Computational Assessment of Building System Performance: Improved Energy Efficiency and Thermal Comfortability for the Future

by

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Abstract

Energy expenditure is one of the significant overheads in the lifespan of multi-storeyed buildings. Reliable and proficient functions of Heating, Ventilation and Air Conditioning (HVAC) systems are further imperative as a result of the climbing price of electricity. This research recommends that the compounded energy utilisation to meet the demand from high humidity and temperature could be minimised by adopting the alternative high-performance building envelope and low emission cooling method along with the optimised control of additional operational parameters. The core purpose of this research is to computationally evaluate the performance of various alternative building envelopes and low energy cooling methods to determine the best performing envelop and cooling method to enhance the energy efficacy and human comfort in buildings in a subtropical climate in Australia.

Firstly, a detailed energy assessment of the current building systems is undertaken on a selected case study building in Rockhampton, Central Queensland. Then, a comprehensive energy simulation model is developed, employing a building energy simulation algorithm. The modelled energy and comfort data of the building systems are validated by means of on-site recorded data. The substantiated model is then expanded to evaluate the efficacy of several alternative building envelopes such as bio-phase change material (BioPCM), cavity wall, Trombe wall, building integrated photovoltaic (BIPV) and low emission cooling methods such as, cooled Beam, ground source heat pump, variable air volume, variable refrigerant flow system to secure better comfort and energy savings in both summer and winter months. Furthermore, an extensive multicriteria based optimisation is undertaken to determine combined

alternative envelope and cooling method for retrofitting of the existing systems that will meet the requisite of the present and the future depending on the potential climate change scenario.

This study found that both cooled beam and ground source heat pump as low energy high-performance cooling alternatives, and BioPCM as high-performance building envelope have the higher potential for energy conservation and better thermal comfort based on the present and future weather conditions. Through multi-criteria optimisation, the study found that BioPCM and Cooled Beam as an integrated mechanism can be successfully incorporated into buildings in subtropical climate to improve the energy efficiency by 30% and human comfort which have not been evaluated in any other studies in the past. Furthermore, the use of the combined optimised approach, i.e. integration of BioPCM and Cooled Beam, produces significantly less emission (21%) per year at the same time ensures the comfortability of the occupants which is the utmost consideration in the study. Finally, the study offered a net positive energy operating method to ensure that carbon footprint is minimised considering the present and future weather conditions. Overall, a practical thermal simulation orientated optimisation framework is developed and executed that unites the objective of minimising energy consumption of building systems as well as maintaining superior comfort of the people based on the present and future weather conditions.

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Nomenclature

AIRAH	Australian Institute of Refrigeration, Air-conditioning and Heating
ASHRAE	American Society of Heating, Ventilation and Air-conditioning
TW	Trombe Wall
PMV	Predicted Mean Vote
PPD	Percent People Dissatisfied
BMS	Building Management System
CB	Cooled Beam
DB	DesignBuilder
CW	Cavity Wall
EP	EnergyPlus
EPW	EnergyPlus Weather
CFD	Computational Fluid Dynamics
GSHP	Ground Source Heat Pump
VAV	Variable Air Volume
VRF	Variable Refrigerant Flow
BEPS	Building Energy Performance Simulation
BioPCM	Bio-phase Change Materials
BIPV	Building Integrated Photovoltaic
BMS	Building Management System
SET	Standard Effective Temperature
ET	Effective Temperature
POE	Post Occupancy Examination
AC	Air Conditioning
FV	Finite Volume
COP	Coefficient of Performance
SIMPLER	Semi-Implicit Method for Pressure Linked Equations – Revised
HVAC	Heating, Ventilation and Air-conditioning
WCS	World Coordinate System
IEA	International Energy Agency

Publications, Declaration of Co-Authorship and Co-Contribution

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Nature of the Candidate's Contribution (Including Percentage of Total):

In conducting the study, as a first author, I was responsible for preparing the problem statement, reviewing the relevant literature, undertaking the energy auditing, developing the building simulation model and CFD analysis, capturing the findings, writing the full draft and revising the paper based on the feedback.

This publication was written by me, and my contribution was 85% overall.

Nature of Co-Authors' Contributions (Including Percentage of Total):

My co-authors, [Rasul, M.G. (principal supervisor) and Khan, M.M.K. (associate supervisor)], contributed to the paper by a combined discussion with valuable feedback on the drafted paper. Rasul, M.G. helped in the organisation of information in the draft. Khan, M.M.K. helped in addressing the reviewers' comments [Co-authors' contribution: Rasul, M.G. 10% overall and Khan, M.M.K. 5% overall].

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Principal Supervisor's confirmation

I have sighted email or other correspondence from all co-authors confirming their certifying authorship.

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Research Higher Degree Thesis Declaration

Candidate's statement

By submitting this thesis for formal examination at CQUniversity Australia, I declare that it meets all requirements as outlined in the Research Higher Degree Theses Policy and Procedure.

Statement authorship and originality

By submitting this thesis for formal examination at CQUniversity Australia, I declare that all of the research and discussion presented in this thesis is original work performed by the author. No content of this thesis has been submitted or considered either in whole or in part, at any tertiary institute or university for a degree or any other category of award. I also declare that any material presented in this thesis performed by another person or institute has been referenced and listed in the reference section.

Copyright statement

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Chapter 1: Introduction

1.1 BACKGROUND

Energy use in the building makes up more than 30% of the overall energy usage around the world (IEA, 2007). The usage of energy by mechanical ventilation and air conditioning system makes up of 40% of the overall energy use in a mainstream building to support the thermal equilibrium of the people in the indoor space (Yang, Yan &Lam 2014). The energy use related to air-conditioning exhibits a potential risk to the transformation of climate pattern and places the impending global citizens in danger.

The Energy Efficiency 2018 record released by International Energy Association stated that elevated temperatures, expanding population, and monetary development have resulted in double the usage of ventilation and air conditioning system in buildings compared to the year 2000, producing increasing power end-use in building structures as shown in Figure 1.1 (Rocky Mountain Institute, 2019). The Australian Federal Government aims to improve energy efficiency by 26–28% lower than 2005 levels by the year 2030 (Australian Government, 2018). The government introduced a countrywide attempt to developing crucial guidelines to achieve the target, consisting of boosting the energy efficacy in buildings nationwide, developing the energy efficacy of building equipment, and enhancing the effectiveness of the systems.

Energy sustainability is a critical problem that properly needs debate and practises. Greenhouse gas pollution presents a significant danger to the planet's biodiversity. The power infrastructure is now stressed and will tend to be increasingly challenged in heavily inhabited regions (Supree, 2000). Improvement in energy conservation is a critical problem that is likely to be faced by engineering and society in the coming decades. Green technologies and other associated strategies are only implemented slower than required in cities and buildings (Benavente-Peces and Ibadah, 2020). The creation of subsequent decades of communities where impacts of energy use on the atmosphere must be as significantly minimised as possible.

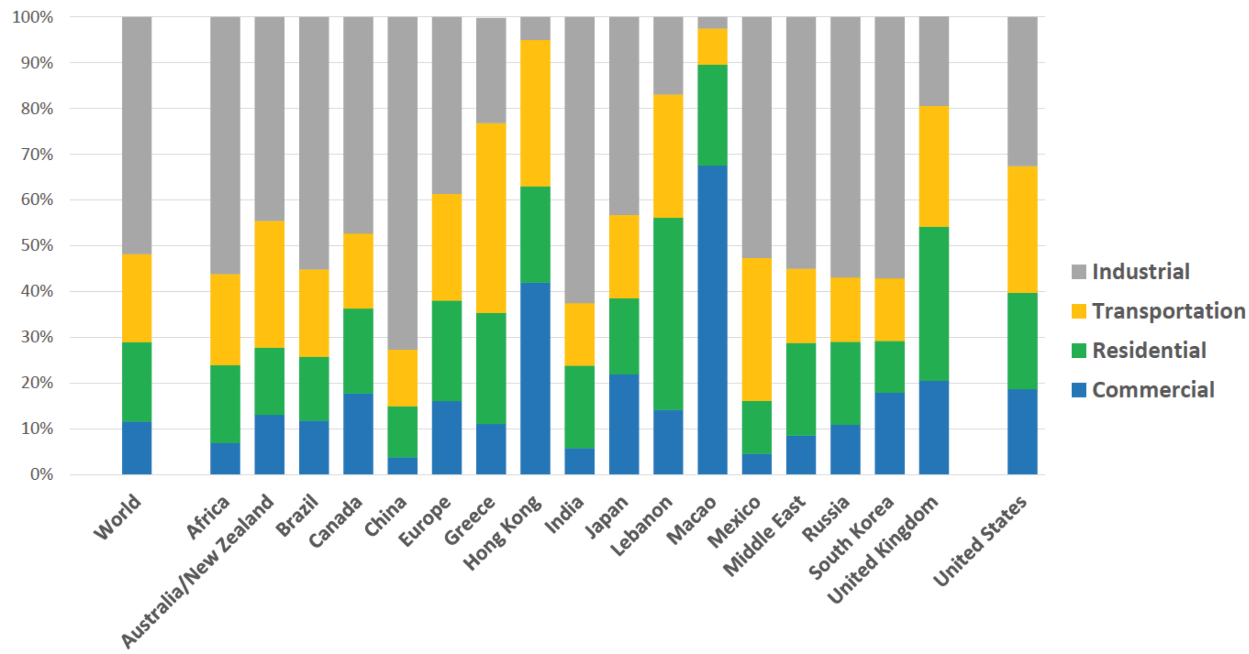


Figure 1.1 International energy usage in the built environment (Rocky Mountain Institute, 2019)

There is actually no metric that takes into account clean forms of electricity when calculating energy output. Suplee (2020) introduces the Net Power Index, which contrasts a building's net electricity consumption with the building's floor area to assess power quality and make suggestions for improvement. Often, it is a valuable method for calculating construction performance. Benavente-Peces and Ibadah (2020) highlighted all relevant factors which influence the efficacy of energy in building systems. Therefore, it is important that the factors are critically analysed in the context by considering the associated uncertainties and evaluate the practical implication of the given scenario.

