment as well as a sign that building maintenance and operating costs are increasing (D. Wang *et al*. 2005).

Another important condition is whether the performance indicators are effective. Cobb and Rixford (1988) learnt that comprehensiveness might be the enemy of effectiveness, so a few insightful KPIs can be more powerful than a long list of performance indicators, and in the present context a high-level assessment at portfolio level cannot be too extensive or detailed.

The second step in establishing KPIs was analysis of data that was readily available for higher education facilities. Accessible data in Australian tertiary institutions includes building construction floor plans of relatively new buildings, metered or billed energy and water, a space database manually collected by auditing building spaces (TEFMA 2009), and human resource data on turnover and absenteeism. In some instances, data also included unsolicited complaints from a variety of aspects such as Heating, Ventilation, and Air-Conditioning (HVAC) maintenance, indoor environmental quality, or facilities performance.

The final list of KPIs is shown in Figure 4.3. All the interviewees agreed those KPIs were suitable, and following an interviewee suggestion, functional KPIs were also

included. Operational and functional KPIs are related to how a building functions and its adequateness for the users, including: a) water performance and water consumption per UFA, b) energy performance, which includes electricity consumption per UFA, gas consumption per UFA, HVAC consumption per UFA, and peak-to-average load, c) envelope performance, which is unsolicited complaints related to the building fabric per UFA and the energy signature method, d) building facilities performance, namely unsolicited complaints related to lighting, HVAC and plumbing per UFA, e) space utilisation, defined as the utilisation rate of lecture theatres, classrooms and laboratories, and f) productivity, defined as the rate of occupant turnover and absentees per year.

Conditional KPIs are measures of the state of the facility, e.g. i) maintenance and running costs of the facility per UFA, and backlog maintenance per UFA, ii) incidences of poor occupant comfort and health and unsolicited complaints related to the thermal, acoustic and visual comfort per UFA and Workplace Health and Safety temperature related hazard events per year, and iii) any non-compliance issues with the building.

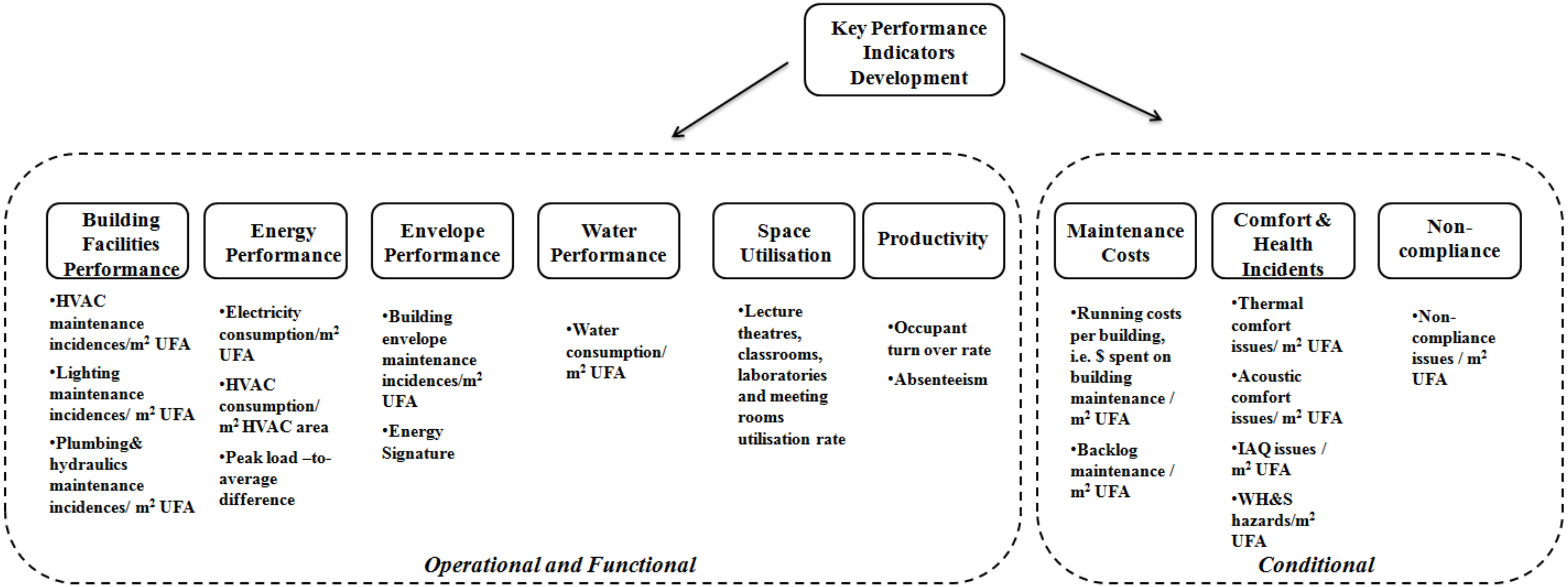


Figure 4.3 Final list of KPIs developed for building performance characterisation.

KPI Baseline Acquisition

Once the KPIs are established, their individual value for every building must be determined by acquiring data from numerous databases. This data should be campus-wide with building-level granularity. These records include items such as: the number of occupants per building, space type (% of conditioned and unconditioned space and typical usage, e.g. laboratories, offices, classrooms, etc.), the year of construction and the construction materials. Those values are the foundation on which to build the KPIs:

i. energy performance, obtained from monitored energy or utility bills;
ii. HVAC performance based on monitored HVAC consumption and the energy signature method, where the daily HVAC consumption is correlated to the daily mean outdoor temperature. This method is used to understand HVAC consumption and detect any malfunctions deriving to higher or inconsistent HVAC consumption;
iii. water performance from metered water consumption or utility bills;
iv. envelope performance obtained from the fabric of the building, and unsolicited complaints and building energy signature method;
v. the performance of the building facilities, collected from the unsolicited complaints' maintenance database;
vi. space utilisation, gathered from the space utilisation survey following TEFMA space planning guidelines (TEFMA 2009);
vii. productivity, gathered from the university human resources;
viii. Work Health and Safety (WHS) temperature related hazards, assembled from university human resources department.

Developing KPIs is the first step in the benchmarking facilities (Ho *et al*. 2006). It should be noted that even if the data exist, it might not be possible to access it due to data confidentiality and privacy.

4.4.2 Benchmarking

It is important to benchmark the KPIs in order to understand how a specific building is performing compared to a standard. Through benchmarking, the indicators can also be compared across the building portfolio by recognising for each KPI how buildings perform against each other, so as to judge which building and KPI need to be addressed

first in an upgrade or retrofitting program (ALwaer & Clements-Croome 2010). The benchmarks used in the present study were based on either:

a. Established external benchmarks, such as Tertiary Education Facilities Management Association (TEFMA 2011) or the Commercial Buildings Baseline Study (CBBS) (pitt& sherry 2012); or

b. Internal university benchmarks that were defined on the historical average performance of the building portfolio. They were used in the absence of an established benchmark such as unsolicited complaints or WHS issues.

Typical KPIs and best practice benchmarks, including their source, are shown in Table 4.1. Typical TEFMA benchmarks for electricity, gas, and water consumption, CO_2 emissions, space utilisation and maintenance costs were extracted from the TEFMA Benchmark Business Partner Report 2011 (TEFMA 2011). This report was developed by surveying 43 Australian universities. As well as the TEFMA typical practice benchmark for electricity and gas consumption, the Commercial Buildings Baseline Study (CBBS) benchmark 2011 for NSW tertiary buildings was also adopted, which included energy consumption monitored from a sample of 38 NSW tertiary institutions over a nine-year period (2001-2011).

Best practice *per se* was not identifiable from the TEFMA or CBBS data since individual values for institutions were not provided, so other sources were used to define the best practise benchmark. Green Star (GBCA 2013c) was used to obtain water consumption, and peak-to-average load difference typical practice benchmarks. In those KPIs that lacked a reference benchmark, e.g. unsolicited complaints or WHS hazards, the average of the university building portfolio was used.

Table 4.1 KPI benchmarks utilised in the decision support framework.

KPI	BENCHMARK				
	Units	**Best Practice Benchmark**	**Reference**	**Typical Practice Benchmark**	**Reference**
Electricity/m^2 UFA	kWh/m^2	68.6	(GBCA 2009)	211/168.3	(TEFMA 2011)/(pitt& sherry 2012)
Gas/m^2 UFA	kWh/m^2	3.97	(GBCA 2009)	86	(TEFMA 2011)
CO_2 -e/m^2 UFA	kg/m^2	73	(GBCA 2013c)	214.7	(TEFMA 2011)
Peak load-to-average ratio	-	0.2	(GBCA 2013a)	0.4	(GBCA 2013c)
Water/m^2 UFA	kL/m^2	0.43	(GBCA 2013c)	0.98	(TEFMA 2011)
Complaints/ m^2 UFA	Number of complaints normalised by the total complaints/ m^2 UFA	0		University portfolio internal benchmark	
HVAC complaints/m^2					
Envelope complaints/m^2					
Lighting complaints/m^2					
Plumbing complaints/m^2					
Thermal comfort					
IAQ complaints/m^2					
WH&S incidences/m^2					
Space Utilisation	%	66	Teaching spaces(UK Higher Education SMG 2006)	33	(TEFMA 2011)
Backlog maintenance costs/m^2 UFA	number/m^2 UFA			University portfolio internal benchmark	
Maintenance costs/m^2 UFA	number/m^2 UFA			28.41	(TEFMA 2011)

4.4.3 Development of an Integrated KPI Weighting Scheme

A set of weighting factors were used to define the importance of each KPI relative to the others. Indicators or KPIs do not typically have the same significance for all decision

makers (Yoon & Hwang 1995), so finding suitable weighting factors for the indicators was essential. In general, weighting methods are classified as either objective or subjective. Subjective weighting is based on surveys of experts and professionals and feedback so the resultant weights not only depend on the decision maker, they also reflect their interests. Conversely, objective weights are determined from data. In this study the objective and subjective approaches were integrated, as described in detail in subsequent sections covering:

i. normalising the KPI baseline value;
ii. obtaining the KPI weighting factors;
iii. obtaining the subjective score per each KPI from the decision maker and;
iv. aggregating the weighting factors.

The weighting scheme was a key element of the decision support tool because it enabled a comparison to be made across different buildings and indicators.

Objective Weighting Factors: KPI Normalisation

In order to compare the relative importance of KPIs the baseline performance values must be normalised. Several normalisation techniques for indicators can be found in the handbook for constructing composite indicators (OECD 2010). Here, a 'range normalisation' that scales data by expressing data points relative to a benchmark was used. Typically, the normalisation process scales data between two arbitrary limits, e.g. 0 to 100 or 0 to 1 (Ebert & Welsch 2004). However, in the present study it was decided that the typical benchmark would provide the base reference, 0, while the best practice benchmark would equal 100. The nomenclature used when normalising baseline performance is explained in Table 4.2.

Table 4.2 Nomenclature used in the weighting factor scheme.

Symbol	Description
β_T	Typical practice benchmark (same units as the indicator/KPI).
β_B	Best practice benchmark (same units as the indicator/KPI).
φ	Baseline value (same units as the indicator/KPI).
Φ	Normalised value (non-dimensional).
ϖ	Overall objective weighting factor (non-dimensional).
ψ	Subjective weighting factor, which represents the relative importance that decision makers give to the KPIs (non-dimensional).
ω	Aggregate weighting factor, which incorporates objective and subjective weights (non-dimensional).

Normalising the KPI baseline value, i.e. normalising the KPI raw data, was based on its distance to the typical benchmark β_T, divided by the difference between the best and typical practice benchmark, β_B and β_T respectively, as shown in Figure 4.4.

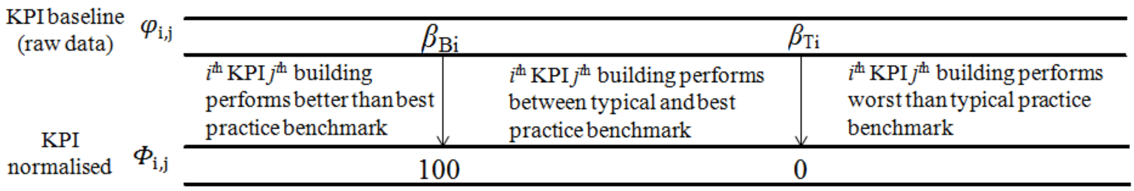


Figure 4.4 Prototype of the Decision Support Tool interface where the KPIs' significance need to be selected.

If there are "*m*" buildings and "*n*" KPIs, the normalised value for the i^{th} KPI of the j^{th} building, $\Phi_{i,j}$, was calculated from the difference between the i^{th} KPI of the j^{th} building and the i^{th} KPI typical practice benchmark, β_{Ti}, divided by the difference between the β_{Ti} and β_{Bi}, via the following equation:

$$\Phi_{i,j} = \frac{(\varphi_{i,j} - \beta_{Ti})}{(\beta_{Bi} - \beta_{Ti})} \tag{4.1}$$

A negative normalised value, i.e. $\Phi_{i,j} < 0$, indicated that $\varphi_{i,j}$ for the i^{th} KPI and j^{th} building, was worse than the typical benchmark, β_{Ti} whilst a normalised value $\Phi_{i,j} > 100$ indicated that this j^{th} building performed better than the best practice benchmark, β_{Bi} for the i^{th} KPI. If $0 < \Phi_{i,j} < 100$ then the j^{th} building for the i^{th} KPI performed between the β_{Ti}, and β_{Bi}. If $\Phi_{i,j}=0$, then the performance of the j^{th} building for the i^{th} KPI was exactly β_{Ti}.

Then, the overall objective weighting for the j^{th} building considering all the *n* different KPIs together for *m* different buildings and *n* different KPIs is defined as:

$$\varpi_j = \frac{\sum_i^n \Phi_{i,j}}{n} \tag{4.2}$$

As an illustrative example, let us assume a given KPI was an energy performance indicator, a typical benchmark for that KPI could be $\beta_{Tenergy\ consumption}$= 180kWh/m^2, the best practice benchmark could be $\beta_{Benergy\ cosnumption}$= 60kWh/m^2 and the baseline value for a Building "j" was $\varphi_{energy\ consumption,\ building\ j}$=195 kWh/m^2, then the normalised KPI value would have been calculated as follows with Eq. 4.1:

$$\Phi_{energy\ consumption,\ building\ j} = \frac{(\varphi_{i,j} - \beta_{Ti})}{(\beta_{Bi} - \beta_{Ti})} = \frac{100*(195-180)}{60-180} = -12.5 \tag{4.3}$$

If the water consumption KPI, for j^{th} building is $\varphi_{\text{energy consumption, building j}}$ =1.31kL/m^2 and $\beta_{\text{Twater consumption}}$= 0.97 kL/m^2, $\beta_{\text{Bwater consumption}}$= 0.43 kL/m^2 then the normalised KPI is $\Phi_{\text{water consumption, Building j}}$ = -62.7. Applying Eq. 4.2 the overall objective weighting factor for the j^{th} building is then:

$$\varpi_j = \frac{\sum_i^n \Phi_{i,j}}{n} = \frac{-62.7-12.5}{2} = -37.6 \qquad (4.4)$$

Therefore, the results of the overall objective weight when combining water and energy consumption for the j^{th} building were -37.6. This means that the combined performance is below the typical benchmark.

Subjective Weighting Factors

The level of significance attributed to each KPI by the decision maker is accounted using subjective weighting factors, classified from "not important" to "critically important" (Zardari *et al*. 2014). These rating were translated to a numerical scale (0 to 2) as shown in Table 4.3.

The significance of a KPI could change depending on who is making the decision and the aims of the assessment, so ideally the framework should be incorporated into a tool that can recalculate the significance of the KPIs if the objectives of the portfolio assessment vary. A prototype of an interface for the decision support framework is depicted in Figure 4.5 and shows how the decision maker can choose the importance of a KPI via the interface of the decision support tool.

Table 4.3 KPI subjective significance and quantitative scores for subjective weighting factors.

KPI Significance	Subjective Weight, ψ
Critically important	2
Very important	1.5
Important	1
Fairly unimportant	0.5
Not important	0

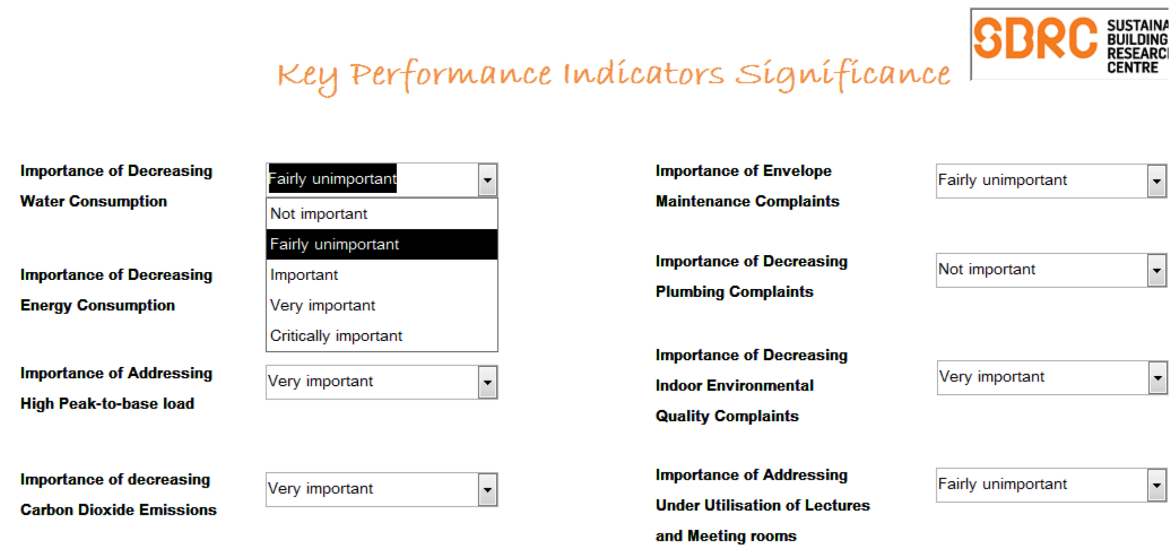


Figure 4.5 Prototype of the Decision Support Tool interface where the KPIs' significance need to be selected.

Determining the Default Subjective Weighting

There are instances where decision makers might not select the objectives weights, in which case two options are available; they either decide to rely solely on the objective weighting or they could include the significance of the KPIs extracted from the experts' interviews. Nevertheless, if the default weighting is used then the significance of KPIs becomes aligned with the interests of the interviewees, which might differ from the interest of the current decision maker.

Determining the Integrated Weighting

After determining the subjective and objective weights for all KPIs, the aggregate weighting factor ω could then be calculated by multiplying $\Phi_{i,j}$ by the normalised KPI value by the normalised subjective weight. ω_{ij} is defined as follows:

$$\omega_{i,j} = \sum_0^n \frac{\psi_i \, \Phi_{i,j}}{\sum_0^n \psi_i} \qquad (4.5)$$

The aggregated weighting factor determines how crucial the j^{th} building is for the i^{th} KPI to be considered for refurbishment.

4.5 Summary

This chapter has described the development of a framework to characterise higher education facilities via Key Performance Indicators (KPIs). A weighting scheme that includes subjective and objective weighting factors for the KPIs has been proposed.

Subjective weighting underlines the importance of each KPI according to the views of decision makers, whereas objective weightings are based on the normalised data for KPIs and buildings. The weighting scheme enables KPIs to be compared and forms the basis for the decision support framework designed to assist higher education facility management teams in characterising their building portfolios. The next chapter validates this decision support framework using the University of Wollongong (UOW) as a case study to demonstrate its efficacy and utility.

5. Portfolio Characterisation and Decision Support Framework - A Case Study

This chapter describes how the framework developed in Chapter 4 was applied to University of Wollongong (UOW) main campus building portfolio as a case study to exemplify the university precinct characterisation process. This portfolio of building characteristics was first mapped using Key Performance Indicators (KPIs), the correlations between KPIs and space use characteristics were investigated, and then the decision support framework was implemented through the application of the integrated weighting scheme to KPIs for energy performance and overall building performance.

5.1 Overview of Building Portfolio Case Study

At the time of writing the main campus at UOW had a total of 71 buildings. Of these a number were not included in the present case study including: sixteen (16) buildings were demountables, one was used to store gas, one was a substation building, four were used for university accommodation, one was a coffee kiosk, two others were dedicated to control access to the campus by motor vehicles, one building was still under construction and another was in the process of being demolished. The remaining 44 buildings from the main campus were considered in this portfolio assessment. (It should be noted that depending on the KPI and the information available at the building level granularity, the number of buildings for each KPI analysis varies).

The UOW building stock is diverse because the dates of construction vary from the early 1960s up to the present day and the usable floor areas (UFAs) range from 274 m^2 to 12,129 m^2, with an average UFA of 2,750 m^2. The total UFA of the stock considered in this study was approximately 144,500 m^2. This value is slightly below the mean UFA of Australian universities, 180,000 m^2, and more than four times bigger than the minimum UFA of Australian universities (TEFMA 2011) . An aerial photograph of the UOW main campus is shown in Figure 5.1.

Figure 5.1 An aerial view of the University of Wollongong campus from Google maps (Map data ©2015 Google, Wollongong).

5.2 Experimental Equipment

The KPI baseline values for each building were calculated based on data collected experimentally. The types and periods of measurements are summarised in Table 5.1. University of Wollongong has utility metering and management system installed across the main and innovation campuses. The monitored consumption of electricity, gas and water are wireless fed daily to the University's Data and Analytics Self-service Hub (DASH) portal, which provides the means for accessing the data. The DASH portal can be accessed online with a special permission; a sample screen shot of the DASH interface portal for hourly electricity consumption reporting is presented in Figure 5.2.

The Heating, Ventilation and Air-Conditioning (HVAC) energy consumption was assessed on buildings where HVAC sub-metering was conducted (DASH portal). Unsolicited complaints were collected from the BEIMS maintenance reporting and tracking system (BEIMS 1989). This included complaints about the building fabric maintenance, performance of building facilities, i.e. HVAC, plumbing and lighting maintenance complaints, health and comfort performance (i.e. indoor environmental quality and thermal comfort issues). The temperature related hazards were obtained from the reported incidences to the WHS department. Space utilisation was obtained from the space survey results. Number of non-compliance issues, back-log maintenance

value and year due for major capital investment was acquired from the condition appraisal report conducted to all buildings.

Table 5.1 Description of University of Wollongong monitored KPIs.

Parameter	Measurement type	Sample rate	Duration	Measurement equipment	Accuracy
Energy	Energy consumption	Hourly	3 years (2012-2014)	Electricity meter *Secure Sprint*	Class 1.0 (IEC 62053-21 2003)
	Gas consumption	Hourly	3 years (2012-2014)	Gas meters *Roots Solid State Pulsar*	Accuracy Curve for Model 11C145
Water	Water consumption	Hourly	1 year (2013)	Water meter water meter V100(PSM-T)	Minimum flow rate: ±5% Transitional flow rate: ±5%
Unsolicited complaints	Complain log	Whenever occupants placed a complaint	1 year (2012)	Online reporting	
WHS	WHS officer	Whenever occupants experienced a hazard	1 year (2013)	WHS officer reporting	
Energy Signature	HVAC consumption versus outdoor air temperature	Daily	2 years (2012-2013)	Electricity meter and onsite weather station	
Space Utilisation	Room frequency x room occupancy		2 weeks (2013)	Visual inspection	
Non compliance	Condition appraisal report	N/A	1 day per bldg (2009)	Visual inspection	
Back-log maintenance					
Due for major capital investment					

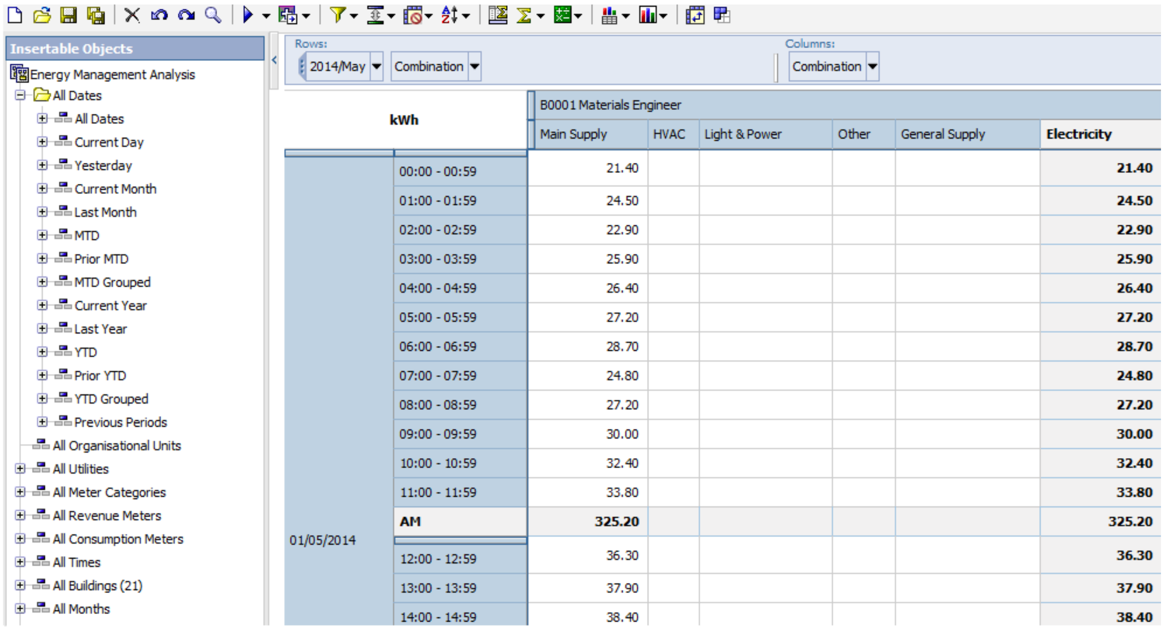


Figure 5.2 Screen shot of the electricity consumption reporting in the DASH portal.

Whilst acquiring all the aforementioned data, its quality was assessed based on its consistency and completeness. A dataset was considered to be incomplete when 5% or more values were missing and therefore it was not used. This percentage was selected since, according to Schafer (1999), a missing rate of 5% or less has negligible consequences in a dataset analysis. The data corresponding to productivity was not provided due to the sensitive nature of the information and difficulty in evaluating this parameter.

5.3 Results of the Building Portfolio Characterisation

The analysis and results of the UOW main campus building portfolio characterisation are presented herein. Firstly, the types of spaces on campus are shown, followed by the comparison between buildings KPI baseline and KPIs normalised performance values.

Historical values are shown whenever data was available and complete, and were used to identify anomalies or scope for potential interventions.

5.3.1 Campus Space Characteristics

A wide range of ways could be found to characterise non-domestic building stock (Liddiard 2012), including higher education buildings where there are several built forms, activities, and modes of operation (Amaratunga & Baldry 2000a).

This section classifies the types of spaces in the UOW main campus building stock. This classification was used in *§5.3* to identify the relationship between KPIs and space-

use characteristics of the buildings. The space usage presented in Figure 5.3 is the percentage of space type area normalised by the total area of building stock studied. Spaces in the UOW main campus consisted of naturally ventilated and HVAC serviced wet laboratories, dry laboratories, workshops and studios, teaching spaces, offices, computer laboratories, gym, library, tenancy (i.e. a few retail shops and cafés), common spaces including collaborative spaces, lobbies, tea or kitchen spaces, and other space categorisations, which included circulation spaces, toilets, plant rooms, and storage rooms (Appendix B has a table with the building name and characteristics).

The results showed that approximately half of the areas studied were conditioned. Most spaces in the UOW campus were offices. The remaining spaces consisted mostly the library, HVAC-serviced common spaces, dry and wet laboratories, computer laboratories and teaching spaces. The next section overviews each KPI individually. (Typical benchmarks used were previously described in *§4.4.2* Table 4.1).

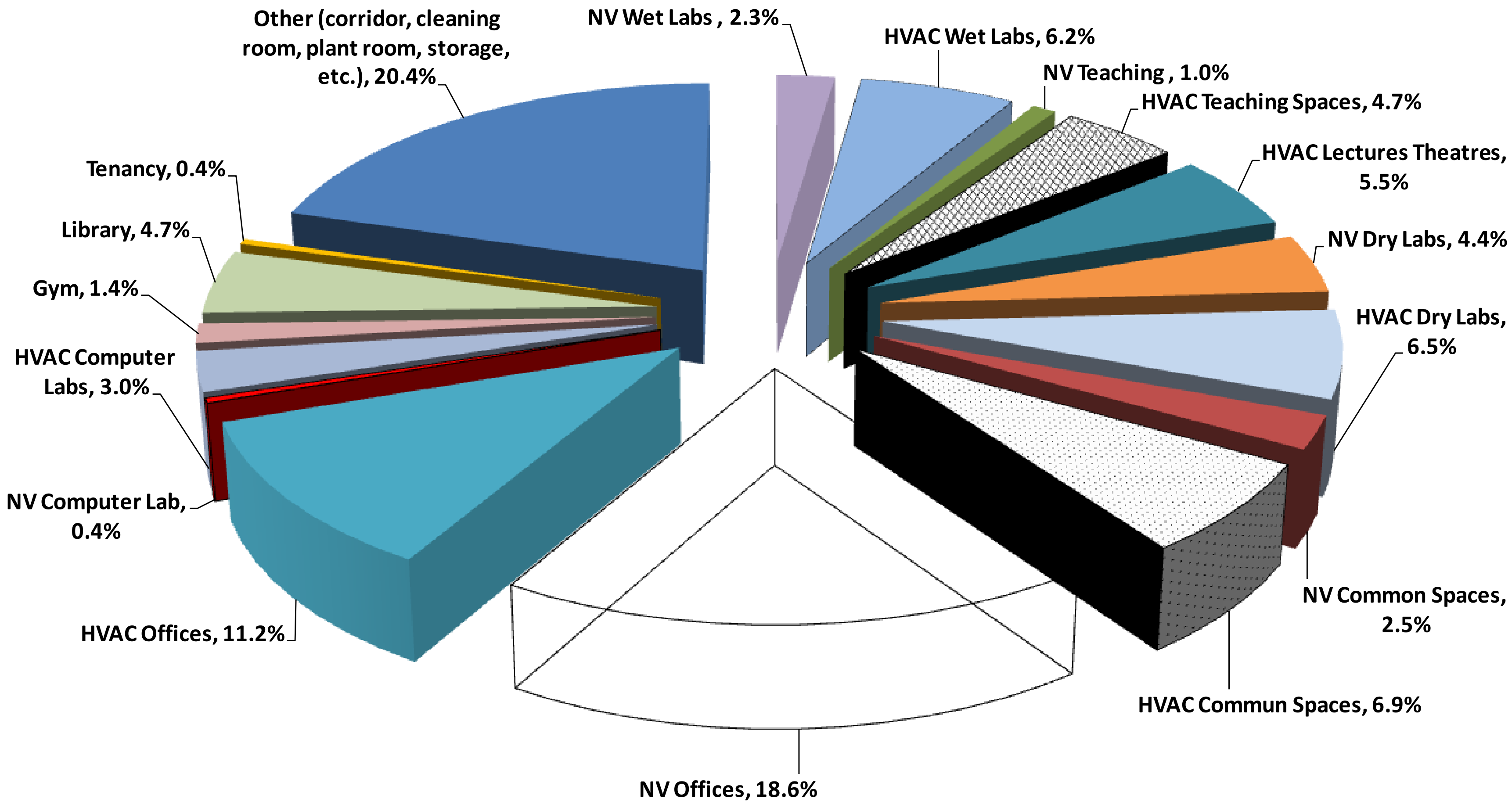


Figure 5.3 Percentage of different space typologies at UOW.

5.3.2 Energy Performance KPI

The energy performance was characterised by the annual variable intensity, i.e. electricity consumption per usable floor area (UFA), gas consumption per UFA, HVAC consumption per UFA and the difference between peak-to-average electricity demand ratio. It should be noted that the sub-monitored HVAC systems at UOW are electric HVAC. The electricity consumption also included the HVAC consumption (as it is electrical consumption), but the HVAC was just the electric HVAC consumption.

Electricity Consumption

A total of 36 buildings from the UOW main campus were included in the electricity consumption analysis (some buildings without electrical meters were not included). Seven (7) buildings from Innovation Campus (iC) were also studied, i.e. buildings numbered 200, 230, 231, 232, 233, 234 and 235.

The buildings were ranked from the highest to the lowest user of electricity for year 2014. A mixture of conditioned and unconditioned spaces was indicated by *M*, when at least 70% of the spaces were conditioned was denoted by *C*, while *U* indicates that at least 70% of the spaces in the building were unconditioned. Typical consumption benchmarks for electricity consumption have been taken from the Tertiary Education Facilities Management Association (TEFMA) and Commercial Building Baseline Study (CBBS). These values corresponded to annual consumptions of 211 kWh/m^2 and 168 kWh/m^2, respectively. These values were then divided by the average electricity consumption at UOW in 2014 (178.3 kWh/m^2) to give an indication of their performance compared to the portfolio studied.

Historical energy consumption trends revealed that all the highest consuming buildings above the TEFMA benchmark were conditioned (C) or mixed spaces (M), as shown in Figure 5.4, where a missing data point in the Figure implies there was insufficient data to calculate the yearly consumption. Laboratories spaces were in almost all buildings that have electricity consumptions above TEFMA benchmarks. On the other hand, the lowest consuming buildings were largely unconditioned office spaces.

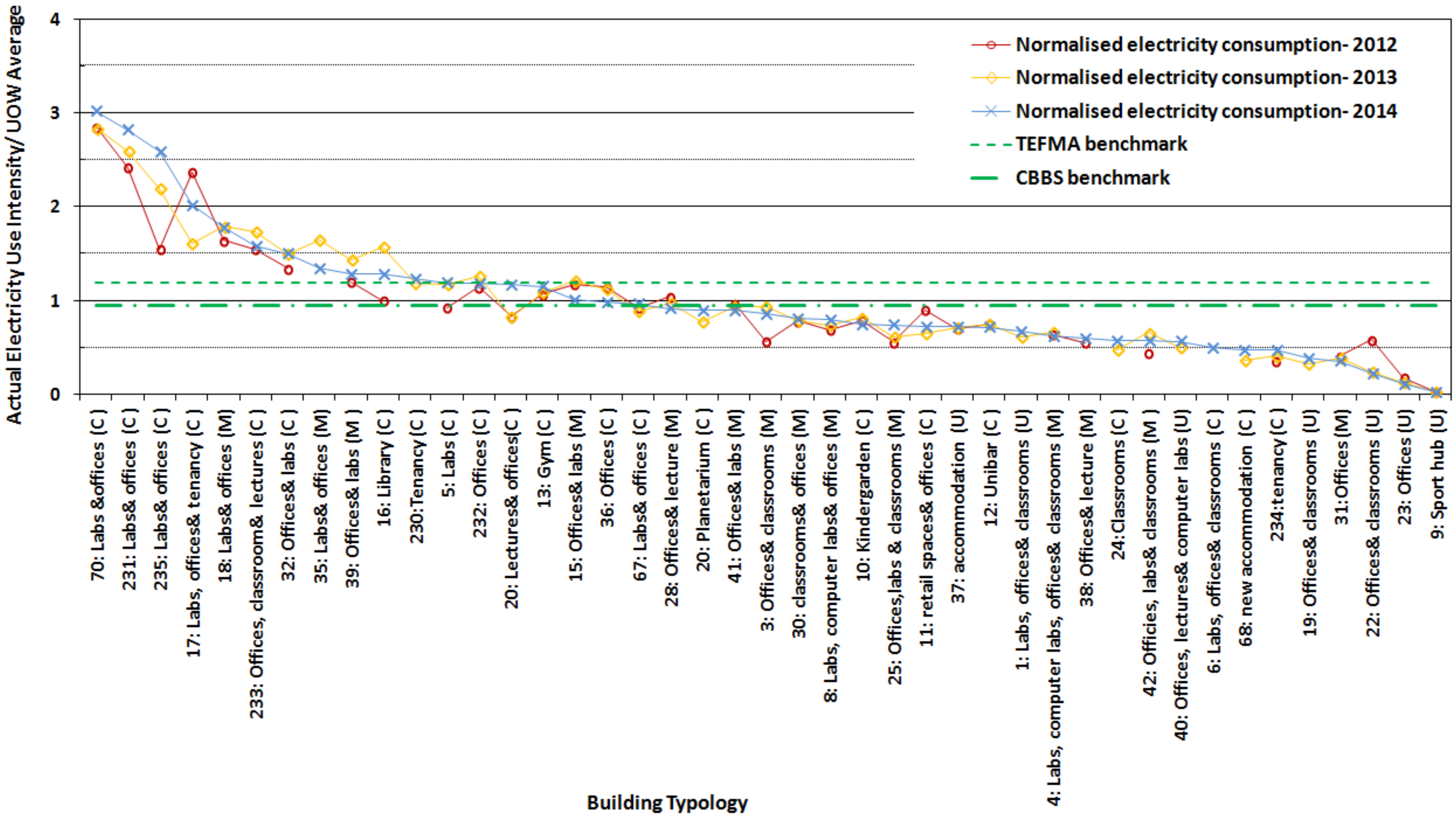


Figure 5.4 Electricity intensity for each building for 2012, 2013 and 2014 normalised against the average for all the studied buildings at the University of Wollongong.

Building 70 had the highest energy intensity, almost three times larger than the average UOW consumption and CBBS benchmark, and more than double the TEFMA benchmark. This high use of energy in Building 70 was attributed to a laboratory running constantly with the HVAC system continually bringing fresh air inside the facilities. The second- and third-highest electricity consumers were located at iC; both had a high base load, indicating that some equipment was running all night, e.g. lighting and/or experiments in the laboratories. In contrast, Building 9, which was a non-conditioned sports hub, consumed the minimum amount of electricity per square metre, probably due to the relatively low load associated with the sparse use of lighting.

Analysis of the historical trends revealed that the five highest building consumers from 2012 were still on top in 2014, indeed their consumption of electricity had progressively increased from 2012. The only exception was Building 17 which showed a decrease in 2012, probably because it was vacant for several months. The two highest consumers from the Innovation Campus (Buildings 235 and 231) experienced the highest rise electricity consumption over the 2 year period, probably due to increased activity in their laboratories.

Gas Consumption

The gas intensity normalised by the total average gas consumption at UOW is shown in Figure 5.5. Only a limited number of UOW buildings used gas, and gas meters were only installed in 13 buildings at the time of writing, and since two meters were not in working order data from only 11 meters was used in the analysis described below.

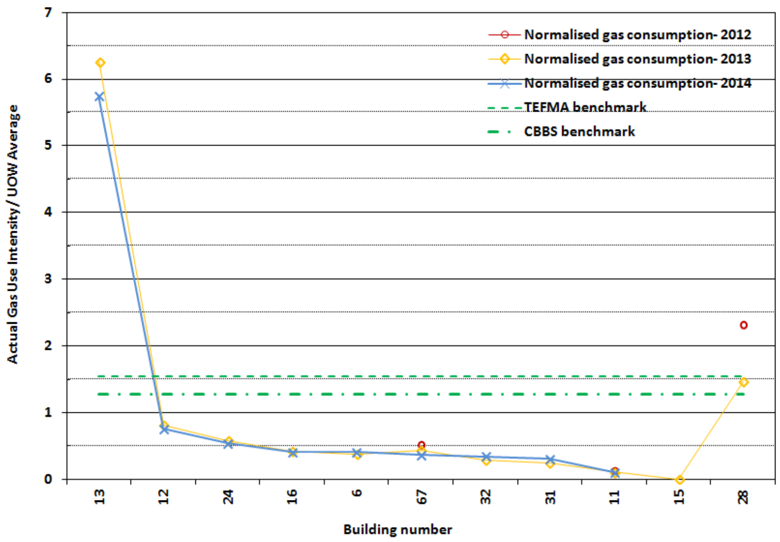


Figure 5.5 Normalised gas intensity for each building for 2012, 2013 and 2014.

The typical benchmark for gas consumption was obtained from TEFMA as an annual consumption of 84.48 kWh/m^2. This value was normalised by dividing by the average gas consumption at UOW in 2014 (54.94 kWh/m^2).

All buildings (except for Building 13) were relatively low consumers of gas as compared to electricity. That is the annual gas consumption ranged from 5.7 kWh/m^2 to 42 kWh/m^2 except for Building 13, the University Recreation and Aquatic Centre, which reached 315 kWh/m^2. This value was almost six times more than the average UOW gas consumption and almost four times the TEFMA typical benchmark due to gas being used to heat the outdoor swimming pool all year round. Similar consumption trend was shown through the past three years.

HVAC Consumption

The HVAC assessment is presented as the annual HVAC consumption intensity divided by the average HVAC consumption for UOW, 53.89 kWh/m^2 (Figure 5.6). There were a limited number of UOW buildings with HVAC sub-metering. Here the benchmark was from the Green Star Education v1 (GBCA 2009) extracted as an average of space types, i.e. offices, laboratories and teaching spaces, which corresponded to a consumption of 33.20 kWh/m^2 annually.

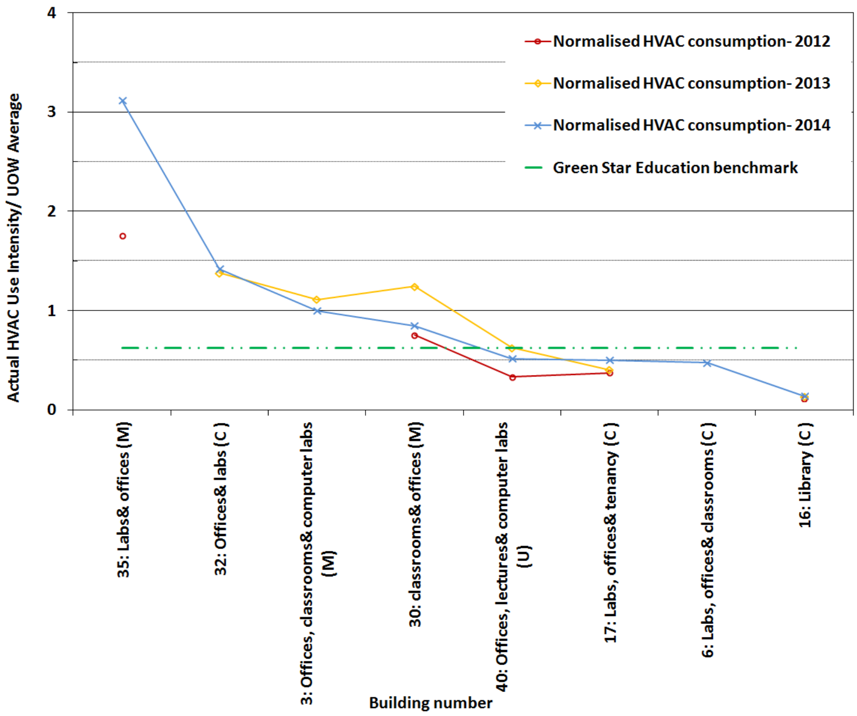


Figure 5.6 Normalised HVAC intensity for each building for 2012, 2013 and 2014. A missing mark implies there was insufficient data to calculate the yearly HVAC consumption.

The buildings were ordered from the highest HVAC user to the lowest HVAC consumer during 2014. Approximately 50% of the buildings showed an HVAC consumption that was higher than the benchmark, while Building 35, which contains a mixture of laboratories, offices, and a lecture theatre, had an HVAC consumption of almost three times the UOW average.

The historical HVAC consumption trends showed slight variations between years, except for Building 35 where, during 2014, its HVAC consumption increased due to the implementation of HVAC in the building, i.e. there were more conditioned spaces than in 2012.

Peak-to-Average Demand Ratio

Peak and average difference energy demand was assessed using the ratio between peak and average demand. Figure 5.7 shows that buildings with high peak-to-average demand ratios typically had somewhat lower average load intensities.

As an example, the creative arts, performance space and gallery building, Building 25, shows a 72% difference between average daily peak demand and overall average demand due to the high usage of facilities at certain points during the day, e.g. recording equipment and a number of conditioned spaces, reaching a high peak, whereas at night almost every device is off. However, buildings 235, 18 and 232, which are buildings with a mixture of laboratories and offices, had the lowest peak-to-average demand ratio whilst their average demand was approximately twice the average demand intensity. This might indicate that those buildings have some equipment or internal loads running all day. Knowing which buildings have a high peak demand ratio can aid in identifying issues in the buildings such as malfunctioning of the equipment or exploring the possibility of onsite generation.