Energy management systems have a tremendous ability to maximise the efficiency of energy use in buildings. There are various modelling techniques, such as mathematical models and data-driven approaches for building systems are available. Methods such as online scheduling, model predictive control (MPC), and stochastic dynamic programming (SDP) are very widely accepted in the industry (Kianpoor et al., 2020). The algorithm selects the best starting point for each period, based on the weights of the appliance and the availability of power. A few literatures provided evidence of the optimization algorithm's success and how such a programme would efficiently reduce energy usage by implementing and utilising the demand response programmes(Khorram et al., 2020). The modelling techniques can be applied to assess the proper efficiency of the building systems and to improve operational strategies.

Energy usage illustrates some of the principal threats to the climate at present. The practical regulating plans to decrease power usage and to improve the general satisfaction of wellbeing in institutional and commercial buildings are currently regarded as a key consideration in the sector. HVAC systems represent a few of the major energy-intensive systems in buildings. A number of technologies and strategies can be applied to address such issues. Power supply companies have ongoing wide-ranging charges to penalise high energy consumption at facilities. Raising prices of power must lead to an instantaneous rate of efficiency growth in energy usage and also diligence measures to retrofit the existing energy systems.

The present demand and public sentiment necessitate energy efficacy and emission declines in Australia, however, such demand comes with significant opportunities and challenges. Therefore, most patrons should work together to adhere to and potentially fulfil the public sentiment, because we would all be keen to work in this movement to energy efficacy and low emissions. The first chapter of this study outlines the problem statement, significance, the contents, importance and objectives along with the limitations.

1.2 ENERGY RESILIENT BUILDING SYSTEM AND THERMAL COMFORT

Air-conditioning has gained much mainstream press attention in what is called "among the world's biggest overlooked sector" by *The Economist*, a renowned media outlet (The Economist, 2018, p. 1). The overall statements indicate that the danger posed by this convenience of ensuring the comfort of people was underestimated. Even as recently as the Paris environment settlements, the risk represented by this essential element of building mechanical system was largely ignored. The IEA has established that air-conditioning is one of the solitary end-use risks to our atmosphere since the use of power for cooling has more than tripled between 1990 and 2016 (IEA, 2018).

Australia, as a signatory, has committed to the transition to lowering emissions by 2050. That has consequences for regional and state authorities. Queensland, together with all Australian states, has duties under the Montreal Protocol, the Paris CoP21 deal and regional and global agreements. Queensland is one of Australia's states that is greatest in danger of climate change impact with coastal areas prone to flooding and cyclones, as well as fires endangering property and life.

1.2.1 Building HVAC Systems and Comfort

Buildings in tropical climate demand continuous air conditioning to maintain comfort in a tropical climate. The cooling by passive means offers relaxation and enhances people's performance. Energy usage is believed to constitute an integral portion of greenhouse emissions. Alternative HVAC systems offer enhanced occupants comfort and enrich the performance of the occupants of a building. The functioning of this developed environment can act a great task in CO_2 emission reduction and energy consumption. Passive air-conditioning approaches are needed as these are usually low energy systems. The enhancement of the mechanical HVAC system is important to minimise greenhouse gas discharges. Research on evaluating the energy performance in buildings and residents' convenience under different air-conditioning methods are essential and hence are evaluated in this thesis in diverse operational settings.

1.2.2 Performance Evaluation of Building Systems

The calculation of energy performance in the processes of mechanical systems within a building's HVAC system is a multifaceted experience. It is challenging to forecast the annual power consumption, relevant prices as well as the capability to maintain thermal convenience. Building Energy Performance Simulation (BEPS) algorithms can evaluate all the power streams in detail as well as forecast energy usages and indoor thermal conditions by applying relevant mathematical relationships to account for all the potential external and internal variables. The analysis explains the usage of a BEPS tool to assess different HVAC systems and envelop systems that employ in a selected case study office building. In this research, the selected algorithm is adopted to calculate the energy usage and to assess thermal comfortability under various HVAC processes as well as envelop setups with an aim to create an optimised self-sustaining net-positive building. The thesis will present strategies that will ensure the decrease and reduction of the environmental effects and also the primer of climate resilience in the tropical environment zone in Queensland.

1.3 PROBLEM STATEMENT AND RESEARCH MOTIVATION

The ambitious objective of reducing construction GHG emissions up to 75% by 2050 by Queensland Government (2016) remains difficult because of fragmented solutions that highlight one driving variable, for example, an advanced energy system or constraint of climate tipping points etc. can fall short of their desired outcomes that minimise ecological impacts while achieving healthy, flexible, and resilient buildings that are productive. Buildings constitute an opportunity to demonstrate sustainability for the future as well as possessing challenges considering the uncertainty around the weather. Population, economic growth and urbanisation, with the rising interest in energy use, currently results in major environmental and economic transformations. Where people invest over 90 per cent of their hours, buildings are therefore a manifestation of the growth. However, what's the reality of energy usage in buildings, especially in a tropical climate? Is it true that the mixture of renewable energy technologies and energy-efficient appliances, and thermally efficient construction cubes is resulting in more resilient buildings for the future?

1.4 RESEARCH QUESTIONS

- What is the method of identifying the overall energy efficacy of an existing system in buildings where the energy usage indicator is top?
- How do we co-relate the comfortability of the occupant with building systems? With increasing temperatures, assuming the occupants can influence the indoor atmosphere, are higher room temperatures be meeting the comfort requirements of the occupants?

- How can optimum retrofitting strategies be formulated in order to minimise energy consumption whilst improving or maintaining occupant comfort satisfaction?
- How can we decrease the operational usages of energy and emission of CO_2 through the combination of passive external envelope strategies?
- How does a different cooling method persuade the energy behaviour of the building system in regard to energy usages and thermal comfort?
- How can we quantify the energy outcome of building at present and ensure the exact optimised energy lead to future with present technology?
- What will be the interaction of future building's HVAC performance with the natural environment?
- What is the potential of identifying the optimum operating condition of low energy building and then even transform it into a positive zero net energy building through the contribution of environment-friendly energy source?

1.5 RESEARCH AIMS AND OBJECTIVES

This study intends to analyse and measure the operation of alternative HVAC cooling methods in indoor office space in tropical weather in order to achieve enhanced energy performance and improved comfort of occupants. The analysis identified suitable HVAC technologies as well as envelop settings that would satisfy the requirement in a tropical climate at the present and the future. The study also aims to identify appropriate HVAC technology that could ensure operating energy and cost savings with an optimised self-sustaining net positive energy building in the future. The specific objectives are to:

- Assessment of the present building systems linked with HVAC (for instance, air-handling components, air-conditioning components, etc.), office and lighting equipment in a humid climate, analyse the benefits of the climate and air-conditioning methods and utilise indoor environmental requirements that increase energy efficiency.
- Develop and apply the energy performance simulation algorithm to the selected building systems and compare the results with all the data that are measured on-site.
- Investigate energy savings from the selected retrofitting alternative HVAC and envelope systems, and establish suitable strategies that could ensure better energy efficacy for the people in the building.
- Perform energy and comfort evaluation of all the retrofitting, to support decision-making and to examine the comfort level of the occupants.
- Optimise building HVAC system and envelope performance to ensure climate-responsive operational strategies and better comfort of the occupants considering the future predicted weather condition.

1.6 LIMITATION OF THE STUDY

This analysis emphasises a suburban academic office building located in a tropical climate in Australia. In this study, the features of BEPS are adapted to the case study built environment to numerically analyse the overall energy performance with the assistance of a computer-based simulation algorithm. The extent of the study is to detect the appropriate HVAC climate-responsive technologies along with a suitable building design that will meet specific comfort standards for the tropical climate. A reference case study building has been chosen for extended analysis. Identification of alternate means to make use of tropical climate problems for retrofitting-based energy efficacy is expressed. The study anticipates that its outcome could extend beneficial advice for assessing and attaining optimised energy efficacy in weather responsive HVAC systems in the building.