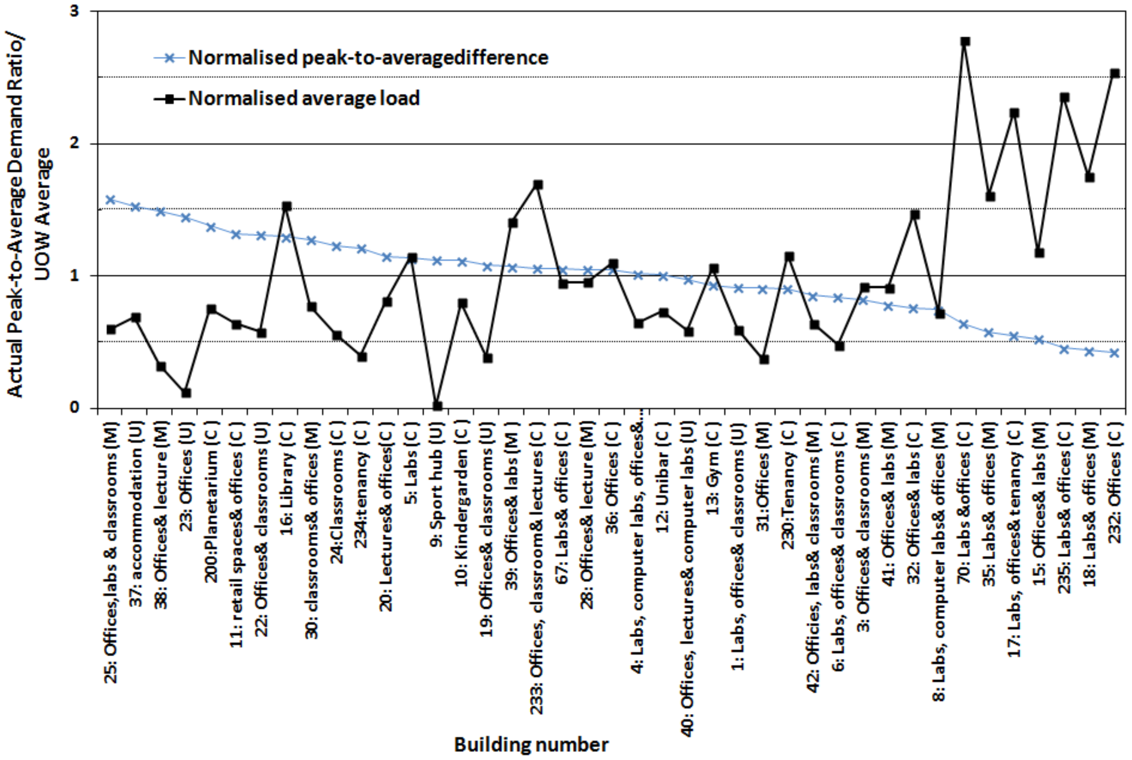


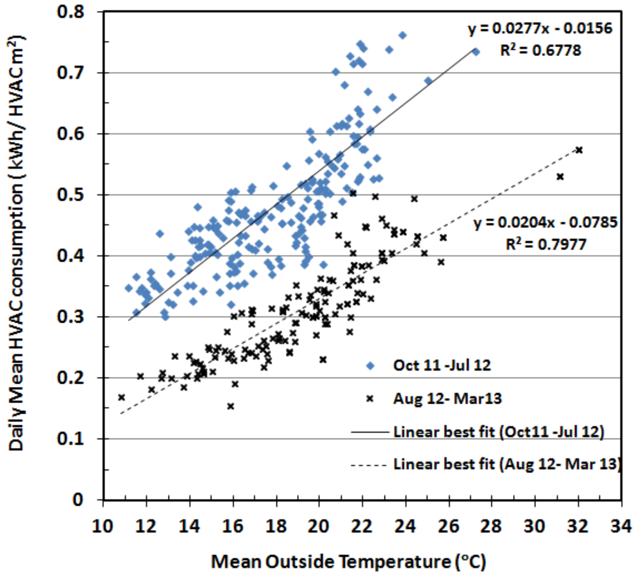
Figure 5.7 Peak-to-average load ratio and average load intensity normalised against the average for all studied buildings at the University of Wollongong.

Energy Signature Method

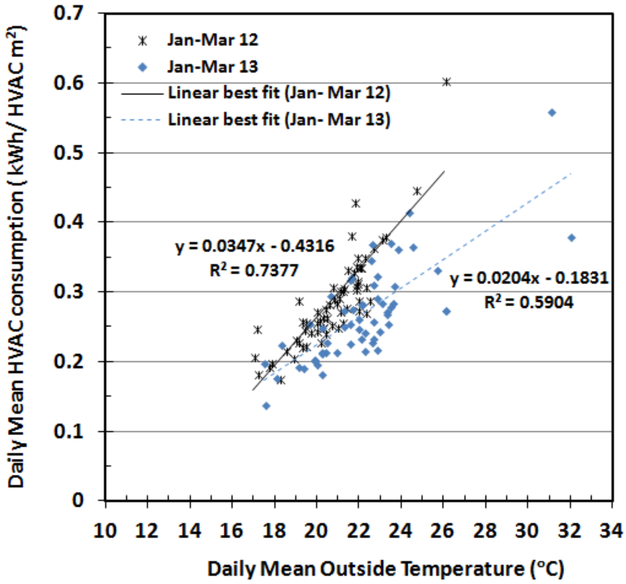
The Energy Signature (ES) method is a way of identifying the effects of previous interventions and upgrades to improve energy efficiency while accounting for variations in the weather. This was used to assess the hourly HVAC consumption for UOW buildings with HVAC energy consumption sub-metering. Eleven buildings at the main campus had HVAC sub-metering, so they were the ones considered in this section.

The value of ES as a diagnostic tool is illustrated in Figures 5.8 to 5.10, where each data point represents the daily HVAC energy consumption for the average hourly outside temperature for that particular day. A 24-hour average was used so that the dynamic effects of the building are less important (Hammarsten 1987).

The ES plots of Figure 5.8 show the HVAC consumption for two buildings at two different time periods, and demonstrates the effect of an intervention. In this case the results of recommissioning the Building Management System (BMS) (Figure 5.8a) and a voltage reduction (Figure 5.8b) are presented.



(a)



(b)

Figure 5.8 Energy Signature method used to evaluate two interventions in two different buildings: a) rectifying the control system, and b) voltage reduction.

Figure 5.8a shows that the ES gradient two different time periods was almost identical but shifted vertically. There was a consistent decrease in the daily HVAC consumption between October 2011–July 2012 and August 2012-March 2013. This difference was attributed to a malfunction in the building control system, i.e. the HVAC system of the building was operating for 24 hours. This was noticed and subsequently rectified, with the HVAC system turned off overnight. The associated ES showed a clear improvement, i.e. a decrease in HVAC consumption.

Figure 5.8b shows the effectiveness of dropping the voltage at the building substation by 4.5% in late December 2012. Note that overall consumption decreased during the

summer of 2012 and 2013, despite both years having similar outdoor temperatures, and more warmer days in 2013. The slope of the linear regression for 2013 (0.0204) compared to 2012 (0.0347) was lower, indicating that the demand for cooling was less.

Variations in building performance at different time periods are shown in Figure 5.9, and indicate that the demand for cooling from February to May was higher than from November to January because in the latter period the building had fewer occupants, i.e. it was university session break. However, the building has two large lecture theatres that corresponded to 6% of the total floor area, while the remainder of the building was laboratories and offices for staff undertaking research activities. Hence, the decrease in HVAC consumption during a session break period could be attributed to laboratories shutting down during this time.

The HVAC consumption normalised by the total HVAC area of the building for summer 2012 and summer 2013 is shown in Figure 5.10. Both periods had a similar trend but then shifted by approximately 0.03kWh/m^2-of-conditioned-space. HVAC consumption in summer 2013 was higher than summer 2012, probably because HVAC was running for longer times than in 2012. Similar tendencies, but opposite values (from higher consumption to lower), can be seen in Figure 5.8a for rectifying the air-conditioning system running for 24 hours/day. In that case an intervention was implemented, whereas here an HVAC malfunction was identified.

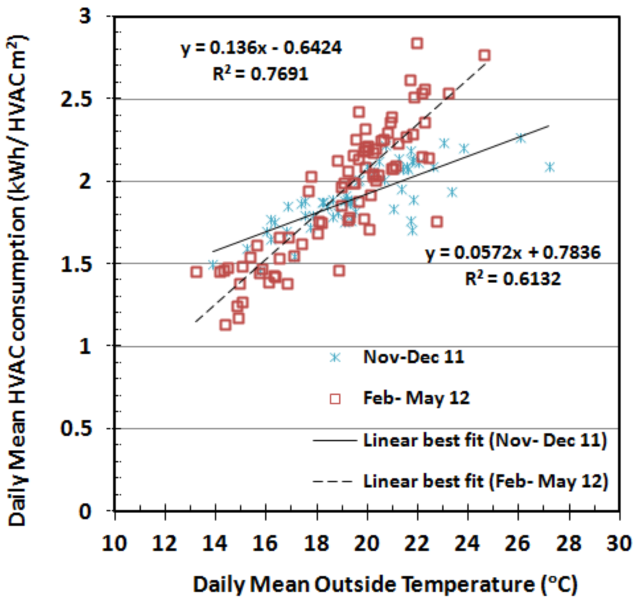


Figure 5.9 ES method to assess the HVAC consumption in different periods during and out of session during summer.

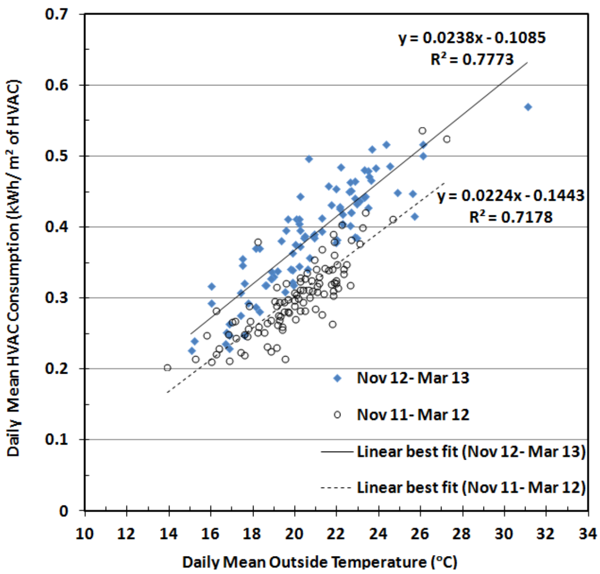


Figure 5.10 Energy Signature method used to assess HVAC consumption during two consecutive summers (2012 and 2013) for Building.

The ES method also enabled the physical parameters of buildings to be identified:

- Base load air-conditioning consumption, as a measure of minimum air-conditioning energy consumption when the building is unoccupied.
- Cooling slope, measuring the looseness of the building, i.e. a poorly insulated building envelope or excessive outside air through ventilation or infiltration and air-conditioning efficiency.
- Reference change-point temperature, reflecting the value of the air-conditioning system temperature set-point.

ES was then used to determine the 'cooling slope' (CS) of the building, where CS is defined as the gradient of the increase in the energy use as a function of daily average outdoor temperature. It was derived from Eq. 5.1 and it comes from a steady state energy balance, its derivation can be found in Kissock and Mulqueen (2008):

$$E_{HVAC} = E_0 + CS(T_o - T_{cp}) \tag{5.1}$$

$$CS = \frac{(\Sigma U_j A_j + V\rho_a C_p)}{\eta} \tag{5.2}$$

Where E_o is the HVAC base load consumption independent of the weather (kW/m^2), T_o is the outdoor air temperature (°C), T_{cp} is the cooling change-point temperature (°C), CS is the cooling slope (W/m^{2}K), U_j is the overall heat transfer coefficient (W/m^{2}K), A_j is the area of each exposed surface (m^2), V is the volume flow rate of air entering the building (m^3/s), ρ_a is the density of air (kg/m^3), C_p is the heat capacity of the air

(kJ/kgK), and η is the efficiency (or Coefficient of Performance) of the air-conditioning system. Cooling coefficients and air-conditioning base load for buildings with HVAC sub-metering are shown in Table 5.2 for summer 2013.

Table 5.2 Buildings' cooling coefficient and air-conditioning base load.

Building	Cooling Slope (W/m^2K)	Air-conditioning Base Load (W/m^2)
35	2.4	25
24	1.31	4.17
3	1.13	8.33
15	0.97	10.3
28	0.85	7.5
40	0.69	4.58
6	0.28	3.33

Buildings 35 and 24 had the highest cooling slope, indicating poor air-conditioning efficiency, a poorly insulated building envelope and/or high infiltration/ventilation (e.g. a leaky building and/or windows being opened by occupants when the cooling system was running). Building 6 on the other hand had the lowest cooling slope and the minimum air-conditioning base load; it is one of the newest buildings on campus and thus its construction had to comply with the current Building Code of Australia (BCA). Moreover, the windows in this 'mixed-mode' building were automatically opened, and the occupants can not open them while the air-conditioning is on.

5.3.3 Water Performance KPI

KPI water performance was evaluated through annual water intensity normalised by the UOW average (Figure 5.11). Since not all buildings had a water meter, 16 buildings were considered for the KPI water performance. The TEFMA and Sydney Water typical office benchmark were used to show typical water consumption in offices at university, excluding laboratories.

Although definitive historical data was not available, the UOW water savings action plan (WSAP) (Miller & Hazelton 2014) stated that almost 203,000 kL of water was saved in 2013 compared to the previous year at a campus level. This was approximately equal to the water intensity consumed by the building with the third highest water usage. However, there were three buildings above the TEFMA benchmark which should be further investigated. Building 1 and 5 have 20% and 57% UFA as laboratory spaces, whereas Building 12 and 10 correspond to the Uni Bar and Kids Uni, respectively.

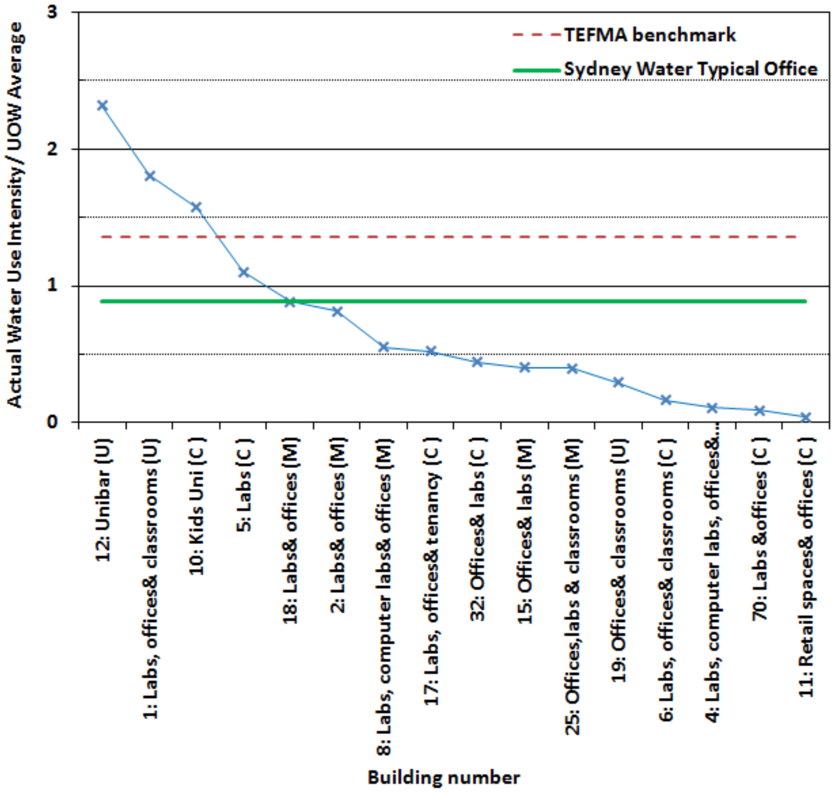


Figure 5.11 Normalised water intensity for each building.

5.3.4 Building Envelope and Facilities Performance KPI

Unsolicited maintenance complaints intensity related to envelope, HVAC and plumbing and hydraulics are shown in Figure 5.12. The intensity of unsolicited complaints is defined as the number of complaints received per UFA. Then this value is normalised by the UOW average of each complaint.

Unsolicited building envelope complaints were incorporated into any complaint concerning maintenance of the building fabric. This was categorised as ceilings, flooring, internal and external walls, internal and external doors, fabric, screen windows and windows, roof and coverings maintenance jobs requested by building users.

Unsolicited HVAC maintenance complaints corresponded to occupants' complaints on HVAC malfunctions, repairs, and corrective maintenance while complaints about plumbing maintenance are defined as complaints involving any repair work related to hydraulics such as toilets, water tanks and pumps, cisterns, sinks, etc.

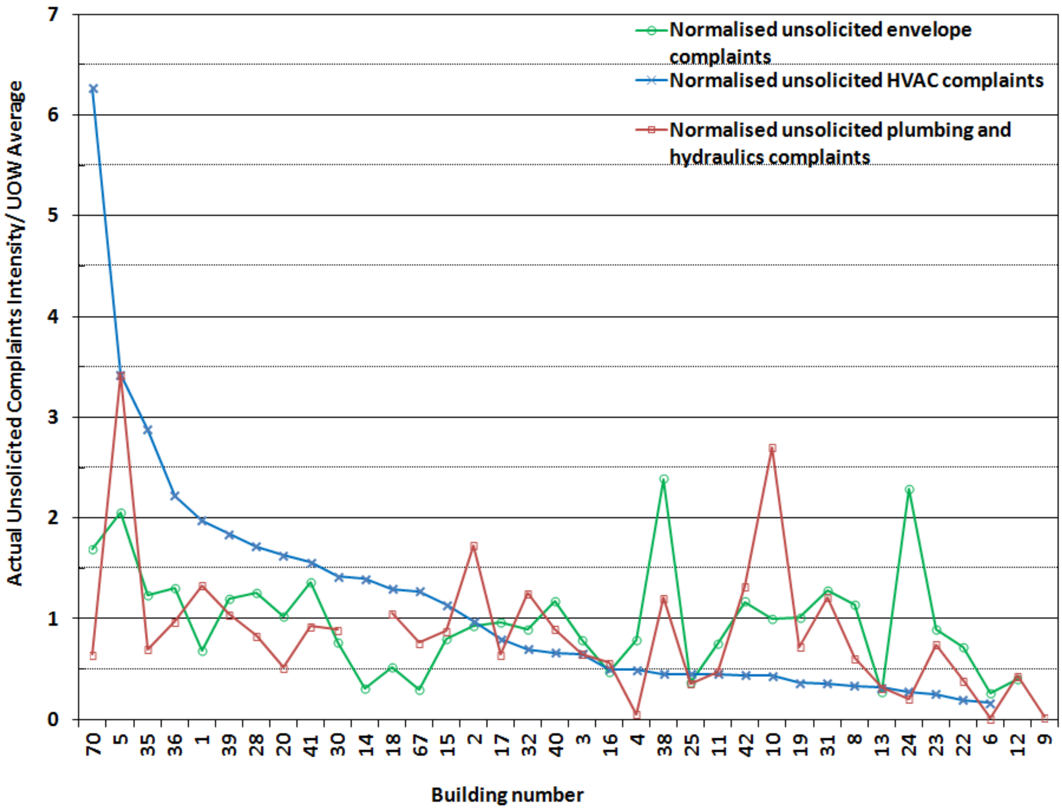


Figure 5.12 Normalised unsolicited envelope, HVAC and plumbing maintenance complaints intensity for each building.

HVAC maintenance complaints have a similar trend as envelope complaints where the top four buildings can be found in both figures. Buildings 70 and 5 are laboratories with 100% and 50% of their respective areas conditioned. They must have HVAC operating constantly at certain temperatures ranges for 24 hours, so it is critical that HVAC functions correctly and any fault is reported promptly. Building 35 is the biology building with around 30% of its space being conditioned laboratories. The labs in Building 35 also require controlled HVAC conditions, so any malfunctions are reported punctually. As mentioned before in the building envelope, Building 36 is due for capital investment and therefore its HVAC also needs an upgrade.

The fume cupboards are included in HVAC maintenance, which is why Building 1 appears in the top five of the graph. Although its conditioned area is only 15% of the total area, more than 50% of the spaces are laboratories that include fume cupboards which trigger most maintenance complaints.

Likewise, the lowest number of complaints was for the newest building of those considered in this study. The second lowest was the psychology building, where

approximately half the building is conditioned with relatively new HVAC (2004) and most spaces are office where no precise temperature control is required.

The highest value of envelope maintenance complaints corresponded to Building 38, which consists of lecture theatres, classrooms, administration offices and student enquires. The condition appraisal report of this particular building shows that in 2016 the building was due for capital investment to refurbish the fabric, so it was expected to encounter a large number of unsolicited maintenance complaints from its occupants regarding the condition of the fabric. Building 6 is on the other end of the graph, and it has the lowest envelope complaint number, but it is the newest building in the UOW portfolio, being constructed at the end of 2010.

The worst performing buildings in relation to plumbing complaints per square metre are Buildings 5 and 10. Both have a mixture of block pipes leaking, toilet cisterns, pipes or/and boiler. Building 10 is the Kids Uni, where facilities such as toilets and kitchen are constantly being used, so any underperform is notorious and must be reported.

The lowest plumbing complaints are for Buildings 6 and 14. Building 14 is a single lecture theatre, without any plumbing infrastructure, whereas Building 6 is relatively new.

Backlog Maintenance

The cost of backlog maintenance is defined here as planned maintenance work costs that will be scheduled. The values obtained from the backlog maintenance costs were extracted from the UOW condition appraisal reports. The highest backlog maintenance corresponded to a building (Building 22) where a non-compliant lift was replaced. Building 20 also needed to address a compliance issue with disability access. Both buildings had approximately seven and two point five times higher backlog maintenance than the UOW average, respectively. The sports Hub and Library have the lowest backlog maintenance costs allocated because the functionality spaces in the library were recently upgraded (2010) and the sports hub has no non-compliance issues.

5.3.5 KPI: Space Management

Spaces within higher education facilities are the most expensive asset owned (Abdullah *et al*. 2012) and expenses associated with space are the second highest cost after staff salaries (Ibrahim *et al*. 2012). Therefore, universities should be functioning in an efficient way to enable the best use of resources in terms of space. Nevertheless,

numerous higher education institutions are dealing with space management problems such as the low utilisation rate of teaching spaces (Abdullah *et al*. 2012). A space management analysis was conducted for UOW based on building space utilisation as defined by TEFMA Space Guidelines (TEFMA 2009). The space utilisation information is shown in Figure 5.13. To measure the space utilisation on campus, a series of room audits were conducted to evaluate the number of students and staff using the facilities at different times over one week each semester (TEFMA 2009). The spaces considered in the analysis included computer laboratories, laboratories, workshops, studios, lecture theatres, meeting rooms, classrooms, library and food outlets, i.e. the uni bar.

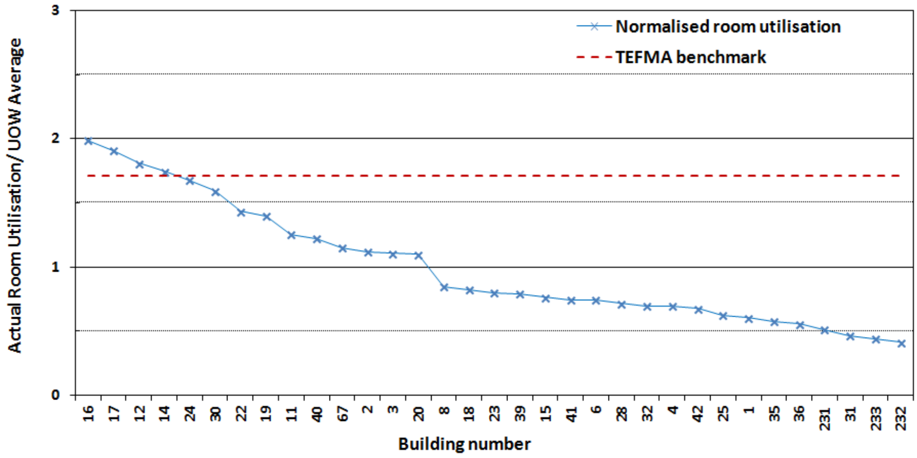


Figure 5.13 Normalised room utilisation for each building.

The buildings with the highest rate of space utilisation were Building 16 (library spaces), Building 17 (IT Resources Centre), and Building 12 (Uni bar) and Building 14 (lecture theatre). These high occupation rates are not surprising because the library and IT resources centre provide shared and common study rooms, and have most of the shared computer laboratories on campus. In contrast, the buildings presenting the lowest utilisation rate are buildings located at the innovation campus, i.e. Buildings 231, 232 and 233. Most of these spaces are laboratories that have equipment that runs autonomously, i.e. often remotely controlled, and require minimal supervision by their users. Moreover, one of the buildings, despite having a low space utilisation (i.e. Building 231 corresponds to Australian Institute of Innovative Materials, AIIM) has one of the highest energy consumptions recorded on campus. While, this correlation requires further investigation, it is suspected that the laboratories operate 24 hours a day without needing occupants to supervise the experiments.

The overall space utilisation average of UOW is 17.5%, which is almost 40% lower than the TEFMA space utilisation average. Proposed solutions to increase space utilisation could be by introducing new modes of teaching and learning in universities such as implementing outcome-based education (Abdullah *et al*. 2012) or implementing a space charging model (Ibrahim *et al*. 2011). This approach introduces costs on the space of a building that is not fully utilised.

5.4 Building Space Characteristics and KPI Relationships

Efficient use of space is essential to the operation of modern universities, and research is needed to understand the connections between space type and institutional effectiveness (Temple 2008). In a university context, space and learning are connected, so improvements in spaces can potentially result in learning benefits. Therefore, this section aims to investigate the connection between KPIs and types of space utilization/function, and KPIs interrelationship. The investigation was conducted using IBM® SPSS® Statistics Version 21.

The initial analysis involved the visual exploration of the data through 'scatter dot' plots. Building space typologies (i.e. laboratories, common spaces, classrooms, offices and lecture theatres) are plotted with KPIs in Figure 5.14. Visual inspection of plots such as this allowed the qualitative identification of variables with strong statistical relationships. Pairs of variables with strong interrelationships are indicated in Figure 5.14 by highlighted circles and include the following:

- Conditioned HVAC spaces with laboratories, electricity intensity, and total of common spaces.
- Offices with intensity of envelope complaints
- Laboratories with intensity of comfort complaints, the year when the building is due for capital works and the intensity of the plumbing complaints.
- Computer Laboratories with the average room utilisation.
- Total common spaces with electricity intensity, intensity of complaints, intensity of envelope complaints and average room utilisation.
- Electricity intensity with conditioned space, total common spaces, intensity of complaints and building age.
- Intensity of complaints with total common spaces.
- Comfort complaints with envelope complaints and year due for capital works.

- Year due for capital works with the laboratories spaces.
- Water intensity with the intensity of plumbing complaints.
- Building Age with the intensity of envelope complaints.

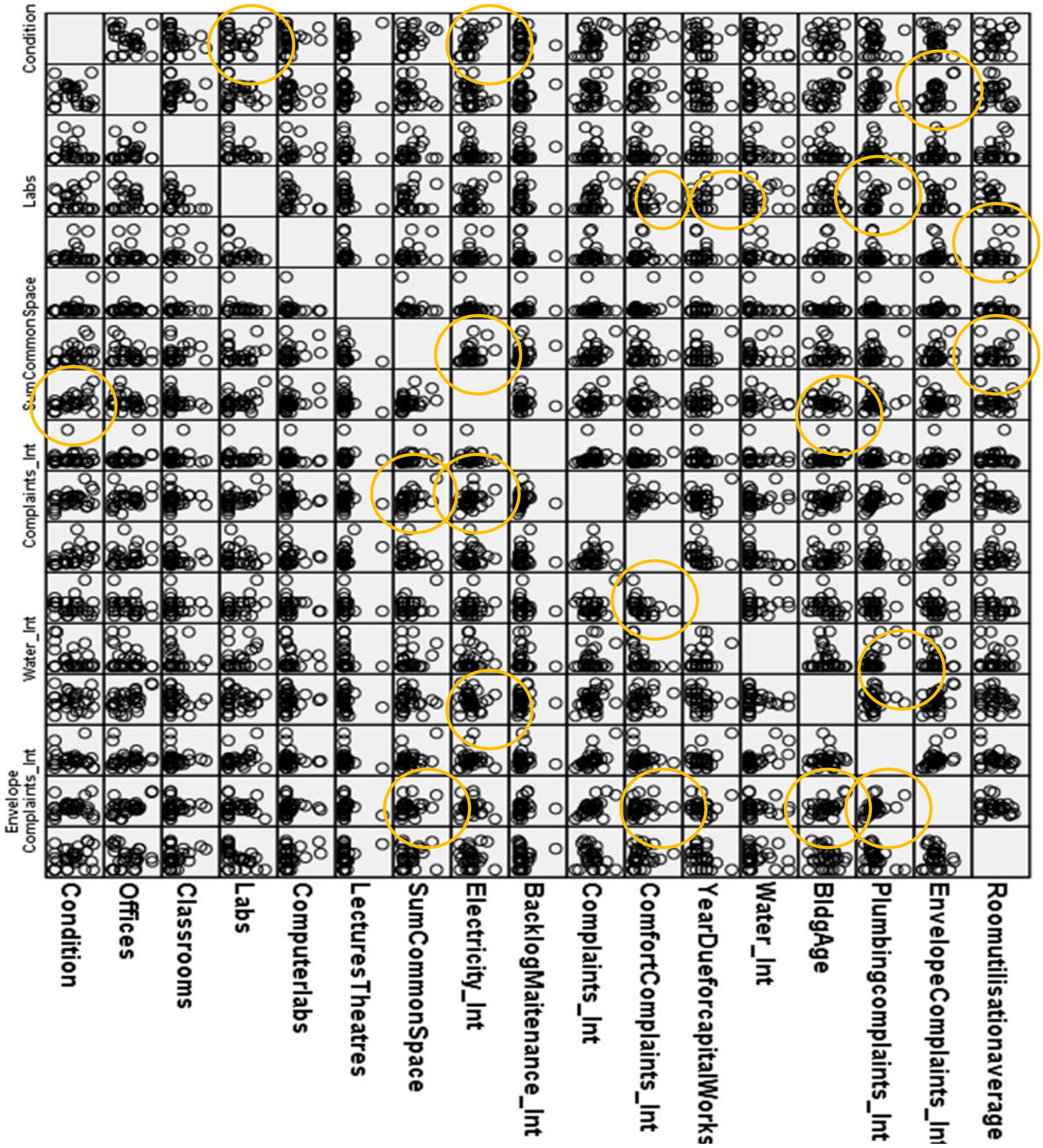


Figure 5.14 Matrix scatter plot of space typology and KPIs; which was used to explore interrelationships within the data.

Thereafter, these variables were further investigated for correlations using other tools. Correlations using Pearson test should be conducted if the data is linear (Field 2013). Then, to establish if the correlation was significant, normality in the data is required. If normality test failed, then a transformation in the data, e.g. logarithm (log), natural logarithm (ln), inverse (inv) or square root (sqrt) need to be performed. In case the data could not be normalised, then Spearman's correlation test was applied, which only

assumes a monotonic relationship in the data. The results presented in the next section only show the statistically significant correlations, i.e. where $p < 0.05$, between variables where a relationship could be found from Figure 5.14. Spaces such as gyms, libraries or tenancies were excluded because of the limited number of buildings with these type of spaces in the sample.

5.4.1 Relationship Between KPIs and Building Space Typology

The correlations between KPIs and building space typology are shown in Table 5.3. Due to not being able to normalise the typology data through different transformations, the non-parametric test, i.e. Spearman correlation, where normality in the data is not necessary, was conducted. The strength of the Spearman correlation is given by ρ.

It was observed that electricity intensity was correlated with space type such that there was a positive relationship with conditioned spaces (ρ=0.38), i.e. that buildings with a higher proportion of conditioned floor area had higher electricity consumption. Also, a building with more common spaces (e.g. atrium, shared meeting rooms, tea facilities or learning spaces) tend to use more electricity as shown in the positive, though moderate, correlation ($\rho = 0.35$). This might be attributed to equipment and internal loads such as lighting running all day.

Another relationship was found between room utilisation and space type, so buildings with a higher proportion of laboratories tended to have lower space utilisation rates, as the moderately negative relationship indicates ($\rho = -0.51$). Furthermore, laboratories showed a positive relationship with base load intensity ($\rho = 0.4$), which indicated that despite the fact that buildings with a higher proportion of laboratories are less utilised, the equipment or/and lighting in these spaces is most probably running all day, since the base load of laboratories tends to be higher.

Table 5.3 Statistically significant correlations between KPIs and space typology using Spearman's correlation.

Variable		Conditioned Space (%)	Labs (%)	Classrooms (%)	Computer Labs (%)	Common Spaces (%)	Offices (%)
Electricity Intensity(kWh/m^2)	ρ	0.38				0.36	
	n	36				36	
Base Load Intensity (kWh/m^2)	ρ		0.4				
	n		34				
HVAC Consumption Intensity (kWh/m^2)	ρ				0.53		
	n				35		
Complaints Intensity (number/m^2)	ρ					0.37	
	n					36	
Room Utilisation Average (%)	ρ		-0.51				
	n		36				
Comfort Complaints (number/m^2)	ρ	0.46					
	n	34					
Age (years)	ρ						0.34
	n						36

5.4.2 KPI Interrelationships

The connection between different building characteristics was investigated in this section. The correlations between KPIs are shown in Table 5.4. The HVAC maintenance complaint rate had a statistically significant correlation with the rates of electricity and HVAC consumption. The correlation between the HVAC maintenance complaint rate and energy consumption was moderately positive (ρ = 0.42), which indicated that a building with a high HVAC maintenance complaint rate will be inclined to have high energy consumption, whilst strong relationship with the HVAC consumption (ρ = 0.87) implied that higher rate of conditioned spaces tend to have higher complaints on HVAC maintenance. This is an indication of the importance of including unsolicited complaints to understand the performance of the building, as it might indicate that a malfunction of the HVAC is leading to high energy usage.

Similarly, there was a correlation between HVAC maintenance complaints with envelope complaints (ρ = 0.48), plumbing complaints (ρ = 0.5) and thermal comfort (ρ = 0.45) was moderately positive which means that typically when the HVAC complaints rate is high, a high rate of envelope, plumbing and thermal comfort complaints is expected and vice versa. This could be attributed to the fact that the occupants that choose to complain do so in more than one aspect.

Table 5.4 Statistical significant correlations between KPIs using Spearman's correlation.

Variables		Electricity Intensity (kWh/m²)	HVAC Consumption Intensity (kWh/m²)	Envelope Complaints Intensity (number/ m²)	Plumbing Complaints Intensity (number/ m²)	Comfort Complaints Intensity (number/ m²)	Age (number/ m²)
Complaints Intensity (number/ m²)	ρ	0.40					
	n	36					
Comfort Complaints Intensity (number/ m²)	ρ		0.7				
	n		9				
HVAC Complaints Intensity (number/ m²)	ρ	0.42	0.87	0.48	0.5	0.45	
	n	36	9	38	31	34	
Envelope Complaints Intensity (number/ m²)	ρ				0.48		0.34
	n				36		36
Room Utilisation Average (%)	ρ						
	n						
Due for Capital Works (years)	ρ			-0.56		-0.56	-0.48
	n			31		31	33

The age of a building showed a statistically significant relationship with the degree to which the building was due for major refurbishment (i.e. due for capital works), and the intensity of the envelope and thermal comfort complaints. A moderately negative (ρ = -0.48) correlation between age and the date when capital works were due indicates that older buildings are due for capital work before newer buildings. The moderately negative correlation between the envelope and thermal comfort complaints intensity indicated that newer buildings tend to have a lower rate of occupant complaints, and therefore older buildings are expected to require more maintenance than newer buildings.

5.5 Decision Support Framework Results

The weighting scheme introduced in §*4.4.3* was used to analyse UOW building portfolio. The results of this analysis are outlined in detail in this section. One of the

goals was to incorporate the framework into a decision support tool. The outputs provided by the decision support tool were as follows:

- Individual KPI baseline values for a particular building. This enabled the major issues in a building to be understood.
- Normalised baseline value for each KPI for all buildings. That allowed for provision of a list of building performance rankings which in turn, provided a building prioritisation ranking.

The building portfolio prioritisation list that considers the KPI Energy Performance is outlined, and then an overall building performance assessment with all the KPIs is presented.

5.5.1 Energy Performance

The performance of building for the KPI "Energy Consumption" is shown in Table 5.5. The table includes the building name, its annual energy consumption, the difference between peak-to-average demand, and the normalised performance value calculated through Eq. 5.1. In this case, the resultant priority list through the ranking considered electricity consumption and peak-to-average demand ratio. The method followed is described in *§4.4.3* Eq. 4.1 and Eq. 4.5. In this case, it was considered that peak-to-average demand ratio was very important ($\psi_{\text{peak-to-average demand ratio}}$ =1.5) while electricity consumption was important ($\psi_{\text{electricity consumtpion}}$=1).

Table 5.5 shows the worst 10 building, all of which had negative scores, meaning that those buildings had an energy performance that was worse than that considered as 'typical practice'. As described in *§4.4.2* Table 4.1, typical practice refers to the TEFMA benchmark for electricity consumption, i.e. 211 kWh/m^2 and best practice benchmark corresponds to the Green Star benchmark, i.e. 68.6 kWh/m^2. In the peak-to-average demand ratio, the typical practice benchmark was 0.4 and the best practice benchmark was 0.2 (as determined from Green Buildings Council of Australia, GBCA).

On the Energy Intensity KPI, half of the buildings investigated would be judged as significantly worse than typical practice, with energy intensities of 400kWh/m^2 and higher. In reality, only five buildings met the best practice level. Similarly, just one building met best practice on the peak-to-average demand ratio KPI. The lowest normalised energy performance value (shown in Building 70) was 26 times lower than the mean of the portfolio for this KPI

Table 5.5 Prioritisation list for electricity and peak-to-average demand ratio, where φ is the baseline value, Φ is the normalised value of the indicator and □□is the aggregate weight.

Rank	**Building**	$\varphi_{\text{electricity consumption}}$	$\Phi_{\text{electricity consumption}}$	$\varphi_{\text{peak-to-average demand ratio}}$	$\Phi_{\text{peak-to-average demand ratio}}$	$\omega_{\text{energy performance}}$
1	70	522.2	-218.5	0.29	54.0	-78.2
2	16	313.2	-71.8	0.59	-95.4	-58.0
3	231	465.4	-178.7	0.19	103.4	-47.0
4	235	457.6	-173.2	0.21	96.4	-46.7
5	233	312.6	-71.3	0.48	-41.3	-42.4
6	17	406.5	-137.3	0.25	75.2	-37.3
7	28	262.2	-36.0	0.48	-38.6	-26.5
8	39	255.6	-31.3	0.49	-44.0	-26.0
9	37	128.6	57.9	0.70	-148.4	-17.6
10	25	109.9	71.0	0.72	-160.3	-15.4

5.5.2 Overall Building Performance

After examining the values of all the aforementioned KPIs, the normalised value for each building Φ_j was obtained. In this example, for simplicity the subjective weighting was assumed the same across all KPIs, whereas typically it was expected to vary in each case depending on stakeholder needs and priorities. Table 5.6 shows the priority list of overall performance value, averaging all KPIs for the worst 15 buildings. The KPIs considered here were energy performance (electricity consumption and peak-to-average demand ratio), water consumption, complaints performance (comfort complaints, envelope complaints, plumbing and HVAC maintenance complains), Work, Health and Safety (WHS) hazards related with temperature and space utilisation. They included ranking, building name and performance value calculated following *§4.4.2* Eq. 4.6.

Table 5.6 Prioritisation list for all KPI

Rank	Building	Aggregated Weighting, ω
1	18	-208.2
2	41	-181.3
3	5	-107.7
4	20	-106.7
5	42	-97.8
6	36	-94.9
7	28	-77.8
8	39	-76.3
9	37	-70.6
10	2	-67.6
11	35	-62.3
12	10	-61.4
13	30	-61.4
14	4	-55.1
15	1	-47.9

Table 5.7 provides information available for UOW Main Campus buildings with respect to when they were due for capital investment and/or replacement, i.e. significant work with an expenditure above $30,000 within two years of the time of writing, and the anticipated nature of the works, as recommended in the Building Condition Appraisal Reports. The buildings that showed the worst overall performance (Table 5.6) were typically scheduled for capital works in the following year (Table 5.7), e.g. Building 18, 41, 20, 31 and 36.

Table 5.7 Building year due for capital investment and type of replacement for the next three years

Building number	Year due for capital investment	Type of capital investment/replacement
20	2014	Office Level 1 refurbish/Lecture theatre refurbish
11		Office spaces (west) and HVAC refurbish
36		HVAC and electrical upgrades
39		Security system and fire system upgrades
22		Upper level refurbish/Lower level refurbish
4		staff offices, circulation spaces and electrical distribution upgrades/ refurbish research student offices and teaching spaces
2		HVAC upgrades
41		offices and corridors upgrades
17	2015	HVAC upgrades & student central and ground floor upgrades
16		Lighting upgrades/ Roof upgrades
14		Lecture theatre sittings and finishes and lighting control upgrades
67		Office refurbishment/ HVAC upgrades
19		Upgrade security
3		HVAC upgrades
40		HVAC upgrades/ lighting upgrades
10	2016	bathroom and HVAC upgrades
18		HVAC upgrade, i.e. replace fume cupboards and lab finishes
25		spaces upgrades (teaching rooms, lecture theatres, performance theatre and music rooms)/offices upgrades
28		Offices and teaching spaces upgrades
36		Fabric (walls, ceiling and tiles) upgrades
23		Ground level upgrades

This procedure facilitated the comparison of the buildings performance across different KPIs. It was possible to examine the performance of a particular building further. This was demonstrated via the results obtained from the in-depth audits, modelling, and retrofit identification outlined in the next chapters.

5.6 Summary

This chapter has outlined how the proposed building portfolio characterisation process and decision support framework was applied to the University of Wollongong building stock portfolio as a case study.

Relationships between space typologies and KPIs were investigated. Laboratories were found to be the space type with the highest energy consumption, whilst buildings with naturally ventilated offices demonstrated lower energy consumption compared to other spaces. The building performance for each KPI and the probable reasons for any high and low performance were investigated and then, the correlations between the different KPIs were examined. Results indicated that recently constructed buildings tended to have less complaints recorded than older buildings, but those buildings due for capital investment/work were more likely to have higher occupant’s complaints. Therefore, a larger budget should be allocated to maintenance of older buildings.

The framework proposed provided a normalised baseline performance for each KPI and building, and allowed each building to be ranked on the value of the KPI. This combination through the objective weighting of KPIs for each building resulted in a ranked list of UOW buildings for upgrading.

Once a building has been selected for upgrading, the next step was to conduct a comprehensive audit to understand how the building performs across a broad range of attributes, which, in turn, will reveal the detailed building characteristics and help to identify an optimal retrofit strategy. The methodology for determining the best retrofit strategy is explained in the next chapter.

6. Building Retrofit Optimisation Methodology

6.1 Introduction

This chapter describes the methodology used to identify optimal retrofit strategies to be implemented on individual university buildings. It is divided into two major parts as shown in Figure 6.1.

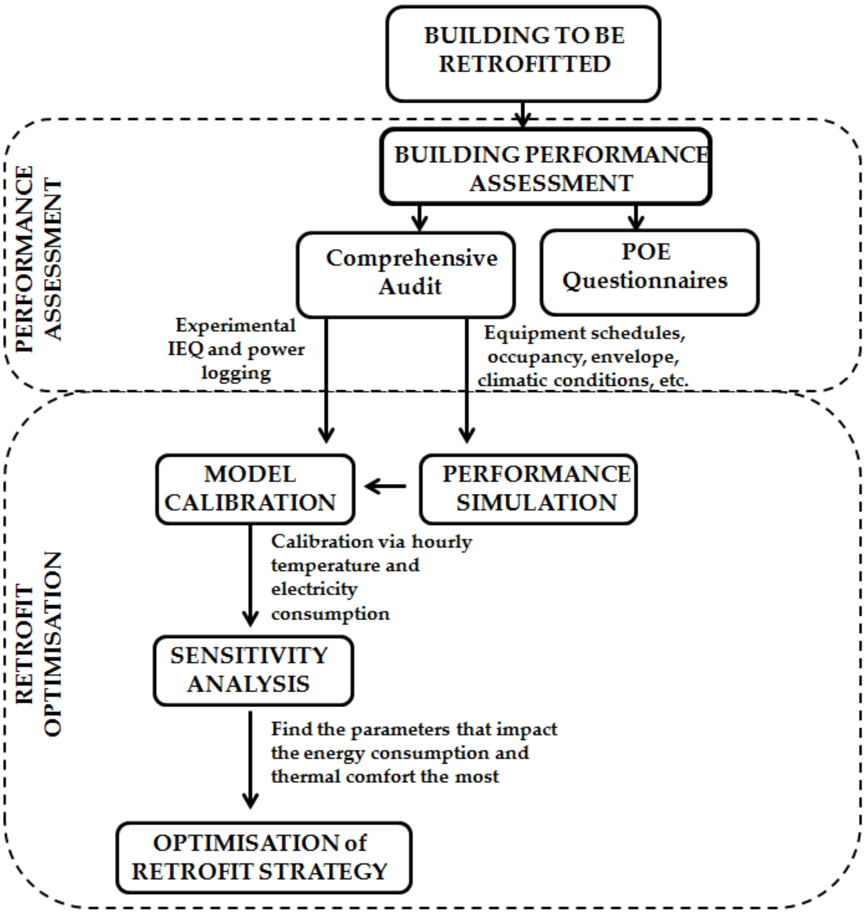


Figure 6.1 Process schematic to find an optimal retrofit strategy.

The method involves:

- Building Performance Assessment. Experimental techniques are used to evaluate building performance, revealing how data is collected through a comprehensive audit and survey of occupant perceptions via a Post Occupancy Evaluation (POE).
- Retrofit Optimisation. Entails simulating a building to create a calibrated model and then performing a sensitivity analysis to reveal the most significant parameters affecting energy consumption and thermal comfort. Those

parameters and their associated costs in retrofitting are then used to define an 'objective function', which is then minimised to provide optimal values of the parameters of interest.

The following sections outline the methodology used for assessing building performance and developing the building simulations.

6.2 Building Performance Assessment

Before identifying any upgrades for an existing building, its baseline must be determined to understand its behaviour and to identify those areas that need improvement. This means investigating the current condition, performance, utilisation and occupant perceptions and attitudes towards a building. This investigation can be undertaken through a comprehensive sustainability audit and a Post Occupancy Evaluation (POE) questionnaire. The designer/project manager can then focus at the specific problem area level, instead of at the whole building level, and thus the retrofits are treated via a more manageable, practical, and efficient process. The other aim of the audit is to collect the data needed to calibrate a building energy simulation model. This data consists of onsite monitored weather conditions, building characteristics, indoor temperatures and power consumption that will help in a detailed calibration of the building model. The procedure adopted in the present study is illustrated in Figure 6.2.