Similar to many other simulation-based studies, there is some unpredictability in the input data as it is hard to attain the exact historical information that includes building construction description, variables related to outside weather (wind, moisture as well as solar radiation) etc. In lots of those situations, estimate entails weather data recorded via an adjacent meteorological recording point, which produces unambiguity as well as accuracy in the meteorological information specifically crucial for the current research study. Estimation and simulation of genuine buildings may impose uncertainties due to the lack of historical information. Reasonable steps were undertaken to collect that information along with the historical weather data with the assistance of facilities management and typical meteorological year weather data derived from a number of public sources including the Onebuilding weather portal (http://climate.onebuilding.org/).

1.7 THESIS OUTLINE

After a wide-ranging assessment, the thesis discusses the discoveries from the energy inspection of the case study building, which are essential for the numerical simulation. The energy performance simulation model for the existing systems is then prepared and standardised using the measured data to establish the reliability of the model's performance. Six different HVAC control strategies along with a few enveloping systems are judged with the current settings to categorise apposite external climate-responsive HVAC technologies that can provide superior energy savings and improved thermal equilibrium for the people in the building. Subsequently, the comfort evaluation of each retrofitting setting is compared, and computational fluid dynamics (CFD) based comfort analysis is performed to ensure greater accuracy of comfort analysis throughout the building. Finally, a genetic algorithm-based optimisation analysis is performed, in light of the historical average and prospective future climate, situations to provide better decisions on choices for overall retrofitting exercises.

Chapter 1 explains the overall importance and background, research statement, research problems, and purposes of the analysis. Limitations and the extent of this study are also clarified.

Chapter 2 reviews the literature associated with BEPS techniques now available for analysis, simulation of energy usages & comfort, active & passive HVAC technologies, current development in building internal and external envelop systems along with optimisation algorithms that can identify a relevant suitable system taking into account the factors influencing the overall building performance in extreme climatic conditions. An EnergyPlus based dynamic energy simulation process and genetic algorithm-based optimisation approaches are the suitable techniques to model the potential energy usages and comfort characteristics in buildings.

Chapter 3 presents the findings of the energy audit which presents the overall energy usages profile of the building complex as a whole, and some specific details of the indoor environment and energy usage pattern of the selected case study building.

Chapter 4 describes the computational techniques for investigating the energy and comfort index of the case study building. The theories are discussed, and the simulation application is chosen to conduct and establish the base case analysis. A simulation model was created employing DesignBuilder and the simulation algorithm EnergyPlus. Validation of the model is also debated in this chapter.

Chapter 5 explains the performance of alternative HVAC technologies and evaluation of consumption of cooling and total energy with the reference scenario.

Chapter 6 describes and evaluates the comfort and energy efficacy of different external envelopes in the selected weather conditions. The overall effects are discussed and assessed with the existing reference scenario.

Chapter 7 discusses the findings of overall comfort assessment of the occupants in the selected building, taking into consideration the alternative HVAC and envelope systems.

Chapter 8 discusses the outcome of BEPS optimisation study, considering the historical average to facilitate overall improved retrofitting of the building energy systems.

Chapter 9 explains the impact of emerging climate transformation in energy efficacy and comfort to facilitate overall improved retrofitting of the building energy systems for the future. The chapter also includes an approach to positive zero net energy building through the contribution of environment-friendly energy source.

Chapter 10 sums up the core conclusions of this extensive case study for improving the building energy as well as thermal efficiency through optimisation for the current and future operating conditions and advises additional research emerging from this research.

Chapter 2: Building System Efficiency and Thermal Comfort

2.1 ENERGY EFFECTIVENESS WITHIN BUILDING SYSTEMS

The impending energy issue is significantly vital throughout the world because of its ecological and economic measurements. As a result of the high energy requirements, buildings have a significant share of total power intake. Accordingly, the plan of the eco-friendly building that uses energy successfully or the conversion of existing buildings into efficient users has become a concern in the plans of many nations today. Chapter two summarises the current progress and comprehension of the pieces of literature related to energy efficacy of technologies of a building mechanical system as well as the efficient envelope systems and algorithms to compute the efficacy of the systems in real buildings. The fundamental concepts of comfort and energy are explained as an exchange of the simulation as well as retrofit measures in existing buildings followed by optimisation processes for improved efficacy considering the climatic condition.

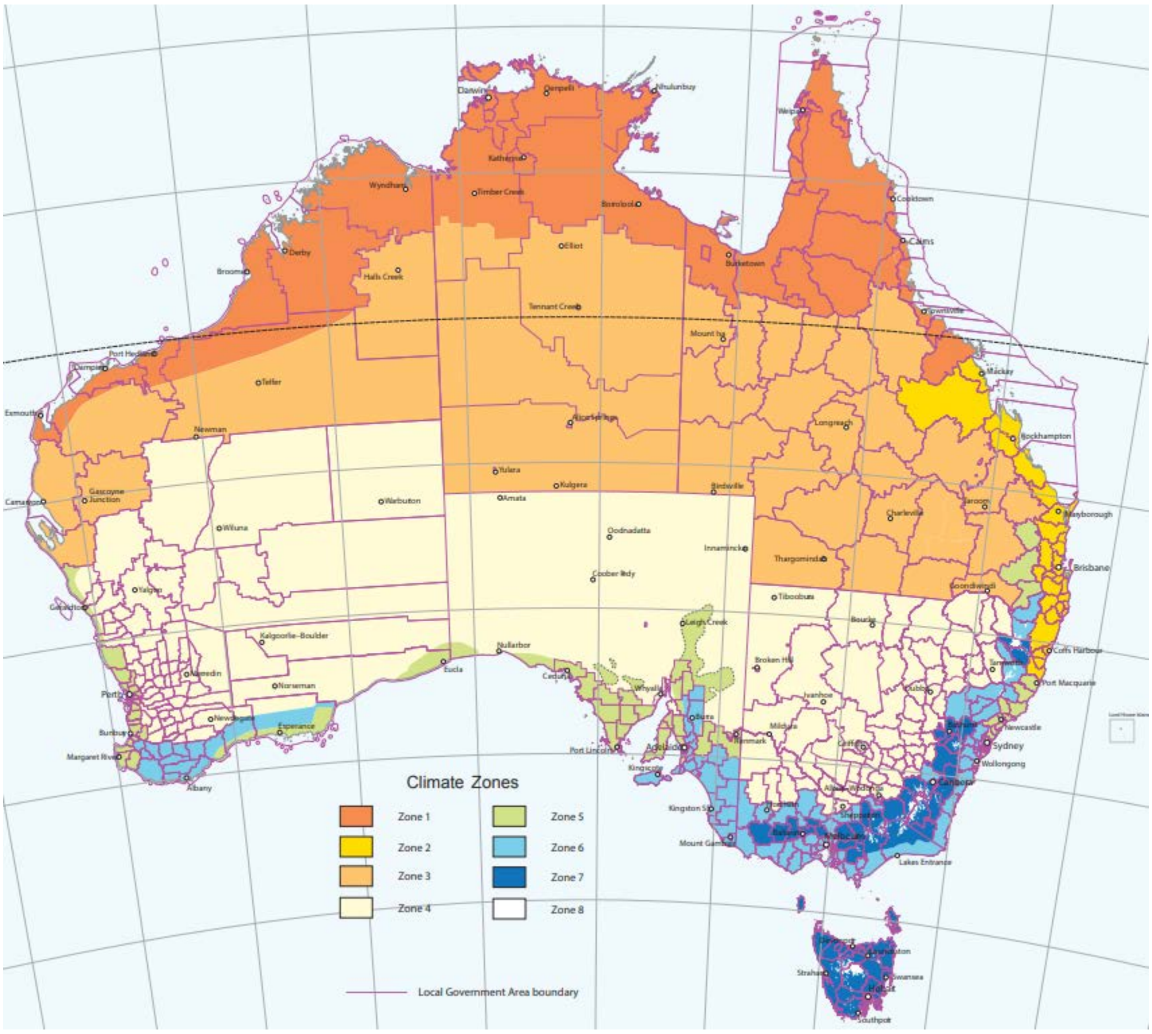
2.2 AUSTRALIAN WEATHER ZONES

The Australian Bureau of Meteorology annual weather declaration for 2018 indicated that the third hottest year on record was the year 2018. The hottest year on record was 2013. In that year temperature levels were 1.33 ºC above the 1961 to 1990 mean. The second hottest year was 2005 at 1.15ºC over the mean, directly beating 2018 at 1.14 ºC above the mean (Australian Government, 2018). The bureau associated these years of atmospheric extremes to both climate adjustment and natural irregularity. The report said Australia's environment "is progressively affected by global warming” and has warmed by just over one degree since 1910 (Australian Government, 2018, p.15). The rain reduced by 11% since 2005. The reduced rains finished in “serious drought” between July and December 2018 (Australian Government, 2018, p. 2). September had the least rains on record across the country as well as additionally the second-lowest for any month since April 1902 (Australian Government, 2018).

As per the Bureau of Meteorology’s forecast yearly environment statement for 2018, the background heating trend is attributed to human impact on the world climate (Australian Government, 2018). Consequently, it stated that radical, speedy efforts must be taken to suppress greenhouse gas air pollution to maintain the global temperature rise below the critical 1.5-degree Celsius threshold (Australian Government, 2018).