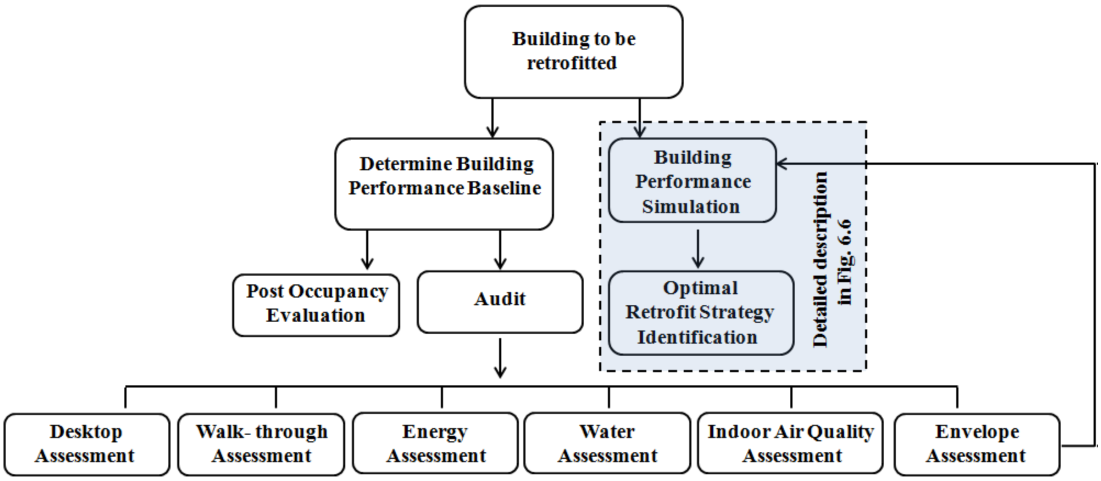


Figure 6.2 Flow chart illustrating the building performance assessment process.

The methodology developed for the building audit and post occupancy evaluation of the present study is described in the subsequent sections.

6.2.1 Comprehensive Building Audit Methodology

To the best of the author's knowledge, audit method guidelines targeting higher education buildings are usually focussed only on a few parameters such as their physical condition, utilisation of facilities or an energy assessment (Kaiser 1993). However, these parameters are too restrictive to facilitate holistic retrofit decisions for achieving a liveable university building, so apart from assessing the operational energy or condition of the building, the planned steps also include the health, well-being and education of the occupants and an investigation of the building envelope performance.

To evaluate the building performance it was proposed that the assessment include:

- A desktop assessment;
- A walk-through audit;
- An energy, water and Indoor Environmental Quality (IEQ) assessment; and
- An envelope performance assessment.

The desktop assessment was to be carried out before conducting a walk-through audit. This involved collecting all relevant existing information available on the building, such as floor plans, construction materials or building databases from the Building Management System; this information then assisted in preparation for the walk-through. The following features were to be captured in the walk-through audit via field observation:

- Occupant density, including the types and schedules for each space;
- Existing HVAC or portable heaters, their type, capacity, and current condition;
- Lighting nameplate power and the number of lights;
- Types of electronic equipment, including their nameplate power and number;
- Photograph typical spaces, e.g. offices, atria etc, and various features of the building.

This information is the basis on which to develop a monitoring plan and serve as inputs for a detailed building model. The monitoring plan determines the spaces to be measured and the length of the measurements. All the façades should be captured as well as all the room types. For instance, if classrooms, lecture theatres, laboratories, and offices are present in the building, then at least one of each should be included in the monitoring. In case different space types are located in different façades, they must also be monitored. Energy, water and IEQ, specifically the temperature and humidity are to

be measured by following the Performance Measurement Protocols for Commercial Buildings (PMP) (ASHRAE 2010). This means trying to achieve advanced performance methods where the highest level of granularity, i.e. hourly data sampling is required, as a minimum. This is because the collected data has a twofold objective; on the one hand, the overall performance of the building can be assessed, but on the other, the temperature and energy consumption data is used to calibrate the detailed model

Energy Assessment

Electricity consumption is to be monitored for the whole-building with electricity metering equipment. Major breakouts of end uses of energy are to be sub-monitored. The accuracy of the sensors need to ensure to meet the objectives of the assessment, and therefore an accuracy of 2% of the reading is necessary (Kenneth et al. 2007).

Indoor Environmental Quality Assessment

IEQ assessment is to be conducted through spot check measurements of IAQ, namely CO_2, CO and Total Volatile Compounds (TVC), illuminance and weighted sound pressure level (dBA) to selected spaces determined in the monitor plan.

Envelope Assessment

<u>Thermal Imaging</u>

Thermal imaging facilitates a qualitative assessment of the thermal characteristics of the building envelope, and allows the identification of missing insulation, roof leaks, cold/hot spots or heat/cool spills (Turner & Doty 2007). It has also been claimed that thermal imaging can be used to estimate the heat transfer coefficient and U-value of the building envelope, and that this method is very quick compared to its counterpart in a field survey, i.e. a heat flow meter (Dall'O *et al*. 2013).

Firstly, the heat flux, ϕ_f (W/m^2) between two spaces separated by a wall can be calculated, assuming steady state heat transfer, as a function of the heat transfer coefficient of the wall U_w (W/m^{2}K), and the difference between internal temperature of the space T_{in} and external temperature T_o :

$$\phi_f = U_w(T_{in} - T_o) \quad (6.1)$$

The heat flux can also be calculated with the external heat transfer coefficient h_s, the external surface temperature of the wall T_s, and the external temperature, T_0:

$$\phi = h_s(T_s - T_o) \quad (6.2)$$

Then, by combining both equations, the heat transfer coefficient of the wall can be found:

$$U_w = \frac{h_s(T_s - T_o)}{(T_{in} - T_o)} \quad (6.3)$$

Therefore, if the surface of the wall is derived from a thermal map, the indoor and outdoor temperatures are measured and the internal convective heat transfer coefficient is known/calculated, it is then possible to estimate U_w.

The external heat transfer coefficient h_s (W/m^{2}K) was calculated using Jurges equation (Albatici & Tonelli 2010), and it included the wind velocity, v :

$$h_s = 5.8 + 3.8054v \ (v < 5 \text{ m/s}) \quad (6.4)$$

The U-value was estimated as an indicative result to support all the other experimental measurements that assessed the building fabric performance, i.e. a quantitative assessment by temperature logging and an air permeability test, and a qualitative assessment via thermo-graphic images. Typical equipment used to take thermal images is shown in Figure 6.3.

Figure 6.3 Typical thermal imaging camera.

Air Permeability Test

Infiltration has an important effect on HVAC system energy use and it might compromise indoor air quality in some circumstances. Air leakage through the building envelope may be measured via a blower door test, following ISO 9972:2006 (2006) . A typical blower door test set-up, as used in this study, is illustrated in Figure 6.4.

Figure 6.4 The author's blower door test set-up conducted in a case study building.

Physical onsite monitoring and spot check measurements were completed with the occupant questionnaires, as described in the following section.

6.2.2 Post Occupancy Evaluation (POE) Surveys

The POE surveys provided qualitative and quantitative feedback from building occupants, including subjective ratings of perceived satisfaction of: a) measures of the occupant well-being, such as health, safety, comfort or productivity; b) perceived building advantages/character like space, design or work area arrangements; c) building management such as cleanliness, response to complaints from facilities management, or individual environmental control.

Building Use Studies (BUS) (2012) was the existing POE chosen for use in the present study. As determined in *§2.5.2*, the circumstances and goals of the project normally dictate which POE is used. The rational for choosing the BUS method was that it is one of the most well established POE surveys, which database contains Australian higher education institutions for benchmarking purposes. In addition, it can aid FM improving the overall quality of their portfolio through measuring building performance

particularly in relation to end users' productivity and satisfaction. As an example, estimating how the occupants' productivity at work is decrease or increased by the environmental conditions of the building conditions was asked. This, in turn, enabled to evaluate one element of the practical existing building performance, which related to the author of this thesis research questions.

The building audit and POE aided in: understanding the current building performance; determining the building performance baseline for comparison against other benchmarks; and identifying the underperforming spaces. The subsequent steps involved modelling a building to assess the impact of different parameters on building performance, particularly on thermal comfort and energy consumption. The following section reveals the approach undertaken for this building simulation technique.

6.3 Building Retrofit Optimisation Methodology

Buildings are complex socio-physical systems, and computer simulations tools are needed so that they can evaluate the impact of different retrofits and their interactions more efficiently, comprehensively, and accurately than other available methods (Kaplan & Caner 1992). The building physics simulation engine used in this thesis was EnergyPlus (EnergyPlus 2014). EnergyPlus is the U.S. Department of Energy's dynamic building energy simulation engine for modelling building energy flows. The choice of EnergyPlus was driven by its widespread usage, as it is the most accepted simulation software in the world (Xu *et al*. 2012) and because it covered all the required analysis types anticipated in the present study.

The process to achieve the best retrofit strategy through building simulation is shown schematically in Figure 6.5, and is divided into three main steps.

- Building model set-up and calibration. This entailed using the technical and occupancy data collected in the audit to develop the building model. The experimental temperatures and power consumption were then compared to the output predicted by the model for calibration.
- Local sensitivity analysis. Each parameter of interest from a subset of the building model inputs was varied between constrained minimum and maximum values. The key parameters with the highest effect on the energy consumption and thermal comfort were selected as the decision variables for potential retrofitting.

- Optimisation. An objective function was defined as a function of the decision variables, operational, maintenance and productivity loss costs. The minimum objective function cost was determined, which then gave the optimal values of retrofitting the decision variables.

The steps are explained in the following sections.

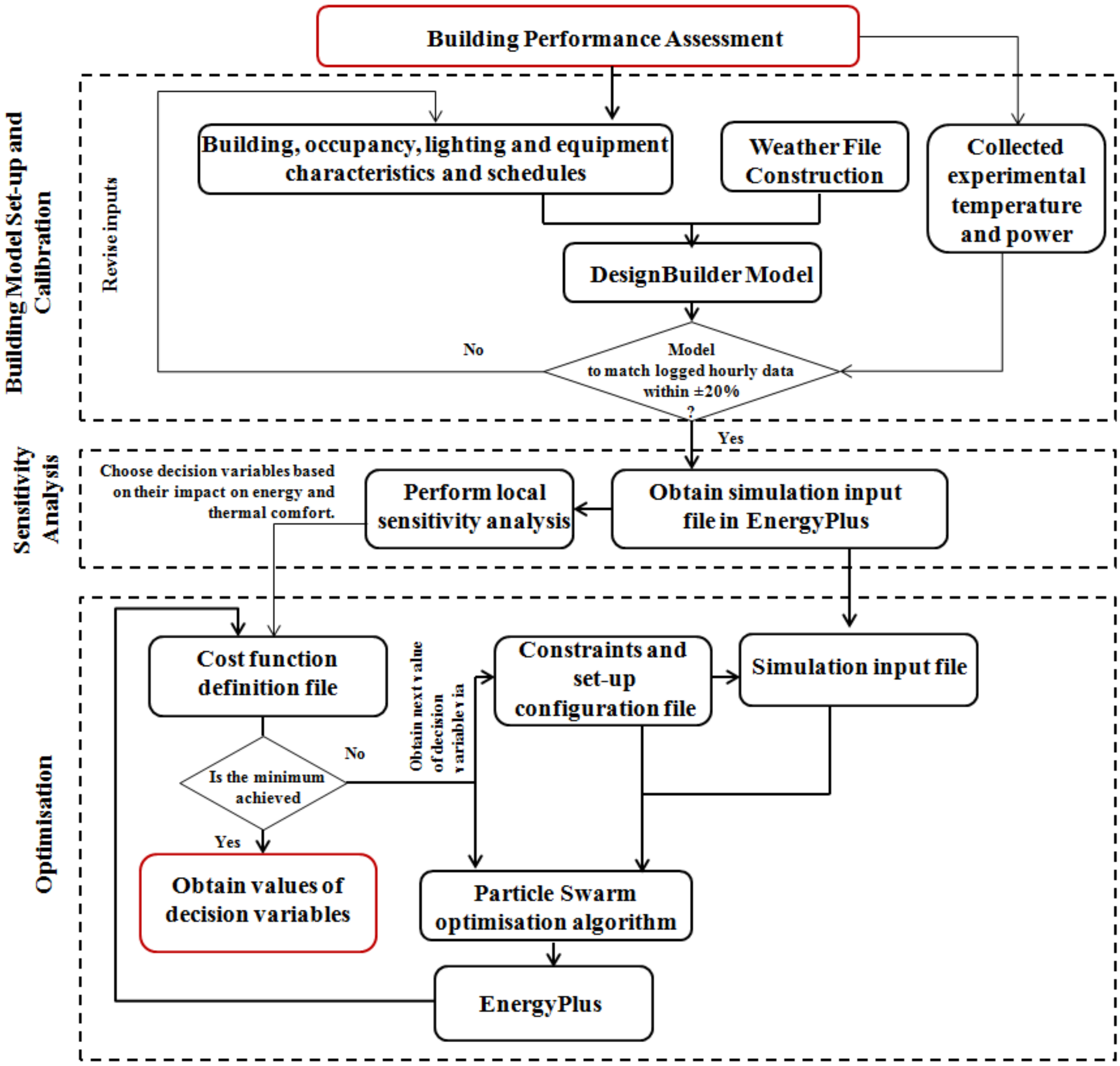


Figure 6.5 Diagram of the building simulation methodology used to obtain the decision variables that minimise the cost function and therefore the optimal retrofit strategy.

6.3.1 Calibration Weather Data File

Before constructing the model, the local climatic conditions needed to be considered in the simulation via the weather files. A weather file is formed by a reference weather year that consists of hourly data, 8760 hours, of a selected range of meteorological parameters. One of the most widely used weather files for EnergyPlus is the International Weather Years for Energy Calculations (IWECs) format. These files are

created by assembling twelve months of data from previous years using the most representative months of the set. A detailed explanation of how they are created can be found in weather files for current and future climates (University of Exeter 2012). Since only the structure of the weather file is required, the procedure depicted below can be implemented in any type of weather file.

To represent the weather conditions accurately, the weather file used in the energy model was constructed using monitored on-site weather data rather than a typical year of weather data supplied by the building simulation software. The monitored dry bulb temperature, relative humidity, direct solar radiation, wind speed, wind direction and precipitation were used from the weather station mounted on-site by the author (as described in §*7.2.1*) and used in the weather file. Other parameters needed to construct the weather file, i.e. extra-terrestrial direct normal radiation, extra-terrestrial radiation on a horizontal surface diffuse radiation, beam radiation and dew point temperature, should be calculated for each hour of the year. These parameters were derived using the following equations from Duffie and Beckman (2013). Firstly, the extra-terrestrial direct normal radiation (W/m^2) was calculated using:

$$G_0 = G_{sc}\left(1 + 0.033\cos\frac{360n}{365}\right)(cos\phi cos\delta cos\omega_a + sin\phi sin\delta) \tag{6.6}$$

where G_{sc} is the solar constant (1367 W/m^2), n is the day-number of the year, ϕ is the latitude (in degrees), δ is the declination (in degrees) and ω_a is the hour angle (in degrees).

The extra-terrestrial horizontal radiation (W/m^2) for an hour period was obtained through:

$$I_0 = \frac{12G_{sc}}{\pi}\left(1 + 0.033\cos\frac{360n}{365}\right)\left[cos\phi cos\delta(sin\omega_2 - sin\omega_1) + \frac{\pi(\omega_2 - \omega_1)}{180}sin\phi sin\delta)\right] \tag{6.7}$$

Where ω_1 and ω_2 define an hour angles (in degrees), and ω_2 is the larger.

The hourly clearness index was obtained through:

$$k_T = \frac{I}{I_0} \tag{6.8}$$

where I is the global horizontal radiation (W/m^2), obtained experimentally from the measurements of total solar radiation on a horizontal surface from the pyranometer of the weather station, and I_0 is the hourly extra-terrestrial radiation on a horizontal surface calculated from Eq. 6.7.

Once a clearness index was calculated from Eq. 6.8, the diffuse component of hourly radiation could be calculated using the following equation:

$$\frac{I_d}{I} = \begin{cases} 1 - 0.249k_T & for\ 0 \leq k_T \leq 0.35 \\ 1.557 - 1.84k_T & for\ 0 < k_T \leq 0.75 \\ 0.177 & for\ k_T > 0.75 \end{cases} \tag{6.9}$$

Considering that the beam and diffuse radiation results were combined to calculate the global horizontal radiation, the beam radiation component of hourly radiation was calculated via:

$$I_b = {(I - I_d)}/{\cos\theta_z} \tag{6.10}$$

Where θ_z is the zenith angle defined in Duffie and Beckman (2013). The dew-point temperature was calculated using the state equations for moist air (Barenbrug 1974):

$$T_{dp} = \frac{237.3\left(\frac{\ln\left(\frac{H_r}{100}\right)+\left(\frac{17.27T_0}{237.3+T_0}\right)}{17.37}\right)}{1-\left(\frac{\ln\left(\frac{H_r}{100}\right)+\left(\frac{17.27T_0}{237.3+T_0}\right)}{17.37}\right)} \tag{6.11}$$

Where H_r is the relative humidity and T_o is the outdoor air temperature (°C).

6.3.2 Building Energy Model Set-up Procedure

An EnergyPlus model that replicated real building behaviour needed to be constructed, so the knowledge gained from walking through the building and the desktop analysis are essential. The inputs outlined in Table 6.1 are also needed to set-up the model.

Table 6.1 Inputs for the building simulation model construction.

Inputs	Sources
Geometry, orientation, construction materials, windows size and location, building layout, HVAC type and location.	Floor plans, construction plans and mechanical plans through the desktop assessment or visual inspection.
Number of occupants per space type, occupancy and HVAC capacity and schedules, internal and external window shading, window percentage aperture, temperature set-points for windows and HVAC, lighting type and location, computer and equipment both type and schedules.	Visual inspection via the walkthrough. Questioning occupants about occupancy and services schedules. Confirm that construction materials and windows floor plans correspond to as-built situation through visual inspection.
Infiltration rate	Blower door testing of building envelope air tightness.
Weather conditions	Data acquired from weather station on-site or nearby. Weather file is to be constructed following *§6.3.1*.

To ensure that model used is valid, it must be calibrated as described in the following section.

6.3.3 Model Calibration

The building model was to be compared to the performance of the real building, which meant that the output of the building model is evaluated against the experimental data. In this study, the calibration consisted of first modelling the building when it was not occupied, i.e. without internal loads and running services, and then simulating it with different input variables, i.e. operating as usual, with occupants and services working as for a typical week. In both cases the weather file used in the model is to be constructed by following the procedure in §6.3.1, and the climate variables must correspond to the same time period when the internal air temperatures were monitored and collected.

Building without Occupancy Validation

To minimise the uncertainty around the actual occupancy schedules and internal loads it was postulated that using a time period when the university building is closed, or has minimal occupancy (e.g. during holidays) is the best time to attempt to validate the building envelope modelling. The settings implemented in the model were as follows:

- The density of building occupancy must be set to zero for the whole period.
- Only internal loads that are on continuously (e.g. emergency exit lights should be on).
- HVAC and computers should be switched off at all times.
- All windows were defined as closed during this period.

Hourly modelled and experimental internal temperatures were then compared. The target error between modelled and experimental hourly data should be within ±20% (ASHRAE Guideline 14 2002). Once the building has been calibrated, the next step is to compare the energy consumption predicted by the model with the monitored energy consumption.

HVAC Consumption Validation

Energy consumption predicted by the simulations must be validated while the building is running under business-as-usual conditions. The power was to be monitored during that period and then compared to the power consumption predicted by the model. The following parameters were set in the model:

- Typical occupancy schedule, i.e. working hours and the number of occupants in the space as a function of time.

- Window opening control, i.e. using temperature set-point and schedule control.
- Lighting levels as stated in the nameplate power and the number of lights. Estimated lighting schedule and load based on the occupancy schedule.
- Equipment (e.g. computer power density) schedules estimated from occupancy schedule.
- HVAC capacities and set-points as the as-built specifications.

If possible, the power on a distribution board should be monitored because it provides the required level of granularity (e.g. monitoring of the general power outlets (GPOs), lighting and experimental HVAC energy consumption, from different offices, classrooms, lecture theatres and laboratories of the building). This data can be used directly as an input into the model to create an internal load profile in order to predict HVAC energy consumption that can then be compared to the monitored HVAC energy consumption more accurately than monitoring the power lumped together (at the whole-of-building level).

After running the simulation, the hourly modelled and experimental HVAC consumption were to be compared, and the error between the modelled and experimental data should be within ±20% (ASHRAE Guideline 14 2002). Once the building model was calibrated, a sensitivity analysis on the influence must then be carried out on potential energy efficiency retrofit measures.

6.3.4 Identification of Most Influential Parameters

In order to determine the most influential parameters, a Sensitivity Analysis (SA) was designed to determine which parameters impact energy consumption and thermal comfort the most. This, in turn provided the basis for recommending various retrofit strategies. Before detailing the procedure, the definition of some of the important wording is described in Table 6.2.

Table 6.2 Inputs for the building simulation model construction

Inputs	Description
Parameters	All variables included in the sensitivity analysis.
Decision Variable	Sub-set of the parameters identified in the sensitivity analysis as the most influential parameters for energy consumption and thermal comfort.
Retrofit Option	Possible upgrade for a decision variable

A local sensitivity analysis via a finite difference method was used because it represented a relatively fast and straightforward examination of the building whilst

providing information on the relative importance of the input parameters (Cheng & Steemers 2011). ‘Local’ refers to assessing the sensitivity relative to a fixed point of the parameter value (Hamby 1995). Each retrofit design input parameter was changed one at a time, while the remaining variables were kept constant at their base values, and then the effect that changing the input has in the output was investigated. Local sensitivity cannot account for interactions between parameters, the primary purpose of this task was to identify the parameters that impacted energy consumption and thermal comfort the most, and changing one parameter at the time was deemed to be sufficiently accurate. During the more rigorous optimisation procedure (explained in the next section) all the parameters were varied concurrently.

The generic SA method is outlined below and was based on the work of previous studies (e.g. Firth *et al*. 2010; Kavgic *et al*. 2013; Cheng & Steemers 2011) :

1. Define the parameters of interest.
2. Simulate the building by varying each parameter of interest between the minimum and maximum values, while keeping all the other parameters constant at their base values.
3. Obtain the normalised sensitivity coefficients for each parameter of interest.
4. Analyse the results.

Each of the aforementioned points is explained below.

1. <u>Definition of the Parameters of Interest</u>

Energy modelling has many input parameters to describe the characteristics of a building and its site; they include the geometric properties, physical properties, lighting and equipment properties, HVAC characteristics, occupancy and equipment schedules, and the climatic conditions. A sub-set of these parameters was considered for the sensitivity analysis based on the scope/aims of the retrofit. Here, the aim was to decrease energy consumption while maintaining thermal comfort, and one prerequisite was that major disruptions to staff and classrooms had to be avoided during retrofits, hence no major structural retrofits were considered. The parameters selected for retrofitting were based on the building design parameters, internal loads, and HVAC characteristics covering a reduction in the heat losses and heat gains from the building envelope, lighting and computer type, and the heating and air-conditioning systems capacity. These proposed parameters are shown on Table 6.3.

Table 6.3 The parameters considered in the local sensitivity analysis.

Model parameter	
Building envelope characteristics	Roof R-value (m^2 K/W)
	Roof emissivity
	Floor R-value
	External wall R-value (m^2 K/w)
	Window U-value (W/m^2 K)
	Thermal mass
	Solar gains through the window (W/m^2)
	Infiltration rate
Internal Loads	Computer power density
	Lighting power density
HVAC systems	Temperature set-points modification (heating and cooling)
	Heating and cooling capacity

2. Sensitivity Analysis of Parameters of Interest

Simulations were then carried out by varying each parameter (within defined constraints) while keeping the remaining parameters constant. The size of the increments in parameters between iterations was important, since if the change was too small there might be potential rounding errors, and too large a change would probably be impacted by the non-linearity of the model (Firth *et al*. 2010). Consequently, by following the suggestions made in the literature (Saltelli *et al*. 2000) the inputs were changed by ±1% for a given parameter at each iteration.

3. Normalised Sensitivity Coefficients

After conducting the simulations, the sensitivity coefficients for each parameter were calculated. For a model investigating *m* inputs and *n* output parameters, the sensitivity coefficients, $\partial x_i/\partial k_j$, were defined by Eq. 6.12 (Firth *et al*. 2010):

$$\frac{\partial x_i}{\partial k_j} \approx \frac{x_i(k_j+\Delta k_j)-y_i(k_j-\Delta k_j)}{2\Delta k_j} \qquad (6.12)$$

$$i = 1,\ldots, n \text{ and } j = 1,\ldots, m$$

where x_i is the i^{th} output variable, k_j is the j^{th} input variable, $x_i(k_j + \Delta k_j)$ is the value of the output y_i when the input parameter k_j has increased by a small increment Δk_j, *n* is the number of inputs, and *m* is the number of outputs. In this example, *n* = 13 (the inputs in Table 6.3) and *m* = 2, i.e. energy consumption and the percentage of time outside the ASHRAE Standard 55 (2013) comfort zone during occupied periods.

To compare different sensitivity coefficients a normalisation process was carried out such that the normalised sensitivity coefficient, S, was calculated using the following:

$$S_{i,j} = \frac{k_j}{y_i}\frac{\partial y_i}{\partial k_j} \tag{6.13}$$

i = 1, …, n and j = 1, …, m

The parameters with the largest absolute normalised sensitivity coefficient were considered for the following step.

6.3.5 Optimisation Procedure

The most influential parameters, i.e. those associated with the highest normalised sensitivity coefficients, were selected for attention in the optimisation process as decision variables. For a specific building/retrofit situation the desired objective function must be defined (e.g. one that includes the costs of the retrofit options for the decision variables and post-retrofitting building operational costs). In the present study, productivity loss due to thermal discomfort 'costs' were also included in the objective function by including a penalty function. The objective function then had to be minimised via an optimisation engine varying the decision variables within specified constraints. The major steps in the optimisation methodology are explained below.

1. Cost of retrofit measures

An average cost per unit for installing a particular retrofit measure (e.g. $/m^2 of roof insulation) needed to be established, which was equivalent to the cost for retrofitting each 'decision variable'. Retrofitting costs can be estimated from a number of sources, both internal and external to the organization carrying out the retrofitting. In the present project approximate cost estimates of retrofitting tasks (for each decision variable) were sourced from a cost guide that is widely used throughout the Australian construction industry (Rawlinsons 2012). The numeric values used are summarised in Table 6.4.

Table 6.4 Retrofit options with associated costs for each parameter of interest – data for the Sydney region (Rawlinsons 2012).

Possible Decision Variables		Retrofit Option Suggestion	Average Cost Installed
Building envelope	Roof R-value	Insulation added/improved Cold bridge eliminated	Depending on R-value. R1.5 costs 7 $\$/m^2$, R3 12$\$/m^2$
	Roof emissivity	Reflective paint	55$\$/m^2$
	Floor R-value	Carpet with underlay or insulation	Wool tufted carpet with rubber underneath 53.70$\$/m^2$
	External wall R-value	Insulation	Glasswool batts. R2 costs 10.10 $\$/m^2$ and R3 10.7 $\$/m^2$
	Window U-value	Double glazing	257 $\$/m^2$
	Thermal mass	Expose thermal mass	Surface finishes: 27.5$\$/m^2$
	External or internal solar shading	Louvers, Blinds (venetian)	39 $\$/m^2$ 130 $\$/m^2$
	Solar Heat Gain Coefficient (SHGC)	Window film	60 $\$/m^2$
	Infiltration rate	Draught proofing	Window and door sealer: 3.25 $\$/m^2$, Door seal 36.10 $\$/ m^2$
Internal Loads	Lighting	Luminaire upgrades	60 $ to 172 $ depending if it is T8 upgrade to: T5 or energy efficient E1 lighting
	Computer	Computer upgrades	~475$ for thin client and energy efficiency screen.
HVAC	HVAC	Replace existing heating/cooling system	80-240 $\$/m^2$ (depending on capacity)
	Set-points modification	Modify temperature set-points	0$ but thermal comfort might be compromised.

2. Constraints on Decision Variables

Realistic ranges for the decision variables had to be defined. This was a somewhat subjective task and was related to what extent a particular parameter could be changed in practice by current retrofit technologies and systems. For example, the lower boundary of window U-value was represented in this study by high quality double glazing, since triple glazing is virtually never used in Australia. Similarly, the minimum practical value of a window Solar Heat Gain Coefficient (SHGC) that can be presently achieved by retrofitting of window film to the glazing was approximately 0.2. In the case of changing HVAC temperature set-points through control system re-

commissioning/upgrades, the limits on the range that could be practically implemented were taken to be the thermal comfort boundaries defined in ASHRAE 55 (2013) or alternatively by the local university thermal comfort guidelines.

3. Definition of the Objective Function

A number of approach can be taken to define an appropriate objective function in a given optimisation problem. Following the literature review it was decided to adopt the EU Delegate Regulation No 244/2012 (2012) for a financial calculation, as it was seen to be well accepted (BPIE 2013) and used by others (Ascione *et al.* 2015), hence it had been subjected to significant scrutiny. The main variation that was implemented compared to the original equation was the inclusion of a productivity penalty function (PPF) to account for the degree of thermal discomfort and associated loss of occupant productivity in a given building. The implications and definition of PPF are discussed in more detail below (point 4). The overall lifetime cost, C_{total} (objective function), of a set of retrofit options (decision variables) is therefore defined as:

$$C_{\text{total}} = \sum_{i=1}^{n}(y_i C_I(i) + \sum_{z=1}^{\tau} \left[(C_{a,z}(i) + PPF)R_d(z) + C_{c,z}(i) - V_\tau(i)\right] \quad (6.14)$$

where n is the number of decision variables, y_j is the number of times the retrofit must be renewed in situations where the lifetime of the building component is shorter than the remaining life of building, $C_I(i)$ is the initial financial investment cost of the i^{th} decision variable, z is the year number, τ is the remaining life of the building, $C_{a,z}(i)$ is the annual cost of the i^{th} measure for a typical year, including the annual operating, maintenance, and repair costs. PPF is the productivity penalty function (defined below in 4) and $R_d(z)$ is the discount factor per year. The discount factor is defined as $R_d(z) = \left(\frac{1}{1+r}\right)^{\tau}$ where r is the real interest rate on the time of the considered cost. The real interest rate r, in Australia in 2014 corresponded to approximately 4.0% (The World Bank 2014). This results in a discount factor $R_d(z) \approx 13.4$. $C_{c,z}(i)$ is the annual carbon cost of a retrofit or, set of retrofits, for a given year. This cost is over and above utility costs of energy, e.g. potential penalty costs for the university exceeding emissions thresholds.

The annual operation costs $C_{a,z}(i)$ included the annual maintenance operation and repair costs of the measure (if applicable) and the cost of the electricity, which was estimated to be 0.17 \$/kWh at 2015 prices. The values of maintenance and life span of

different components can be found in the Energy Efficiency for Buildings CEN/TC 228 (2006). $V_\tau(i)$ is the residual value of a set of retrofit measures at the end of the calculation period. However, the end of the calculation period is the end of the life of the building and it is highly unlikely that the retrofit measure will have any value by that time. Therefore, the residual value was not used in the present study.

1. Definition of the Productivity Penalty Function (*PPF*)

Anecdotal evidence (e.g. interviewees described in Chapter 3) suggested that one of the key drivers of university HVAC upgrade and retrofits programs was thermal discomfort. There are a number of aspects associated with productivity loss due to thermal discomfort. These include the following: staff and students underperforming or experiencing difficulties in learning/concentration; research or experiments at risk of disruption; FM tackling discomfort issues though different actions, e.g. time required for meetings to deal with occupants' complaints, extra hours for HVAC maintenance contractor personnel fixing problems, etc. Therefore, thermal discomfort is clearly a potential operational cost to a university. In this present work, it was decided to model this issue through the development of the productivity penalty function. The productivity, P, was adapted from the empirical relationship developed by Seppänen *et al.* (2006):

$$P = (aT - bT^2 + cT^3 - d) \tag{6.15}$$

Where, a = 0.1647524, b=0.0058274, c=0.0000623 and d=0.4685328.

Then, the instantaneous thermal comfort penalty function (TCPF) is defined as:

$$TCPF = n_{occ}\bar{S}_{occ}(1 - P) \tag{6.16}$$

Where n_{occ} is defined as the number of occupants in the space to be retrofitted and $\bar{S}_{occ}$ is the average salary of the occupants per hour and P was defined as the productivity in Eq. 6.15. It should be noted here that relatively little quantitative evidence can be found in the literature as to the influence of thermal discomfort on productivity, and that the further studies are needed to provide greater certainty as to this effect. Nevertheless, the work by Seppänen *et al.* (2006) is seen as a reasonable starting point for incorporation of this issue into the evaluation of various energy efficiency retrofit strategies.

An illustrative example of the calculation of Productivity (P) and instantaneous *TCPF* using indoor temperatures monitored by the present author over the course of one week

(20th to 28th of December 2013) for one office located in the first floor of the east wing of the case study building (exact location of the temperature measurements via thermocouples is shown in *§7.2* Figure 7.3) is presented in Figure 6.6.

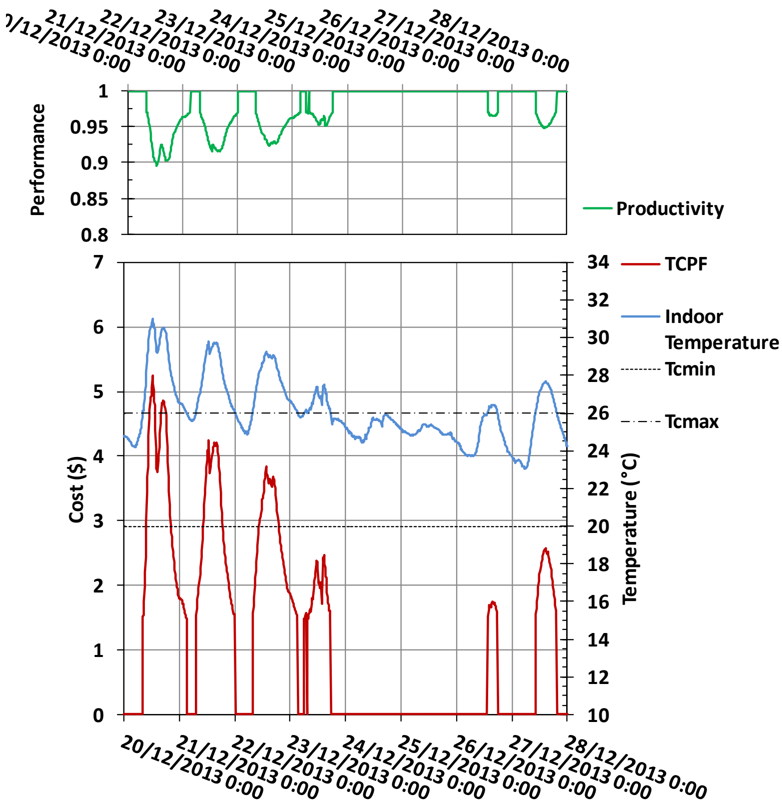


Figure 6.6 Calculated productivity, *P*, and instantaneous thermal comfort penalty function, *TCPF*, as a function of time during the last week of December 2013, for a research fellow's office (4.129). Also shown are indoor temperature, and the minimum, T_{cmin}, and maximum, T_{cmax}, of the thermal comfort band.

An illustrative example of the calculation of Productivity (*P*) and instantaneous *TCPF* using indoor temperatures monitored by the present author over the course of one week (20th to 28th of December 2013) for one office located in the first floor of the east wing of the case study building is presented in Figure 6.6, the exact location of the temperature measurements via thermocouples is shown in *§7.2* Figure 7.3.

TCPF is calculated based on Eq. 6.16, where n_{occ} =1, $\bar{S}_{\text{occ}}$=65$/hours and *P* is given by Eq. 6.15. These values were based on number and type of occupant located in this office, which in this example was a single senior research fellow. His approximate salary was $100,000 per year, then divided by 1540 hours working hours during the year resulted in $\bar{S}_{occ}$=65$/hours. For instance, on the 20th of December at 12pm the indoor office temperature was 30.61°C, *P* was 0.9 thereby the *TCPF* was $6.42. An increase of the indoor temperature above the upper thermal comfort band (T_{cmax})

resulted in a decreased in the productivity, indicated in the y-axes of the Figure as performance, below one. This in turn increased the TCPF, and thereby the costs.

The overall impact on productivity over a given period (e.g. a representative year) is then equal to the time-integral of instantaneous *TCPF*:

$$PPF = \int TCPF(t)\, dt \tag{6.17}$$

In the above example, the whole week corresponded to a *PPF* of \$226.

1. Optimisation Set-up

A 'generic optimisation' software package called GenOpt (Wetter 2015) was used to determine the optimal retrofit solution for a particular buildings. GenOpt was developed by Lawrence Berkley National Laboratory and worked by automatically performing iterative energy simulations while varying the user-defined parameters within specified user-defined limits.

The minimisation algorithm, which used a mixture of continuous and discrete decision variables, was known as a Hybrid Generalised Pattern Search Algorithm with Particle Swarm Optimisation. This hybrid algorithm begins with a Particle Swarm Optimisation (PSO) on a mesh for a user-defined number of generations of the discrete variables. Then, the continuous independent variables with the particle that had the lowest cost function used the Hooke-Jeeves Generalised Pattern Search (GPS) algorithm where the discrete decision variables were kept constant at the value of the particle with the lowest cost function (Wetter 2001). The combination of parameters that provides the minimum cost function was considered to be the optimal.

The files description used by GenOpt are listed below.

- The Input file used in EnergyPlus, where the energy model was detailed.
- The Command file where the names of the decision variables, initial values, constraints, and the optimisation algorithm were defined.
- The Template file, which was a duplicate of the input file, where the decision variables were specified. The numerical value of the decision variables were replaced by its name enclosed in percentage signs. This is how GenOpt understand that this was a decision variable that must be varied after each simulation run (iteration) by the possible values defined by the user in the command file.

- An Initialisation file where the paths giving the location of relevant files were specified.
- A Configuration file where the EnergyPlus location path was defined.

A custom script, programmed by the present author in Python, was used to obtain the frequency of indoor temperature occurrences outside the comfort zone. GenOpt could only retrieve single values from EnergyPlus output files, however, the frequency distribution of temperatures was given by EnergyPlus in an array, so that a ‘wrapper’ program was written to obtain the temperatures data required to calculate the penalty function.

6.4 Modified Method to the Typical Approach to Retrofitting Higher Education Buildings

The methodology developed in this work, i.e. the assessment of higher education portfolios through the decision framework detailed in Chapter 4 and the optimisation of particular building retrofits presented in this chapter, was integrated to improve on the current practices approach identified in the interviews with different Australian and New Zealand higher education FM teams (introduced in *§3.6.1* Figure 3.1). This integration resulted in the proposed method to retrofit higher education buildings shown in Figure 6.7.

The principal additions to the current practices approach were the use of: i) KPIs based on the existing data and ii) the strategic priorities of the decision makers. The combination of this both aspects through a weighting scheme aided the selection of the building for retrofitting. Thereafter, a systematic method to identifying the optimal retrofit strategy to minimise energy consumption whilst improve thermal comfort was included. This, in turn, strongly supported the business case and thereby any investment decision, as the outcomes of the retrofit became tangible.

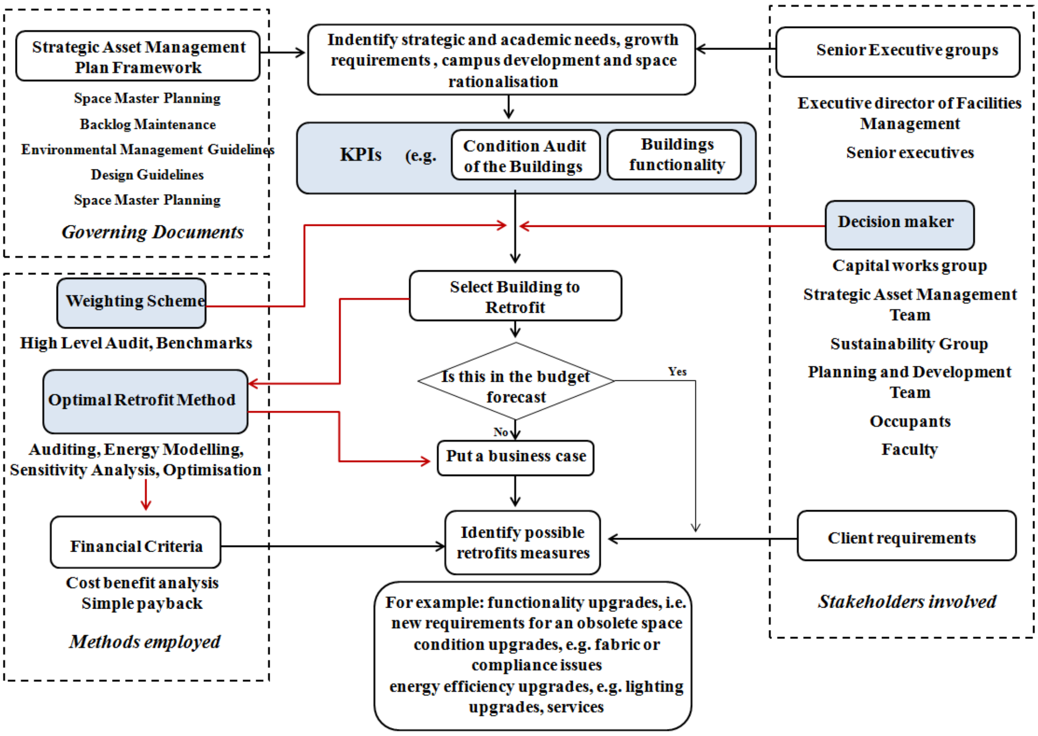


Figure 6.7 Integrated method to decision making for higher education building retrofits; to improve on the current practices approach detailed in *§3.6.1* Figure 3.1.

6.5 Summary

This chapter has described the methodology used to identify optimal retrofit strategies to be implemented on particular university buildings.

Firstly, a comprehensive method for assessing building performance was described, and indicated how the data collection approach was carried out through a comprehensive technical audit and a Post Occupancy Evaluation (POE) survey of occupant perceptions. Then the method for simulating buildings was described. The primary steps involved were: 1) creating and calibrating a building simulation model; 2) conducting a sensitivity analysis to reveal the parameters that affect energy consumption and thermal comfort the most - these parameters (i.e. ‘decision variables’) are the ones proposed for retrofit optimisation; 3) defining a cost function for the decision variables. The cost function accounts for the costs associated with the retrofit such as: initial financial investment, retrofit lifespan, annual cost including operation, repair and service costs, and the loss of occupant productivity due to indoor conditions being outside the thermal comfort zone. The minimisation of the cost function was to provide the optimal values of the decision variables to be retrofitted.

The building retrofit optimisation methodology is demonstrated in the following chapters where its application to a case study building is described.

7. Existing Building Performance Assessment: A Case Study

This chapter describes the application of the building performance assessment method, previously outlined in *§6.2*, to a case study building of the University of Wollongong (UOW). The case study includes a description of the following:

- The equipment used and experiments conducted in the case study building.
- The outcomes of the physical building audit detailing the results to determine the baseline performance for energy, water, building envelope, and indoor environmental quality. The underperforming areas in need of improvement are also identified.
- The results from a Post Occupancy Evaluation (POE) revealing occupants' perceptions and attitudes towards different aspects of the building, including the main issues affecting their health and wellbeing.
- Initial results of applying building simulation as an investigative tool to understand the effect of different retrofit measures on the energy consumption and thermal comfort.

7.1 Case Study Building Overview

The case study building was located at the main campus of the University of Wollongong (UOW), Northfields Avenue, Wollongong, NSW, Australia. The building was known as Building 4 and accommodated the School of Civil, Mining and Environmental Engineering. The characteristics of Building 4 and the physical measurements conducted are detailed below.

7.1.1 Building Characteristics

Building 4 was a two-storey building, with a central atrium, high-bay workshops on the south, laboratories on the western and southern ground floor, and mostly offices on the northern and eastern sides. It also had two computer labs, a kitchenette for staff, administration offices for the engineering faculty and a couple of classrooms. Hence, it is a multi-purpose building with a variety of users including academic, executive, technical and administrative staff, students, and intermittent external visitors. The total floor area of the building was 5440m^2.

The building was an amalgamation of a number of older buildings, dating from 1959, and a more recent extension built in 1992. The building characteristics, envelope construction, finishes and design parameters are summarised in Table 7.1. An overall view of the east wing façade of the building is shown in Figure 7.1.

Table 7.1 Overview of the base case university building.