Australia has a diverse environment with varying building cooling energy needs. To make up these changes, the energy performance specifications differ from place to place, and for simplicity, places with about equivalent settings have been incorporated into eight environment locations. These eight-atmosphere areas are highlighted in a setting area map generated using BOM forecasting weather condition information with two complementary areas (ABCB, 2019). A succinct description of each zone is appended below in Figure 2.1, which is consistent with the Australian National Building Construction Code (NCC).

The weather area limits are also lined up with local government areas and are as a result conditional once in a while. Annual mean temperature levels were above standard for nearly all of Australia, as shown in Figure 2.2. Maximum temperature levels for the year were additionally above typical throughout almost all of Australia. They were in the highest possible 10 per cent of historical observations for nearly all of Australia. Yearly mean minimal temperatures were additionally above standard for much of the country, although some locations were below the median (Australian Government 2018).



Climate zone 1 - High humidity summer, warm winter
Climate zone 2 - Warm humid summer, mild winter
Climate zone 3 - Hot dry summer, warm winter
Climate zone 4 - Hot dry summer, cool winter
Climate zone 5 - Warm temperate
Climate zone 6 - Mild temperate
Climate zone 7 - Cool temperate
Climate zone 8 - Alpine

Figure 2.1 Australian climate zone map (ABCB 2019)

(Note: Available Creative Commons Attribution-No Derivatives—4.0 International licence https://www.abcb.gov.au/Resources/Tools-Calculators/Climate-Zone-Map-Australia-Wide)

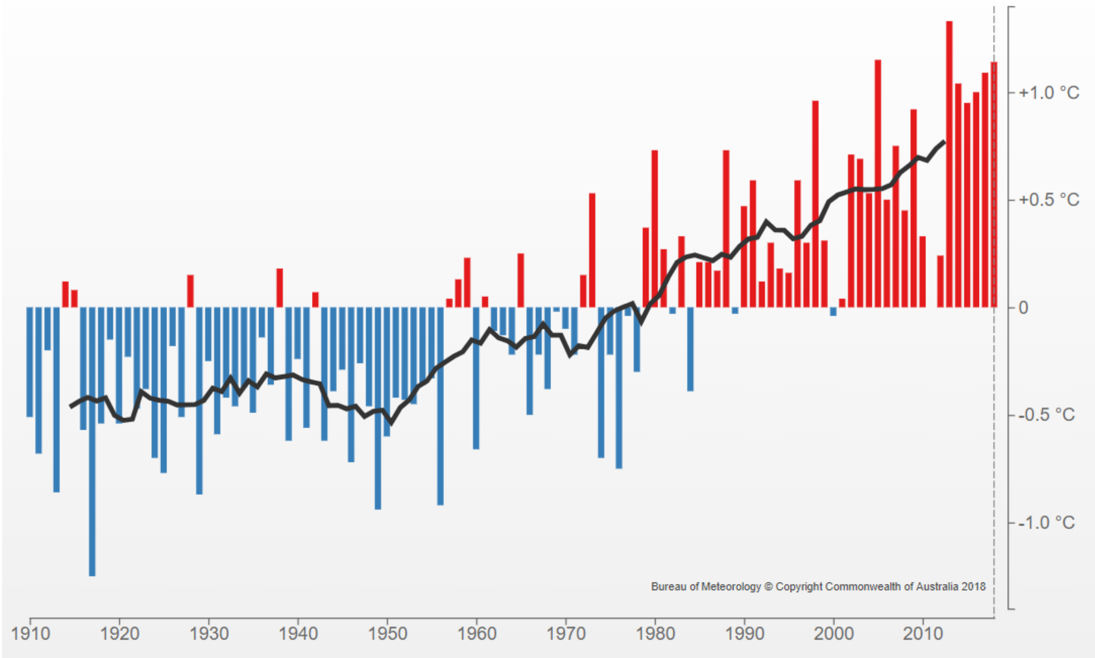


Figure 2.2 Australian mean temperature anomaly in the last 100 years (Australian Government, 2019).

(Note: Available under Creative Commons Attribution Australia Licence http://www.bom.gov.au/climate/change/#tabs=Tracker&tracker=timeseries&tQ=graph%3Dtmean%26area%3Daus%26season%3D0112%26ave_yr%3D0)

2.3 AUSTRALIA'S COMMITMENT TO EMISSION REDUCTION

Buildings absorb around 70 per cent of energy for cooling, heating, ventilation and lighting (Queensland Government, 2016). Higher energy consumption by the mechanical systems is not essential to attain comfort as exhibited from the literature. By allowing systems to use a selection of operational strategies, massive quantities of energy could be stored. Building thermal comfort has currently attracted the interest of scientists worldwide. Considering that the significance of climate change and also the rising costs of energy, it is increasingly crucial to optimise the comfort requirements to think about climate change and energy usage. Buildings' mechanical systems could have numerous negative effects and consume enormous amounts of money if efficient technologies are not in place. As the significance of sustainability has become evident, HVAC engineers make an effort to identify an efficient envelope and cooling system while still maintaining their appeal to the occupants. Residential buildings have been projected to add 13% emissions of greenhouse gases in Australia. The percentage is agreed to increase by 1.3% each year (Australian Government, 2018).

The fact that the planet is warming is not a surprise aspect of conversation worldwide. At the 21st UN Resolution on Climate Change Meeting in December 2015, almost two hundred countries, comprising Australia and other crucial trading companions, authorised the Paris Contract (Australian Government, 2015). In December 2015, the worldwide neighbourhood all took on an enthusiastic arrangement to decarbonise the worldwide economic situation as well as to restrict the effect of environment adjustment. To attain this objective, global carbon contamination will require to get to the web absolutely no around the centre of this century. New technology is altering how power is generated. We can produce work as well as boost living criteria locally and globally while lowering CO_2 and CO exhaust at the same time. State, as well as Local Governments, are currently devoted to achieving zero carbon pollution by 2050 (Queensland Government, 2016).

Figure 2.3 represents the total emissions in different parts of Australia in 2013. The government aims to lower carbon releases up to 28% of the year 2005 levels not later than 2030 (Australian Government, 2015). This is rather small when considering the commitments of various other industrial territories such as the United States of America, Germany, and the UK. While Queensland is familiar with extreme and unpredictable weather, environmental adjustment is anticipated to magnify the regularity, circulation and also intensity of severe weather events. Boosted ordinary temperature levels, more warm days, more extreme as well as constant harsh weather conditions will undoubtedly transform what it resembles to reside in Queensland. It is apparent from the long term weather data that Queensland's environment is currently altering. Specialists concur that the world is currently 1 °C hotter compared to prior the Industrialisation and the increasing agreement is that previous greenhouse gas discharges might currently secure 1.5 °C of warming, and also emissions predicted to occur in approximately 2020 (Queensland Government 2016). Without robust worldwide environmental adjustment activity, there is a good chance that Australia may encounter a typical temperature rise of 4 ºC at the end of the century with ordinary temperature levels 3–5 ºC greater in seaside locations and 4–6 ºC greater in the inward locations (Queensland Government, 2016). That's why the state of Queensland is passionate about adding to the worldwide initiative so that the temperature rise remains well below 2 °C as outlined in the Paris Settlement (Queensland Government, 2016).

The use of energy for room air-conditioning is expanding quicker than for any other end-use in buildings, more than tripling between 1990 and 2016 (Campbell *et al.* 2018). In the meantime, CO_2 exhausts due to cooling down have multiplied threefold to 1130 million tonnes since 1990 (Campbell *et al*., 2018). The increasing need for area air-conditioning is currently placing substantial stress on electrical energy systems in many nations, as well as driving up exhaust from the systems. There is no doubt that the need for space for air-conditioning and the power required to run it will certainly increase for years to come. Australia's commitment to lower emissions by 2030 stands for a 50 to 52 per cent decrease in discharges of greenhouse gases per person as well as a 64 to 65 per cent decrease in the emission amount from 2005 to 2030 as shown in Figure 2.4 (Australian Government, 2015). It is now well documented that Australia outshined its goal under the Kyoto method. Considering the strength of emissions as well as decrease of emission per person, Australia's goal will go beyond the developed countries of the world. This is a substantial success considered that discharges are related to population and financial development. The population of Australia is anticipated to increase by 1.5% per year to 2030. The rate of increase is considerably greater than the average of OECD (Organisation for Economic Co-operation and Development) countries (Australian Government 2015).

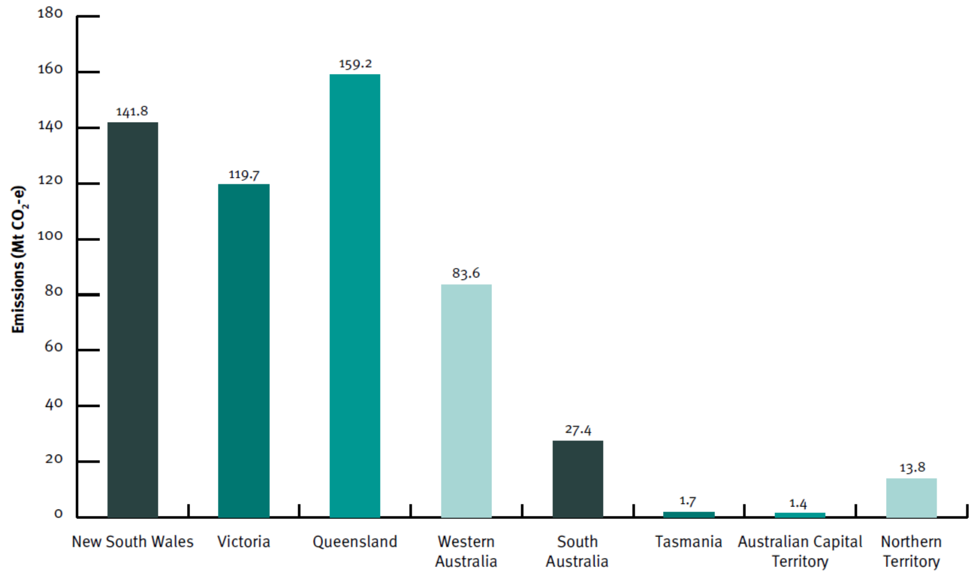


Figure 2.3Total Emissions in different parts of Australia in 2013 (Queensland Government, 2016).

(Note: Available under Creative Commons Licence https://www.qld.gov.au/ data/assets/pdf file/0022/66505/advancing-climate-action.pdf)

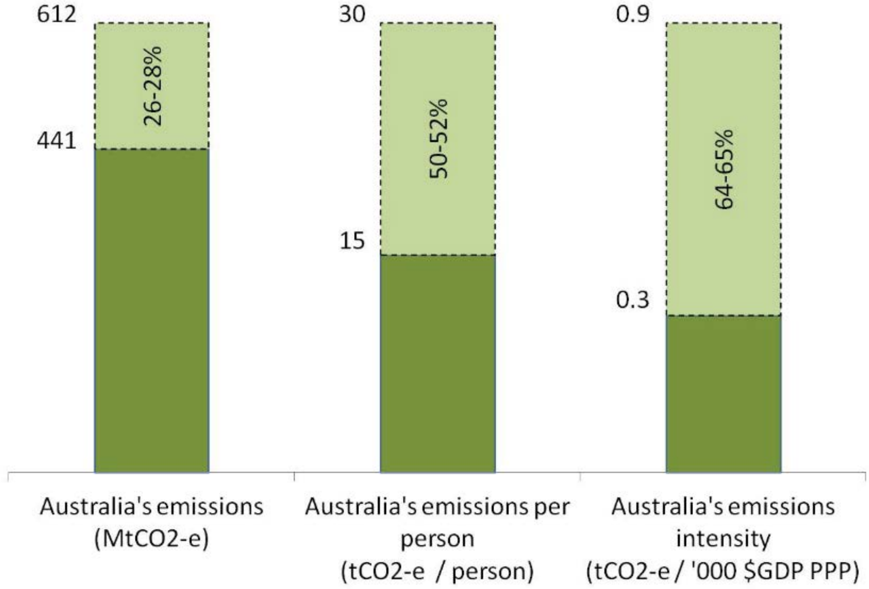


Figure 2.4 Australia’s targets of emissions reduction between 2005 to 2030 (Australian Government, 2015)

(Note: Available under Creative Commons Attribution Australia Licence https://www.pmc.gov.au/resource-centre/domestic-policy/fact-sheet-australia%E2%80%99s-2030-climate-change-target)

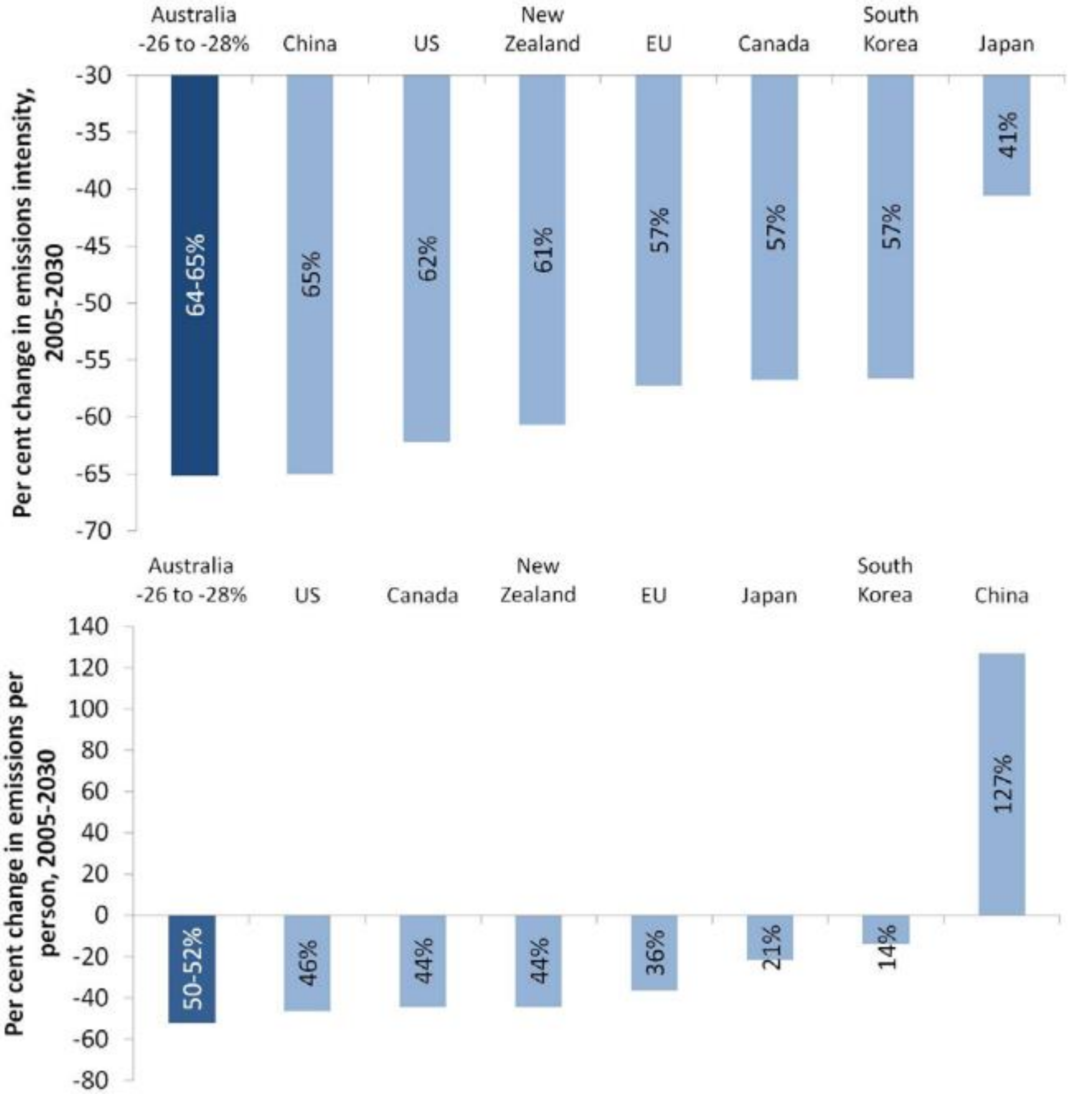


Figure 2.5 Targeted emissions concentration and per person emissions between 2005 to 2030 (Australian Government, 2015).

(Note: Available under Creative Commons Attribution Australia Licence https://www.pmc.gov.au/resource-centre/domestic-policy/fact-sheet-australia%E2%80%99s-2030-climate-change-target)

Figure 2.5 represents the targeted emissions concentration and per person emissions worldwide between 2005 to 2030. Australia's 2030 goal in making use of various resources of reduction consists of modern technological advancement as well as innovations, and different services. Buildings utilise a considerable sum of electrical energy that result in emissions equal to the emission released by the entire farming sector in Queensland. They additionally signify a few functional and cost-effective possibilities to lower discharges of greenhouse gases. Therefore, reliable steps of decreasing building energy consumption are usually a high priority in climate-responsive strategies for commercial activities as well as for the governments alike.

2.4 THERMAL COMFORT

The usual strategy for defining occupants' comfort in an indoor space has been to associate the outcomes of investigation to the variable of thermal analysis. According to the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the thermal perception scale response or Predicted Mean Vote (PMV) is a mean reaction of thermal feeling against the perception criteria. The society clarified the comfortability as an emotional state that articulates contentment in people. The state of mind is dependent upon physiological and psychological elements, and changes from individual to individual (ASHRAE, 2017).

Therefore, the perceived thermal complete satisfaction varies among people, making it difficult to determine a situation where a person is completely thermodynamically contented. In general, the criteria for comfort is related to an individualised psychological state that is continually altering, differs based on numerous influences. Therefore, it is difficult to be gauged objectively. The quantification of comfort is a complicated job and is impacted by many factors, including moisture, air motion and quality, temperature, sound, clothes, light, activity, the capacity to regulate the setting, and individual preferences. Thus, both physiological activities and subjective measures need to be researched, quantified and assessed to define a thermal zone in a building space.