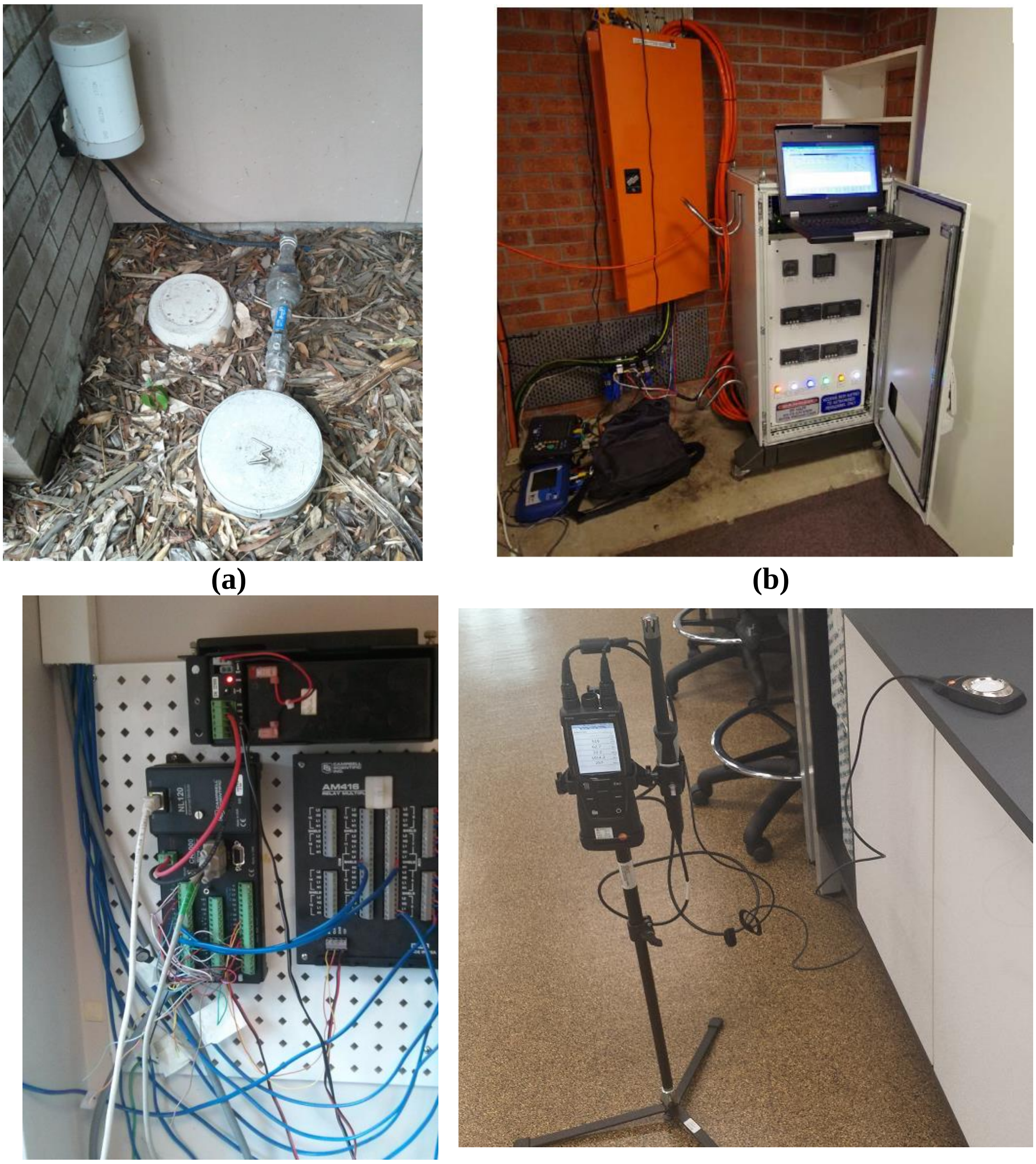
Location	Wollongong, -34.40° latitude, 150.88° longitude
Building type	Higher education building with mixed usage (offices, laboratories, and classrooms).
Floor area (m^2)	5440, of which 1476 was conditioned and 2675 was unconditioned space.
Floor height (m)	Ground floor-to-suspended ceiling height was 2.75 m high, while the height of the 1st Floor was 2.7 m. The two suspended ceilings were 0.59 m and 0.4 m, respectively.
Glazing fraction	~25% of the gross wall area.
Building Construction	External walls were a mixture of double brick and pre-cast concrete panels with plasterboard as interior surface. There was a 150mm-thick concrete slab for the ground floor and a 190mm-thick concrete slab for the first floor. Roof was metal deck on steel rafters. Suspended ceilings with ceiling tiles and an air gap. Metal-framed windows have 3mm clear single glazing. The external façade has fibre-cement sheet sunshades mounted on steel frames. Carpet throughout the offices, classroom, computer labs and circulation spaces, while hard-flooring was present in the wet laboratories and exposed concrete floors in high-bay workshops. Appendix B shows the floor plan of Building 4 with the different uses).

Figure 7.1 Building 4 east wing façade.

7.2 Experimental Equipment

A summary is presented in Table 7.2 of the equipment used and experimental measurements conducted to assess the local weather conditions and the building performance in terms of energy consumption, water consumption, indoor environmental

quality (IEQ), envelope tightness through the infiltration rate and qualitative analysis of the building fabric thermal performance via thermal imaging. Examples are shown in Figure 7.2 of the equipment used to assess the performance namely a water meter, power meter, the data logger where the thermocouples and the instruments of the weather station were being logged and the Indoor Environmental Quality (IEQ) instruments. The location of the measurement sensors is summarised in Figure 7.3.



(a) (b) (c) (d)

Figure 7.2 Equipment employed to assess Building 4 performance a) water meter at a whole-building level, b) power to monitor the different circuits from one of Building 4's distribution boards, c) data logger and multiplexer with the connected cables of the sensors (thermocouples and weather station instruments) and d)IEQ instruments (i.e. temperature, humidity, CO_2 and lux levels).

Table 7.2 Summary of experimental measurements.

Assessment		Measurement/Scope	Measurement type	Sample interval	Date	Measurement equipment	Accuracy
Weather conditions		rain fall, outdoor temperature and relative humidity, wind speed, wind direction	logging	5-minutes	14st February 2013 to date	rain gauge, hygrometer, anemometer,SP-110 pyranometer	(McVan Instruments 2006; Amalgamated Instrument 2001; Campbell Scientific 2005; Apogee Instruments 2013)
Energy		electricity-building level	logging	hourly	year 2013	*Secure Sprint* electricity meter ; data acquired from UOW DASH Portal (§5.2.1)	Class 1.0
		Power at one distribution board level with a total of 30 circuits, i.e. office circuits included lighting, general power outlets, kitchenette, amenities and services (HVAC).	logging	10- seconds	3rd to 10th March 2014	power quality analyser PW3198	voltage: ±0.1% of nominal voltage vurrent: ±0.2 % reading ±0.1 % f.s. active power: ±0.2 % reading. ±0.1 % f.s.
Water		water-building level	logging	hourly	Year 2013	water meter V100(PSM-T); data acquired from UOW DASH Portal (§5.2.1)	minimum flow rate: ±5% transitional flow rate: ±5%
Indoor environmental quality	**Thermal Comfort**	indoor temperature for three offices	logging	5-minutes	1st November 2011to date	type-K thermocouples data logger and multiplexer AM416	±0.5 °C
		indoor temperature and humidity (40 locations)	logging	15-minutes	18st November 2013 to 23rd Jan 2014	iButtons *A*	±0.5 °C ±0.5%
		indoor temperature (10 locations)	logging	15-minutes	19th December 2014 to 19th February 2015	iButtons *B*	±0.5 °C ±0.5%
	Air Quality	total volatile organic compounds (TVOC)	spot-check		18th December 2013	3M™ Quest EVM-7 environmental monitor	± 5%
		CO					± 5%
		CO$_2$				IAQ probe 0632 1534 used in conjunction with Testo 480	± 75 ppm (0 to 5000 ppm CO$_2$)
	Acoustic comfort	acoustics				A-weighted sound pressure level	± 2dB
	visual comfort	illuminance levels				illuminance meter Testo 480	± 6%
Envelope		air tightness test	spot-check	3h-5h/test	15th February 2014	Retrotect™ blower door	Fan flow ±3%
		thermal imaging	spot-check		December 2013	Testo 890-2 0563 0890 V2 IR Infrared Thermal Imaging Camera	±2 °C, ±2 % of m.v.(±3 °C of m.v. at -30 to -22 °C)

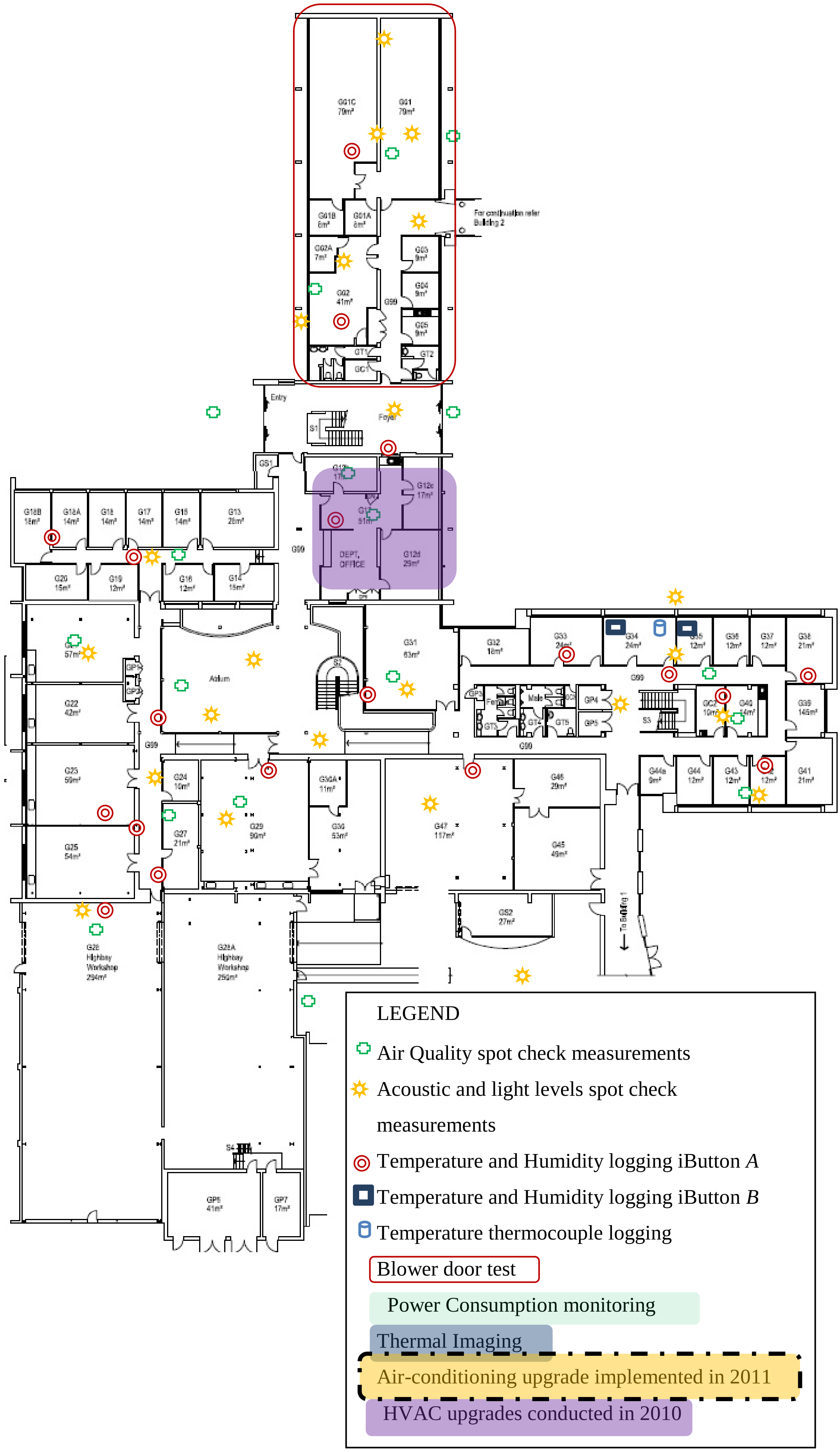

LEGEND
Air Quality spot check measurements
Acoustic and light levels spot check measurements
Temperature and Humidity logging iButton A
Temperature and Humidity logging iButton B
Temperature thermocouple logging
Blower door test
Power Consumption monitoring
Thermal Imaging
Air-conditioning upgrade implemented in 2011
HVAC upgrades conducted in 2010

Figure 7.3 Monitoring plan for ground floor and first floor of Building 4, with location types of logging, spot checks measurements and tests conducted.

7.2.1 Local weather conditions

Building 4 was situated in the Illawarra Region of New South Wales, Australia. This region is defined as being in “Australia Climate Zone 5” characterised by a mild, humid, oceanic climate with warm summers and cool winters. The outdoor weather is very important to contextualise the building performance because a realistic simulation prediction requires accurate meteorological conditions (Chow *et al.* 2006). The nearest Bureau of Meteorology weather station was over 10km away, and that station did not have solar radiation data available. Hence, a local weather station was purchased and installed on the roof of Building 4 to capture local meteorological conditions. A range of

meteorological instruments, including an anemometer (Amalgamated Instrument 2001) , pyranometer (Apogee Instruments 2013), pluviometer (McVan Instruments 2006), thermometer and hygrometer (Campbell Scientific 2005) were selected, and then mounting poles were designed by the present author and installed so that the instruments were in the positions recommended by their manuals and "A guide to the siting, exposure and calibration of automatic weather station for synoptic and climatological observation" (Overton 2009). The weather station mounted on the rooftop is shown in Figure 7.4.

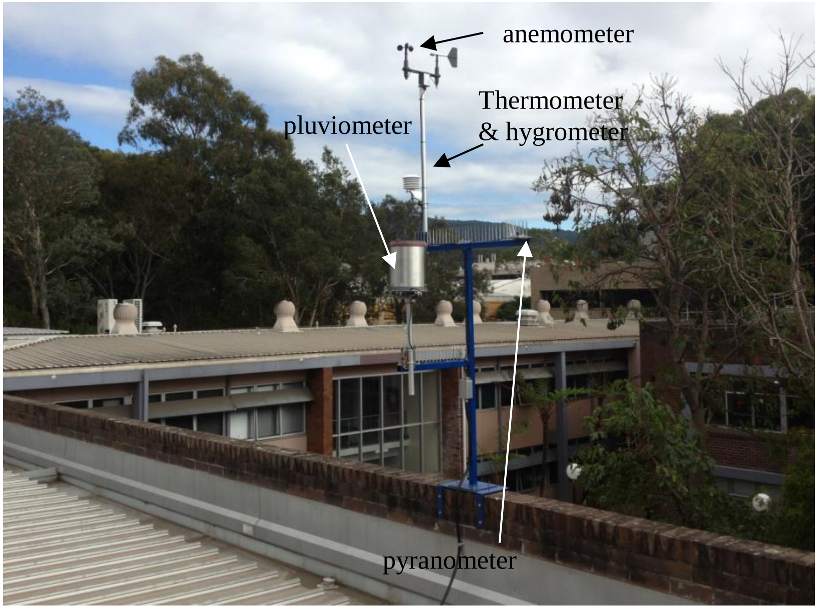


Figure 7.4 Weather station mounted on the top of Building 4.

7.3 Existing Building Performance Results

The results of the comprehensive building audit investigation carried out by the present author are divided into the following main categories:

1) An assessment of previous upgrades. This entailed assessing the effectiveness of the air-conditioning incorporated in the first floor of the east wing of Building 4 by comparing before and after measurements in terms of:
    a. energy consumption via the energy signature method;
    b. thermal comfort evaluation through monitored temperatures.
2) Current building performance assessment. This included:
    a. walk-through assessment where the functionality and major operational features were identified/evaluated;
    b. energy consumption and water consumption;

c. IEQ assessment via thermal comfort, air quality, visual comfort, and acoustic comfort.
d. envelope air-tightness via the infiltration rate and qualitative analysis of the building fabric thermal performance via thermal imaging.

7.3.1 Previous Upgrades Assessment

During the summers of 2008, 2009 and 2010, the Facilities Management Division (FMD) at UOW received a high number of complaints due to thermal discomfort from the occupants located mainly in the first floor (4.109-4.109a, which are labelled as air-conditioning upgrade conducted in 2010 in Figure 7.3) and north facing offices in the east wing of Building 4. Occupants' complaints triggered FMD actions to assess the indoor environmental quality in office 4.109, 4.109a and 4.109b. Hence, during summer 2009-2010, specifically from 14/12/2009 to 17/12/2009 for offices 4.109 and 4.109a, and from 5/03/2010 to 12/03/2010 for office 4.109b, indoor air temperature and relative humidity monitoring along with air quality spot check measurements, principally CO_2 and CO, were conducted. Results showed that monitored indoor temperatures fluctuated, but most of the time exceeded the acceptable temperature range of 20°C-26°C. Mean temperatures were 26.1°C for 4.109-4.109a and 25.8°C for 4.109b, reaching a maximum temperature of 29.3°C and 27.3°C, respectively. Based on these results, air-conditioned was installed in these offices. In regards to air quality, the readings were below the maximum limit from ASHRAE Standard 62.1 (2007). However, no measurements were taken for the first floor north-facing offices located in the east wing, where also numerous occupants complained due to thermal discomfort. Therefore, one of the occupants located in this area, specifically in 4.129, set-up thermocouples (Figure 7.3 shows the location of the thermocouples measurements) to monitor indoor air temperatures over summer 2010, from 1st November 2010 to 28th February 2011, in three offices deemed as uncomfortable, i.e. 4.129, 4.130 and 4.G34. The mean and maximum indoor air temperature recorded during the monitored period is described in Table 7.3.

Table 7.3 Monitored mean indoor air temperature and maximum indoor temperature from 1st November 2010 to 28th February 2011 for offices located in the east wing of Building 4.

Office	Indoor mean temperature (°C)	Indoor maximum temperature (°C)	Standard deviation (°C)
4.130	26.3	34.4	2.2
4.129	25.8	34	2.6
4.G34	25.5	33.5	1.6

The high indoor temperature readings over summer 2010 were provided to FMD as evidence of the overheating issues. The data shows that temperatures consistently above 26ºC were reached in the first floor offices, with maximum indoor temperature over 34ºC. Complaints reached a crescendo leading to the Deputy Vice-Chancellor (Operations) meeting with the affected staff to try to resolve the problem. This, in turn, prompted a decision by senior management and FMD to install a 23-kW Daikin air-conditioning system servicing the first floor north facing offices of the east wing in January 2012 (specified as air-conditioning upgrade implemented in 2011 in Figure 7.3). The assessment of alternative retrofit measures that potentially could have avoided the installation of the air-conditioning system is presented in *§7.4*.

Building 4 Energy Signature Assessment

Energy consumption data was acquired and analysed from the 1st November to the 15th December for each of the years 2011, 2012, and 2013, both before and after the air-conditioning system upgrade. Similarly, the ambient hourly dry bulb temperature was extracted from the Bureau of Meteorology's Bellambi weather station dataset for the years 2011 and 2012 and from the roof-top weather station on Building 4 (installed by the present author) for 2013. The resultant energy signatures, constructed with the total energy consumption monitored for these periods, is shown in Figure 7.5. The parameters of linear best fit, i.e. coefficient of determination and the slope of the linear regression are presented in Table 7.4.

The energy signatures showed lower daily energy consumption for given outside air temperature for 2013 as compared to 2011 and 2012. This could be attributed to changing the air-conditioning set-point in some parts of the building (for instance increasing the temperature set-point of the air-conditioning) or lower internal loads, e.g. lower lighting consumption due to a few inoperable light fittings or occupant behaviour. A slight difference in slopes was also observed. The lower slope in 2011 was likely to

be primarily due to the lower demand for cooling because of the air-conditioning upgrades in early January 2012.

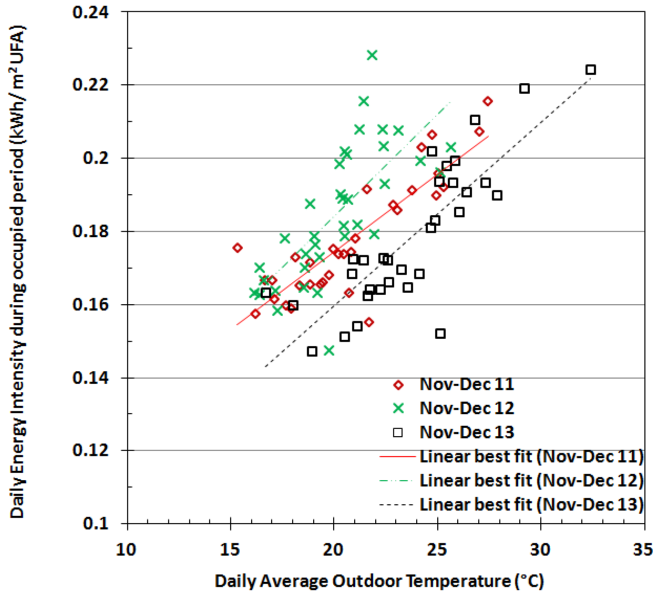


Figure 7.5 Energy Signature for Building 4 comparing the period 1st November-15th December 2011, 2012 and 2013. Each point represents the daily energy intensity (8.00am to 5.00pm) against the daily average air temperature for weekdays.

Table 7.4 Slope and coefficient of the determination for the linear best fit of the different energy signatures.

Year	Energy Signature Slope (kWh/m^2 °C)	R^2
2011	0.00425	0.73
2012	0.00556	0.52
2013	0.00501	0.69

Buildings at UOW main campus that were similar to Building 4 in terms of construction characteristics (Building 18), decade where the building was built/ major refurbishment was undertaken (Building 3 and Building 22) as well as a recently constructed building (Building 32) were compared against Building 4 energy signature (Figure 7.6 and Table 7.5). Their energy consumption data was obtained following *§5.2*) and analysed from the 1st November to the 15th December 2012.

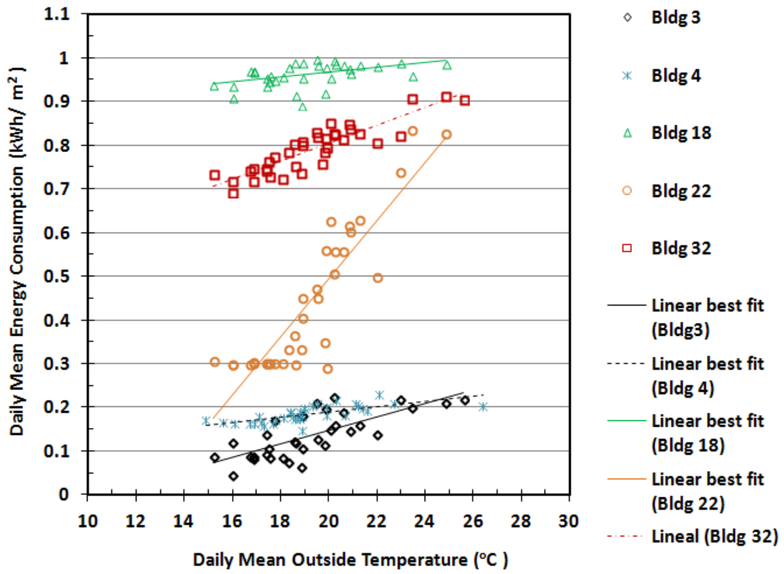


Figure 7.6 Energy Signature for different buildings at UOW main campus from 1st November 2012 to 15th December 2012. Each point represents the daily energy intensity (8.00am to 5.00pm) against the daily average air temperature.

Table 7.5 Slope and coefficient of the determination for the linear best fit of the different energy signatures of the buildings in Figure 7.6.

Building	Energy Signature Slope (kWh/m^2 °C)	R^2
3	0.016	0.56
4	0.0056	0.52
18	0.0054	0.21
22	0.067	0.80
32	0.021	0.79

Building 4 presented comparable energy signature slope with Building 18 (Table 7.5). This is most probably attributed to the characteristics of the buildings. That is both buildings have similar percentage of conditioned spaces (40% versus 45%) and similar construction materials, i.e. external walls are double brick, with concrete slab floor, approximately 20% of fenestration and metal deck roof. The energy intensity in Building 18 was around six times higher than Building 4 due to the amount of laboratories and fume cupboards present.

Similar decade buildings (i.e. 3 and 22 from the late 90s early 00s, respectively) presented higher slopes than Building 4 despite both buildings showed equal or lower percentage of conditioned spaces. Therefore, possibly the higher cooling slope might be due to lower air-conditioning system COP. Additionally, the building fabric thermal performance could be poorer in Building 22 than Building 4; Building 22 was initially build in the mid 60s despite undergoing through major refurbishments in 1997.

The newest building of the studied in this section, 32, also presented a higher slope than Building 4. This is most probably because of a higher cooling demand, i.e. this building has 90% of the spaces, mostly offices, laboratories and lecture theatres, conditioned through the BMS during occupancy times.

Thermal Comfort Assessment

The indoor temperature measurements were conducted one year before installation of the new 23-kW air-conditioning (i.e. from 15th November 2010 to 24th January 2011) and after two years of the air-conditioning operation (15th November 2013 to 24th January 2014). The thermal comfort results for the two offices monitored with thermocouples (i.e 4.120 and 4.129, which location is shown in Figure 7.3) in terms of the percentage of occupied time exceeding certain temperatures are shown in Figure 7.7. According to UOW Work Health and Safety (WHS) guidelines, a thermally comfortable work space should be between 20°C to 26°C (UOW WHS Unit 2012). Two additional offices (4.126 and 4.132) were monitored only after the air-conditioning retrofit (15th November 2013 to 24th January 2014) with the iButtons *A* (iButtons are separated in *A* and *B* as defined in Figure 7.3, depending on the period and locations of the measurements) in terms of temperature and relative humidity. In this case, as humidity was considered, ASHRAE 55-2013 was applied to assess the thermal comfort results.

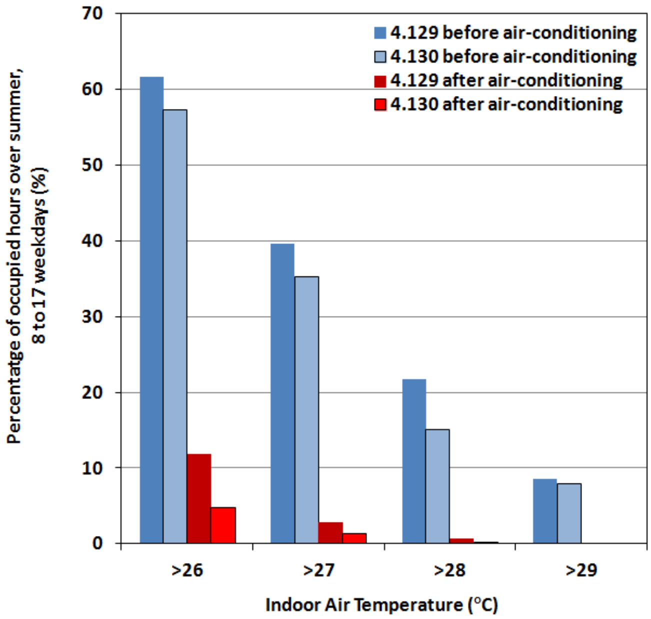


Figure 7.7 Percentage of occupied hours (8.00am to 5.00pm weekdays) when given temperatures were exceeded. The measurement period corresponds to before and after the air-conditioning was installed. That is from 15st November 2010 to 24st January 2011, and from 15st November 2013 to 24st January 2014, respectively. The Christmas period from 20th December to 3rd January was not included.

It is appreciated that installing air-conditioning reduced by 10 times the indoor air temperatures above 26°C in these two offices. The dry-bulb air temperature, humidity ratio, and comfort limits are shown in Figure 7.8. The percentage of time office 4.132 was outside the comfort zone, during normal occupancy hours, was approximately 30%, using the ASHRAE 55-2013 criteria. Indoor temperatures above 28°C occurred during more than 10% of the occupied period. In contrast, office 4.126 was outside the comfort limits only 13% of the occupied time, with temperatures above 28°C for less than 1% of the time. Therefore, the installation of air-conditioning appeared to address the overheating problem for offices 4.126, 4.129 and 4.130. However, the results in Figure 7.8 showed that office 4.132 was still uncomfortable for much of the time. To explore this issue further, indoor air temperatures were correlated with outdoor temperatures for conditioned office 4.126 and 4.132. Unconditioned office 4.G34 is also shown to demonstrate the correlation between indoor air temperature of unconditioned offices with the outdoors air temperature (Figure 7.9).

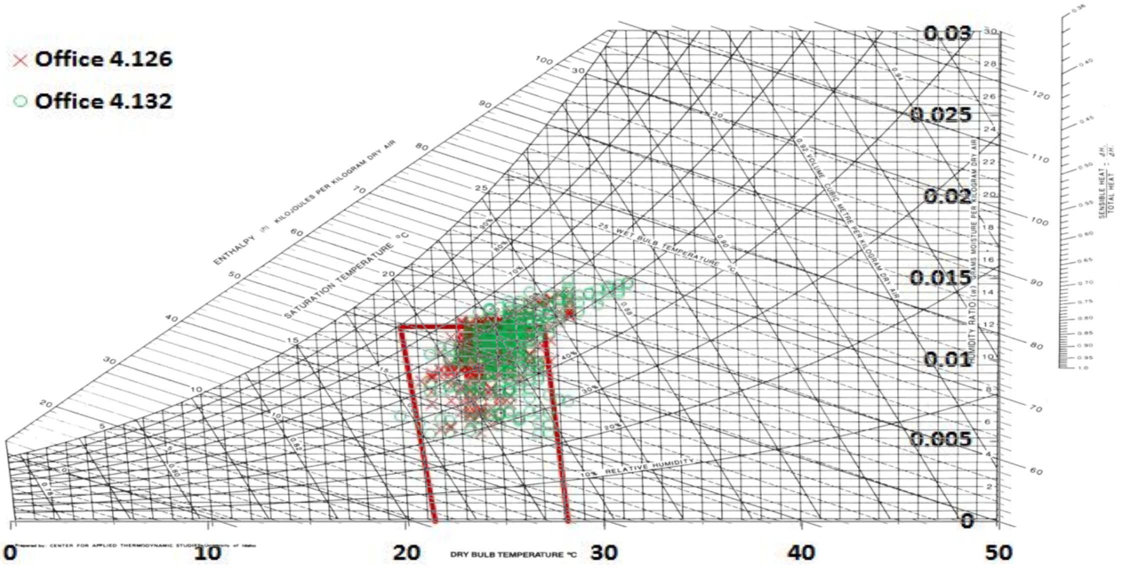


Figure 7.8 Air temperatures with acceptable comfort zone for summer and winter clothing for office 4.126 and 4.132 (Air temperature is used instead of operative temperature, however as it is summer, the radiant temperature is expected to be higher than the air temperature and therefore operative temperature > air temperature).

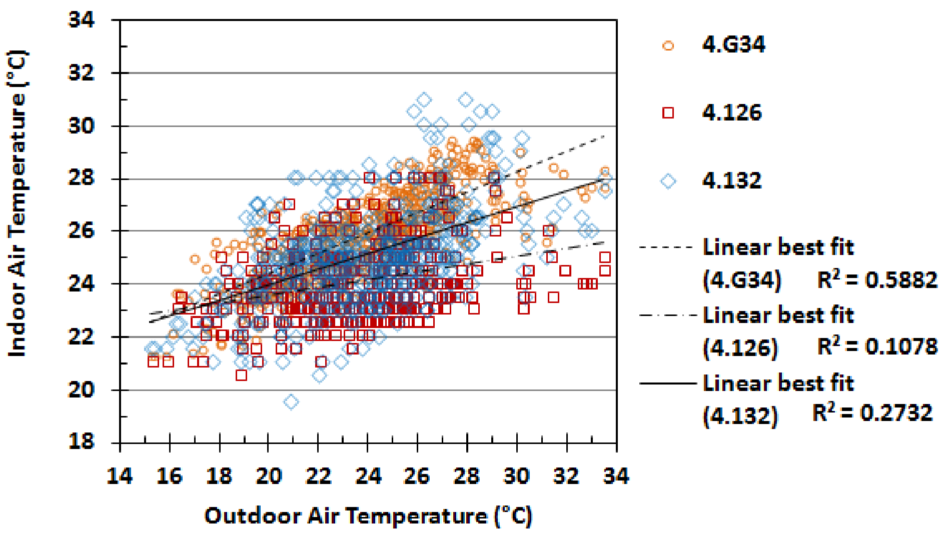


Figure 7.9 Indoor air temperature correlated with outdoor air temperatures for two conditioned offices (4.126 and 4.132) and unconditioned ground floor office (4.G34).

The smallest coefficient of determination between indoor and outdoor temperature is presented for the conditioned office 4.126, whilst the higher correlation between indoor and outdoor temperature is the non-conditioned office (4.G34). Office 4.132 shows a coefficient of determination slightly higher (r^2=0.27) than 4.126. This indicated that the relationship between the indoor and outdoor temperature is stronger in 4.132 than in 4.126, supporting the idea that the air-conditioning is probably not working as intended for that particular office. Therefore, the air-conditioning should be re-commissioned to determine whether there are any problems in the ducting system or the diffusers need to be balanced.

7.3.2 Walk-through Assessment

Knowledge of the building's functionality, layout, and number of occupants per space type, including their schedules and HVAC type, was acquired in a walk through assessment (see Figure 7.10). Figure 7.10a shows the tendency to install more air-conditioning in the building to solve the problem of poor thermal comfort and overheating. However, a split system blowing air straight into a roof extract fan can be seen in Figure 7.10b. A typical office for academic staff is shown in Figure 7.10c, with relatively high internal loads (printer, desktop computer, and T8 fluorescent lighting). As well as collecting some information for the model inputs, the walk through also helped to develop the monitoring plan (presented in Figure 7.3).

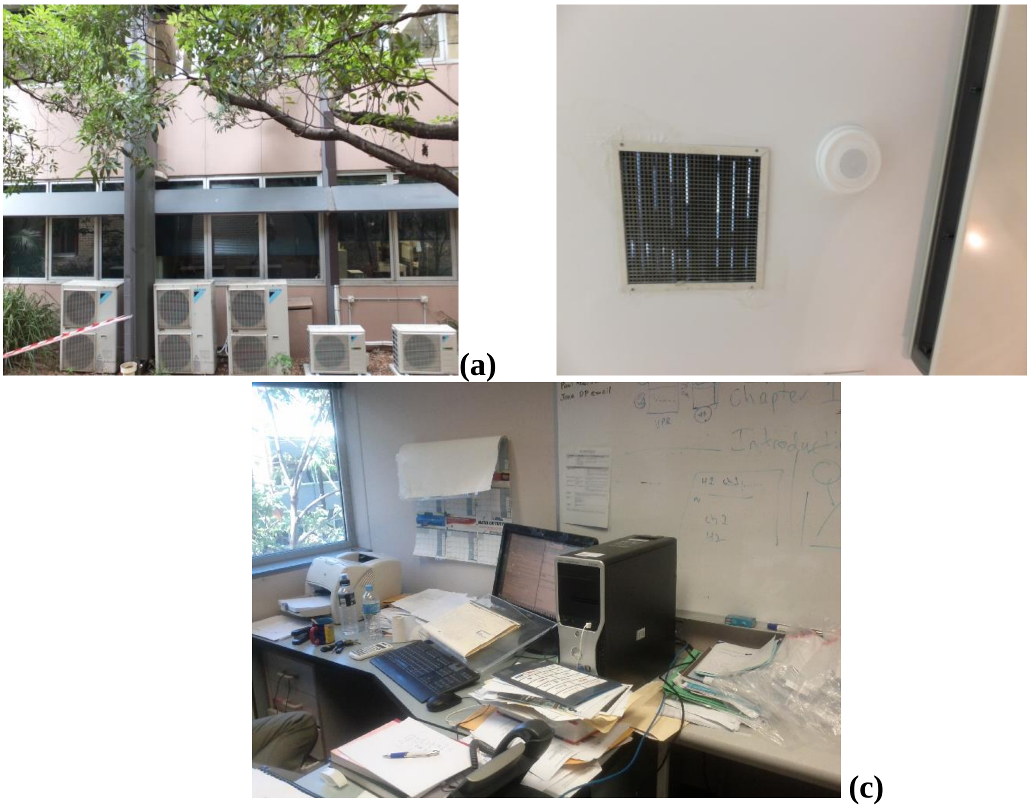


Figure 7.10 Different parts of the building photographed during the walk through: a) west façade with outdoor air-conditioning units, b) split system mounted in front of an extractor fan, c) Office located in the east wing facing north**.**

7.3.3 Energy Assessment

Energy consumption on 2014 for Building 4 was 115 kWh/m^{2}UFA. This is typical/standard practice energy consumption. Sub-monitoring of the distribution board DB1A (the spaces served are shown in Figure 7.3) was conducted on the first week of autumn session in 2014 (3rd March to 9th March) to investigate end use consumption breakdowns (Figure 7.11).

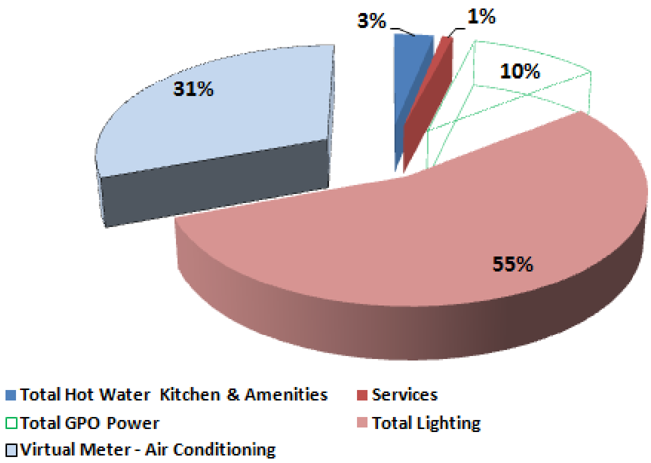


Figure 7.11 Detailed power logging by end use.

Lighting and air-conditioning represented 86% of the total energy consumption. Over half of the energy consumed was attributed to the lighting, principally due to type of luminaries and operation, i.e. T8 fluorescents in the corridors are working 24/7 (as shown in Figure 7.12) with an average lighting level of 190 lux (§7.3.4*)*. Therefore, there is potential for luminaires upgrades.

Figure 7.12 Building 4 east wing lighting arrangement.

7.3.4 Indoor Environmental Quality Assessment Results

Thermal Comfort

iButtons *A* (Figure 7.3) were used to evaluate the thermal comfort conditions from 15th of November until the 23rd of January from 8am to 5pm. The percentage of time when the monitored room was above a certain temperature is shown in Figure 7.13. It was clear that most of the spaces that were uncomfortable over summer were located in the east side of the building. The two spaces located on the west side of the building were an unoccupied mezzanine (south east) and a postgraduate office without exterior windows.

Figure 7.13 First Floor monitored spaces coloured as they exceeded 1% of occupied time above a certain temperature during summer. This translated into indoor air temperature above 28 °C for more than 1% of the occupied time (indicated in red). Temperatures above 26°C for more than 1% of the occupied time are shown in yellow, and green indicated no thermal comfort issues with the space.

Air quality Assessment

<u>CO2 and CO</u>

Carbon dioxide spot check measurements were below 700ppm for all the spaces. The readings ranged from a minimum of 389ppm to a maximum of 678ppm, with a standard deviation of 67.7ppm. Therefore, the exchange of air with the outdoors through the building was considered acceptable (ASHRAE Standard 62.1 2007). This result was

confirmed with the air tightness test (the results are shown in §7.3.5), for the reason that the building was found to be leaky.

However, there were some particular spaces (e.g. air-conditioning offices or internal corridors) where the CO_2 readings deviated significantly from the average. The offices with air-conditioning had lower CO_2 readings whereas internal corridors had the highest concentrations of CO_2/occupant for the whole building. This, in turn, evidences the need for extra ventilation/fresh air in these spaces.

With regards to the CO readings, none of the measured spaces exceeded 3ppm, ASHRAE 62.1 (2007) states a maximum concentration average for a 8 hours period of 9 ppm.

Visual Comfort Assessment

Lux levels varied significantly around the building (Figure 7.14). The minimum average lighting for spaces such as laboratories with power machinery, i.e. the high bay and the dry laboratory located in 4.G47, showed 320 lux and 280 lux, respectively. The shared teaching space in 4.118 presented 180 lux. These readings did not comply with AS/NZS 1680 (2008) because the minimum average lux levels should be 600 lux and 240 lux respectively. Conversely, spaces such as the computer laboratory and shared offices (4.138 or 4.141) had high luminance levels up to 890 lux, while the kitchen (4.G40) was measured to have 750 lux, which was between two and three times higher than the requirement standard.

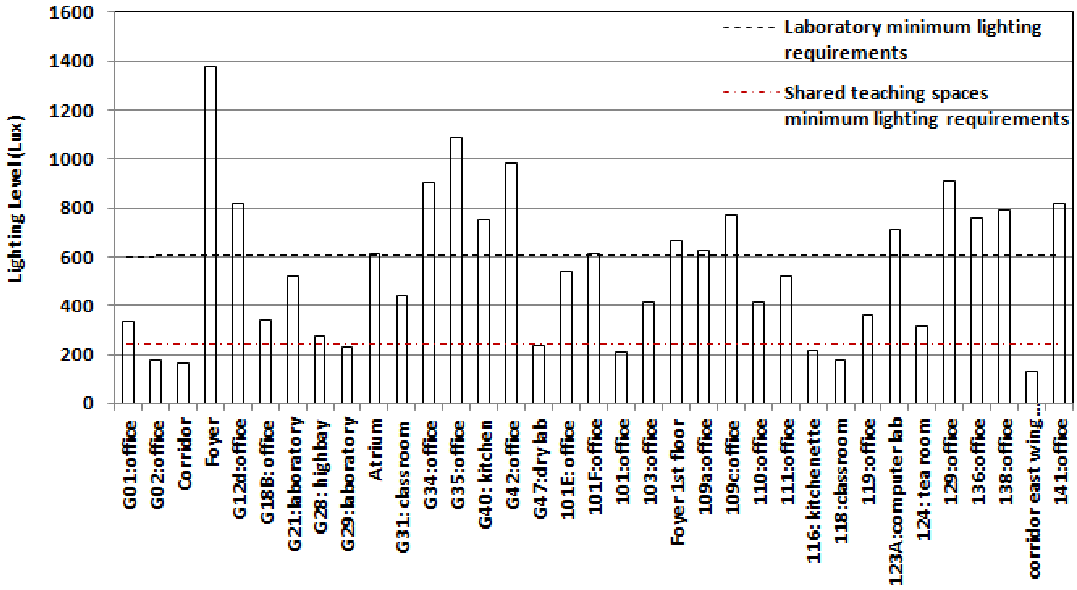


Figure 7.14 Lighting levels across different areas of Building 4.

7.3.5 Envelope Assessment

Air Permeability Test

A blower test was conducted on the 15th of February 2014 in the area corresponding to six conditioned offices on the first floor (see Figure 7.3). The results for the depressurisation and pressurisation test are shown in Figure 7.15. The air change rate obtained was 24.6 ACH (calculations following the ISO standard are attached in Appendix D). The results indicated an air permeability level three times higher than that recommended by the Air Tightness Testing and Measurements Association (ATTMA) for schools as standard practice (ATTMA 2010). This result was in line with air permeability tests conducted in six commercial buildings in Canberra (Egan 2011). In other words, air leakage in Australian buildings is much higher than those in Europe or the United States of America.

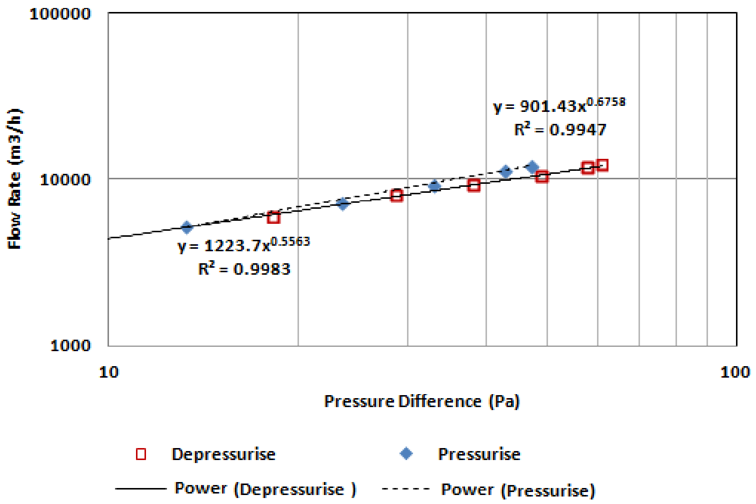
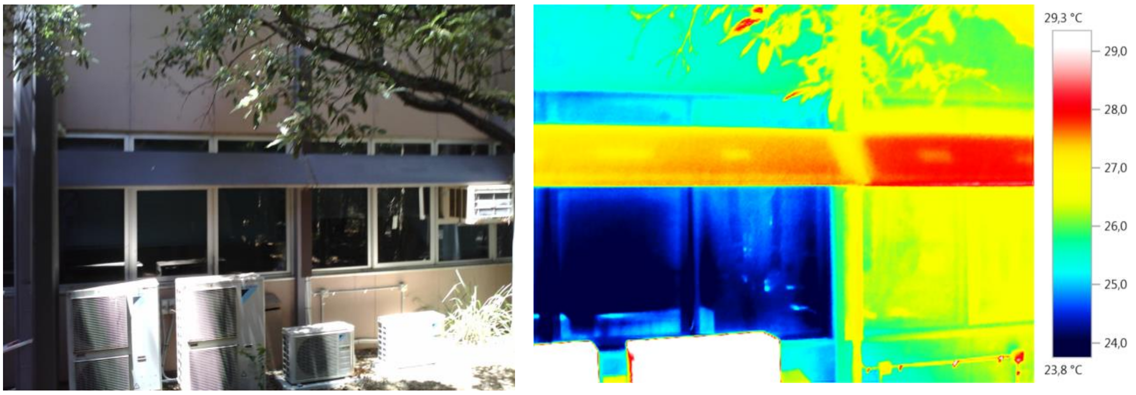


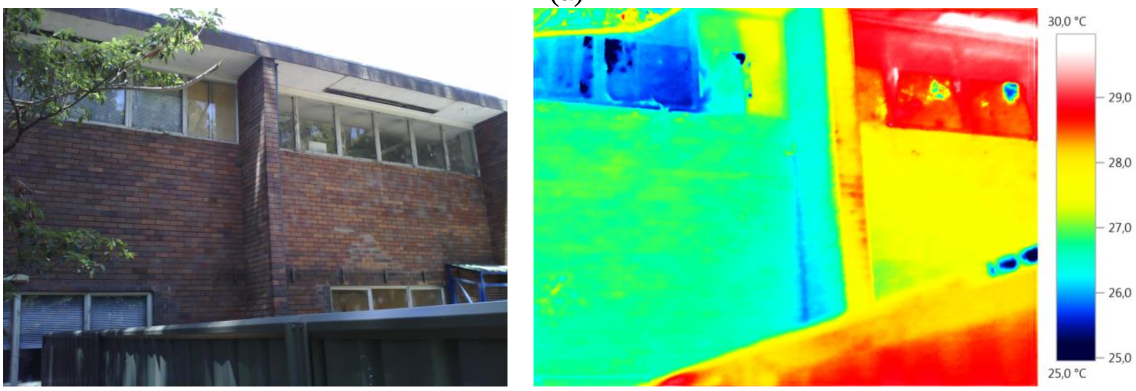
Figure 7.15 Depressurisation and pressurisation test.