2.4.1 Thermal Comfort Philosophies

The calculation of comfort remains in two phases: the first requires the location of the settings for an equilibrium of thermal sensitivity. The basic thermal equilibrium formula is (EnergyPlus, 2019):

$$H - E_{is} - E_{sw} - E_{res} - C_{res} = K = R + C \tag{2.1}$$

where

H = the remaining metabolic warmness (metabolic rate minus work completed)
K = the handover of heat from the skin to the external area of the attired human body by transmission through the clothing
R = Radiant heat loss
C = Convective heat loss
E_{is}, E_{sw}, Er_{es} = the outer surface and heat losses via evaporation from skin by sweating and from respiration
C_{res} = heat loss via convection from breathing

Formulas can be obtained for every one of these individual contributions to the heat equilibrium formula if the rate of metabolic change, the thermal endurance of the outfit and the four indoor air factors such as moisture, radiant and air temperatures as well as air rate are understood. Professor Ole Fanger (1986) developed an equilibrium formula and also an index named as PMV that reveals the sensation of thermal equilibrium created by a pattern of environmental criteria. Professor Fanger recommended that besides the four substantial variables (air temperature, glowing temperature levels, relative moisture as well as air rate) and individual variables (task and apparel), other aspects have no considerable results on occupants' comfort. His evaluation specified that the thermal comfort experience was most dramatically deduced through slim variations of temperature of the skin and sweat dissipation price, varying upon task difficulty. By integrating these details with the thermal equilibrium balance equation, he established the PMV with respect to six variables: air temperature, airflow rate, moisture content, radiant mean temperature level, garments resistance, and task level.

For typical everyday situations, the indicators utilised are the PPD and PMV indicator developed by Professor Ole Fanger (1986), and the Effective Temperature (ET) & Standard Effective Temperature (SET) indicators established by Gagge *et al.* (1986). Comfort method proposed by ASHRAE's layout and also Professor Ole Fanger's theory is based upon stable state conditions. To forecast comfort for a brief period, a two-node model was established for low as well as modest task levels in cold to really warm atmospheres (ASHRAE, 2004).

The PMV forecasts the comfort vote from a group of topics arising from a collection of environmental conditions for different clothing insulation as well as the rate of metabolic change. BS EN ISO 7730 provides a data table where the PMV is offered for different environments for given garments and rate of metabolic adjustment. The PMV has been prolonged to forecast the percentage of any population that will be displeased by way of the atmosphere. The Predicted Percentage of Dissatisfied (PPD) is specified in terms of the PMV. Fanger associated PMV as a feature of thermodynamic loads of the human, L, which is outlined as the distinction among the metabolic change of heat demise as well as the estimated heat demise from the human to the actual ecological settings presuming these settings for optimum control. The heat transfer via radiation and convection are the features of clothes warmth level, that is influenced by the warmth level of the skin.

PPD and PMV are expressed as by Professor Fanger:

$$PMV = 3.155[0.303 \cdot e^{-0.114M} + 0.028]L \tag{2.2}$$

$$PPD = 100 - 95e^{\left[-\left(0.03353PMV^4 + 0..2179PMV^2\right)\right]} \tag{2.3}$$

$$L = q_{met,heat} - f_{cl}h_c(T_{cl} - T_a) - f_{cl}h_r(T_{cl} - T_r) - 156(W_{sk,req} - W_a) - 0.42(q_{meat,heat} - 18.43)$$
$$-0.00077M(93.2 - T_a) - 2.78M(0.0365 - W_a) \tag{2.4}$$

Here ,

M = rate of metabolic generation per unit surface area

T_{cl} = average surface temperature of clothed body, °C

f_{cl} = ratio of clothed surface area to surface area

R_{cl} = effective thermal resistance (R-value) of clothing m^2°Ch/J

T_a = air temperature, °C

h_c = convection heat transfer coefficient, J/h m^2°C

T_r = mean radiant temperature, °C

h_r = radiative heat transfer coefficient, J/h m_2°C

W_a = air humidity ratio

W_{sk} = saturated humidity ratio at the skin temperature

2.4.2 Standards of Thermal Comfort

Much investigation related to human comfort and thermal equilibrium has been accomplished in various nations with various environmental and geographical areas. Various research projects of ASHRAE studied the influences of the thermal settings on human comfort in cold and muggy weathers. In ASHRAE Standard 55 (2017), the comfort of the human is specified as a psychological state that shares contentment through the surrounding atmosphere and is examined under prejudiced criteria. Aside from social impacts, comfort relies on personal as well as ecological factors. The global standards to examine the comfortability are BS 15251 (2007), ISO 7730 (2005) as well as ASHRAE 55 (2013). For a traditional air-conditioned building, ASHRAE Standard 55 (ASHRAE, 2017) follows the form of ISO 7730. BS 15251 considers that the internal ecological measures for assessment of energy efficacy in buildings seek to specify indoor settings constant to guarantee that maximum performance is achieved with less impact on the comfort, performance or wellness of building occupants. Like

ASHRAE Standard 55, BS EN 15251 has different environmental requirements for mechanically cooled buildings.

The ASHRAE Standard 55 was released in 1966 and is upgraded every three to seven years based upon existing research, practical experience, and recommendations from designers, manufacturers, and end-users. The most noteworthy, in addition to newest versions of the standard, are 2004, 2010, and 2017 upgraded variations. The ASHRAE Standard 55 (2017) defines the various mixes of environmental elements of indoor thermal equilibrium as well as personal aspects that will create environmentally friendly settings appropriate to the occupants within the building.

The 2004 ASHRAE update introduced a few crucial modifications that reduced the requirements space between it and its ISO basic equivalents. This included the adoption of the computer model technique, the adaptive approach (or design that relates indoor style temperature ranges to outdoor meteorological specifications) based upon research study that supports natural ventilation styles, and the acknowledgment of raised airspeed choice for general resident thermal comfort. The 2010 update re-established basic result temperature level as a technique of examining as well as identifying the cooling impact of increased speed of air and movement of the indoor air all together; made significant modifications to openly define obligatory bare minimum needs in analysis and documents towards the provision (Simscale, 2019). Post-occupancy examination (POE) is a technique of pre-emptively and retroactively examining thermal comfort for residents in an area (Simscale, 2019). The most recent 2017 ASHRAE 55 standard update consists of a new component that can consider the modification in residents' thermal convenience from direct solar radiation, in addition to the existing scope, requirements, conditions, and parameters listed in the following page in Table 2.1. ASHRAE Standard 55 (2017) utilises the comfort index value establishing the criteria for interior thermal settings which demand a minimum satisfaction of 80% of the occupants.

The requirement was mostly developed for thermal comfort in spaces where residents remain in inactive states (i.e. office work). However, it can also be utilised to cover other kinds of indoor environments, excluding extreme conditions that can be discovered in ISO 7243, ISO 11079 and ISO 7933. The PMV and PPD approach is the foundation of ISO Standard 7730 (2005) as well as the visual and methodical zone approaches in the ASHRAE Standards 55 (2017). DIN EN 15251 (2007) and ASHRAE Standards 55 (2017) applied the flexible technique to evaluate the interior atmosphere in buildings. The ISO Standard 7730 (2005) did not include the comfort technique via adaptability but defines that the interior comfort setting should be 70% of the expected range in a normally aerated building space.

Table 2.1: Thermal comfort index (ASHRAE 55, ISO 7730)

Value	ASHRAE 55 Thermal Sensation	ISO 7730 Thermal Sensation	Bedford Scale Comfort Perception	Modified ASHRAE Scale (Humphrey and Nicol 2004)
+3	Hot	Hot	Much too warm	Much too warm
+2	Warm	Warm	Tool warm	Too warm
+1	Slightly Warm	Slightly warm	Comfortable warm	Slight too warm
0	Neutral	Neutral	Comfortable	Just right
-1	Slightly Cool	Slightly cool	Comfortable cool	Slightly too cool
-2	Cool	Cool	Tool cool	Too cool
-3	Cold	Cold	Much too cool	Much too cool

2.4.3 Comfort Models

Two main diverse models that may be utilised to calculate the comfort are PPD-PMV model and the adaptive model.

PMV-PPD Model

ISO Standard 7730 consisted of the PPD-PMV indicators, which was authorised as the EU requirement. Forecasting the thermal experience of individuals is a needed action in recognising conditions that ensure individuals' comfortability; it is more valuable to think about whether people will be pleased with the indoor environment. An indicator that anticipates the average value of ballots of a team of occupants arranged on a 7-point range that considers the equilibrium of warmness within the body is embraced to determine the comfortability of the occupants.

Different techniques can be used to evaluate this for different mixes of metabolic rate, insulation, temperature level, airspeed, show glowing humidity and temperature. The outcome of the thermal comfortability measures and occupants' satisfaction could be revealed by PPD value derived from the relevant PMV value. As per the relationship between PPD and PMV, PMV zero value represents 5% PPD value, i.e. the disappointment rate of the occupant is 5% with that specific indoor settings. Similarly, 10% PPD value resulted from a ± 0.5 PMV value that represents that 10% of occupants are discontented with that specific indoor settings.

ASHRAE Standard 55 (2017) described the comfortable environment in regard to personal temperature. The ASHRAE Standard 55 specifies that 90% of the people would be thermally contented to satisfy the requirements set by the Standard. ISO 7730 advised 10% discontent as the boundary of their comfortable atmosphere. Therefore, the recommended PMV value will be within the range of ± 0.5. It really is numerically and emotionally oriented when judged against the ASHRAE Standard 55 (2017). ASHRAE Standard 55 (2017) categorises the surroundings as thermally tolerable when eighty per cent of those people are happy. It follows a setting between -1 to +1 thermal sensation value (TSV) is acceptable. Figure 2.6 represents the relationship between PPD index and PMV index, and Figure 2.7 represents the comfort area as per the ASHRAE Standard 55 (2017). Table 2.2 represents the temperature band and PMV values for buildings with mechanical ventilation as per BS EN 15251.

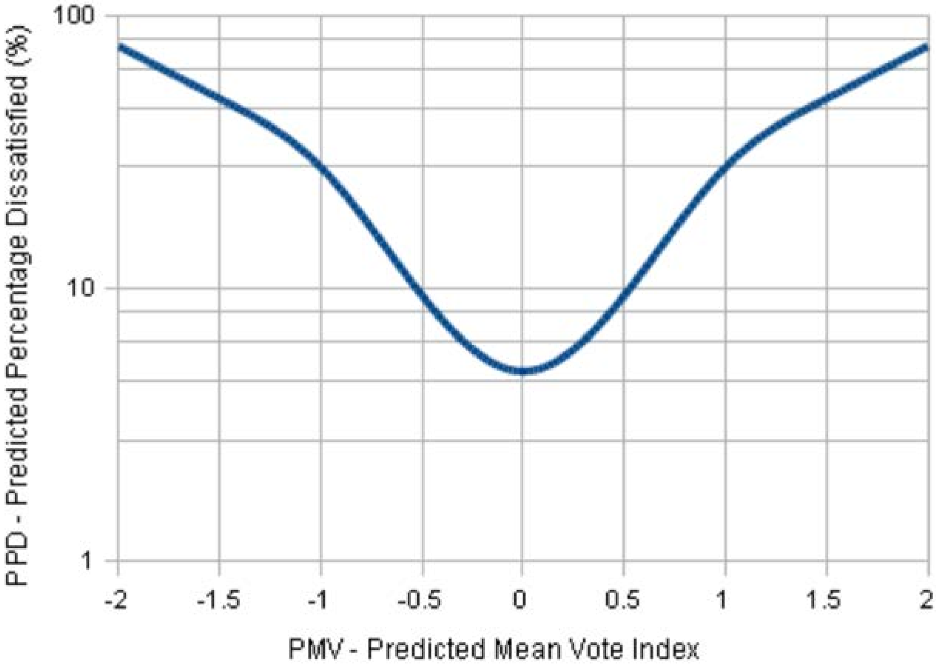


Figure 2.6 Correlation PMV and PPD value (Engineering ToolBox, 2010).

Table 2.2 Temperature band and PMV for buildings with mechanical ventilation as per BS EN 15251(Nicol *et al.* 2016)

Recommended Temperature band (K)	Recommended PMV index range	Description
±2	±0.2	High level of expectation just used for areas occupied by delicate and sensitive individuals
±3	±0.5	Typical expectation (for new buildings and makeover)
±4	±0.7	A moderate expectation (utilized for current buildings).
>4	>0.7	Values outside the criteria for the above classifications (just satisfactory for limited days).

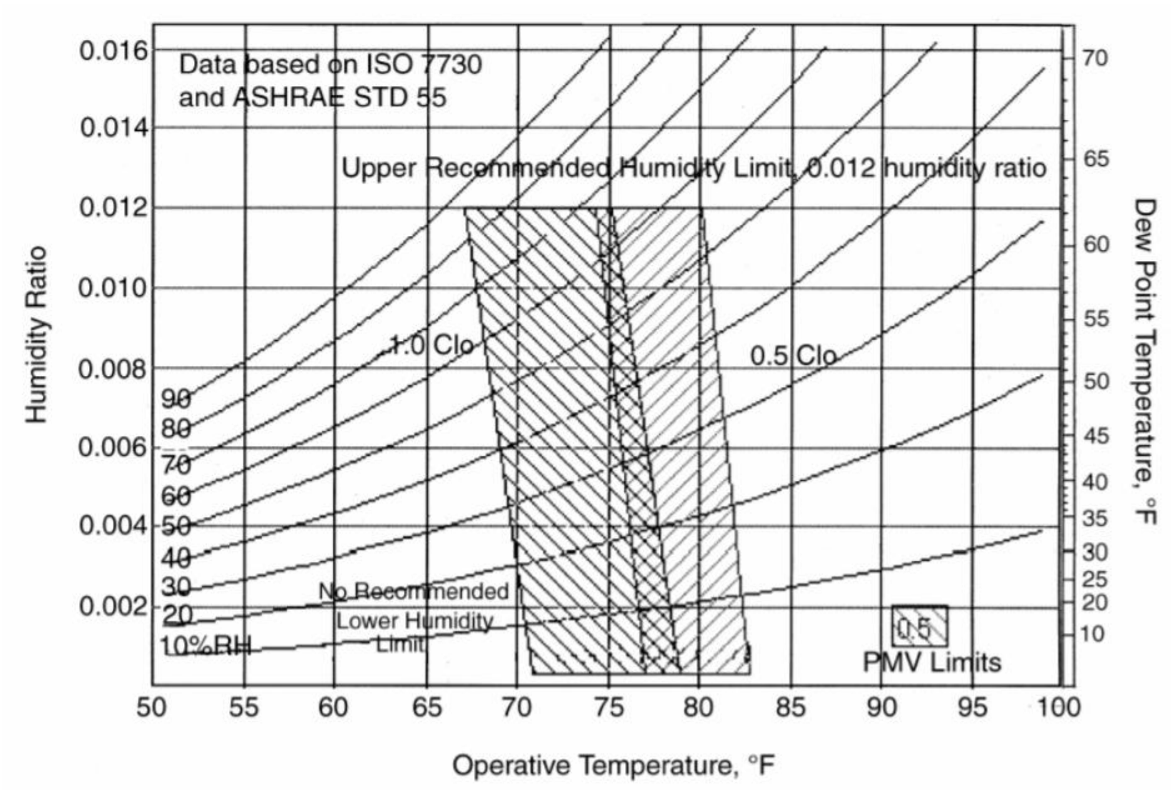


Figure 2.7 ASHRAE comfort zone (ASHRAE, 2017).

Thermally Adaptive Comfort Model

The design is established on the adaptive concept in which the outside environment affects indoor convenience since human beings can adjust to various temperature levels throughout the year. The adaptive theory anticipates that relative elements of comfort are adjected based on the indoor settings of the building. Previous comfort experience can also affect the expectations and preference of the occupants (Zhai et al., 2019; Jindal, 2019). The ASHRAE Standard 55 (2017) presented the dominating mean outside temperature level as the input parameters for the design suitable to adopt in the given condition. It is likewise determined by considering the temperature levels and various constants that indicate the importance of the current temperature levels.

2.4.4 Thermal Comfort Studies

Environment cell experiment and field research are the two methods utilised in thermodynamic comfort study of the occupant. SteadyState designs from test cell-based experiments were adopted by a few researchers, which differs on the exchange mechanism of heat with the body, to express the PPD – PMV values. Several studies reveal the temperature level for comfortability in aerated buildings or buildings with mixed-mode ventilation is broader than the predicted PPD and PMV values (De Dear and Brager, 2002; Bessoudo, 2008; Nicol and Humphreys, 2010). The majority of the SteadyState patterns were established before the on-site field studies. The adaptive approach was established from field studies in a general office complex by relating indoor personnel temperature levels (appropriate varieties) to external temperatures. Thermal comfort is specific, subjective as well as there may be no independent solution that meets the comfort requirement for all the occupants all the time. The space heating as well as cooling down capacities would certainly be costly if the appropriate temperature range must be fulfilled for 100% of the occupied period as well as throughout the extreme weather periods (Yang *et al.,* 2014; Nag, 2019; Song *et al.,* 2019).

Practical studies were carried out in buildings that aided the development of an adaptive thermal comfort model assuming that dwellers were not passive and active relating to their thermal environment (Damiati, 2019; Wu *et al.*, 2019). The theory of adaptive thermodynamic comfort considers that people will gradually reduce the individual reaction to the recurrent change in thermal settings throughout the behavioural, physiological, psychological alteration. The thermal background plays a great role in personalising the occupant's thermal expectations and tastes; for instance, people in hot climates will probably favour higher indoor humidity levels compared to people living in cool surroundings (Van Hoof *et al.* 2010; Humphreys *et al.* 2013; Humphreys *et al.* 2015). Zhai *et al.* (2019) and Jindal (2019) presented the findings on SteadyState and Adaptive comfort value and standards for aerated naturally mixed and air-conditioned buildings. As discussed, these research findings explored the effects of energy usages on the human comfort in indoor settings and can be organised into two areas: fundamental case studies and impacts on comfort standards (Humphreys *et al.,* 2013; Humphreys *et al.,* 2015; Hoyt *et al.*, 2017).