Thermal-imaging

The thermal imaging taken outside and inside Building 4 (Figures 7.16 and 7.17) are discussed in this section, they were taken on the 15th of January 2014.



(a)



(b)

Figure 7.16 Visual photography and thermographic images of the western façade of Building 4 comparing non-air conditioned versus air conditioned spaces: a) north west and b) south west of Building 4.

Figure 7.16 shows the western façade of Building 4. Both images compared an air-conditioned to a non-air-conditioned space, and shows how cold air is being lost through the fabric and windows. The outside surface temperature for the air conditioned space was approximately two to three degrees lower than the non-air conditioned spaces, which indicated that the building has poor to non-existent thermal insulation because the heat escapes through the external walls.

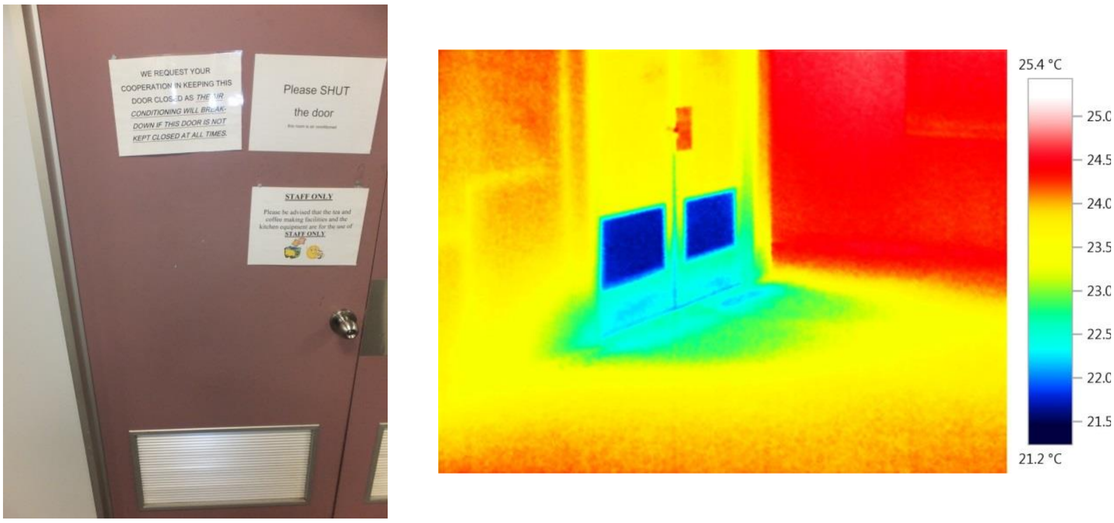
The U-value of various external walls was calculated using infrared images, using the approximate calculation method set out in *§6.2.1*. The surface temperature, T_s, of the wall, as measured using the thermographic camera, T_{in} is the indoor temperature measured through the iButton *A* located at the mezzanine and T_o is the outdoor air temperature measured by the weather station. The external heat transfer coefficient, h_s, was calculated using Jurges equation, where the wind velocity extracted from the onsite weather station at the time of the measurements was equal to 0.1:

$$h_s = 5.8 + 3.8054v = 6.18 \text{ W/m}^2 \ (v \text{ was } 0.1) \tag{7.1}$$

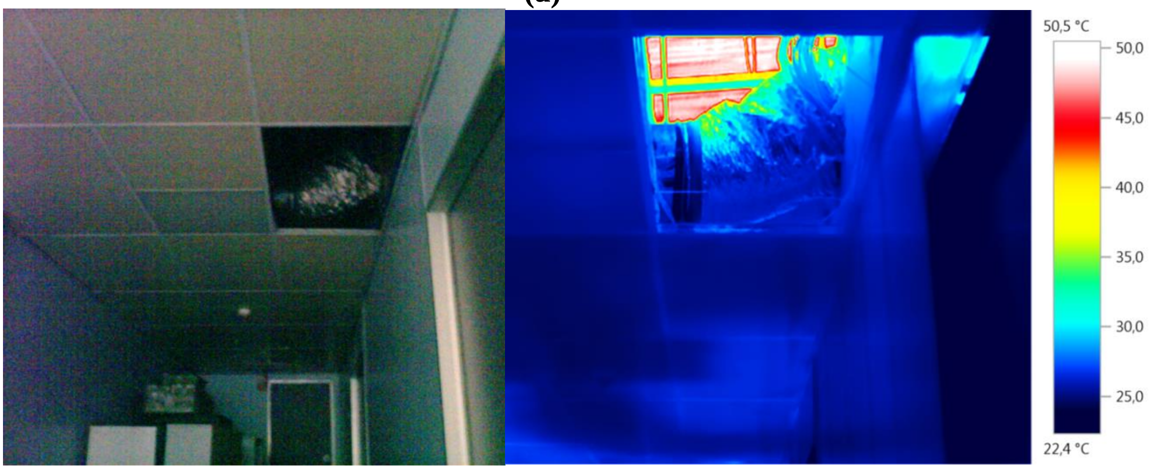
Following Eq. 6.3 *§6.2.1* the estimated heat transfer coefficient of the wall, U_w, is:

$$U_w = \frac{h_s(T_s - T_o)}{(T_{in} - T_o)} = \frac{6.18\ (27.1 - 25.71)}{(30.14 - 25.71)} = 1.93\ \text{W/ m}^2\ \text{K} \qquad (7.2)$$

The hand calculation of the heat transfer coefficient estimated to be U_w= 2.4 W/ m^2 K. Therefore, the value obtained was indicative of the heat transfer coefficient, and corroborated the idea of a poor thermal performance of the building fabric.



(a)



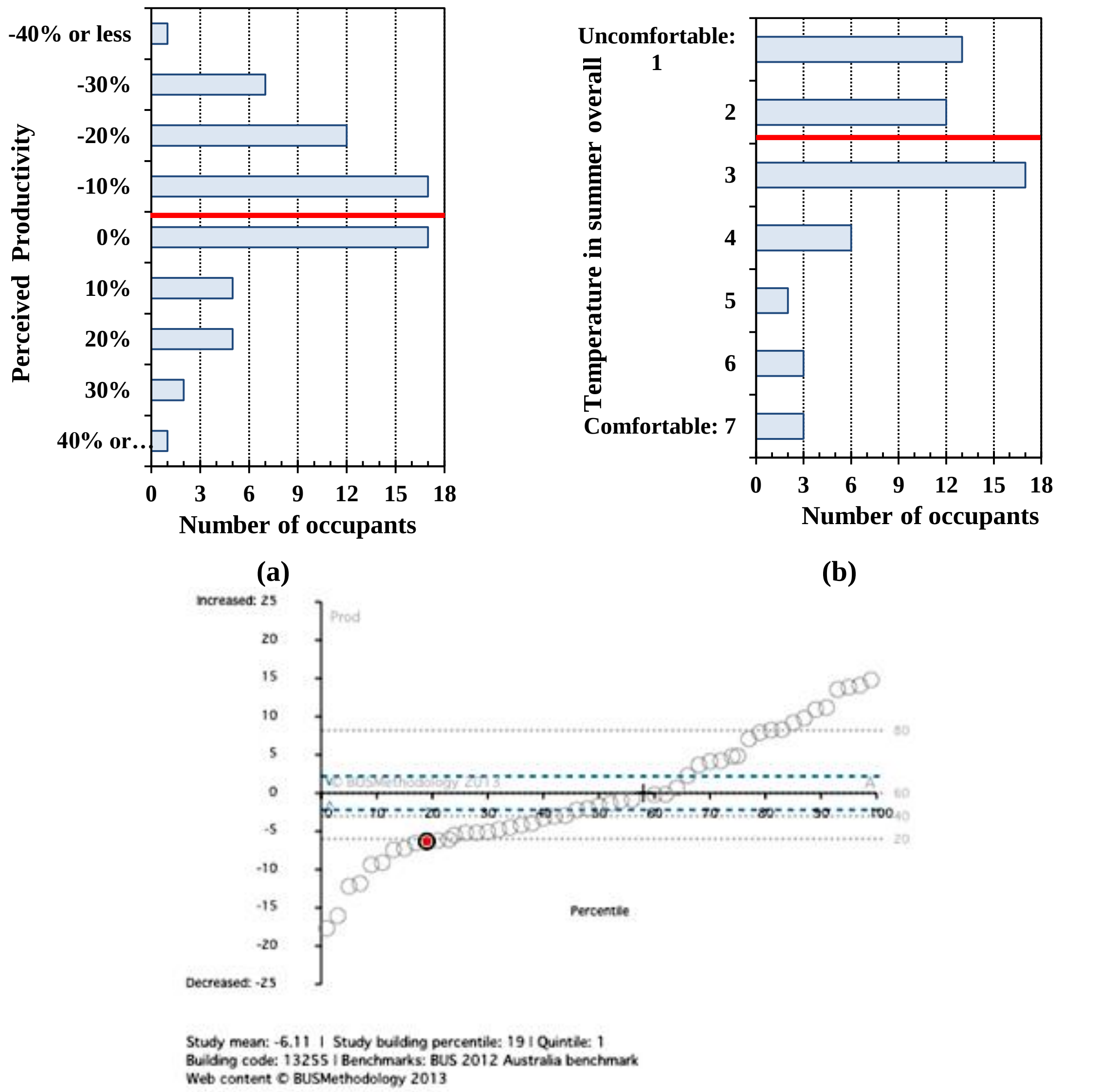
(b)

Figure 7.17 Visual and thermal photogrammetry of the interior of Building 4 showing: a) a door to a conditioned room and the corridor, and b) a duct in an uninsulated ceiling void.

Selected thermal images of Building 4 spaces are shown in Figure 7.17. Particularly the cold air from a conditioned room was escaping through the door grills (Figure 7.17a) and a duct from the air-conditioning system carrying cool air (Figure 7.17b). However, the duct is located inside an uninsulated ceiling void where the corrugated metal reached 50°C. It was appreciated that the top part of the duct was more than five degrees hotter than the lower part.

7.3.6 Occupant Perceptions - Post Occupancy Evaluation (POE) Results

Fifty-nine occupants, representing 62% of the total number of permanent building occupants, responded to the questionnaire in full (only five people did not answer some questions). Key results relating to productivity and thermal comfort are presented in Figure 7.18. The secondary axis relates to the mean of the total responses, which is graphed by a red straight line.



(c)

Figure 7.18 POE responses on a) productivity, b) comfort, in summer and c) productivity figure generated by the BUS method. Each dot represents a building in the BUS dataset. The coloured dot shows where Building 4 is situated in respect to other buildings. The dashed lines indicates each quartile in the dataset.

The productivity results (Figure 7.18a and Figure 7.18c) show the following:

- The average productivity loss perceived by the occupants due to the Building environment was approximately 6%.
- Half of the occupants surveyed rated the building as having a negative effect on their productivity.
- A quarter of the occupants surveyed felt that their perceived productivity increased by being in the building.

Building 4 falls into the bottom 20% of Australian buildings for perceived productivity in the BUS dataset. The typical temperature conditions in summer in an occupant's normal work area (Figure 7.14b) indicated that the overall temperature conditions in summer were poor, as almost ¾ of the occupants rated the overall summer comfort conditions as low. The discontent of the occupants concerning thermal comfort showed that the building fell into the bottom 10% of Australian buildings for perceived overall temperature in summer in the BUS dataset.

Analysis of occupants' comments

Qualitative feedback from the POE respondents provided a deeper understanding of the questionnaire results (Deuble & de Dear 2014). Space for optional additional comments was provided in the BUS questionnaires. Using a similar method to analyse occupant's comments and feedback, as presented by Moezzi and Goins (2011), the feedback collected through the POE was analysed based on themes that emerged through a key words search. Table 7.3 summarises the negative comments category, and the key words used to identify the theme.

A total of 125 complaints were recorded. Thermal comfort was the issue reported most by the Building 4 occupants with 43% of the feedback describing the building as either "*too hot*", "*too cold*" or both. Additionally, occupants complained about not having an air-conditioning despite being thermally uncomfortable. However, respondents' in air-conditioning offices reported frustration with not being able to control the air-conditioning and adjust it to a more suitable temperature. As an example, one of the occupants mentioned the following: '*I turn on the heater in the middle of summer and dress more heavily. It is colder inside than outside*.'

More than half of the respondents (51%) stated they changed their behaviour due to the thermally uncomfortable conditions in the building. Adaptation strategies or leaving the office to work from home were the most cited measures used to tolerate the thermal

discomfort, e.g. '*I try to wear suitable cloths, keep [drinking] water, go to cooler (air-conditioning) areas*', '*I used to go home if it was too hot. Now I still bring appropriate clothes, use fan, open/close windows or doors*' or '*Sometimes it is too cold in the room although is warm outside, so I have to wear a lot of clothes.*'

Complaints about noise made up 22.4% of the negative feedback. Typically, noise coming from colleagues was an issue either because of the proximity of a shared space or coming from adjacent laboratories. As an example "*I [an occupant of a shared office] cannot have phone call or chat with someone without disturbing everyone else*", some measures used to minimise noise were cited as "*I come frequently at night to avoid the noisy day time" or "I use headphones*".

Air quality was another issue, with 21.6% of the complaints being due to poor ventilation or stuffy office spaces, e.g. "*there is no air circulation*", "*it is dusty, and dirty. In some periods we have ants invasion with nests in the offices*".

Visual comfort received the least amount of complaints with 12.8%. No natural light was the biggest issue, e.g. "*I think more sunlight would be perfect (my windows are internal)*", "*No natural light & no windows!*" or "*I cannot even see a window from my desk- more natural light/windows needed*".

Table 7.6 Negative comments provided in the POE grouped by themes, with the key words used to find the complaint, the percentage of occupants complaining about the issue, and the reasons given by the occupants.

Themes	Key words	Percentage (n=125 complaints)	Common reason
Thermal comfort	Hot, cold, heat, air-conditioning	54 (43.2%)	Office is too hot or too cold, no air-conditioning installed, air-conditioning is not in the correct set-point/unable to control it.
Air quality	Air circulation, ventilation, fresh air	27 (21.6%)	Poor air circulation, poor ventilation, dusty air, stuffy and humid office.
Noise	Noise, talking	28 (22.4%)	Neighbouring offices or corridor talks, shared offices, outside noise
Lighting	Light, glare	16 (12.8%)	Lighting insufficient or too bright, glare at certain times, no natural light.

The following section investigates possible correlations between the POE subjective answers and the thermal comfort monitoring results.

Correlation of Subjective and Objective Measurements

Objective monitored temperatures conducted from the 1st of November 2013 to the 21st of January 2014 were correlated with the POE subjective answers obtained between the 5th and 7th of December 2014, whenever possible, that is; where a specific occupant who voluntarily answered the survey also had the temperature monitored in their office. Due to monitoring period, i.e. summer, the correlations have been investigated with the occupants' perceived comfort in summer. However, mean satisfaction of the occupants with overall winter temperature was 4.11, which in a 7-point scale indicated neither comfortable not uncomfortable. Alternative, mean satisfaction of the occupants with overall summer temperature was 2.7, revealing high levels of dissatisfaction from the occupants with indoor summer temperatures. Due to the limited available data in the literature relating perceived comfort, productivity and time outside the comfort zone, the linear best fits correlating the studied variables were arbitrary and represented an indication of the strength of the relationship.

The relationship between the percentage of time an occupant's space was outside the UOW established comfort bands (i.e. from 20°C to 26°C) and the occupant's response as to their perceived overall comfort (where 1 was uncomfortable and 7 represents comfortable) is shown in Figure 7.19.

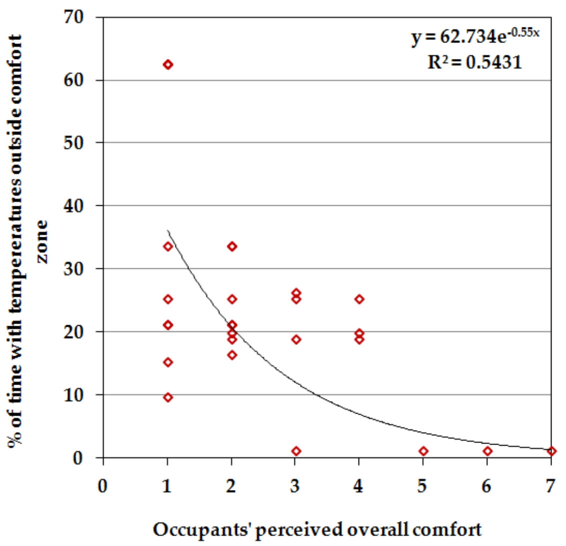


Figure 7.19 Correlation between the monitored percentage of time outside the comfort zone against the occupant's survey answer on their perceived comfort in summer.

There was a relatively strong positive relationship which showed that for rooms with temperatures outside the comfort zone for a high percentage of time, then occupants perceived themselves as being uncomfortable.

Figure 7.20a relates the percentage of time outside the UOW established comfort bands with the occupants' response on their perceived overall productivity, where 1 was defined as the building conditions reduced perceived productivity by 40% or more and 8 indicates that the building increased the perceived productivity by 40% or more. Figure 7.20b) correlates the percentage of time spent outside the UOW established comfort bands with the occupants' response on their perceived overall health, where 1 was defined as the building conditions made the occupant feel less healthy and 7 indicated that the building conditions resulted in the occupant feeling healthier.

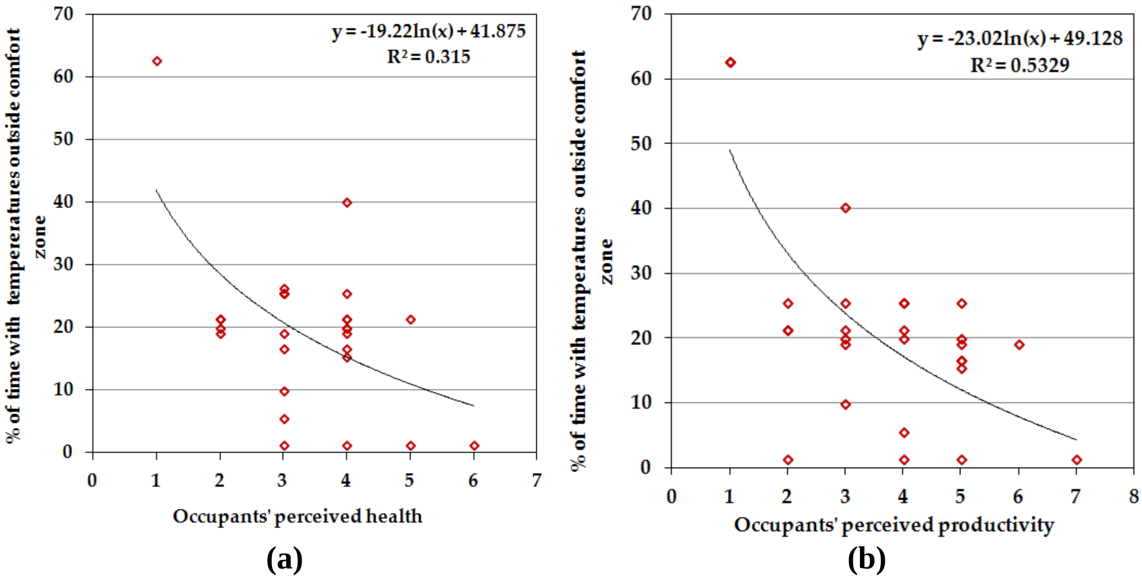


Figure 7.20 Correlation between the monitored percentage of time outside the comfort zone against the occupant's survey answer on the perceived (a) productivity and (b) health.

A moderately positive relationship was observed in both cases, and the Spearman correlation coefficient showed a strong statistically significant relationship, 0.5 for perceived health and 0.6 for perceived productivity. These relationships indicated that a high percentage of time with temperatures outside the comfort zone typically led to a decrease in the occupants' perceived productivity as well as health. This means that thermal comfort was a major issue because it was connected not only to the occupants' overall satisfaction with their environment but also to the productivity and health of the staff and postgraduate students working in the building. This was important because for an Australian university, staff wages account for approximately 64% of their total expenditure (Heaton & Throsby 1997), so a small increase in productivity is more economically attractive than a much larger reduction in electricity costs (Horne & Hu 2008). It should be noted that measuring productivity is complex and there is uncertainty over the results, but the self-estimated productivity obtained through the

Post Occupancy Evaluations demonstrated it to be a tool that is widely used to rate productivity (Khalil & Husin 2009; Peretti & Schiavon 2011; Deuble & de Dear 2012).

7.4 Building Simulation as Investigative Tool: Initial Modelling Results to avoid air -conditioning

Before applying the optimal retrofit methodology, the approach currently undertaken by Australian practitioners as stated by Daly (2014) to select a retrofit or set of retrofits measures via building simulation was implemented. This entailed investigating the effectiveness of a range of a typically used Energy Conservation Measures (ECMs) that can be potentially employed to improve energy performance and thermal comfort of existing university buildings. This investigation aimed to a) understand if the implemented air-conditioning in the north facing offices of the east wing could have been avoided through alternative upgrades via assessing thermal comfort in offices 4.129 and 4.130 (as if no air-conditioning system was installed) and b) to compare piecemeal retrofits implementation as oppose to the method proposed in this work.

7.4.1 Methodology

Overall Modelling Structure and Process

A schematic of the modelling method employed in this section is shown in Figure 7.21.

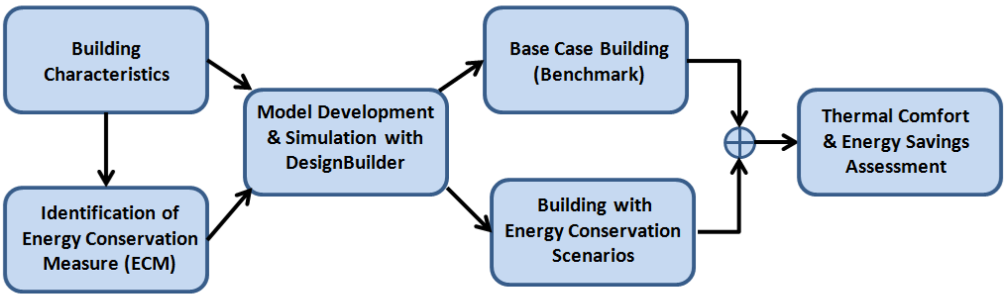


Figure 7.21 Schematic of the modelling method employed.

Firstly, a range of ECMs, as summarised in Table 7.7, were identified based on the characteristics of the audited building. Secondly, a full scale building simulation model which represented the case study building was developed using the building energy simulation software DesignBuilder. Thirdly, the performance of the building without implementation of any ECMs was evaluated and its performance was used as the benchmark. Lastly, different energy conservation scenarios were incorporated into the simulation model and the building energy performance and thermal comfort were then evaluated by comparing with that of the benchmark to provide a qualitative level of

validation.

Table 7.7 Energy Conservation Measure (ECM) Scenarios considered

Scenario	Energy Conservation Measures
I	Base case without implementation of any energy conservation measures
II	Occupant behaviour measures (i.e. Shut down IT equipment overnight, night purge and switch off the lighting when daylight is available).
III	IT equipment and lighting upgrades
IV	Combination of occupant behaviour measures with IT equipment and lighting upgrades.

Model Development

The model focused on the east wing of Building 4 (Figure 7.22). The geometry of the ground floor constructed with DesignBuilder is illustrated in Figure 7.23. The settings used in the model development were as follows:

i) The building occupancy schedule was defined as 8:00am to 18:00pm Monday-Friday.

ii) Natural ventilation was set as "calculated", i.e. the ventilation rate and infiltration are calculated based on the wind and buoyancy-driven pressure, opening sizes and operation, crack sizes, etc.

iii) The IWEC Sydney weather data file was used as a representative for Wollongong climate. A modification was made in the file while conducting the calibration. To validate the model predictions against the indoor experimental temperatures, the collected outside dry bulb temperature from Bellambi weather station was used in the IWEC.

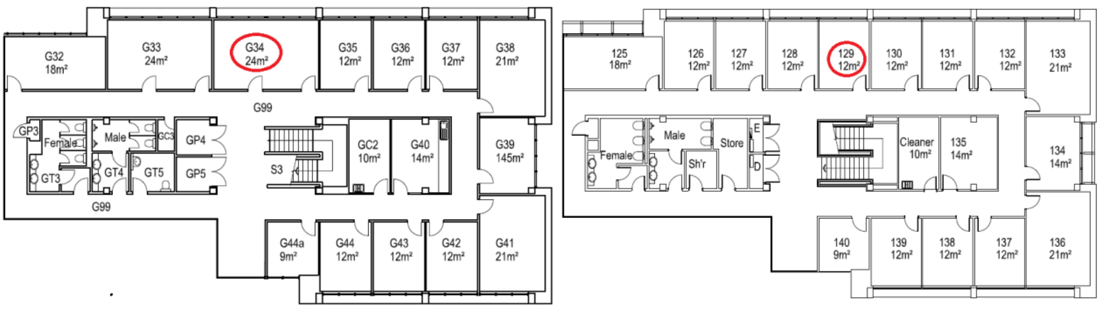


Figure 7.22 Ground and first floor plans of case study building.

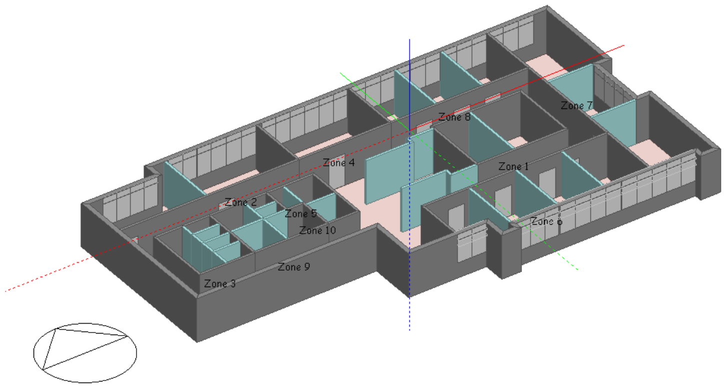


Figure 7.23 Sketch of the ground floor geometry of the case study building.

The building thermal performance was tested and compared to actual measurements in several rooms and the energy performance was estimated for the building as a whole. Room 4.G34 in the ground floor and room 4.129 in the first floor were selected as representative rooms to demonstrate the occupants' thermal comfort by using different energy conservation scenarios. The building internal loads before and after the implementation of ECMs are summarized in Table 7.8.

Table 7.8 Summary of Internal loads before and after the application of the ECMs.

Internal load	Number		Base Case		Upgrades	
	4.G34	4.129	Item description	Average power consumption (W)	Item description	Average power consumption (W)
Office IT equipment	6	-	DELL – Optiplex 755 MT	50	DELL – Optiplex FX 170	10
	6	-	Monitor-Display 1905 FP	40	Monitor - Display IN1930F	13.5
	-	2	Monitor-U2410	64		
	-	1	DELL-Precision T3500	128	DELL Precision T5500	98
	-	1	Laptop Dell Precision M45100	17	Laptop Dell Precision M45100	17
Lighting	10	9	T8 1200 mm	36	T5 1200mm	28
	corridor: 75 x two floors		T8 600mm	24	T5 600mm	18

7.4.2 Comparison of experimental and predicted room temperatures

Before the implementation of ECMs, the performance of the simulation model was compared with monitored experimental data (i.e. indoor temperature) collected with a data logger via a thermocouple located in room 4.G34 (*§7.2* Figure 7.3). Figure 7.24

shows the model predicted and experimental cumulative frequency indoor temperatures for ten days in February (i.e. 15-02-2011 to 25-02-2011). It was found that the model gave results that matched reasonably well with the experimental data for most data points. However, in this first phase of the present study, where only limited data was available on weather and behaviour of occupants (e.g. experimental hourly solar radiation and wind data was not available and the actual internal heat gains due to occupant activities could not be accurately assessed as this modelling was conducted prior the installation of the weather station). Nevertheless the results from the building simulation model gave a reasonably close agreement on the basis of cumulative frequency of hours in the year that the representative rooms were above a given temperature.

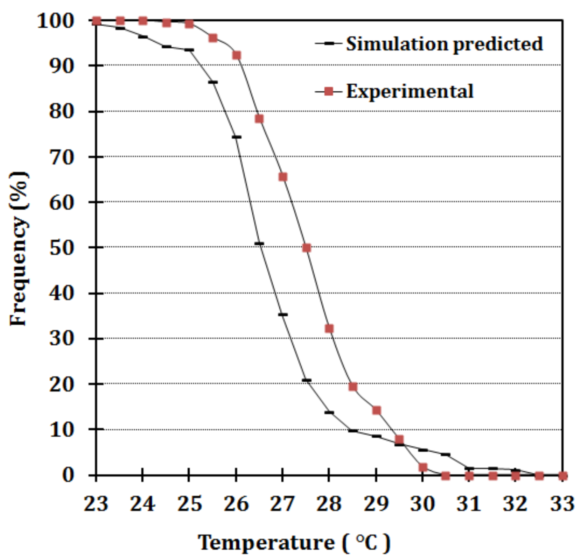


Figure 7.24 Comparison of predicted and experimental cumulative frequency of experimental and predicted temperature in ground floor room 4.G34.

7.4.3 Results and Discussion

The results and analysis of the aforementioned energy conservation scenarios tested in the case study building are presented in this section. The predicted building energy consumption is given for each scenario and together with the potential estimated energy savings. The thermal comfort was assessed by calculating the overheating risk, i.e. operative temperature above 28°C during occupied hours (Race 2006), and subsequently by the adaptive based comfort zones defined in ASHRAE Standard 55 and EN15251 European Standard.

Energy Performance Analysis

The potential energy savings from the computers and lighting by using different energy conservation scenarios are shown in Figure 7.25.

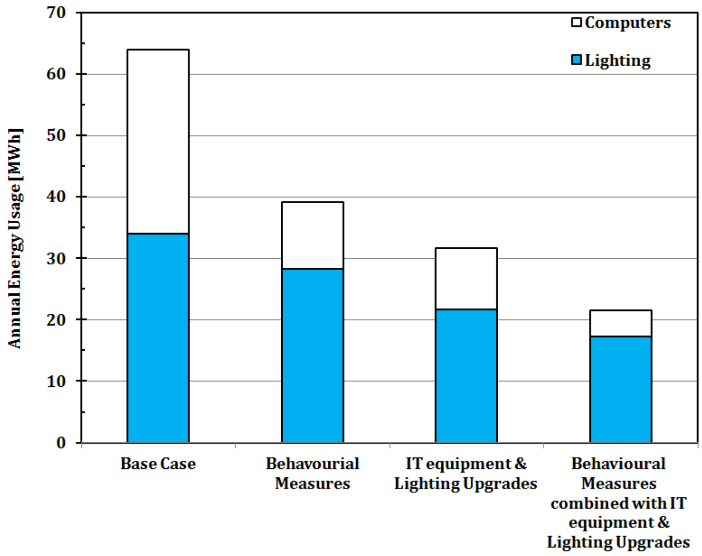


Figure 7.25 Annual energy consumption by using different energy conservation scenarios.

The energy consumption of the base case is illustrated for comparison with the different scenarios. Compared to the base case condition, up to 65% of total energy can be saved by combining the IT equipment & lighting upgrades with behavioural measures. Implementing behavioural measures is predicted to achieve 40% energy savings, while the upgrading of IT equipment & lighting can potentially reduce energy consumption by 50%.

Overheating Hours and Adaptive Thermal Comfort

Overheating Hours

The cumulative hours exceeding a given operative temperature for rooms 4.G34 and 4.129 are presented in Figure 7.26. The indoor operative temperatures for the base case demonstrated that the building has significant overheating problems since around 5% and 9% of the occupied time the operative room temperatures for the rooms 4.G34 and 4.129 was predicted to be above 28°C, respectively.

Compared to the base case, the overheating hours decreased significantly when the ECMs were applied. For instance, the maximum reduction in the temperature above 28°C was obtained with the incorporation of the behavioural measures together with the IT and lighting upgrades. The model predicted a decrease in the number of hours the

temperature exceeded 28°C of approximately 60% and 75% for the rooms 4.G34 and 4.129, respectively. Therefore, when behavioural measures combines with the IT and lighting upgrades are implemented, the building would not suffer a significant overheating risk.

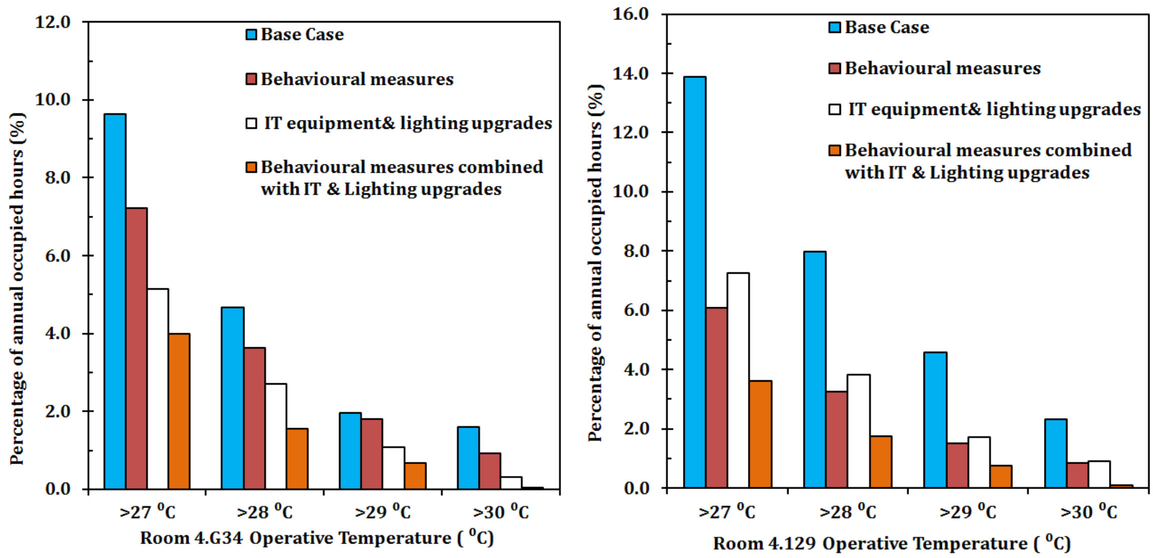


Figure 7.26 Percentage of occupied hours (i.e. from 8am to 6pm weekdays) that internal temperatures are exceeded for different ECM scenarios.

Adaptive Thermal Comfort

Adaptive thermal comfort may be determined from algorithms given in standards such as ASHRAE Standard 55 and EN15251 (§*2.4.1*).

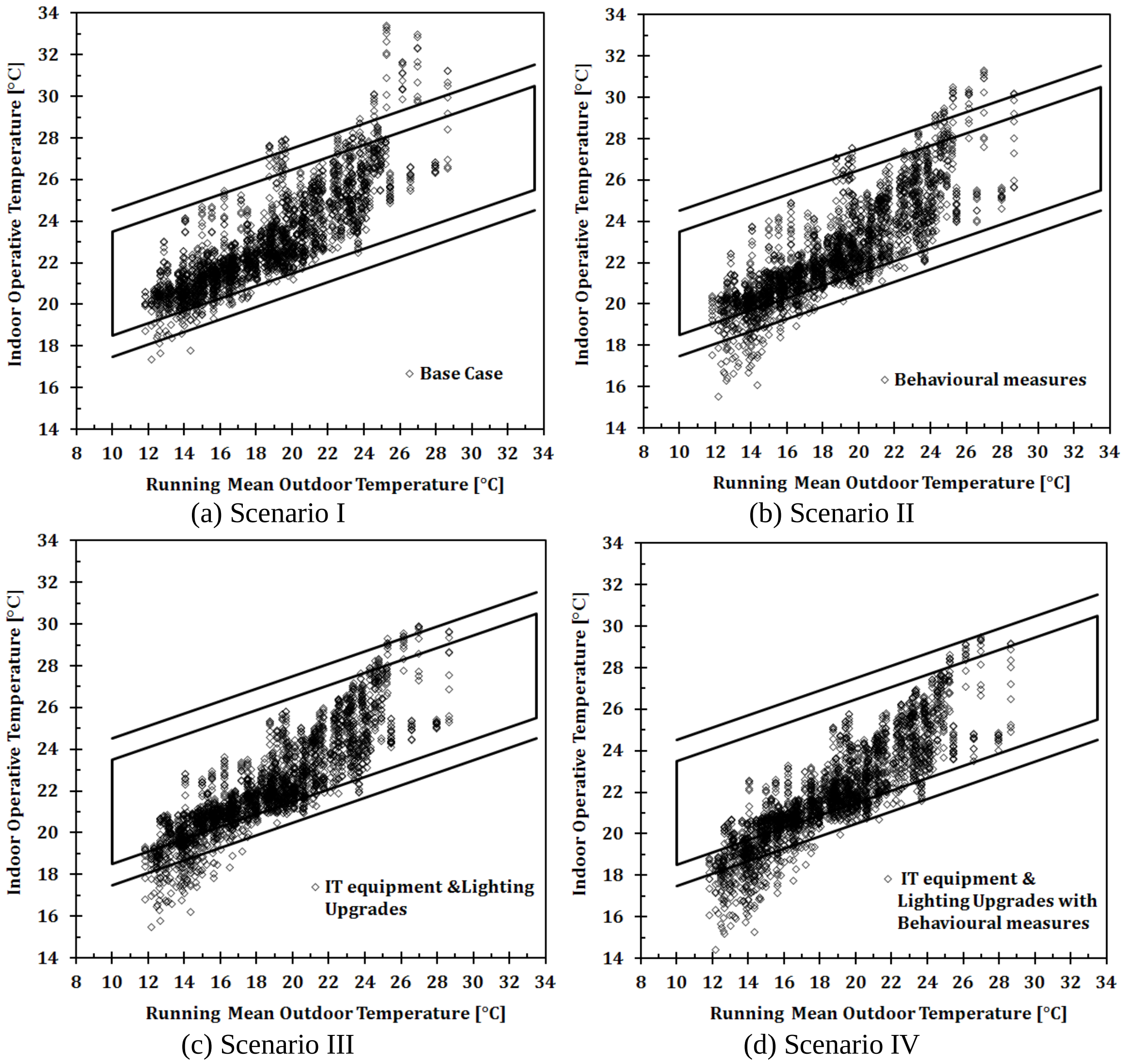
The simulation results for room 4.G34 and room 4.129 are shown against adaptive thermal comfort zones of ASHRAE Standard 55 in Figure 7.27 and 7.28 and against the adaptive thermal comfort zones of EN15251 in Figure 7.29 and 7.30. It should be noted that the ASHRAE chart is slightly modified as it is expressed in terms of the running mean outdoor temperature instead of the monthly mean outdoor temperature. The running mean outdoor temperature, as expressed in Eq.1, is able to handle diurnally changing weather conditions as it is a weighted average of the previous days (Nicol & Humphreys, 2010) rather than a monthly average.

The running mean temperature is defined according to EN15251 (2007) as in Equation 7.3. Equation 7.4 can be used where records of daily mean external temperature are not available. In this study, this formula is applied for the first 7 days and then Equation 7.3 is used.

$$T_{rm} = (1 - \alpha)T_{rm} - \alpha T_{rm-1} \qquad (7.3)$$

$$T_{rm} = (T_{ed-1} + 0.8T_{ed-2} + 0.6T_{ed-3} + 0.5T_{ed-4} + 0.4T_{ed-5} + 0.3T_{ed-6} + +0.2T_{ed-7})/3.8 \quad (7.4)$$

where T_{rm} is the running mean temperature for the ith day; T_{rm-1} is the running mean temperature for the ith-1 day; T_{ed-1} is the daily mean external temperature for the ith-1 day; T_{ed-2} =is the daily mean external temperature for the ith-2; α =is a constant lower than 1 (recommended to use 0.8). The derivations of the acceptability limits for both standards can be found in CEN (2007) and ASHRAE (2004).



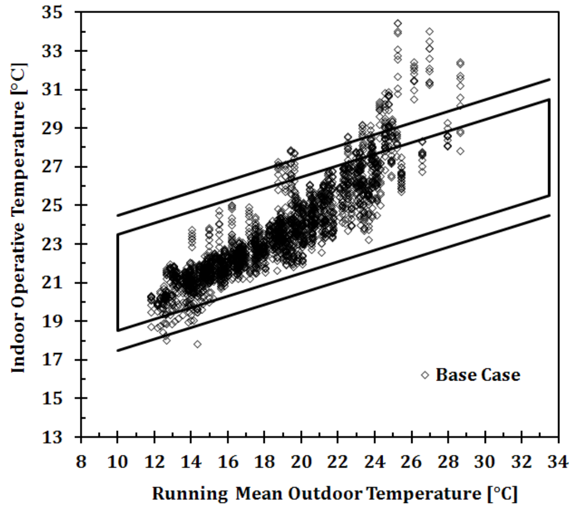
(a) Scenario I (b) Scenario II

(c) Scenario III (d) Scenario IV

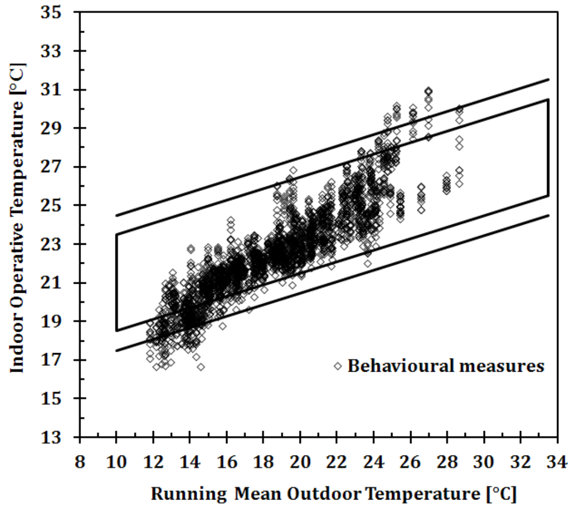
Figure 7.27 Adaptive comfort zones for ASHRAE 55-2004 with the annual indoor operative temperature for room 4.G34 during occupied hours under the different scenarios.

The simulations reveal that each of the implemented energy efficiency measures decreases the overall indoor operative temperatures in the ground floor and first floor rooms throughout the year compared to the base case. This was especially significant during the summer season, in agreement with the reduction in the overheating hours shown in Figure 7.27.

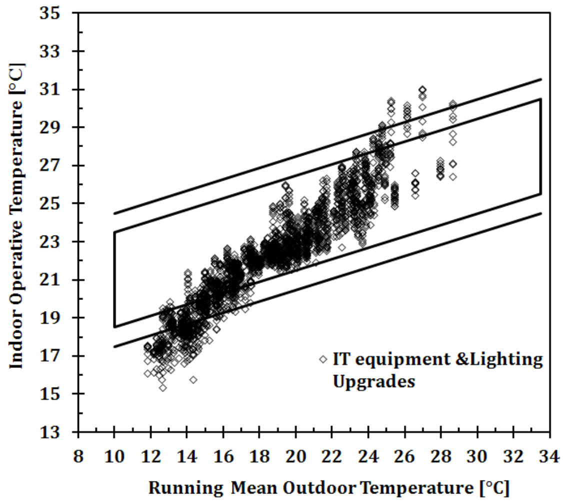
One interesting outcome of the implemented ECMs is the decrease in the indoor temperatures throughout the year including winter and the lower adequacy limits of the adaptive thermal comfort during winter are not fully met. This issue will be addressed in future work by modelling improvements to the building envelop or incorporating heating in the model during the cold period.



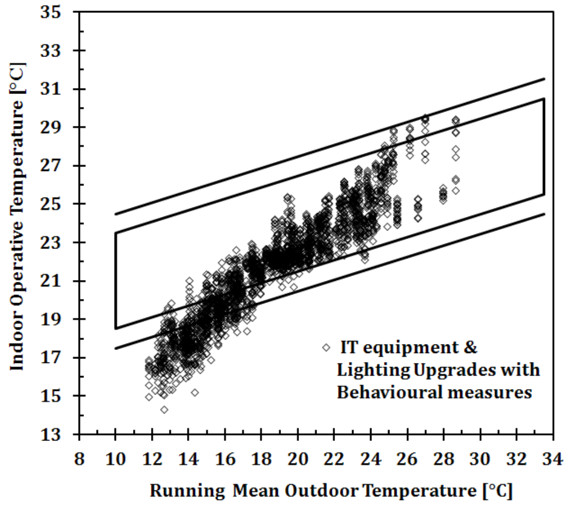
(a) Scenario I



(b) Scenario II



(c) Scenario III

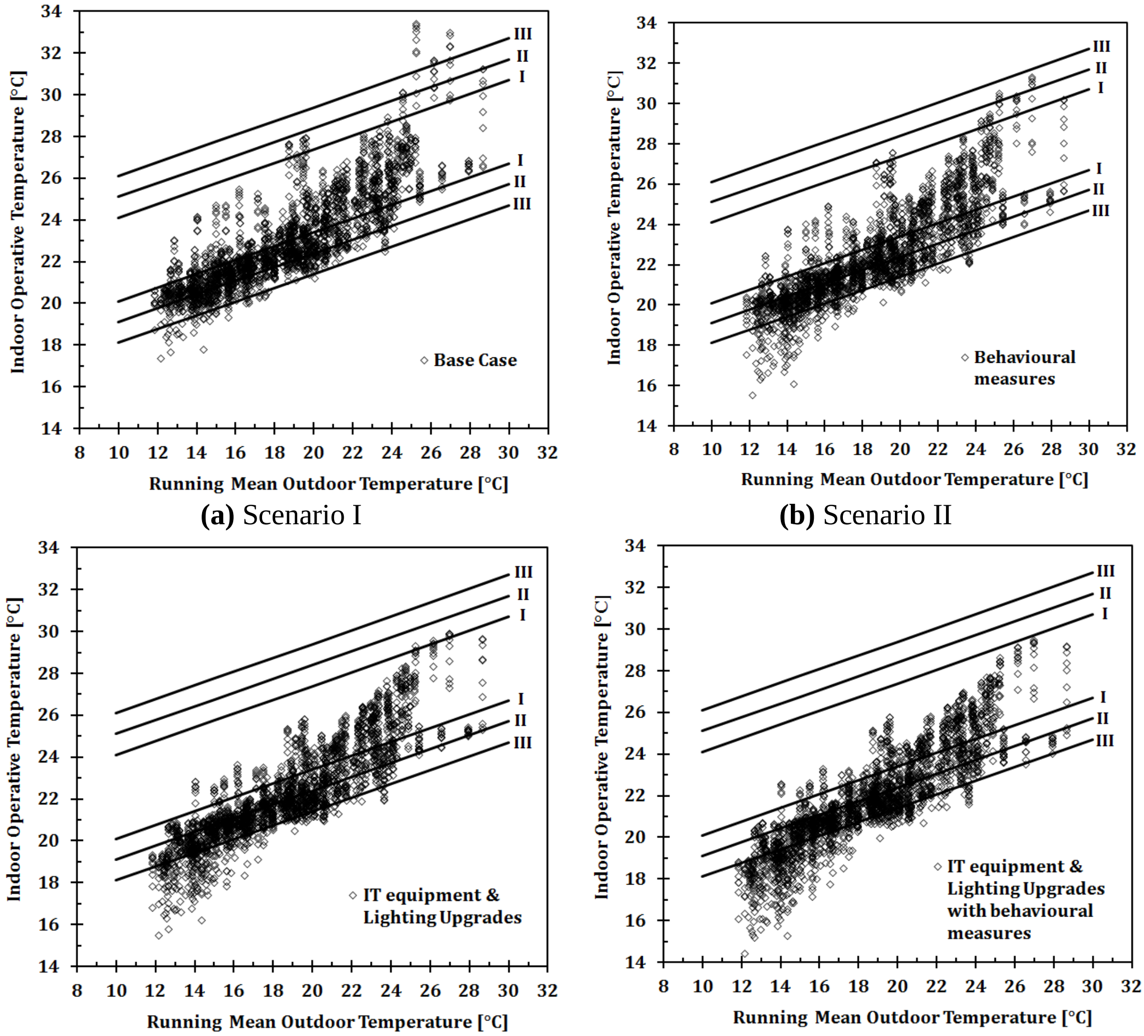


(d) Scenario IV

Figure 7.28 Adaptive comfort zones for ASHRAE 55-2004 with the annual indoor operative temperature for room 4.129 during occupied hours under the different scenarios.

Figure 7.27 for the building's ground floor shows that the incorporation of behavioural measures (Figure 7.27b) resulted in a significant decrease of warm hours outside the comfort zone in comparison with the base case. Three of the scenarios permitted maintenance of thermal comfort during summer within the 80% acceptability requirement, i.e. through upgrades in IT equipment & lighting (Figure 7.27c),

combination of IT equipment & lighting upgrades with behavioural measures (Figure 7.27d).



(a) Scenario I **(b)** Scenario II

(c) Scenario III **(d)** Scenario IV

Figure 7.29 Adaptive comfort zones for EN 15251b with the annual indoor operative temperature for the ground floor room 4.G34 during occupied hours under the different scenarios.

Simulations of the first floor room indicated warmer temperatures than the ground floor (see Figure 7.28). However, the predicted temperature trend for the implemented ECMs showed very similar trends as for the ground floor. The first floor achieved a significant reduction of the summer days outside of the comfort bands with the behavioural measures and IT & lighting upgrades (Figure 7.28b and 7.28c, respectively). The completely satisfactory thermal comfort for summer was reached by implementing the behavioural measures together with IT equipment and lighting upgrades (Figure 7.28d).

When the European Standard was used to correlate the simulated temperature data, the hours within the comfort zone for the summer period increased as compared to case of

using the ASHRAE Standard. It is observed that, all the warm seasons are within the comfort zone for both rooms (Figure 7.29 and Figure 7.30), when the proposed ECMs are simulated.

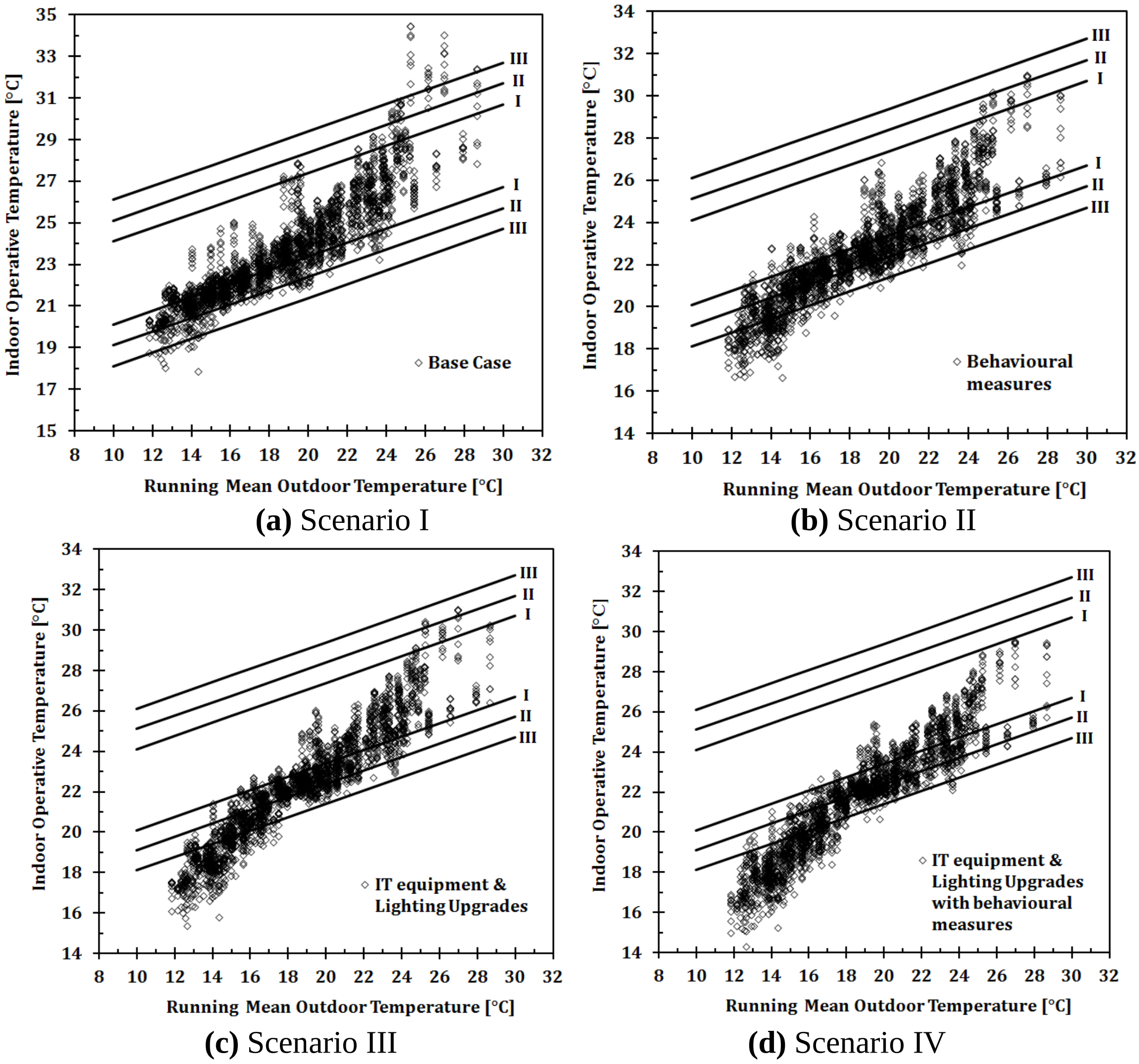


Figure 7.30 Adaptive comfort zones for EN 15251 with the annual indoor operative temperature for room 4.129 during occupied hours under the different scenarios.

The implementation of the IT equipment & lighting upgrades would require a capital investment. A detailed cost-benefit analysis is therefore needed to help the energy management team to determine the best retrofit options. This has yet to be completed. Nevertheless, the implementation of the proposed ECMs could potentially save significant capital expenditure by removing the need to install air-conditioning systems to avoid occupant complaints from overheating during summer. However, the reduction of internal loads does lead to a predicted increase in winter heating requirements, which

in turn could be reduced by improving the thermal performance of the building envelope.

A noticeable increase in days with indoor temperatures outside the comfort zone for both Standards during the cold season appeared with the implementation of the ECMs. Hence, it was decided to add some heating in the model predictions to increase the temperature during the cold season and achieve satisfactory levels of thermal comfort. The heating was included together with all the energy efficiency measures for the ground (Fig. 10) and first (Fig. 11) floor. Additionally, the energy consumption was examined to study the feasibility of incorporating heating during the cold months.

If the heating is incorporated in the model, the ASHRAE standard is no longer valid as the application is condition to a purely naturally ventilated building without any kind of cooling or heating. In contrast the European Standard permits periods with heating/cooling. Nevertheless, the ASHRAE template is kept to demonstrate the temperature change with heater use.

he electric heaters were modelled with a temperature set point of 20 ^{0}C. It should be noted that some cold days the indoor temperature was below 20 ^{0}C at the start of the working day as it takes some time to warm up the office once the heater is switched on.

The improvement of both rooms was remarkable as the majority of the days are within the thermal comfort limits. For the ground floor (Fig. A) a consistently increase in temperature of the cold months is noticed. The first floor (Fig. B) displays hardly any day outside of the comfort zone.

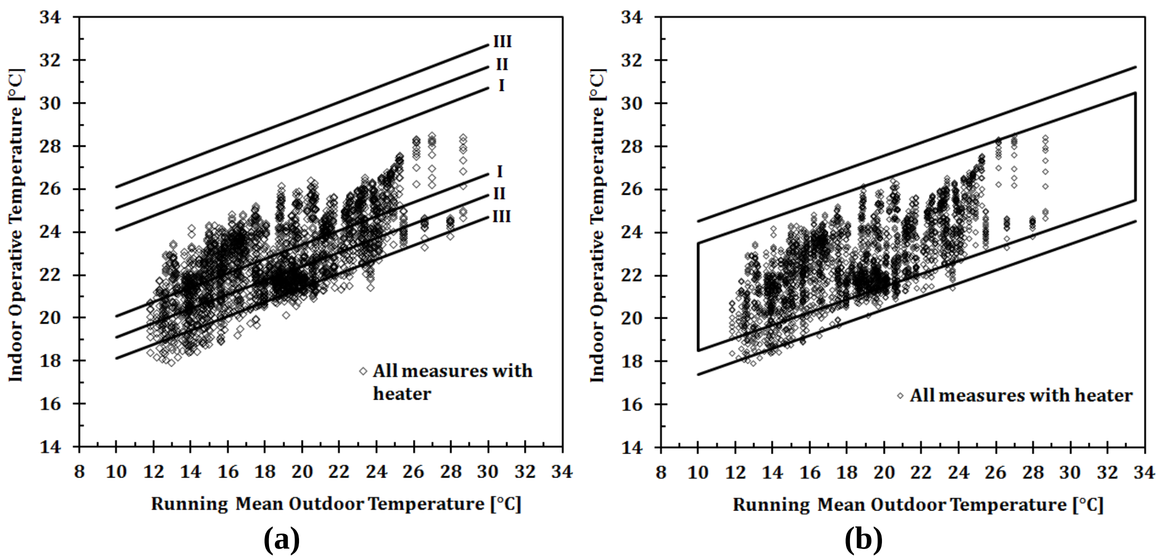


Figure 7.31 Adaptive comfort zones for EN 15251 with the annual indoor operative

temperature for room 4.129 during occupied hours under the different scenarios.

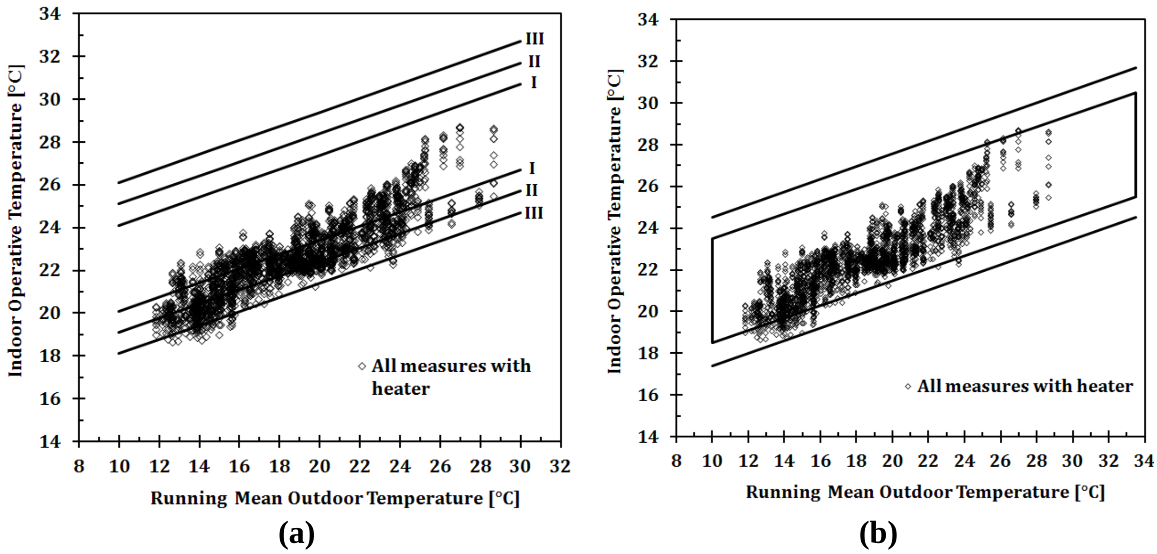


Figure 7.32 Adaptive comfort zones in office 4.129 with all the energy efficiency measures and heaters on for (a) EN15251 and (b) ASHRAE 55-2004.

Energy savings of all the ECMs including heating

All the energy savings for the different retrofit measures are presented in Fig. 7.33. The energy savings if the heaters are incorporated with all the retrofits measures are slightly below than all the retrofit measures by themselves due to the heaters electricity consumption. The heating energy consumption represented 11% of the total energy consumption. To this end, the energy savings is still as high as ~60% compared to the base case building.

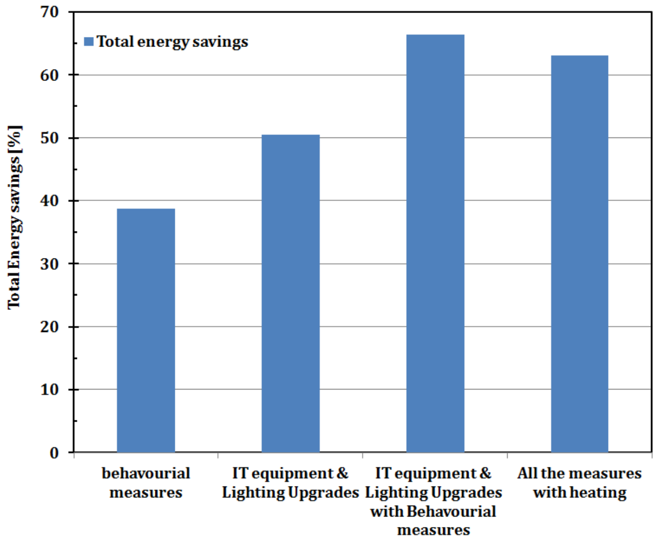


Figure 7.33 Annual percentage of energy savings per each measure compared to the base case.

7.4.4 Conclusions of Initial Modelling

The following conclusions from assessing the effectiveness of a range of Energy Conservation Measures (ECMs) implemented in the east wing of Building 4 as if the air-conditioning system would not have been installed, i.e. as if the building was naturally ventilated, can be drawn:

- Significant energy savings could potentially be achieved by implementing occupant behavioural measures or the IT equipment & lighting upgrades. The combination of both ECMs simultaneously can provide up to 65% energy savings compared to the base case. The equipment upgrades offer a higher energy saving potential (i.e. 10% more savings) than the behaviour change measures, however the investments required to ensure the success of each measure are significantly different. It should be noted that costs for retrofits implementation were not considered in this initial evaluation.
- Two adaptive thermal comfort standards, ASHRAE Standard 55 and EN15251, were used to correlate the thermal results from the simulations. These standards were found to be extremely useful in providing a clear picture of occupant comfort conditions as a function of monthly/seasonal outdoor temperature variations.
- Summer overheating hours were predicted to be reduced significantly with the implementation of the behavioural measures and/or the IT equipment& lighting upgrades that have been proposed and modelled above. The simulations indicated that acceptable comfort conditions, within the bands defined by the ASHRAE and European Standards, can be achieved over the summer months through these ECMs. Therefore, the incorporation of relatively simple interventions and behavioural modifications in the management of the building could avoid the need for retrofitting of air-conditioning systems with a significant reduction in capital and operating costs into the future.
- The use of simple electric heaters, with a COP of 1, during the cold periods together with all the ECMs were predicted to enhance thermal comfort throughout the year. In addition, energy savings were as high as 60% compared to the baseline building

- The changes to occupants' behaviours regarding energy consumption could result in significant energy savings without requiring any additional costs. However, there are many barriers hindering occupant behaviour modification. The UOW Environmental Sustainability Initiatives (ESI) unit is in the process of establishing a range of strategies to inform, educate and motivate the building occupants to drive behavioural transformation.

7.5 Summary

The approach to evaluating the building performance described in Chapter 6 was applied to a case study building, namely Building 4. Empirical results for energy and water consumption, thermal comfort, air quality, lighting and acoustics have been presented. The data acquired enabled a building baseline to be established and the problematic spaces needing improvement to be identified. The audit revealed information about the building across a number of indicators, e.g. the building envelope had a poor thermal performance probably due to it being poorly insulated; only sarking could be found in the roof. The air-tightness was poor and during summer most of the occupants felt quite uncomfortable. Moreover, the occupants perceived their productivity and health to decrease when they were inside the building, and on some occasions they preferred working at home because of the building's poor thermal comfort.

Initial simulations were conducted in the east wing of Building 4 to investigate if the implementation of air-conditioning could have been avoided through implementing alternative passive upgrades. Results demonstrated that the ECMs proposed could have very positive effects on both energy consumption and thermal comfort in naturally ventilated university buildings in regions with climates similar to the Sydney/Wollongong area, as the required levels of thermal comfort were reached. However, there were some limitations in this initial study, e.g. implementation or operational costs were not considered in the assessment and therefore it is improbable that the suggested retrofits combination provided the minimal costs while improving the thermal comfort, due to the uncountable combinations. This is to be investigated in the subsequent chapter. Therefore, although more than one area of the building was in need of an upgrade, it was decided to focus the investigation of the optimal retrofit strategy on a particular area, i.e. the east wing of Building 4. The main reasons for choosing this

area was: the poor thermal comfort and high number of unsolicited occupant complaints in regards to the temperatures, the relatively new air-conditioning system servicing the north-facing offices on the first floor and the UOW Facilities Management Division agenda.

8. Building Retrofit Optimisation: A Case Study

One of the objectives of this study was to develop a methodology to optimise the retrofits to be applied to any given higher education building. Whilst some specific *ad hoc* retrofits were proposed based on an understanding of the building performance determined through the work described in Chapter 7, this piecemeal approach would not lead to an 'optimal' retrofit strategy that minimised operational costs whilst maintaining satisfactory indoor thermal comfort. This chapter applies the method described in *§6.3* to a case study building to find the optimal retrofit strategy for that particular building. Building 4 was introduced in *§7.1* and it is the case study building used herein. This chapter is structured as follows:

- The building simulation model set-up is outlined, and then calibration results are presented comparing a) experimental and modelled temperatures for the naturally ventilated offices; and b) monitored versus modelled predicted air-conditioning power consumption for the conditioned spaces.
- Sensitivity analysis results of the impact of different parameters on the building performance in terms of energy consumption and thermal comfort are shown.
- The most influential parameters determined in the previous point are considered in finding the optimal retrofit strategy, and the combination of parameters that minimises the cost of the upgrades, productivity loss of the occupants and building operation are identified.
- An analysis of the effectiveness of a particular retrofit that was implemented in the case study building via temperature monitoring and building simulation modelling is described.

8.1 Building Thermal Performance Simulation

The detailed building thermal performance simulation model focussed on the east wing of Building 4 (the floor plans of the model are shown in Figure 8.1). The details of the building are also shown in Figure 8.2 through photographs, and the DesignBuilder model in axonometric views for both the whole building and the first floor.

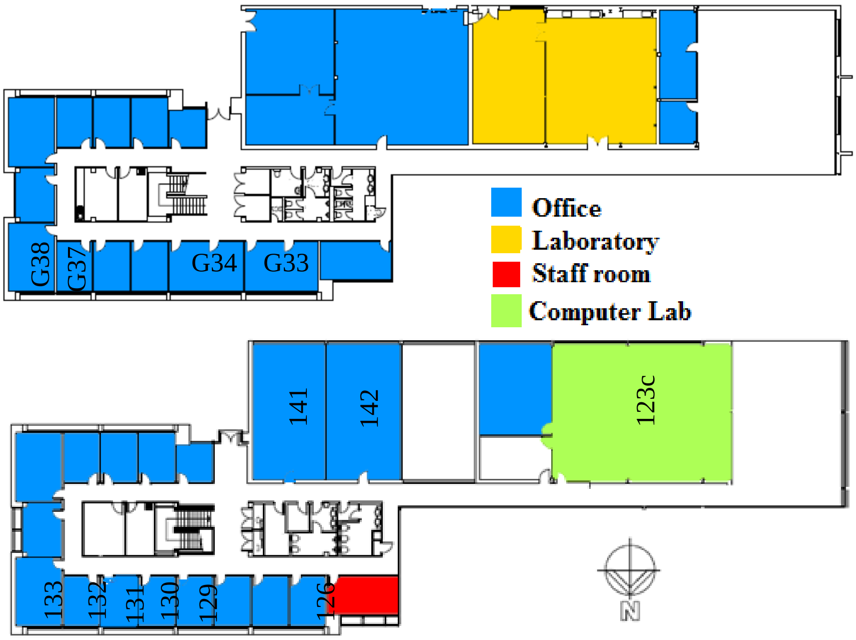
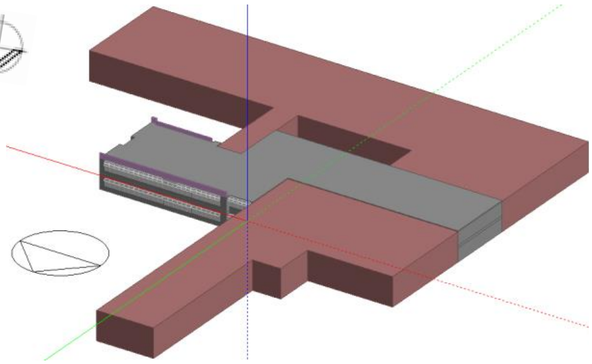
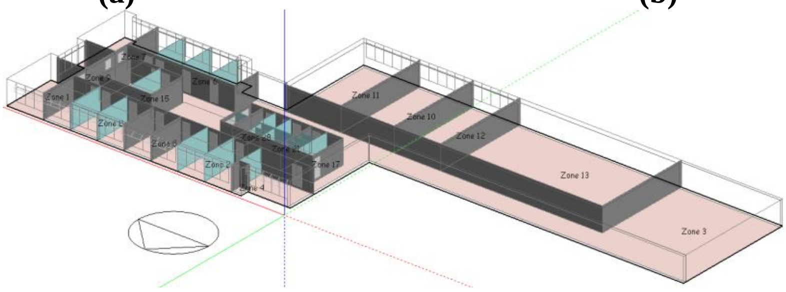


Figure 8.1 Floor plan of the ground floor (upper) and first floor (lower) of the modelled east wing of Building 4 - coloured according to their functions.

(a) **(b)**



(c)

Figure 8.2 Views of Building 4: a) Plan view of the real Building from Google maps. The trees at the northern face of the east wing were cut due to some landscape upgrades at the end of 2012, b) axonometric view of the building model together with the rest of the building and the adjacent building drawn in DesignBuilder, c) an axonometric view of the first floor of the modelled spaces.

The settings used to develop the Building 4 model for all the scenarios this thesis were as follows:

- The building model was divided into four blocks to accurately represent the reality of the building, including the ground floor, the first floor, and two suspended ceilings.
- The eastern wing of the building was modelled such that the walls in contact with the adjacent building, or in contact with Building 4 itself, were set as adiabatic. The adjacent building and that part of Building 4 not modelled in detail were set as component blocks for shading and reflective purposes (Figure8.2b depicts the component blocks in red).
- Natural ventilation was set as a scheduled constraint, i.e. it was defined as an air-change rate modulated by the window opening schedule and temperatures set-points. The permeability of the building envelope was experimentally measured at three different locations (see *§7.2.1* for details of the blower door experimental set-up and calculated air changes per hour) and was set to 24.6 ACH at 50 Pascals in the model.
- The weather data file used for calibration was built as described in *§6.3.1*.
- The internal loads of the building, i.e. occupancy, lighting and computers, during operating hours are summarised in Table 8.1.
- The HVAC system type was set to ‘compact’ with manual sizing, which entailed having to manually input the capacity of each HVAC system for every conditioned space. The capacity, model, and room serviced by each piece of equipment is summarised in Table 8.2.

Table 8.1. Modelled internal loads operation schedules and descriptions.

Operation Schedule	Internal Load/ Service	Description
Weekday from 8am to 6pm	occupancy	1 occupant per 12 m^2 to 1 per 21m^2 for academic staff, and 1 per 6 m^2 for research staff and students.
	lighting	1200mm long T8 fluorescent tubes of 36 W in offices (17 W/m^2) and corridor and15W/m^2.
	computers	DELL Optiplex 755 MT, that generated 50W of heat with an additional 40W for each monitor/display. One each occupant.
Other time	occupancy	None, unoccupied.
	lighting	Corridor (15W/m^2), offices lighting switched off.
	computers	All switched off

Table 8.2. Existing air-conditioning systems monitored from Distribution Board 1A.

Space Served	Cooling Capacity (kW)	Model	Rated COP
Room 123c	6.5	Daikin RXS71	3.59
Room 125- 132	23	Daikin FDYQ250	3.20
Room 133	5	Daikin RY50GAV1A	2.74
Room 141	12	Daikin RZQ125K	2.72
Room 142	12	Daikin RZQ125K	2.72

An adjusted COP of 2.0 for the ducted systems (Rooms 125 to 132) was employed in the DesignBuilder simulations so as to account for the reduction in the rated COP when ducts run through the ceiling (O'Neal et al. 2002). Therefore, the rated COP provided by the manufacturer is adjusted in the building model setting to account for this loss in effectiveness.

8.2 Building Model Calibration

Building model was calibrated against: 1) the monitored indoor temperature data of the building without occupancy and 2) the monitored building HVAC power consumption and indoor temperatures during the business hours (following *§6.3*.3).

8.2.1 Building without Occupancy Validation

The indoor air temperature was monitored via thermocouples from the 22nd to 31st December 2013 (Christmas holidays), in three offices on the east wing of the building (locations are shown in *§7.2* Figure 7.3). The settings used in the model were as defined in *§6.3*.3.

Spaces 4.G34, located in the ground floor, and 4.129, situated immediately above on the first floor, were chosen as the representative offices (the exact locations of these offices are shown in Figure 8.1). The experimental indoor temperature profiles for 4.G34 and 4.129 were compared to that predicted by the simulation and areas shown in Figures 8.3 and 8.4, respectively.

The temperature predicted by the model matched with the experimental measurements for most data points with a goodness of fit r^2=0.87. The maximum difference between the experimental data of the ground floor office (4.G34) and the simulation was less than one degree, although on the 23rd of December.

The first floor office (4.129) had a few data points that differed from the experimental data (the goodness of fit was r^2=0.81). It can be seen that the experimental temperature was higher than the modelled temperature and then it suddenly decreased below the

modelled temperature. This rapid decrease in temperature can most likely be explained by turning the air-conditioning on, which would imply that the office space was occupied and thereby the internal loads were not zero. This would also explain the slight difference between the maximum temperatures for the modelled and the experimental temperatures, that is, the presence of occupant, lighting and office equipment in the space.

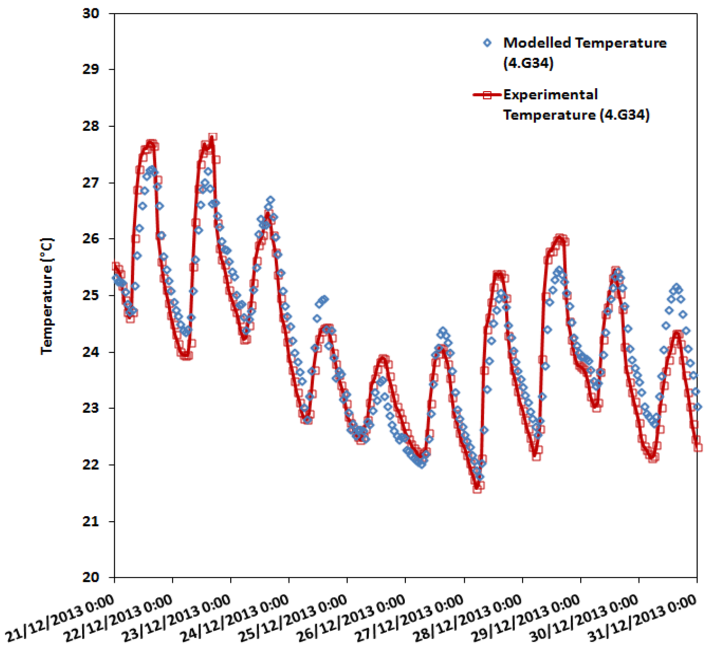


Figure 8.3 Monitored experimental temperature against modelled temperature for the ground floor office (4.G34).

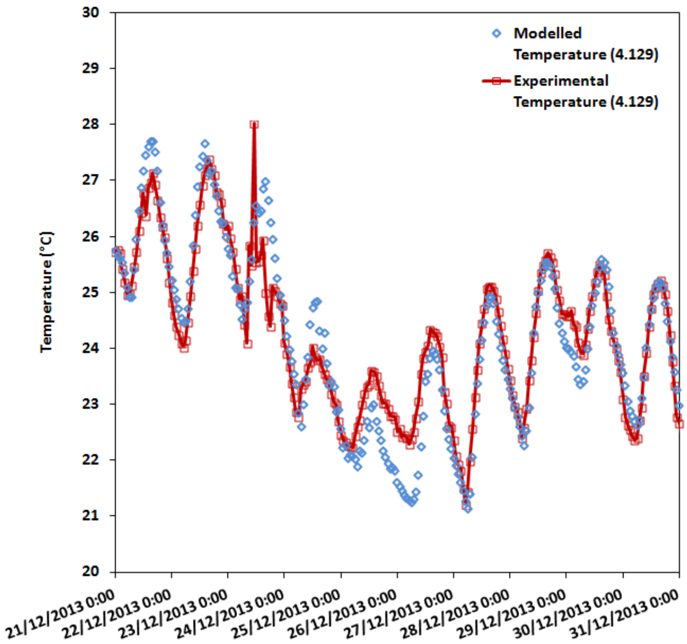


Figure 8.4 Monitored experimental temperature against modelled temperature for the office 4.129.

8.2.2 HVAC Consumption Validation

The power consumed on one distribution board (location and spaces served are shown in *§7.3* Figure 7.3*)* was monitored from the 3rd of March to the 9th of March 2014.

The internal loads monitored were included in the model by calculating the power density (W/m^2) at each half an hour through the monitored power consumption. Due to the characteristics of the DesignBuilder interface, the maximum power density for the whole period was used, then a percentage of utilisation per each half hour was implemented into the model according to the experimental monitored consumption. A screenshot of the schedule implemented for one of those days can be seen in Figure 8.5. The power consumption of the monitored internal loads against the power consumption of the internal loads used in the model (as an input) is shown in Figure 8.6.

Occupancy was determined from building inspections during that week. The natural ventilation set-point and cooling set-point were estimated after the occupants were asked when they were most likely to open the windows and switch on the device. The latter was set to 23.5°C while the former was set to 22°C.

Subsequently, the simulation for the first week in March 2014 was performed. The predicted hourly air-conditioning power consumption was compared against the hourly experimentally monitored air-conditioning power consumption (Figure 8.7). Moreover, the experimental moving average for a 4 hour consumption period was shown to smooth the short term fluctuations due to the air-conditioning kicking in.

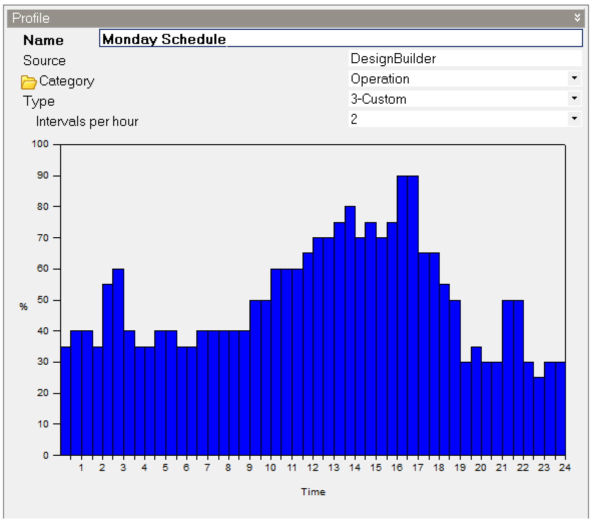


Figure 8.5 Percentage of utilisation of the power density per hour according to the actual power consumption monitored on Monday 4th of March 2014.

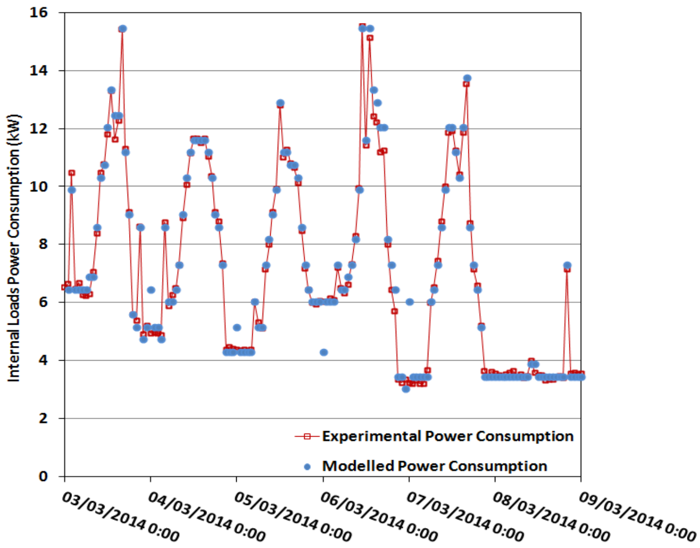


Figure 8.6 Comparison between actual monitored internal loads power consumption and modelled internal loads power consumption from the 3rd March 2014 to 9th March 2014. This modelled internal loads power consumption profile was used in the model as input.

The predicted hourly power consumption matched with the actual moving average relatively well every day during the week, although some discrepancies appeared on the weekend (8th and 9th of March). The goodness of fit of the experimental power consumption against the modelled power consumption, r^2, was 0.55, which indicated a moderate relationship. This was probably due to some occupants in one of the offices turning the air-conditioning on, while the same schedule in the model was set for all the offices over the weekend.

The experimental indoor temperature for one of the offices with air-conditioning (4.129) monitored by thermocouple was compared to the predicted by the simulation during the same period the 3rd of March to the 9th of March 2014 (Figure 8.8). The goodness of fit is r^2 =0.64. Despite that there are some discrepancies, the modelled temperature profile matches the experimental temperature trend.

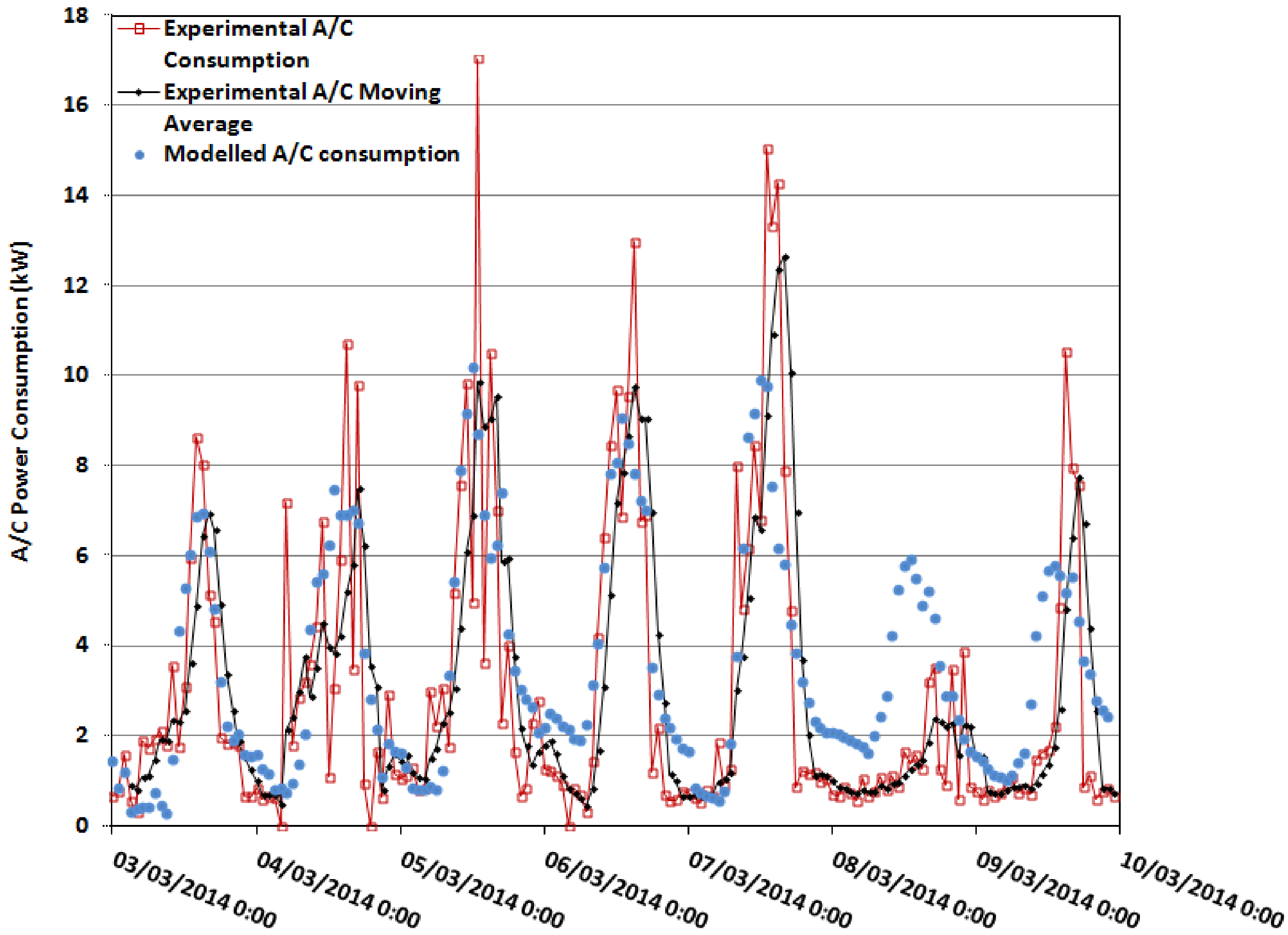


Figure 8.7 Experimental monitored air-conditioning power consumption, experimental moving average air-conditioning power consumption and modelled air-conditioning power consumption.

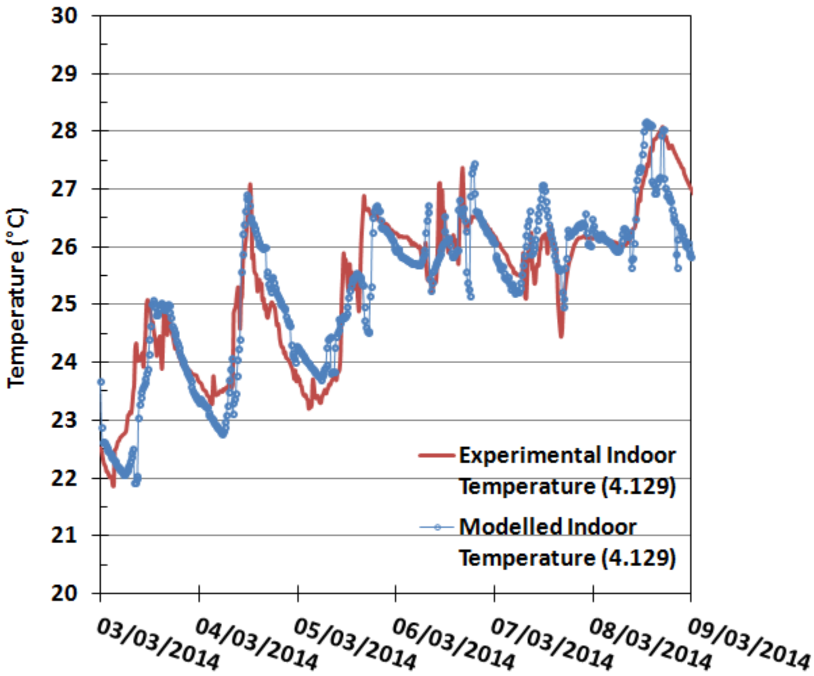


Figure 8.8 Experimental monitored air-conditioning power consumption, experimental moving average air-conditioning power consumption and modelled air-conditioning power consumption.

8.3 Retrofit Optimisation Method

8.3.1 Results of Sensitivity Analysis (SA)

Based on the model calibrated, a local sensitivity analysis was then performed to identify the most critical building parameters following the method described in *§6.3.4*. The spaces being investigated for retrofitting corresponded to eight north facing offices in the first floor of the east wing of the building (Figure 8.9).

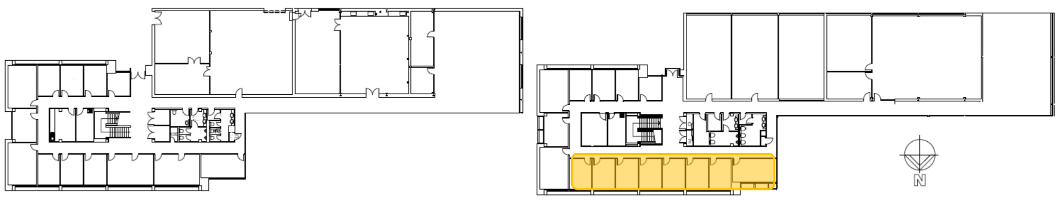


Figure 8.9 Floor plans of the ground (left) and first floor (right) of the modelled east wing of Building 4 with the investigated offices for retrofitting highlighted in yellow.

As described in *§6.3.4*, the focus of this study was on the building envelope, internal loads, temperatures set-point of the HVAC system, and the capacity of the system. This involved investigating the following parameters: the thermal mass of the building, the roof R-value, the external wall R-value, the window U-value, the infiltration rate, the window Solar Heat Gain Coefficient (SHGC), internal loads, especially the lighting and

computers, the heating and cooling temperature set-points and the heating and cooling capacity. Sydney weather condition was investigated as the representative weather of the location of the case study (Wollongong). In addition, the same case study building was investigated with Canberra weather conditions. Eq. 6.1 (*§6.3.4*) was used to calculate the normalised sensitivity coefficient.

Base values of the considered parameters were obtained from the audit as follows: a) details on the roof, wall and floor R-value, U-window, SHGC, roof emissivity were estimated from the building construction documentations, b) lighting, computer loads, exposed thermal mass and cooling and heating capacity were collected from visual inspection during the walk-through and c) blower door test conducted in the building enabled to find the air tightness. The results for the local sensitivity analysis are shown in Table 8.3, including the overall change in the input and output parameters named as input and output changes, correspondingly and the normalised sensitivity coefficients for typical Sydney weather conditions. The change in outputs and normalised sensitivity coefficients for cooling electricity, heating electricity, and total electricity are presented. Similar information is shown in Table 8.4 for the climate at Canberra.

Table 8.3 Sensitivity coefficients for Sydney weather.

Parameter	Base value	Input change	Cooling		Heating		Total electricity		Thermal Discomfort	
			Output change (kW)	Normalised sensitivity coefficient	Output change (kW)	Normalised sensitivity coefficient	Output change (kW)	Normalised sensitivity coefficient	Output change (h)	Normalised sensitivity coefficient
Thermal mass area (m^2)	150	1.5	-2.52	-0.03	-0.16	-0.26	-2.68	-0.01	-0.75	-0.49
R-roof (m^2 K/W)	1.7	0.01	-2.94	-0.03	-0.12	-0.19	-3.06	-0.01	-0.50	-0.32
Lighting (W/m^2)	17	0.17	27.17	0.27	-0.58	-0.92	113.99	0.50	2.00	1.30
Computers (W/m^2)	8	0.08	14.34	0.14	-0.57	-0.91	52.33	0.23	1.75	1.17
Roof emissivity	0.4	0.004	-1.75	-0.02	0.06	0.02	-1.69	-0.01	-0.50	-0.33
Cooling set-point (°C)	24	0.24	-563.03	-5.58	-1.72	-2.76	-564.75	-2.45	14.50	9.42
Heating set-point[1] (°C)	21	0.21	1.30	0.01	38.50	61.79	39.80	0.17	-0.75	-0.49
R-wall (m^2K/W)	1.5	0.015	8.64	0.06	-0.67	-1.07	7.98	0.03	0.00	0.00
Infiltration (ach)	1.2	0.012	-10.14	-0.10	0.73	1.17	-9.41	-0.04	0.50	0.33
U window (W/m^2K)	5.885	0.06	-19.46	-0.19	1.35	2.13	-18.12	-0.08	-0.50	-0.32
SHGC	0.861	0.009	67.33	0.67	-2.53	-4.06	64.81	0.28	5.50	3.57
Floor U-value (W/m^2K)	1.49	0.01	3.21	0.03	-0.606	-0.97	2.61	0.01	-0.50	-0.35
Cooling Capacity(kW)	20	0.2	1.13	0.01	0	0	0	0	0	0
Heating Capacity[1] (kW)	5	0.05	0	0	0.48	0	0	0	0	0

[1]Although there are no heating devices installed in the spaces studied, just for the purpose of evaluating the sensitivity coefficient of the heating capacity a 5-kW system was considered.

Table 8.4 Sensitivity coefficients for Canberra weather.

Parameter	Base value	Input change	Cooling		Heating		Total electricity		Thermal Discomfort	
			Output change (kW)	Normalised Sensitivity Coefficient	Output change (kW)	Normalised Sensitivity Coefficient	Output change (kW)	Normalised Sensitivity Coefficient	Output change (h)	Normalised Sensitivity Coefficient
Thermal mass (m2)	156	1.50	-2.26	-0.08	8.18	0.11	5.93	0.03	0.50	0.06
R-roof (m2 K/W)	1.7	0.01	-2.55	-0.09	-3.33	-0.07	-5.87	-0.03	-0.25	-0.03
Lighting (W/m2)	17	0.17	11.87	0.41	-37.19	-0.52	62.07	0.27	-0.50	-0.06
Computers (W/m2)	8	0.08	6.34	0.22	-8.15	-0.11	36.74	0.16	0.50	0.06
Roof emissivity	0.4	0.00	-0.99	-0.04	9.59	0.03	8.61	0.04	0.25	0.03
Cooling set-point (°C)	24	0.24	-220.34	-7.69	-9.81	-0.14	-230.15	-1.01	4.75	0.612
Heating set-point[1] (°C)	21	0.21	2.37	0.08	2227.33	31.02	2229.69	9.74	-129.00	-16.62
R-wall (m2 K/W)	1.47	0.02	2.39	0.06	-37.59	-0.53	-35.21	-0.11	-2.00	-0.19
Infiltration (ach)	1.2	0.01	-4.19	-0.15	37.28	0.52	33.09	0.15	0.75	0.10
U window (W/m2 K)	5.78	0.06	-5.49	-0.19	39.76	0.55	34.27	0.15	4.75	0.62
SHGC	0.861	0.01	17.67	0.62	-55.48	-0.77	-37.81	-0.17	-3.50	-0.45
Floor R-value (m2 K/W)	1.49	0.01	-0.58	-0.02	-20.30	-0.28	-20.88	-0.01	-3.75	-0.48
Cooling Capacity (kW)	20	0.20	0.14	0.00	0.00	0.00	0.00	0.00	-1.75	-0.06
Heating Capacity[1] (kW)	5	0.05	0.00	0.00	0.59	0.02	0.00	0.00	-0.50	-0.02

The highest normalised sensitivity coefficient in Sydney weather was in the thermostat temperature set-point for air-conditioning, where it was interpreted as 1% increase in the temperature set-point resulted in a 2.45% decrease in the overall building energy consumption and 9.42% increase in the discomfort hours (Table 8.3). Alternatively, the highest normalised sensitivity coefficient for the Canberra climate was shown in the thermostat temperature set-point for heating where an increase of 1% in the heating set-point temperature led to a 9.74% rise in the total energy demand, whilst the discomfort hours decreased by 16.64%. Similarly, Firth *et al.* (2010) found that the temperature set-point had the highest influence in the heating demand in an average domestic dwelling in UK. However, here the effect of the temperature set-point was higher compared to that in Firth *et al.* (2010), most probably because of the characteristics of this educational building compared to the average English dwelling, as our case study building required more energy to heat the building from 21°C to 21.3°C.

The highest normalised sensitivity coefficient for five parameters were selected for retrofitting, but to ensure that important variables were not omitted from the analysis, the difference between the fifth higher normalised sensitive coefficient and the next closest normalised sensitive coefficient was checked. If the difference between the fifth and the subsequent influential parameter exceeded 50%, the subsequent parameter was not included as a decision variable.

The parameters with the highest impact on the overall energy consumption and thermal comfort for Sydney weather were temperature set-points, lighting and computer power density, infiltration, window solar heat gain coefficient (SHGC) and U-value. In addition to these parameters, Canberra weather showed that the R-wall normalised sensitivity coefficient, 0.11, presented a difference in the coefficients below 50% compared to the infiltration normalised sensitivity coefficient (0.14), thereby it was considered as an influential parameter.

Very slightly variations in the air-conditioning and heating capacity did not impact the energy consumption or thermal comfort but the heating capacity was assumed, as no heating was installed in the building. Indeed a change of 1% in the cooling/heating capacity did not affect the operation of the system. However, the implementation of an air-conditioning or a heating system has a major effect on the energy consumption and thermal comfort of the building, and therefore the parameter capacity of the cooling and

heating system needs to be included as a decision variable. If the heating/cooling system were not included, the discomfort hours would have raise dramatically.

It should be noted that the results of the sensitivity coefficients were limited to this particular model and the weather conditions tested, which means that other building characteristics such as the percentage of fenestration, different number of storeys, orientation, thermal performance of the envelope and other climate conditions can lead to a distinct set of influential parameters. On this basis, the detailed approach should be implemented for each model on a case by case basis.

8.3.2 Set-up of Optimisation Method for Retrofit Strategy

The set-up of the proposed optimisation method was presented in *§6.3.5*. Firstly, the investment costs of retrofitting the decision variables were detailed (Table 8.5), then the constraints of the decision variables were specified (Table 8.6), finally the objective function was defined according to *§6.3.5* Eq. 6.14 and the productivity penalty function was included following *§6.3.5* Eq. 6.17. Individual universities may have guidelines regarding acceptable thermal comfort bands for optimal performance of students and staff, so these bands should be considered as the comfort zone, here T_{cmax}=26°C and T_{cmin}=20°C are employed as defined by the UOW WHS Unit (2012).

Cost on Retrofit Options for Decision Variables

The retrofit options considered for the decision variables with the associated investment and maintenance costs and lifespan are shown in Table 8.5. Costs were extracted from Rawlinsons Construction Cost Guide (2012), which provides the average costs of installation including materials and labour costs for a range of construction items in Australia, and $ are in Australian Dollars. The number of times the retrofit must be renewed in situations where the lifetime of the building component is shorter than the remaining life of building is denoted in the Table 8.5 by y_i.

Table 8.5 Building component and retrofit option, investment costs, number of items to be used, lifespan and annual maintenance operation and repair and service factor of the building component

Retrofit option	Investment cost , $c_I(i)$	$c_I(i)$ Reference	Number of items/ area	Lifespan	$c_I(i)y_i$ ($)	Maintenance costs (%)
Lighting upgrade	20$ T5 fluoro lamp adaptor 7$ per T5 lamp 60$ per E1 lighting	Bunnings (2015)	57 lamps	24000h (10 years duration)	3078 for T5 6156 for E1	-
Computer upgrade	DELL – Optiplex 755 MT to DELL – Optiplex FX 170, 450 $/computer Monitor- U2410 to Monitor - IN1930F, 25$	DELL (2015)	9 computers	10 years	6412	
Infiltration: draught proofing	Sealer 3.25 $/m^2$ 7$ Door draught stopper	Rawlinsons (2012)	Windows =24 m^2	20 years	170 to 3333 depending on draught proofing[1]	-
Window U-value: double glazing	U3.1 ≈ double glazing clear 6mm, 257$/m^2$	Rawlinsons (2012)	Windows = 24 m^2	50 years	6168	
SHGC: window film	SHGC= 0.2 for a Stirling 20 window film, 60 $/m^2$	SolarGard (SolarGard 2014) Solar Shade (SolarShade 2014)	Windows =24 m^2	10 years	2880	-
Wall Insulation	Glass wool batts R2≈ 0.05 m thickness, 46.75$/m^2$ R3 ≈ 0.08 m thickness, 47.15$/m^2$	Rawlinsons (2012)	0.940 m high and 31.23 m length	50 years	1366 for R2 1600 for R3	-
Air Handling Unit Upgrade	80-240$/m^2$	Rawlinsons (2012)	8 offices with a total area of 111m^2	20 years	Depending on capacity	4%
Split system (to include heating)	80-240$/m^2$	Rawlinsons (2012)	8 offices with a total area of 111m^2	20 years	Depending on capacity	4%

[1]The approximate costs of reaching a particular air tightness value are unknown, so an assumption was made with the draught proof costs. For the investigated offices with 24 windows, a range of $170 to $3333 for varying the infiltration rate from 1 air change per hour to 0.4 air changes per hour under natural conditions is provided.

Constraints on Decision Variables

The decision variables were a combination of discrete and continuous parameters. Decision variables used, initial values, types and boundaries, i.e. possible values, are defined in Table 8.6.

Table 8.6 Decision variables, constraint and initial base value definition.

Decision Variable	Type	Constraints	Initial Base Value
Cooling set-point temperature (°C)	continuous	23-26	23
Heating set-point temperature (°C)	continuous	20-22	21
Lighting power density (W/m^2)	discrete	17, 12, 6.5	17
Computer power density (W/m^2)	discrete	8, 2	8
Infiltration (air changes per hour)	discrete	1.2, 1, 0.9, 0.8, 0.5, 0.4	1.2
Window U-value (single or double glazing, (W/m^2 K)	discrete	5.78, 3.1	5.78
Solar Heat Gain Coefficient SHGC (-)	discrete	0.86, 0.2	0.86 (for a clear 3mm single glass)
Cooling capacity (kW)	continuous	0-30	20
Heating capacity (kW)	continuous	0-30	0
Wall R-value (Canberra) (m^2 K/W)	discrete	1.47, 2, 3	1.49

8.3.3 Results of the Retrofit Optimisation

The simulations were performed in a *HP Pavilion* 15.6" Laptop - Intel *Core i7*. The summary of the variables used, the simulation running time and the number of iterations conducted for the yearly simulations are presented in Table 8.7.

Table 8.7 Decision variables, constraint and initial base value definition.

Weather Conditions	Decision Variables	Time (h) and number of iterations
Sydney	Cooling and heating capacity and lighting upgrades.	8.5h, 61
Sydney	Cooling and heating capacity, cooling and heating temperature set-point, draught-proofing, double glazing, computer and lighting upgrades.	20h, 192
Canberra	Cooling and heating capacity, cooling and heating temperature set-point, draught-proofing, double glazing, computer, lighting and wall insulation upgrades.	21h, 210

The results are presented in terms of the simulation outputs, i.e. costs including total costs, energy costs (lighting, computer loads and heating and cooling energy

consumption costs), productivity loss costs due to the thermal discomfort (§*6.3*) and investment and maintenance costs, as well as the values of the input decision variable for every simulation.

Before identifying the optimal retrofit strategy for the building employing all the decision variables determined for Sydney and Canberra, an illustrative example varying only three decision variables is presented. The three decision variables employed in the example had a) the highest impact on energy consumption and thermal comfort for the Sydney weather and b) an associated investment cost. Therefore these variables were cooling capacity, heating capacity and lighting power density as introduced in Table 8.7.

Demonstrative Example of Optimal Retrofit Strategy in Sydney

The total costs including energy costs, productivity loss costs and investment and maintenance costs at each iteration are shown in Figure 8.10a. Initially, the costs fluctuated at high levels and, as the simulation progressed, costs kept decreasing. The total costs are increased in iterations 2, 3, 12; this is due to changing the cooling capacity to zero, i.e. there is no cooling system installed in the building. Therefore, the discomfort hours are dramatically increased as observed in the productivity costs. The variations in the cooling capacity, heating capacity and lighting power density are observed in Figure 8.10b, 8.10c and 8.10d, respectively.

The fluctuations in the cost function on the last iterations (e.g. 56 or 57) are due to selecting an air-conditioning system with different capacities than the original ducted one. That is why for iteration 46 or 52, an implementation of a 21kW or 19.8kW cooling system requires an investment cost, as renewing the system for a newer one incurred to an expense. It should be noted that the optimal capacity of the air-conditioned system might not be a commercially available capacity. Therefore, the closest value to the optimal capacity can be selected from the off the shelf products.

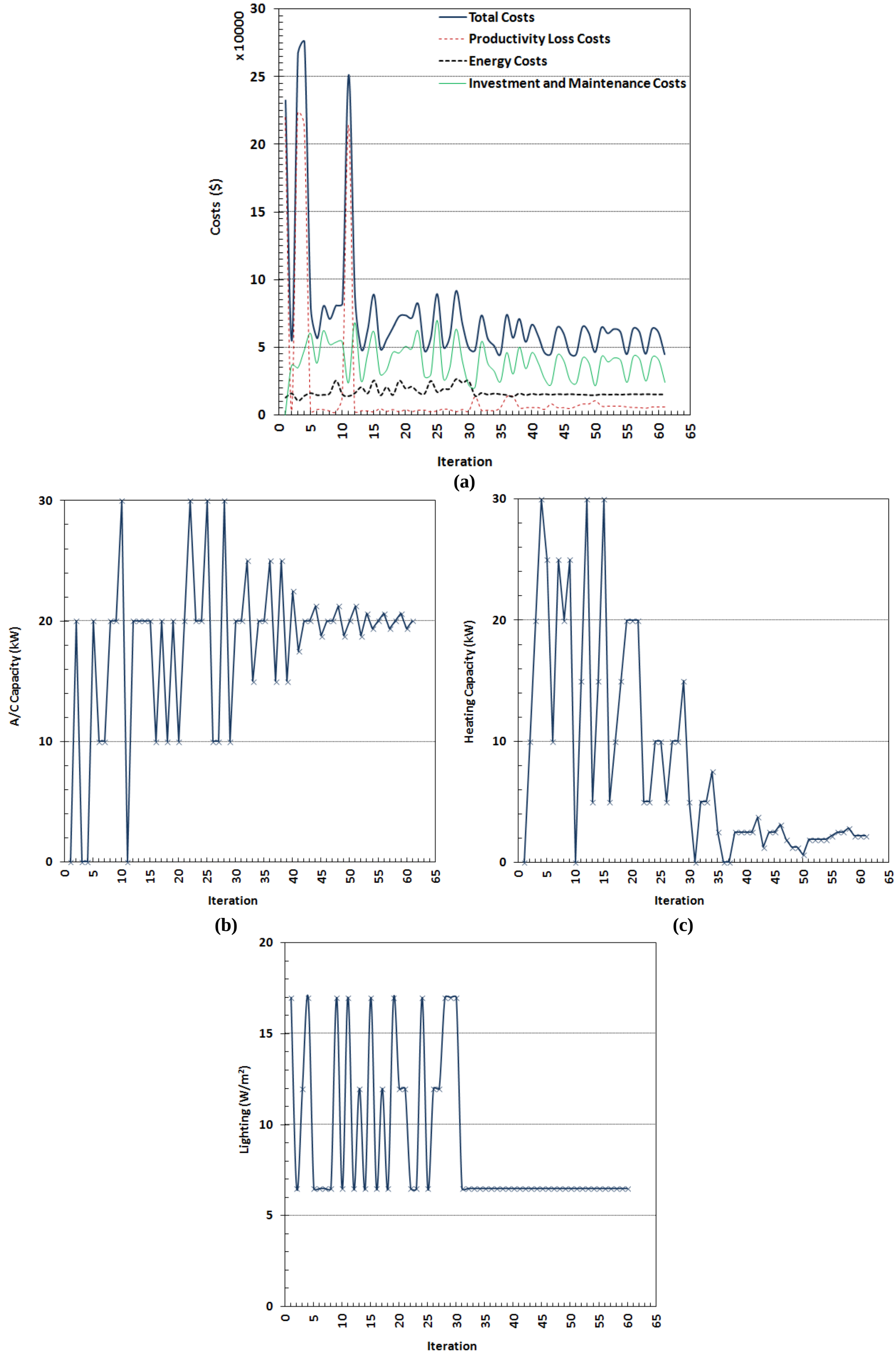


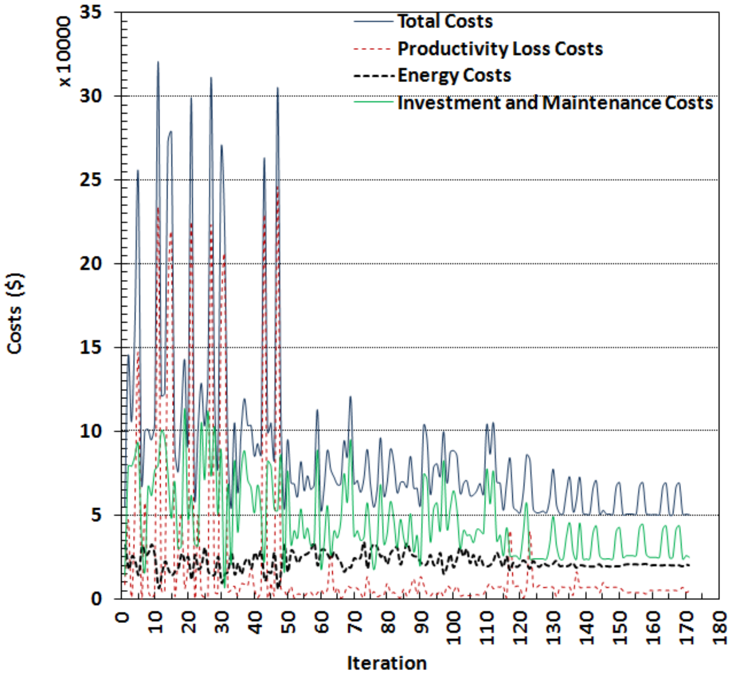
Figure 8.10 The minimisation of the cost function depicting the values of outputs and inputs for all the simulations (a) Total costs, i.e. productivity loss costs due to productivity loss costs, operational costs and investment costs, (b) cooling capacity, (c) heating capacity values and (d) Lighting power density.

In this example, the optimal retrofit strategy was provided by the existing 20-kW air-conditioning, the installation of a 2-kW heating system and the lighting upgrades to E1.

Optimal Retrofit Strategy in Sydney

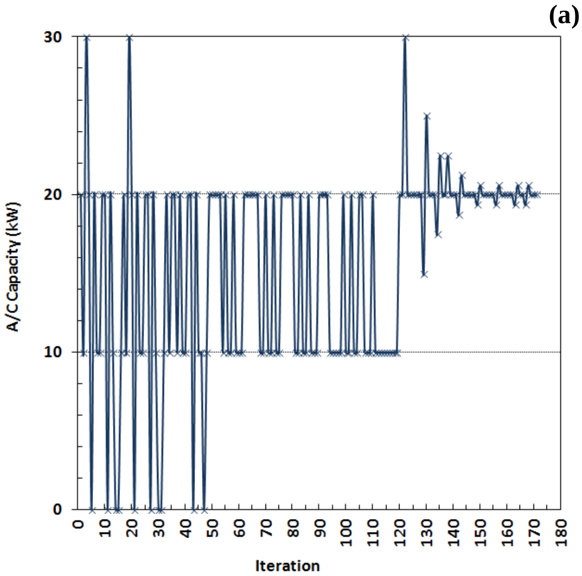
The objective function was defined using *§6.3* Eq. 6.14 with the decision variables described in Table 8.6. This section presents all the simulations conducted to minimise the objective function. The calculated value of the objective function through the total costs, energy costs, investment and maintenance costs and productivity loss costs are determine for each simulation. All output costs with the different input decision variables are shown in Figure 8.11. Firstly the total costs fluctuated at high levels (Figure 8.11a) principally because these iterations (as shown in Figure 8.11b for example for simulation 11, 15, 21, 27, 43 or 47) the cooling capacity was 0-kW, i.e. as if no cooling was installed. This, in turn, dramatically rose the hours of discomfort and thereby the productivity lost costs. In addition, heating for certain simulations was 0-kW (for instance in iteration 15, Figure8.11c) hence the hours below 20°C were also increased. Setting the cooling temperature set-point at 26°C (Figure 8.11d), caused the hours where the operative temperature was above 26°C to rise thereby increasing productivity loss costs (as seen in iteration 5 or 21). Similarly, heating set-point temperature at 20°C (Figure 8.11e) resulted into an increase in the indoor operative temperature below 20°C (e.g. iteration 11). As the optimisation progresses, the total costs were decreased. There are a few higher costs as the simulations progresses, e.g. iterations 59, 69, 91, 110 or 112. These high costs are principally due to high investment cost for changing the air-conditioning to a different capacity (Figure 8.11b), incorporating heating (Figure 8.11c), draught proofing (Figure 8.11f) and/or using window film (Figure 8.10g), double glazing (Figure 8.11h), computer upgrades (Figure 8.11i) and lighting upgrades (Figure 8.11j).

The values that provided the minimum energy, productivity loss and retrofit costs for the typical weather in Sydney during the building lifetime were: the cooling capacity that is already installed (20-kW), installing heating capacity of 0.625-kW, a cooling temperature set-point of 24.4°C, a heating temperature set-point of 20.8°C, a lighting level of 6.5 W/m^2, draught proofing to 0.4 ACH, and no window film, computers or double glazing upgrade.



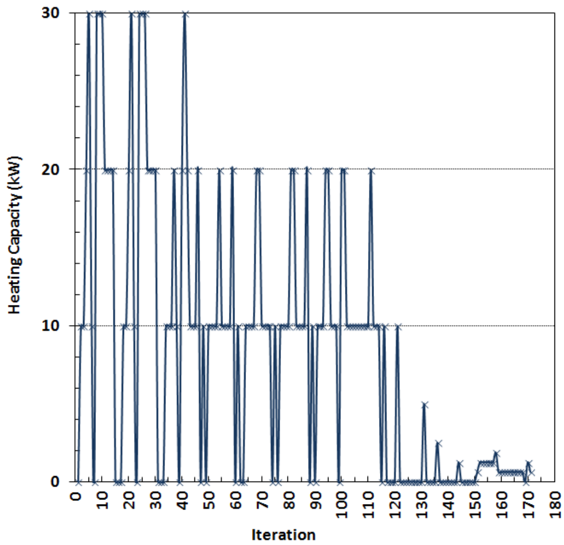
Total Costs
Productivity Loss Costs
Energy Costs
Investment and Maintenance Costs
x 10000
Costs ($)
Iteration

(a)



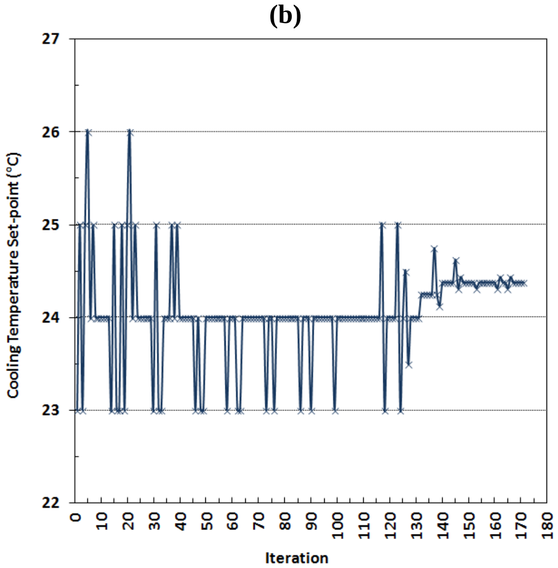
A/C Capacity (kW)
Iteration

(b)



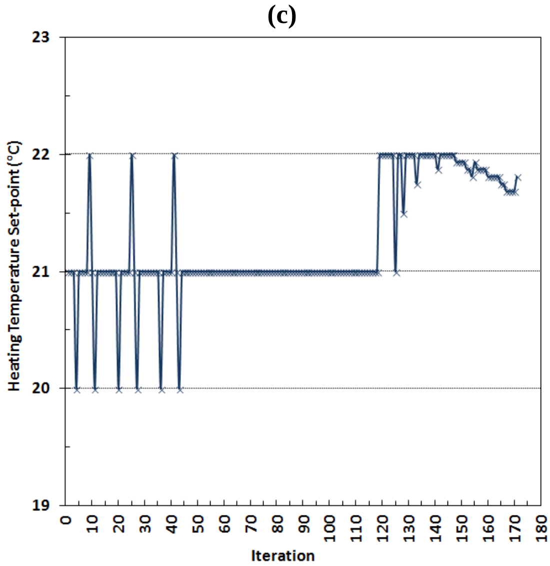
Heating Capacity (kW)
Iteration

(c)



Cooling Temperature Set-point (°C)
Iteration

(d)



Heating Temperature Set-point (°C)
Iteration

(e)

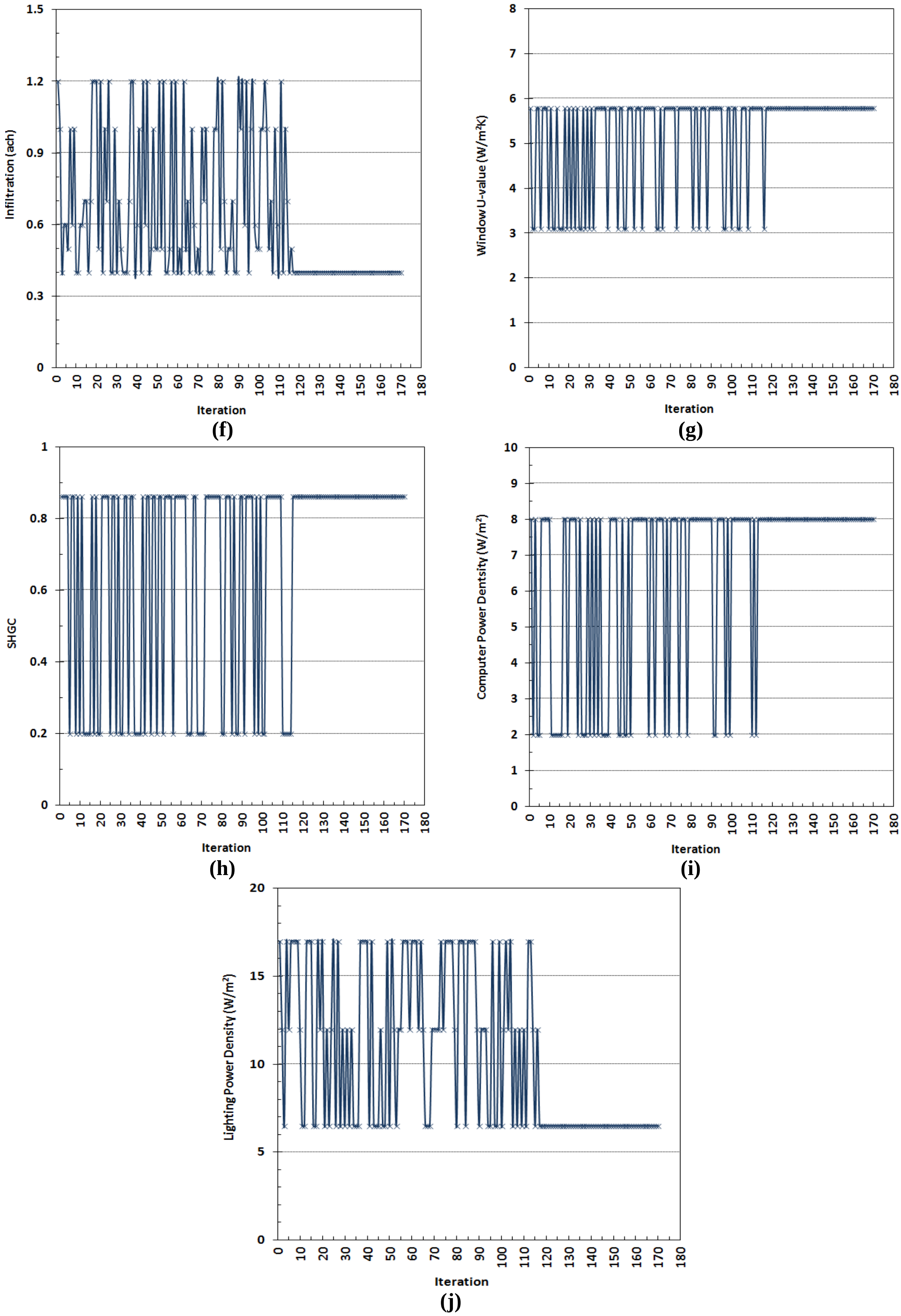


Figure 8.11 Output costs and inputs decision variables values for all the simulations conducted in the optimisation with Sydney typical weather file. (a) Total costs, i.e. productivity loss costs due to thermal discomfort, operational costs and investment costs. Input values for (b) air-conditioning capacity, (c) heating capacity, (d) cooling temperature set-point, (e) heating temperature set-point, (f) infiltration rate, (g) window U-value, (h) SHGC, (i) computer power density and (j) lighting power density.

Overall, the effect that the productivity loss costs had on the total cost were apparent in the cooling capacity as well as cooling and heating temperature set-points. A leakier building with a higher infiltration rate resulted in a slight increase in energy consumption and total costs. This was probably due to a higher exchange of air between indoors and outdoors, with a higher infiltration rate; therefore at the same temperature set-point, more cooling was needed to keep the temperature of the space comfortable. The installation of double glazing, despite decreasing the energy costs and °C/hours of thermal discomfort, actually increased the total costs due to the high investment costs. Similarly, the cost of upgrading computers outweighed the benefit of comfort and energy savings, so they were not implemented. The window film was not selected as a retrofit option. Despite decreasing the solar heat gains in summer and thereby reducing the cooling energy costs these savings were outweighed by the increased heating energy consumption, productivity loss costs in winter and the investment costs.

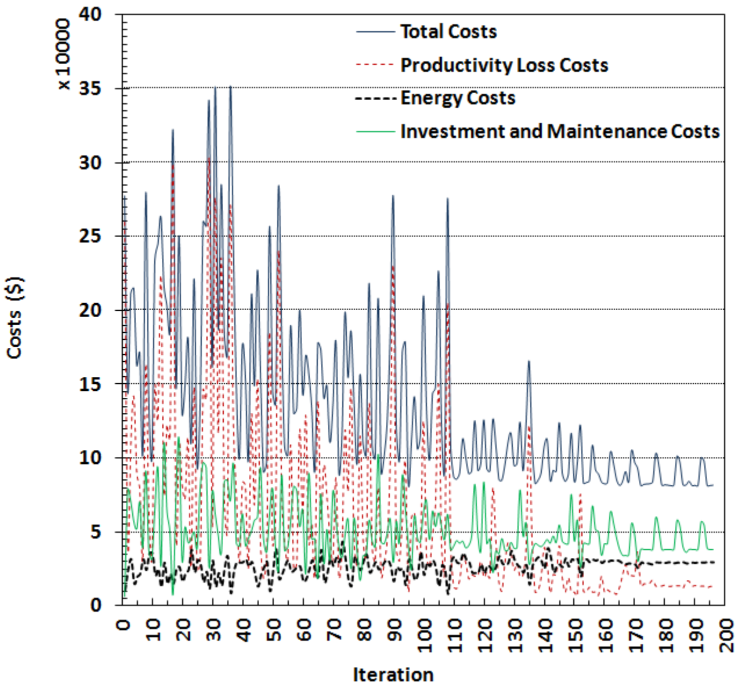
Optimal Retrofit Strategy for Canberra

Here, identical methodology to identify the optimal retrofit strategy for the same case study building but with Canberra weather file is presented. The objective function was defined using *§6.3* Eq. 6.14 with the decision variables described in Table 8.6 and 8.7 for Canberra weather conditions. Output costs (in terms of total costs, energy costs, maintenance and investment costs and productivity loss costs) and the input decision variables values at each simulation for the minimisation of the objective function are shown in Figure 8.12. The high fluctuations of the total costs (Figure 8.12a) are mostly attributed to heating and/or cooling temperature set-points or the heating/cooling capacity of 0kW, i.e. no installation of heating (Figure 8.12c) or cooling system (e.g. iterations 17, 29, 31 or 36 in Figure 8.12b). Another example is presented in simulation 8, where high cooling set-point temperature at 26°C (Figure 8.12d), and low heating set-point temperature at 20°C (Figure 8.12e) led to a high number of hours with operative temperature outside the comfort zone, i.e. >26°C and <20°C, and thereby high productivity loss costs.

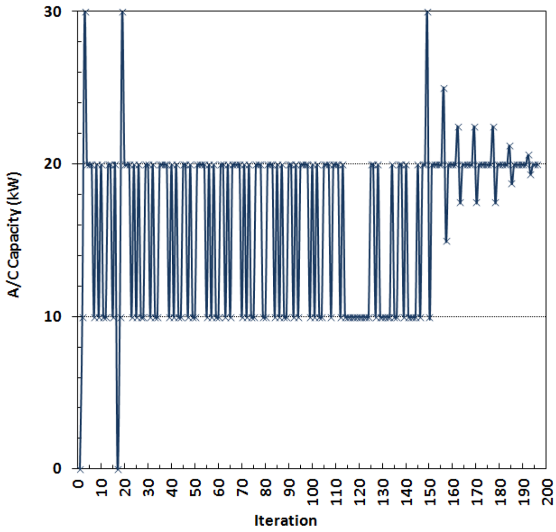
There are a few higher costs as the simulations progresses, e.g. 52, 90, 108 or 135 principally due to the lack of heating (Figure 8.12c). Then, the costs varies depending on implementing different measures, e.g. draught proofing (Figure 8.12f), including

wall insulation (Figure 8.12g), window film (Figure 8.12h), double glazing (Figure 8.12i), computer upgrades (Figure 8.12j) and lighting upgrades (Figure 8.12k).

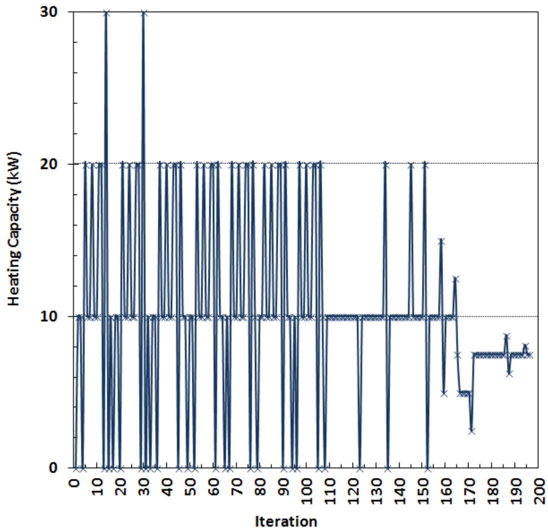
Double glazing and wall insulation were selected as retrofit options because Canberra's climate has more extreme temperatures than Sydney, and therefore requires a better thermal performance envelope. Both options provided higher energy savings and improvements in thermal comfort than the investment costs, while draught-proofing the space indicated a steady decline of energy and the cost of productivity loss which reduced the total costs. The cost of upgrading computers and incorporating window film outweighed the benefits of comfort and energy savings so they were not implemented. The minimum energy and retrofit costs that maximised thermal comfort were achieved via the current air-conditioning unit of 20-kW, installing a heating capacity of 7.5-kW, cooling temperature set-point of 24.4°C, heating temperature set-point of 21.8°C, upgrading the luminaries to a lighting level of 12 W/m^2, draught proofing the space to 0.5 ACH, installing double glazing and wall insulation of R3. Luminaries were upgraded to T5 and not E1 principally because the electricity and cooling savings from E1 were outweighed by the investment and heating savings for T5.



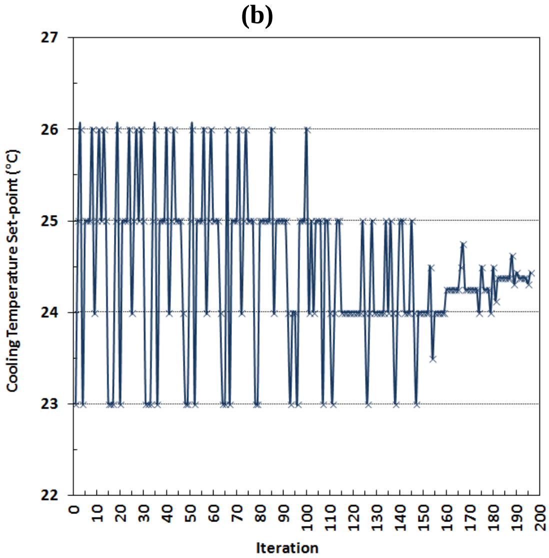
(a)


A/C Capacity (kW)
0
10
20
30
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
Iteration

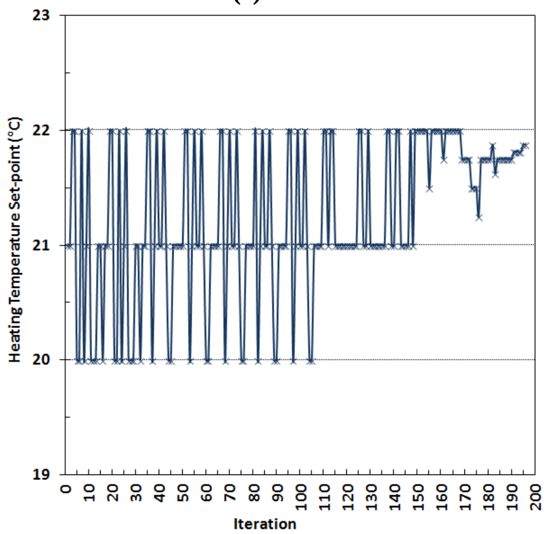
(b)


Heating Capacity (kW)
0
10
20
30
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
Iteration

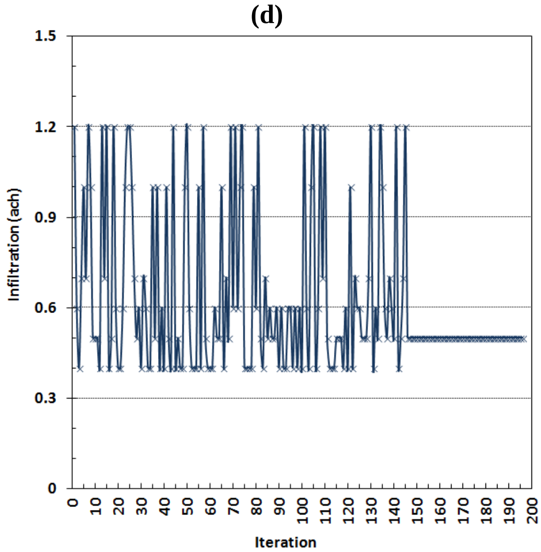
(c)


Cooling Temperature Set-point (°C)
22
23
24
25
26
27
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
Iteration

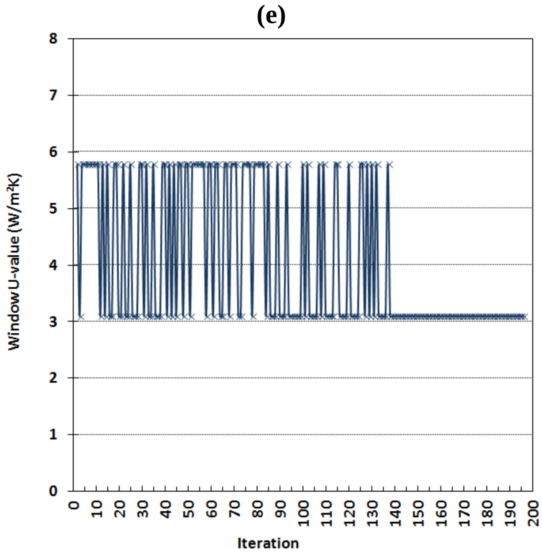
(d)


Heating Temperature Set-point (°C)
19
20
21
22
23
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
Iteration

(e)


Infiltration (ach)
0
0.3
0.6
0.9
1.2
1.5
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
Iteration

(f)


Window U-value (W/m²K)
0
1
2
3
4
5
6
7
8
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170 180 190 200
Iteration

(g)

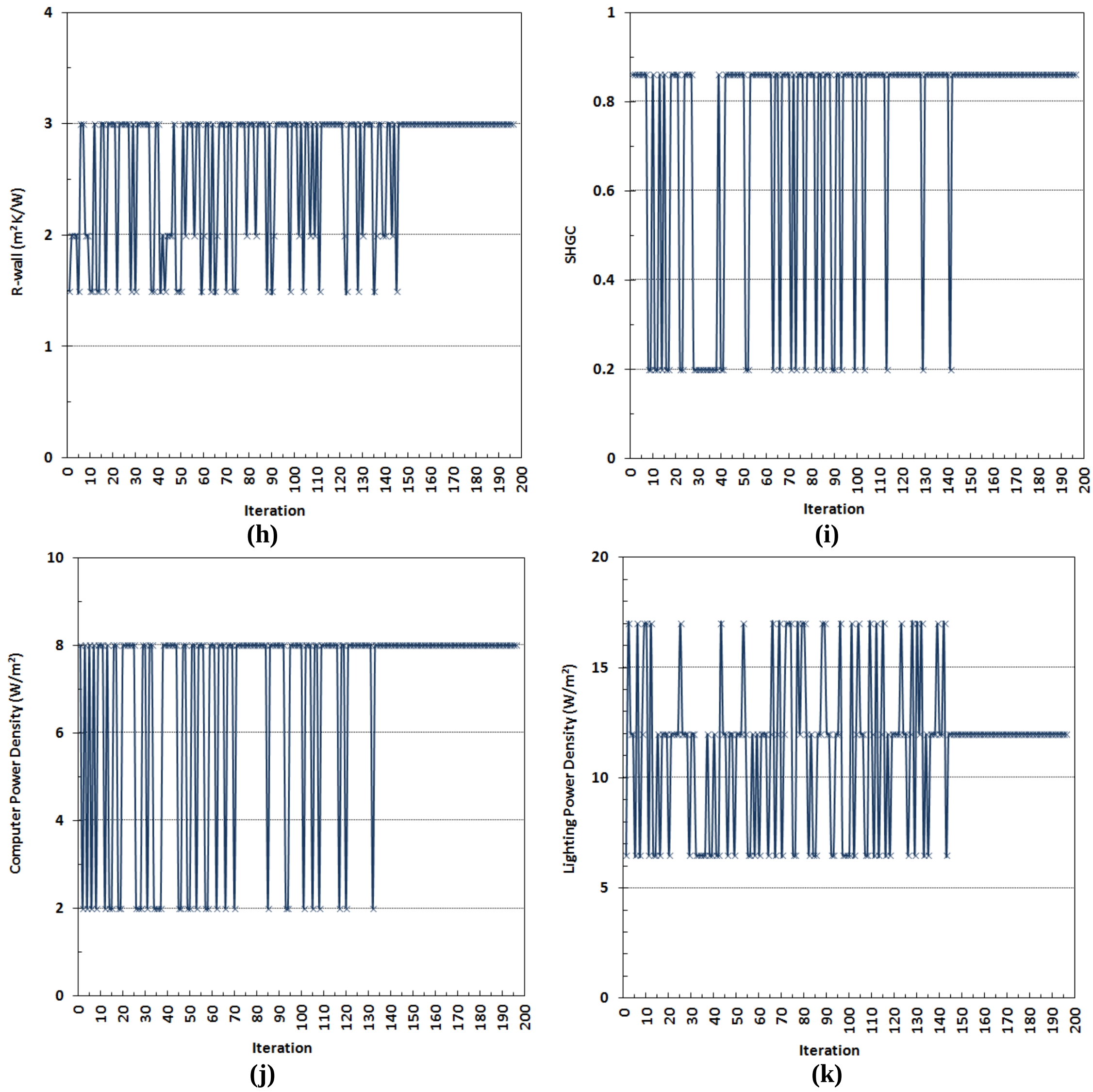


Figure 8.12 Output costs and inputs decision variables values for all the simulations conducted in the optimisation for Canberra typical climate. (a) Total costs, i.e. productivity loss costs due to thermal discomfort, operational costs and investment costs, (b) air-conditioning capacity, (c) heating capacity, (d) cooling temperature set-point, (e) heating temperature set-point, (f) infiltration rate, (g) window U-value, (h) insulation wall R-value, (i) SHGC, (j) computer power density and (k) lighting power density.

The results showed that similar building characteristics with different weather conditions led to communalities in the influential parameters such as temperature set-points, infiltration or window U-value, and retrofit options such as similar heating set-points or lighting upgrades, whereas the differences were principally identified in the envelope parameters. It was found that envelope parameters impacted energy consumption and thermal comfort to a higher extent in more extreme climates, whereas the internal loads and temperature set-points were critical in both climates. Double glazing and wall insulation minimised global costs in Canberra, while wall insulation in

Sydney was not even a decision variable and the cost of double glazing far outweighed the benefits. In both cases, an airtight space improved comfort and decreased energy consumption. Upgrading lighting with different power density depending on the climate improved the thermal comfort and lighting energy costs for both climates and cloud computing had too high investment costs to be viable. Likewise, the installation of window film resulted in higher thermal comfort and heating costs than cooling energy savings.

8.4 Results of Upgrade Implementation

One of the retrofit strategies, i.e. window film, was installed in the north facing offices of the east wing of the case study building to demonstrate its validity and benefits (Figure 8.1 shows the offices location from G33 to G38). Despite window film was not selected as part of the optimal retrofit strategy package, UOW FM division decided to implement this retrofit option on the case study building. This decision underlines the importance of undertaking the full methodology, as probably a more suited retrofit strategy would have been selected if the developed retrofit optimisation method was conducted.

In order to assess the effectiveness of the window film installed, the indoor temperatures of two representative offices (G34 and G33) in the ground floor were monitored with iButtons (*§7.3*). Both offices presented almost identical internal loads, i.e. the number of computers, equipment, occupants and lighting. Moreover both unconditioned offices had the same floor area and orientation, and were adjacent to each other. The window film was installed in G34 (a real photography of both offices from the outside façade is shown in Figure 8.13).

The east wing model of Building 4 introduced in §8.1.1 was used to evaluate the thermal comfort and solar gains through the window. Despite using identical building model geometry (§8.1), the weather file had to be modified to account for the real weather conditions. That was done using the collected data from the weather station for 23rd December 2014 to 4th January 2015 (details of how the weather file was constructed were provided in *§6.3.1*). The results of the model validation are detailed in the following section.

Figure 8.13 Comparison of building 4 façade with the two representative offices chosen to assess the effectiveness of the window film. Office with Sterling 20 window film installed (G34 on the left hand side) and another one, G33, without window film.

8.4.1 Window Film Model Calibration

The test period was from 23rd December 2014 to 4th January 2015. Uncertainty due to occupancy schedules and internal loads was expected to be minimal due to the Christmas period. However, these offices are occupied by post docs whose occupancy schedule was too complex to estimate so the unoccupied periods are assumptions. The settings implemented in the model were the same as those reported in *§6.3.3*, the only difference was a different weather file due to a different period, and the addition of window film. The specifications of the window film Stirling 20- installed in office G38- are defined in Table 8.8.

Table 8.8 Specifications for the clear glass and window film employed in the model and installed in the building.

Product description	Visible Transmittance	Absorptance	Reflectance	Emissivity	SHGC
Clear glass (3mm)	0.83	0.10	0.08	0.84	0.86
Sterling 20	0.18	0.37	0.23	0.67	0.20

Experimental temperatures against the modelled temperatures for G33 (the office without window film) and G34 are shown in Figure 8.14a and 8.14b, respectively.

Note that the predicted and modelled temperatures follow similar trend but the model under predicted the experimental temperature with an offset. As mentioned before, this was due to the uncertainty in the model regarding internal loads, since it was the

Christmas period and it was assumed that lighting and computers were all off, but the data indicated some sort of internal loads on. Therefore, Figure 8.15 presents the same model but with a constant internal load equivalent to one computer running for 24 hours.

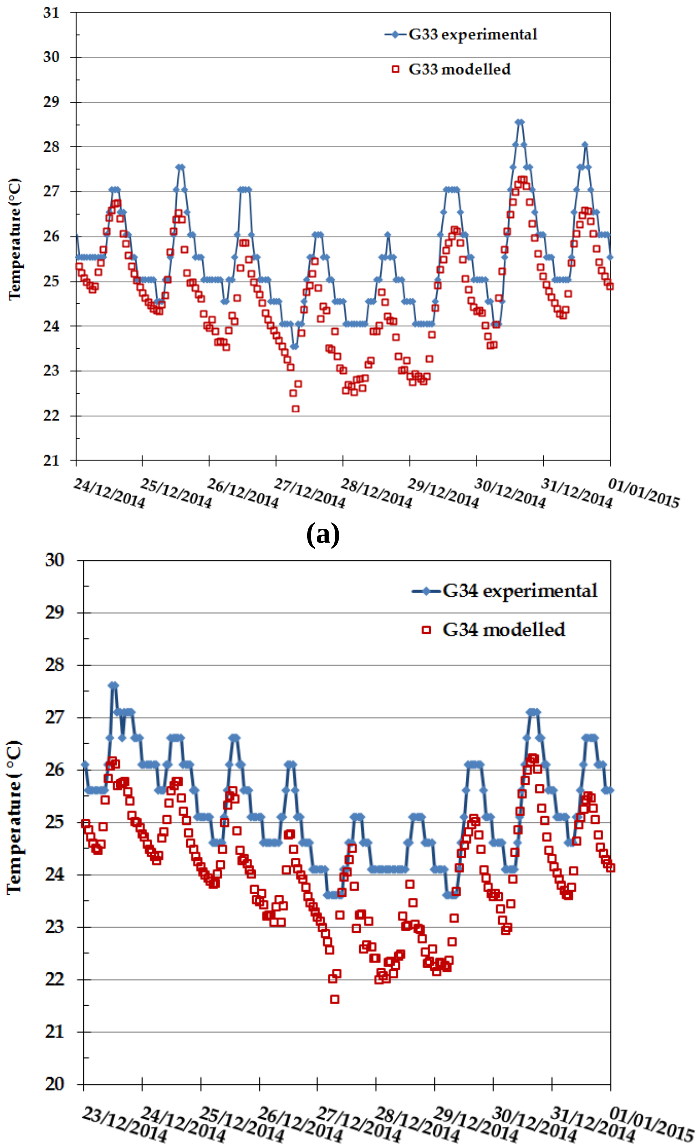
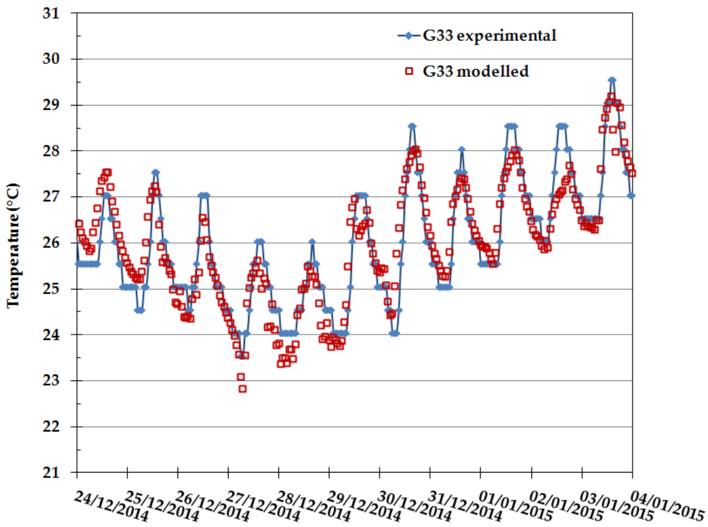
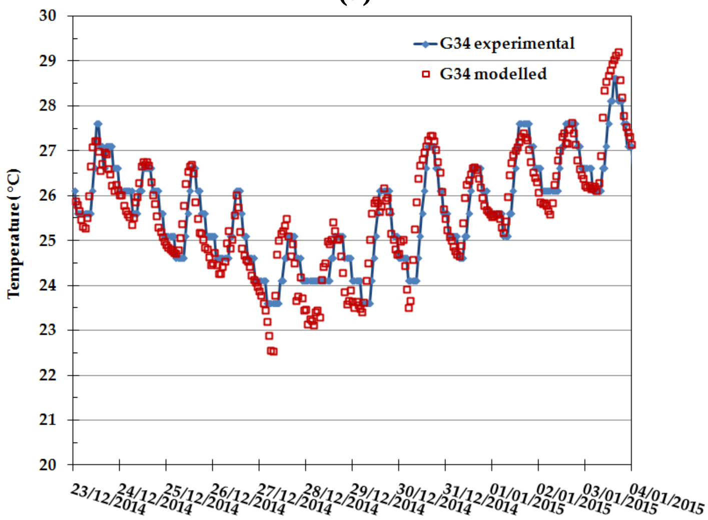


Figure 8.14 Experimental temperatures against modelled temperatures for (a) an office without window film (G33) and (b) office with window film (G34).



(a)



(b)

Figure 8.15 Experimental temperatures against modelled temperatures for (a) an office without window film (G33) and, (b) office with window film (G34) considering the increase in internal loads.

In this case, the temperatures predicted by the model matched with the experimental measurements for most data points, the goodness of fit, r^2, was 0.62. The maximum difference in office G33 (Figure 8.15) on the 3rd of January was almost one degree, probably due higher internal loads in the reality compare to the model, e.g. there was an occupant who turned on the lights and another computer while the model accounted for no-occupancy.

The effectiveness of the window film was evaluated by:

- Comparing monitored indoor temperatures before and after the window film was installed.

- Comparing experimental against modelled indoor temperatures. The model was to predict how the temperatures would have been if the window film would not have been installed. Therefore any reduction in temperature can be calculated.
- Modelled solar gains through the windows.

8.4.2 Experimental Temperatures Before and After the Upgrade

A period in the summer of 2013 where no window film was installed and a period in summer 2014 after installing window film were selected. The periods used for this comparison had to present the outside temperatures as similar as possible; this condition was found from the 19th of December until the 24th of December for 2013 and 2014. Figure 8.16 shows the cumulative frequency for the outside air temperature for this period. Although the temperatures during both periods were similar, 2013 had a slightly higher percentage of time with temperatures above 29 degrees, but these discrepancies were within ±5%.

The cumulative frequency for internal air temperature for offices G34, where window film was installed and G33 without window film for the aforementioned period are presented in Figure 8.17.

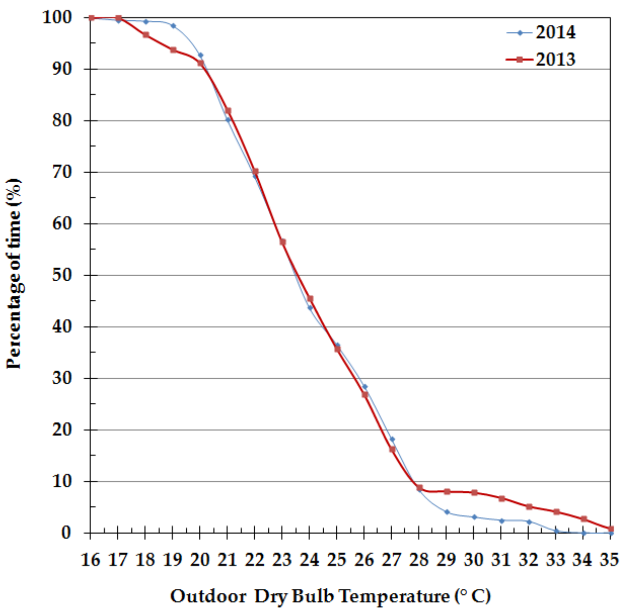


Figure 8.16 Cumulative frequency for outdoor dry bulb temperatures during five days in December 2013 and 2014.

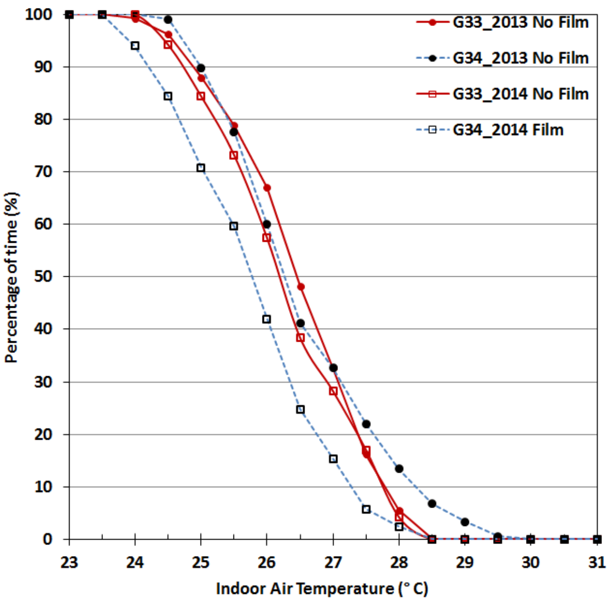


Figure 8.17 Cumulative frequency for internal air temperature during five days in December 2013 and 2014 with very similar outside air temperature.

Both offices without window film in the 2013 period presented a very similar temperature profile. Office G34 showed a slightly higher temperatures above 27.5°C than G33 (the frequency of temperatures above 27.5°C in office G34 was 5% higher than G33), but in 2014, after the installation of window film in the G34 office, the trend was reversed. This means that G33 without the window film had consistently higher temperatures than G34. As an example, the frequency of temperatures above 26°C was around 16% higher for G33.

The cumulative frequency from 19th of December 2013 to 16th January 2014 and from 19th of December 2014 to 16th January 2015 is shown in Figure 8.18. Although in this case the external temperatures differed, the aim was to compare two offices (G33 and G34) in 2013 and then the same offices (G33 and G34) in 2014, after one of them had been upgraded with window film. It is observed that for the 2013 period both offices without window film exhibited very similar temperature profiles, although temperatures above 27.5□C were slightly higher in office G34. However, once the window film was installed in G34 in 2014, consistently lower temperatures were recorded in G34 as compared to office G33 without window film.

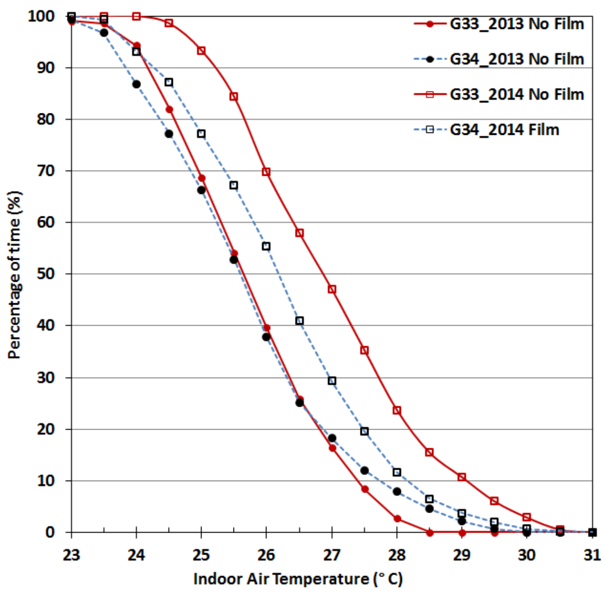


Figure 8.18 Cumulative frequency for the internal temperature for 19th of December 2013 to 16th January 2014 and 19th of December 2014 to 16th January 2015 for G34 office with window film, and G33 office without window film.

8.4.3 Model Predicted Temperatures against Experimental Temperatures

Effectiveness of the window film was explored by modelling on how the indoor temperatures in office G34 would have been without installing the window film and comparing them against the real temperatures monitored in G34 as well as those modelled with window film. The cumulative frequency of the temperatures for office G34 modelled without window film, and G34 modelled with window film and real monitored temperatures, are presented in Figure 8.19.

G34 modelled without window film presents consistently higher temperatures than the model with window film and the real monitored temperatures. The percentage of time with temperatures above 26°C was 26% higher in the modelled scenario without film compared to the real monitored temperatures.

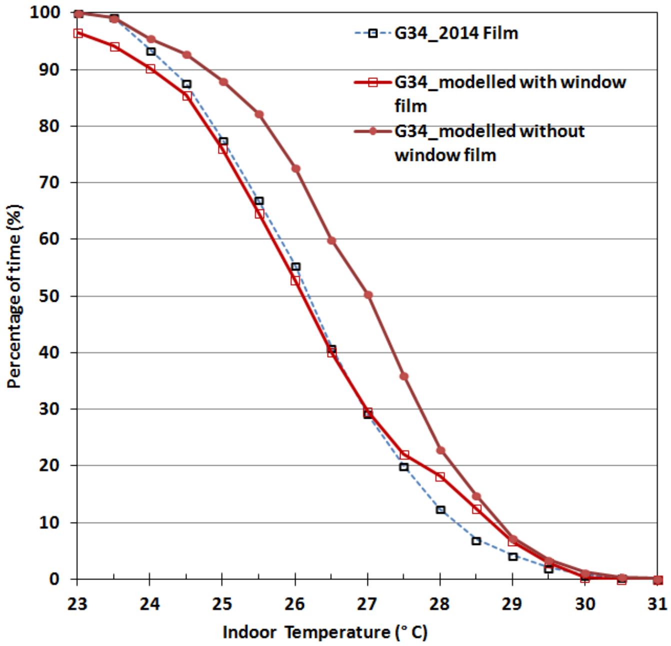


Figure 8.19 Comparison of internal temperature cumulative frequency between modelled and monitored results as in reality (with window film) and modelled without window film (how the internal temperatures would have been).

8.4.4 Modelled Solar Gains

The solar gains through the window were estimated by the model. The model was run with window film in G34 replicating reality, as well as if there was no window film installed in G34. The results are shown in Figure 8.20.

The modelling showed an average 70% decrease in solar gains in the office with the window film compared to the one without film.

A subjective assessment from the occupants reported divergent opinions on their perceived improvement of the window film. The general trend was that occupants in offices without air-conditioning were not satisfied because they did not consider their thermal comfort issue had been addressed, while the occupants with air-conditioning were content with the reduced solar radiation.

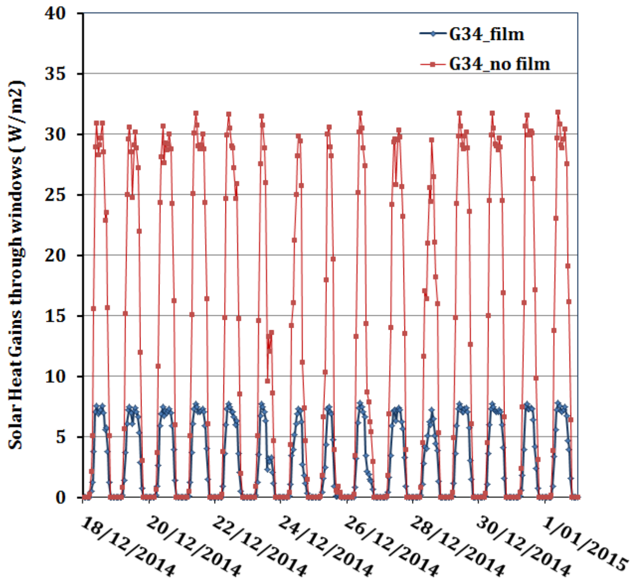


Figure 8.20 Modelled comparison of the solar heat gains between G34 office with window film (as the existing one) and if no window film had been installed.

8.5 Results Discussion

The typical approach to retrofitting higher education buildings followed by facilities management decision makers was identified through interviewing key actors in the Australian and New Zealand higher education facilities management teams (*§3.6.1* Figure 3.1*)*. The combination of the insights from these interviews, the decision support framework developed in this work to assess and prioritise higher education buildings for retrofitting and the developed building optimisation methodology resulted in the approach presented in *§6.4* Figure 6.7. This approach proposed a more holistic portfolio assessment to strengthen the current practice analysis, including a broader set of KPIs weighting based on their performance compared to a benchmark. At a building level, the method combined experimental monitoring with simulations to identify the optimal retrofit strategy for minimal maintenance, operational and investment costs as well as discomfort hours during a building lifetime. The main outcome is that the value of implementing a retrofit strategy becomes apparent and tangible; therefore the results can be used to justify a business case for retrofitting the building. This is crucial as putting a business case is the most widely approach cited by the interviewed decision makers to compete for funding from the client (i.e. University) to retrofit.

The initial modelling results conducted in the case study building (*§7.4.4*) demonstrated that the certain retrofits such as lighting/IT upgrades or night purge could have very positive effects on both energy consumption and thermal comfort in naturally ventilated

university buildings in regions with climates similar to the Sydney region. Nevertheless, this method is fragmentary, did not account for costs and would not lead to an ‘optimal’ retrofit strategy that minimised retrofit implementation, operational costs whilst maintaining satisfactory thermal comfort. Consequently, a more comprehensive optimisation method was demonstrated through a case study building (*§8.4*).

During the course of this study, a closer relationship with the FM department at University of Wollongong was built. This, in turn, initiated a change in culture in their department that translated into them taking on board some of the described methods in this work. As an example they asked the Sustainable Buildings Research Centre (SBRC)- the research centre where I undertook my PhD- to assess the performance of the Chemistry building (this is Building 18), which was identified as the worst performance building based on the evaluated KPIs (*§5.5.2*).

9. Conclusions

This study improved the current understanding of the retrofitting process for existing higher education buildings through an extensive review of the literature, qualitative investigation with leading actors in the higher education Facilities Management (FM) teams, and a comprehensive data and simulation analysis of a case study institution. The key output was a decision support framework, to evaluate and prioritise the upgrade options for energy efficiency and thermal comfort optimisation of a portfolio of higher education buildings.

Developing a detailed understanding of how Australian higher education FM teams conduct their decision making process on the retrofitting of their building stock was a major objective of this research. A detailed review of existing literature revealed limited information related to the approach and practices that Australian stakeholders employ when deciding on which higher education building to retrofit, or which refurbishment strategy to implement on a building. As a result of this limited information, a qualitative investigation formed a significant piece of this research. Insights into the current decision making practices for retrofitting Australian and New Zealand universities were gained via nine semi-structured interviews with key stakeholders involved in the process.

Despite finding that decisions were not always conducted with a systematic or logical approach, some common key features of their typical practice approach were identified. The analysis of the qualitative results provided the background for the definition of several Key Performance Indicators (KPIs) which were used to characterise a portfolio of buildings, and to identify those features in the decision framework that are essential in the decision making process. As an example, the interviews analysis revealed that clear demonstration of the benefits of retrofitting a building was crucial for making any investment decision.

Another objective of this research was to develop a set of KPIs to represent the most important characteristics of university building stock. The KPIs were developed by using a multimethod approach, including i) a comprehensive literature review, ii) a review of university data and resources principally from a case study, and iii) the qualitative investigation of current practices of senior staff and facilities managers

involved in upgrading buildings. The KPIs addressed the operation and condition of higher education building portfolio, which helped in understanding how each individual building performed across different measures. To compare the various KPIs, a weighting scheme based on the normalised experimental data and the subjective importance that the decision makers provided to each KPI was developed. This weighting scheme formed the basis of the decision framework by enabling a single deterministic score to be calculated for each building and each KPI.

The decision support methodology was then applied to the case study university building portfolio, the University of Wollongong. The results showed that buildings with a higher rate of conditioned spaces and common spaces resulted in higher energy consumption. However, spaces with more laboratories tended to have a higher base load, despite being utilised less than other spaces. This indicated that more equipment or/and lighting loads were likely to be running after hours, unlike non laboratory spaces. The results also indicated that unsolicited complaints regarding thermal comfort and HVAC performance should be addressed promptly, as higher rates of HVAC complaints were related to higher HVAC energy consumption, most likely as a result of equipment malfunctioning. Moreover, a larger budget for maintenance should be allocated for older buildings, in which the rate of complaints was found to be higher. Mapping these building characteristics was determined beneficial for the management of resources for retrofitting and maintenance, which in turn can improve the economic, social, and environmental performance of higher education facilities. The weighting scheme was then applied to the UOW portfolio for the determined KPIs to allow the comparison of the building performance across different indicators. The worst performing buildings were found to be the Chemistry Building, Science Building and Research Support Facility. The overall performance of these buildings was identified as three to four times worse than the average performance of the building portfolio. The main issue for the first two was the extremely poor performance in Work, Health and Safety (WHS) temperature hazards while the Research Support Facility presented high normalised values, i.e. poor performance, across different KPIs.

The development of a methodology to identify the optimal retrofit strategy to maximise the cost-effectiveness of upgrades, whilst preserving an acceptable level of thermal comfort for a particular building was another key objective. This was achieved via:

i) An evaluation of the practical performance of existing university buildings across a range of attributes, including a comprehensive energy audit and Post Occupancy Evaluation (POE) of occupants' perceptions.

ii) The creation and calibration of a detailed building model. The model was constructed with the experimental data collected through the audit and calibrated using the monitored weather conditions, indoor temperatures and power consumption;

iii) Conducting a sensitivity analysis to reveal the parameters that most affect the energy consumption and thermal comfort in the calibrated model; these parameters, i.e. decision variables, were then proposed as possible areas for a retrofit to target;

iv) Defining a cost function which included the costs of investment, building operation, services maintenance and productivity penalty function. This study was novel in the inclusion of this penalty function to account for the level of thermal discomfort and associated loss of occupant productivity in a given higher education building.

This methodology was applied in the assessment of a case study building, which was identified in the top fifteen worst performance buildings on UOW campus through the implementation of the decision support framework. It was found that a) the building had a poor building envelope, with poor air tightness and a low thermal performance, b) lighting was one of the highest power consumption in the sub-monitored space, c) occupants were generally dissatisfied with their thermal environment, and d) occupants' perceived their average productivity to be reduced by being inside the building. Despite finding out that more than one area of the building was underperforming, one section was selected to identify an optimal retrofit strategy based principally on the occupants' dissatisfaction. Preliminary analysis showed the potential to decrease energy consumption and improve thermal comfort through a range of different retrofits. However, this piecemeal approach would not lead the identification of an 'optimal' retrofit strategy due to the complexity of the process with innumerable potential retrofit options. To this end, by applying the methodology developed for this study it was possible to identify an optimal retrofit strategy for the given criteria.

The sensitivity analysis demonstrated that the parameters with the highest impact on the overall energy consumption and thermal comfort for Sydney weather were temperature set-points, lighting and computer power density, infiltration, window solar heat gain coefficient (SHGC) and U-value. The optimal retrofit strategy therefore included E1

lighting upgrades, improving the air tightness of the building, and the installation of a 1-kW heating system.

Applying the same methodology to the same building in a more extreme climate, i.e. Canberra, which has a colder winter and warmer summer than Sydney, the results showed similar influential parameters, with the addition that the R-value of the external wall was found to be significant. The optimal retrofit strategy had several communalities, including similar temperature set-points and draught-proofing the building. However, luminaries were upgraded to T5 and the recommended heating capacity was 7.5-kW. Envelope parameters such as R-3 wall insulation and double glazing were also identified as the optimal strategies for retrofitting. This demonstrated that a better thermal performance envelope is required for more extreme climates.

Thereafter, one of the retrofit options, i.e. window film, was installed in the case study building to demonstrate its benefits over summer. The modelled window film revealed the improvements in thermal comfort, measured as the reduction of percentage of time with air temperature above 26°C, of approximately 26% between comparable unconditioned spaces. This result was supported by the temperature monitoring in two adjacent similar unconditioned offices, i.e. one with window film and the other without. It was found that the percentage of time with temperatures above 26°C were approximately 20% more frequent in the office without the window film.

The methodology developed in this work for assessing the overall building portfolio to optimising retrofit strategies formed the basis of an integrated method for decision making for higher education building retrofits, to improve on the current practice approach. This study demonstrated a coherent methodology for understanding a building portfolio and selecting a building for retrofitting based on the existing data and the strategic priorities of the decision makers. Once a building was selected, the approach to identifying the optimal retrofit strategy to maximise energy savings and thermal comfort improvements was demonstrated through numerical simulations.

This decision framework developed in this thesis is replicable for other higher education buildings. It combines the social and financial aspects with the building physics, and has potential to help FM to make informed, systematic decisions to improve the energy efficiency and thermal comfort of their university buildings rather than rely on best guesses based on assumptions or incomplete data. Therefore, this thesis represents a

contribution towards i) rationalising the decision making process of retrofitting higher education portfolios and ii) justifying the business case for retrofitting a particular building with a specific retrofit strategy, as the significance and benefits of implementing this retrofit strategy become tangible.

9.1 Future Work

The methodology proposed in this study aided in the prioritisation of a portfolio of buildings for assessment and refurbishment. There is a great deal of potential for future research in this area and specific recommendations include:

- A similar methodology could be applied to different university building portfolios to explore its applicability. In order to be used by different higher education FM teams, the decision framework was coded in Microsoft Access, but the only output provided was the building prioritisation list. Hence, the decision tool could be coded further to become more functional for the user, e.g. to display the rationale behind the portfolio prioritisation through the creation of a building profile for each building. The profile could include KPI baseline and normalised values, benchmarks, and key building characteristics such as; the year of construction, the % of fenestration, orientation, typical external wall construction, glazing type or dates scheduled for capital works. This, in turn, would facilitate the visualisation and understanding of the building performance. This tool would then be ready to be trialled in different Australian FM Teams and feedback on its functionality could be available.
- The approach outlined in the method identified the optimal retrofit of a particular building, but one of its limitations is that it must be implemented for each building. However, it is recommended that the development of university building archetypes should be investigated. It is suggested that categorising buildings under certain characteristics to build up archetypes or similar building typologies should be examined by undertaking comprehensive audits of university buildings. Although the investment in time and money is predicted to be high, the potential benefits are also important. The archetype buildings for higher education buildings have a twofold purpose; one is that by clustering buildings together results in a more detailed understanding of their performance, and different relationships between characteristics such as energy, water

consumption, construction materials or space types, can be investigated. Alternatively, a similar cluster of buildings might be able to share retrofit technologies, so an investigation of a method to identify the best retrofit strategy at a precinct level instead of just one unique building is suggested. In fact a procedure similar to that explained in the thesis could be used. Considering the buildings at a precinct level can also provide more benefits in terms of operational savings and improvements in thermal comfort compared to the investment costs. This, in turn, can further support the business case for retrofitting.

- The optimisation methodology could potentially be automated via scripting. Then, cloud-computing could be used so as to increase computational power and reduce the computing time. Therefore, it would be possible to include a vast amount of parameters for the sensitivity analysis. In addition, the objective function could expand the term of productivity penalty function through accounting not only for the time of thermal discomfort but for poor indoor air quality, acoustics and visual comfort.
- Assessment of effectiveness of the window film during winter conditions could be conducted. In other words, temperatures and power consumption could be intensively monitored. Potentially, this would corroborate the simulation results, indicating that this window film benefits in summer are outweighed by the thermal discomfort in winter.

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APPENDIX A: ETHICS DOCUMENTATION

PARTICIPANT INFORMATION SHEET FOR DECISION MAKERS AND FACILITIES MANAGEMENT STAFF AT AUSTRALIAN UNIVERSITIES

Project Title: *Decision making Processes Used In Implementing Sustainable Retrofits on University Buildings*

Purpose of the research

The focus of this project is to gain a better understanding of existing decision making practices used in upgrading, refurbishing and retrofitting existing Australian university building stock. In addition, the researchers would like to receive feedback on their proposed methodology for prioritisation of refurbishment of university building portfolios.

Methods and demands on participants

If you choose to be involved in this study, you will be asked to participate in a semi-structured interview conducted by PhD student Laia Ledo. The interview will focus on your tertiary institution decision making processes used in determining existing building retrofits and refurbishments. The interviewer will discuss how your existing decision making processes are conducted, if there are any Key Performance Indicators (KPIs) currently used to assess the buildings portfolio performance, and to critique the researcher's proposed KPIs and rank them based on your opinions and perceptions.

The interview is expected to take about 15 min and will be audio-recorded to ensure accurate transcription. You are invited to request a copy of the transcript, and to submit edits/revisions. The information from your interview, possibly including some direct quotes, may appear in the PhD thesis of the interviewer, and academic journals, subject to your consent. You will be asked if you wish to be given a pseudonym if direct quotations from the transcribed conversations are used in the researcher's PhD thesis or scholarly publications.

Inconveniences and discomforts

The major inconvenience will be your time spent in the interview. Your involvement in the study is voluntary and you may withdraw your participation and any data that you have provided to that point.

The Project Organiser

This project is funded by the Sustainable Buildings Research Centre, University of Wollongong. If you have any enquiries about the project, or would like to volunteer to participate, please contact: Laia Ledo (0426293853; ll996@uowmail.edu.au). This study has been reviewed by the Human Research Ethics Committee (Social Science, Humanities and Behavioural Science) of the University of Wollongong. If you have any concerns or complaints regarding the way this research has been conducted, you can contact the University of Wollongong Ethics Officer on (02) 4221 3386 or email rso-ethics@uow.edu.au.

Thank you for your interest in this study.

Prof Paul Cooper

Director, Sustainable Buildings Research Centre (SBRC)

2nd June 2014

CONSENT FORM FOR PARTICIPANTS:

Decision making Processes Used In Implementing Sustainable Retrofits on University Buildings

You have been asked to participate in a PhD research study conducted by PhD candidate Laia Ledo from the Sustainable Buildings Research Centre (SBRC) at the University of Wollongong. Your participation in the research involves a short interview to aid achieving the study goals. The study aims are as follows:

- to understand current practices and frameworks used for decision making on university building stock retrofits ;
- to develop a method to aid in the decision making process for university building upgrades via prioritising the building stock portfolio.

Please read the information below, and ask questions about anything you do not understand, before deciding whether or not to participate.

The interview is voluntary.

You have the right to withdraw at any time or for any reason from the study.

The interview should take about 15 minutes; you have the right not to answer any particular question if you so wish.

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 completely confidential.

This interview may be recorded for use as a reference for the researcher 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.

By ticking and signing below I am indicating my consent to:

☐ participate in an interview concerning decision making processes related to retrofitting of university buildings.

☐ the interview being recorded by the researcher for later transcription and analysis.

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 allow 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 Laia Ledo (0426 293 853, ll996@uowmail.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.

APPENDIX B UOW BUILDING PORTFOLIO CHARACTERISTICS

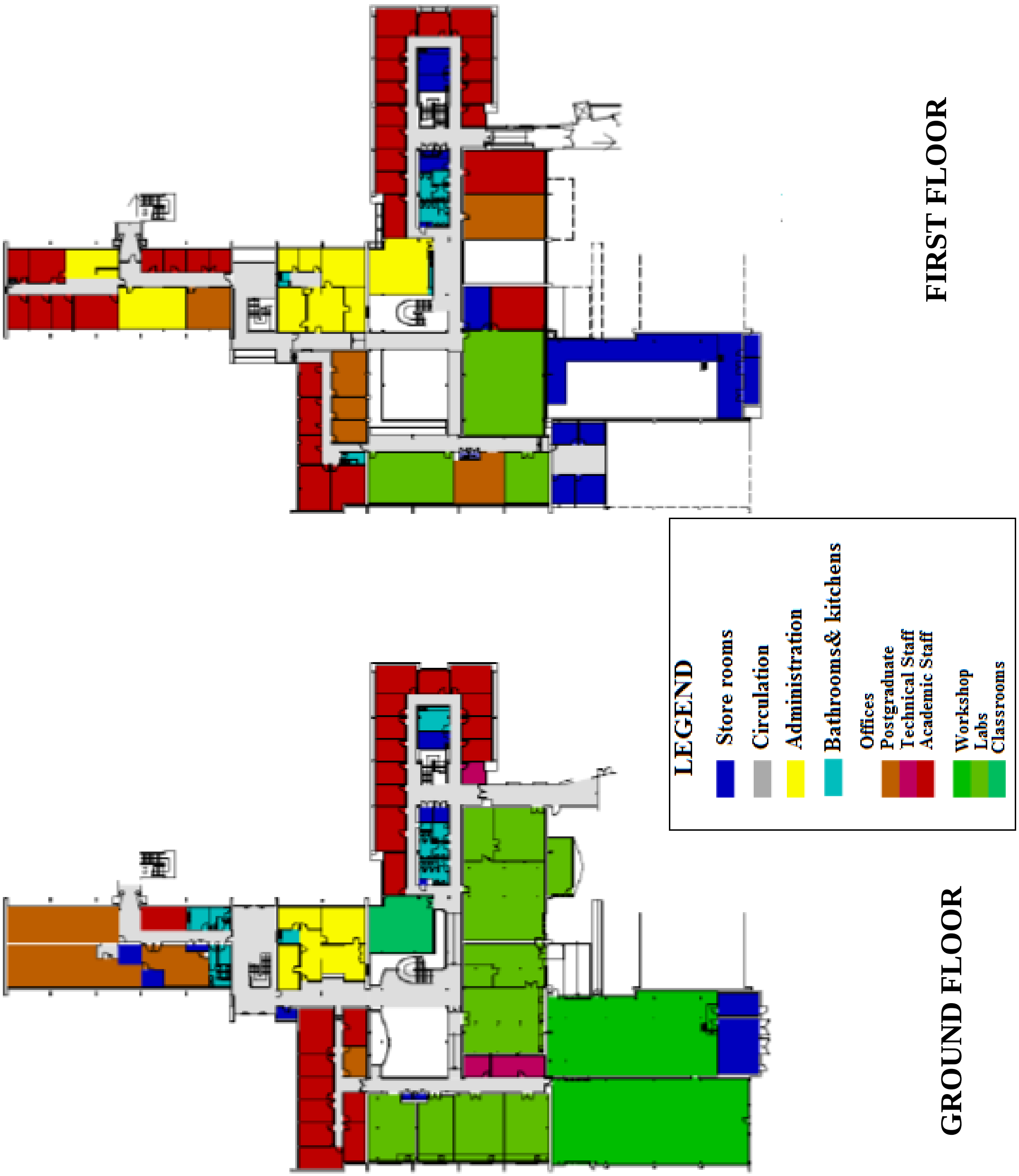
Building number	Usage Type	Wet Lab (m^2)	Wet labs HVAC (m^2)	Teaching Spaces (m^2)	HVAC Teaching (m^2)	HVAC lectures theatres (m^2)	Dry Lab (m^2)	Dry lab HVAC (m^2)	Common spaces (m^2)	HVAC common spaces(m^2)	Offices (m^2)	HVAC offices(m^2)	Computer lab (m^2)	HVAC computer labs (m^2)	Gym (m^2)	Library (m^2)	Tenancy (m^2)	Other(stairs, storage, toilets.etc)	UFA (m^2)	Cond (m^2)	Uncond (m^2)
1	Labs, offices, classrooms	436		270			184	100	275		433							300	2000	100	1900
2	Labs and offices	322					105				503		35					107	1074	0	1074
3	Computer labs, offices, classrooms				267				246	121	1013	241		773				363	3025	1402	1623
4	Labs, computer labs, offices, classrooms	101			63		961	153	121	284	1002	1081		173				538	4481	1755	2725
5	Laboratories and offices							147	29	130	11							19	373	277	96
6	Laboratories, offices, classrooms		339			113	749	2807		282		3921		420				2037	10720	7883	2786
8	Laboratories, computer labs,		385	119					162		388	368		297				366	2085	1049	1036

	offices																			
9	sports hub										980			2620			1866	5466	0	100
11	retail spaces, office spaces									1201		334			7119		2041	9494	79	2041
14	Lecture theatre					236											13	249	236	13
15	offices, labs and classrooms	20	485	78		76	203	118	40		1383	66	122				575	3165	867	2298
16	offices and library									173		597			9746		2467	12983	81	2467
17	retail and offices, data centre?	0	0	0	0		0	0	150	1580	191	378	1125		243	476	512	4655	3802	853
18	offices,labs and classrooms	219	590	0	58		389	413	108	350	818	73	82				307	3408	1567	1841
19	offices and classrooms	0	0	281	1559		0	0		113	3756						1339	7048	1672	1537
20	Lecture theatres	0	0	0	0	793	0	142	38	228	166	566					12	31	17	14

	and offices															02	35	29	06
22	offices and classrooms		65	107					398	933		57			61	170	1790	566	1225
23	office and classroom							13		717						205	935	0	935
24				985				235	65							403	1688	1050	638
25	offices and classrooms	53	173	205	593	693	730	105		1279	125	247				1942	6145	1706	4439
28	offices, classrooms, laboratory, lecture theatre	235		134	106	17	170	34		327	694					374	2091	1339	752
30	offices and classrooms			647					605		142	36	260			1177	2866	1653	1213
31	offices					600			73		730					218	1621	803	818
32	Laboratories, offices	1437			174		150		331	23	706					1336	4157	2798	1359
35	offices, computer lab, labs, classrooms and		777			247	101	692		100	350	210		24			1434	4152	2267

	lecture room														1				
36	offices									374		2329				275	2978	2703	275
38	offices		187		37	116					84					344	768	340	428
39	offices	487								74	572	1484				2050	4667	1558	3109
40	offices, lecture theatre, computer labs				324	477	308	488	89	217	2548	346		114		1424	6335	1966	4369
41	offices, computer lab, labs, classrooms	669	1168	33	313		551	1159	195	93	4481	701	24	397		2643	12427	3831	8596
42	offices,labs, classrooms		95				65	321	15		198					94	787	416	372
67	offices, classrooms, dinning, lecture theatre				760	627			506	911	1225	169				1292	5489	2467	3022
70	offices, labs		299					158		115		112				38	722	684	38

APPENDIX C BUILDING 4 EXISTING ROOM USAGES



APPENDIX D BUILDING 4 BLOWER DOOR TEST SHEET

Status of HVAC Equipment during test

Air Handling	Off
Vents	Sealed
Fireplace	N/A
Heating	Air Con - sealed
Cooling	Air Con -sealed

APARATUS & PROCEDURE

Fan Pressurisation Equipment

Blower Door	QM 3000 fan and panel door
Pressure measurement	Retrotec DM-2A Digital Gauge and Control Package
Control	Retrotec DM-2A Digital Gauge and Control Package

Other test Equipment

Anemometer	Testo 410-2
Temperature	Testo 410-2
Humidity	Testo 410-2
Other	

Equipment setup

Blower Door Location	Only access door to space

Pressure measurement at lowest level of building?	On second floor - at level of measurement
Exterior pressure measurement unaffected by wind?	

TEST DATA

Meteorological Conditions

	External	internal	
Temperature	23	25.7	Deg C
Humidity	51	49	% RH

Wind Speed

Average	0.6	m/s
Gust	0	m/s

Check for significant stack effects

Building height (m)	6.2	
Height x indoor to Outdoor temperature difference (meter.Kelvin)		16.74
Height x indoor to Outdoor temperature difference > 250 meter.Kelvin?		Yes

Zero Flow Pressure Differences

Pre test - Depressurization

$\Delta p_{0,1+}$	-0.1	(Pa)
$\Delta p_{0,1-}$	-0.8	(Pa)
$\Delta p_{0,1}$	-0.45	(Pa)

Preliminary Check of Envelope During (De)Pressurization

Pressure of preliminary check

Pressurisation or depressurisation

As expected - no temporarily sealed openings ventilating

De-Pressurisation test

De-Pressurisation test (if 100 Pa achievable, use 0,20,40,60,80,100) else use (0,10,20,30,40,50 or highest possible)

Pressure Set point	Measured Pressure	Measured Flow Rate	Pressure Corrected for Zero Flow differences	Flow Rate corrected for indoor-outdoor temperature differences	Equipment Notes
(Pa)	(Pa)	(m3/hr)	(Pa)	(m3/hr)	
0					Open
10	-10	3980	8.225	4016.304054	
20	-20	5925	18.225	5979.045608	
30	-30.4	7895	28.625	7967.015203	
40	-39.9	9165	38.125	9248.599662	
50	-50.7	10400	48.925	10494.86486	
60	-59.7	11700	57.925	11806.72297	
70	-62.8	12100	61.025	12210.37162	
80					
90					
100					

Zero Flow Pressure Differences

Post test - Depressurization

$\Delta p_{0,1+}$	-3	(Pa)
$\Delta p_{0,1-}$	-3.2	(Pa)
$\Delta p_{0,1}$	-3.1	(Pa)

Notes on De-Pressurisation test

Pre test - Pressurization

$\Delta p_{0,1+}$	-3	(Pa)
$\Delta p_{0,1-}$	-3.2	(Pa)
$\Delta p_{0,1}$	-3.1	(Pa)

Pressurisation test

Pressurisation test (if 100 Pa achievable, use 0,20,40,60,80,100) else use (0,10,20,30,40,50 or highest possible)

Pressure Set point	Measured Pressure	Measured Flow Rate	Pressure Corrected for Zero Flow differences	Flow Rate corrected for indoor-outdoor temperature differences	Equipment Notes
(Pa)	(Pa)	(m3/hr)	(Pa)	(m3/hr)	
0					Open
10	9.9	5245	13.25	5292.842905	
20	20	7225	23.35	7290.903716	
30	29.4	9330	32.75	9415.10473	
40	39.1	11350	42.45	11453.53041	
50	43.6	12250	46.95	12361.73986	
60					
70					
80					
90					
100					

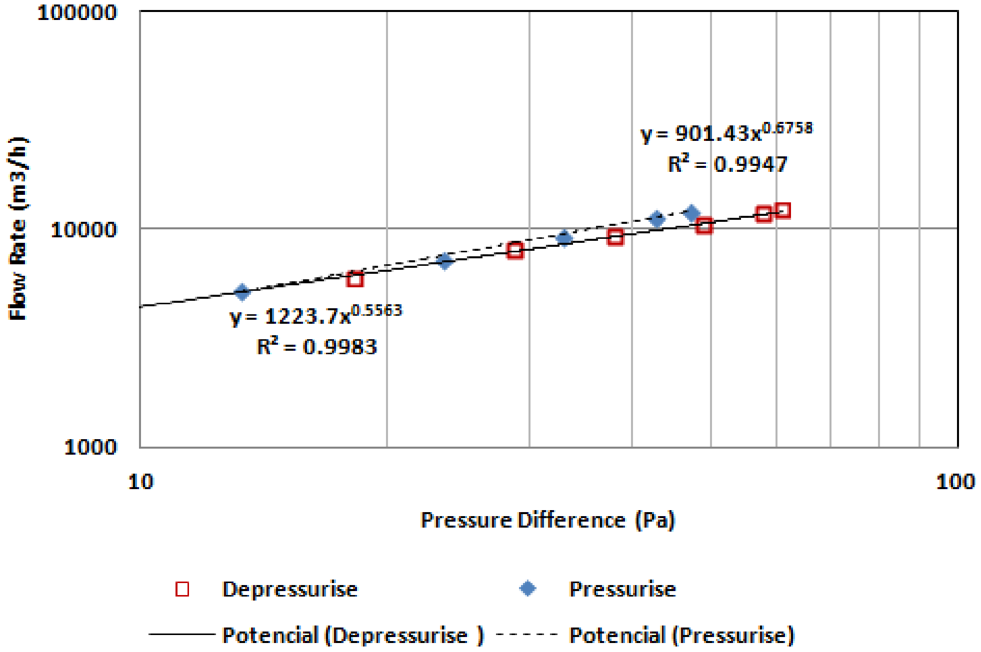
Zero Flow Pressure Differences

Post test - Pressurization

$\Delta p_{0,1+}$	-3.4	(Pa)
$\Delta p_{0,1-}$	-3.8	(Pa)
$\Delta p_{0,1}$	-3.6	(Pa)

Significant difference in Zero Flow Pressure Differences?

No



Derived Quantities

This data analysis is aimed at finding a mathematical relationship between pressure and flow or the form [Flow] = [Air Flow Coefficient] x [Pressure Difference]$^{[\text{Air Flow Exponent}]}$. This analysis utilises the data and relationship determined off the air leakage graph above

Air Flow Coefficient from test data (C_{env})	1170.2
Air Flow Exponent from test data (n)	0.5563

Air Flow Coefficient at Standard Conditions (C_L) (20 degC +/-1 , 101.3 kPa)	1160.2

Air Leakage rate at 50 Pa (q_{50})	10225.5
Air Change Rate at 50 Pa (n_{50})	24.6