To get a more advanced understanding of the compromise between human thermal equilibrium and energy intake, efforts have been devoted to associate cooling energy consumption with matching practical temperature settings (Chowdhury *et al.*, 2010; Han *et al.*, 2019). Another category of control technique considers the vibrant regulation of the temperature setpoint depending on thermally responsive comfort models. Case research studies reveal that considerable energy can be conserved for both office and domestic facilities. Several research articles have examined the prospective energy conservation of non-residential facilities through adaptive thermal benefit techniques under adjustment indoor settings. (Jindal, 2019, Rijal *et al.*, 2019). Case studies based on office buildings show that large scale buildings have been able to supply a highly comfortable indoor environment when all of the theories of contemporary and sustainable design are employed considering the present and forthcoming environments (Draganova *et al.*, 2019; Göçer et al., 2019).

The literature results recommended that individuals have a general impact of a superior requirement of human comfort in traditional buildings compared to new constructions. A research investigation on human comfort suggested that comfort in indoor space is profoundly impacted by the outside environment (Peng, 2019). A polyphase and service-based method to evaluate human comfort issues in buildings recommended the requirement to resolve the thermodynamic comfort issues at the earliest opportunity because the emergence of discontentment with the indoor settings may have an instant effect on occupants' productivity and wellbeing (Wang *et al.*, 2019).

A couple of simulation-based research studies had also examined human comfort and their actions to accomplish and to preserve a comfortable status in the occupied space (Peeters *et al.*, 2009; Buratti *et al.*, 2013; Ascione *et al.*, 2019). Mansy (2019) reported that it is feasible to calculate indoor air parameters in an indoor space in simulating the human comfort and efficacy of the occupants' habits of energy usage in the facilities, and steps to restore the comfort.

2.5 BUILDING ENVELOPE SYSTEMS

The contemporary tendency in building energy study is to boost the eco-friendly aspects in the operational phase of the building. Growth of modern eco-friendly types of machinery is vital to expand eco-friendliness and decrease harmful emissions. Power usage in a public built environment raised significantly over a period of time. Considerable and diverse strategies to enhance energy efficacy in the built environment are deployed. When the building and construction are based on making use of sustainable techniques, it is easier to ensure high interior comfort, which can also reduce the power usage and reduce the environmental footprint.

2.5.1 Sustainability and Performance of Building Envelope

Construction of large facilities, as well as operation, have an enormous effect proceeding the surroundings with respect to energy usages, climatic condition, generation of waste, usage of water, and lots of additional elements related to the operation of the facility. As the economy expands, the construction of larger facilities will face more obstacles to please the new essentials of the individuals for a healthy and balanced lifestyle and productivity while decreasing their impact on the atmosphere. The building envelope is built with external elements of a structure, i.e. walls, roof covering, home windows, doors etc. Since there are varied and often competing functions connected with the building envelope, an integrated, collaborating strategy considering all stages of the facility lifecycle is necessitated. Creating sustainable buildings starts with proper site choice; and also the place, alignment, and even landscape design of a building impact the neighbourhood communities, transportation techniques and energy usage. It usually is more lasting to refurbish an existing structure than to tear it down as well as build a new one. It is good to think about reuse and also retrofit of existing buildings before choosing to construct new. A sustainable building should count on effectiveness and easy style procedures rather than non-renewable fuel sources for its operation. It should satisfy or exceed relevant energy performance requirements. The sustainable building needs to be built of materials that reduce lifecycle effects such as climate change and human toxicity. There is no doubt that high quality indoor ecological environment in a built environment has a substantial influence on occupants' performance, convenience, and wellness.

2.5.2 Impact of Envelope Systems on Energy Usage in Building

An envelope in a building is a barrier that regulates warm exchange between indoor and outdoor surfaces and performs a vital function to ensure thermally comfortable indoor space to the occupants. In recent times, due to the requirement of saving energy as well as stopping enhanced environmental air pollution, the relevance of sustainable building has been doubled (Anbouhi *et al.*, 2016). Anbouhi *et al.* (2016) tested the role of building envelope products in the cooling load, heating load, as well as energy usage in a simulation environment. Outcome of the evaluation demonstrated that making two layers of brick products with an extra thermal insulation layer reduces 4.8% air-conditioning load as well as reduces 62.5% of thermal load.

Ibrahim *et al.* (2015) applied silica aerogels based envelope system to a new building and to an existing building for retrofitting purposes. Results show that the maximum plaster thickness remains within the range of 1.7 to 4.4 centimetres as well as the payback duration in the range of 1.4 to 2.7 years relying on the climate. As energy demand as well as the cost associated with energy consumption increases, aerogel items are anticipated to increase, generally due to having high thermal insulation. Presently, the expense of aerogel products is much greater than conventional insulation; nonetheless, this cost is anticipated to reduce in coming years as a result of the enhancement in the aerogel production developments in addition to the enormous product production resulting in lower system expenditures.

El-Darwish and Gomaa (2017) suggested a method to increase power effectiveness in an academic building located in a dry and hot climate. Upgrading a few of the building's envelope attributes can provide comfort with no endangering practical requirements. It was suggested that retrofit approaches impact human comfort and thus power consumption as well as needs to be considered via a variety of guidelines and relevant standards. Budaiwi *et al.* (2013) utilised modelling and also simulation technique to recognise prospective energy financial reserves due to retrofitting measures and functional procedures while preserving suitable thermal problems. Outcomes disclosed an excellent capacity for power decreases when adequate retrofitting and practical methods are used.

In historical centres, Rosso et al. (2017) considered the exterior layer of the envelope with technological remedies and typical products, for instance, one-layer wall surfaces, while power efficiency is usually maximised employing interior insulation layers. Materials with enhanced energy efficacy and building components in a warm environment are normally light-coloured to mirror the most substantial segment of radiation, thus minimising energy requirements for cooling as well as enhancing comforts for the occupants. Rosso *et al.* (2017) showed that such cool-coloured products could maintain lower surface area temperatures while lowering energy needs for air-conditioning around 3%. Gil-Baez *et al.* (2019) studied the influence of a collection of budget-friendly, accessible refurbishment services to enhance the insulation of institution buildings in the base case building scenario. The outcomes reveal fairly reduced power requirements than that reported in comparable colleges in various other climates. A high possibility for power effectiveness renovation, with cost savings as much as 18% from heating and 16% from air-conditioning was achieved by incorporating passive actions.

Piggot *et al.* (2019) examined the thermal efficiency of wood-frame upright envelope remedies utilised in Canadian facilities as well as examining precisely how these modern technologies add to lowering the power usages of instructional facilities. To enhance the precision of the power need results, the straight thermal passages were acquired for every wall surface remedy location with the remainder of the enclosure's components. The outcomes show that the options examined conserve approximately 51% of the warming need of the facilities throughout the coldest months. Rural housing is a vital component of domestic structures in many parts of China, which constitutes a vast amount of building stocks, consumes extraordinary amounts of energy, and therefore offers enormous capacity for energy saving. Exorbitant building format and inadequate functioning of the building envelope are the primary causes for elevated consumption of energy throughout the year. Cheng, Wang and Liu (2019) use a computer-aided model to mimic the usage of energy in a typical country property and contrasts with various consumptions of energy in various formats as well as the envelope of the buildings. It was reported that rural properties have a significant potential to save energy with the investigation.

Li and Zhao (2019) recently performed a research study to improve the human comfort in farmhouses in summer as well as the cold winter season in China. A country farmhouse in Hubei Province was chosen to recognise ways to improve its room temperature and the thermal performance of its exterior building enclosure. From the measurements in the summer season, the temperature level variance between interior and outside locations was 6 ºC prior to the repair work and also as much as 14 ºC after the repair work. During the after hour and cold season after the repair work, the optimum temperature level variance between interior and exterior places was 1 to 2 degrees celsius. Altering the depth of the protection of thermal sensation in the envelope offers an advantageous impact in summer.

2.5.3 Phase Adjusted Envelopes

A possible way to enhance energy savings by the building system is to boost the thermodynamic efficacy of the envelopes. Phase Change Materials (PCMs) or Organic-Phase Change Materials (o-PCMs) has secured interest as a building envelope considering its phase adjustment properties, particularly in northern environments, given that these materials are applied to boost the thermalisation of the building envelope. Thermal equilibrium properties of building envelope (BE) systems can considerably affect the overall energy efficiency of buildings, and hence the accurate resolution of such buildings is needed.

Phase adjusted materials have high unrealised warmth; as a result, they store vast amounts of thermal power in a single volume. The storage capacity of latent heat is superior than the sensible heat in phase adjusted materials (Kumar *et al.*, 2019). The heat storage capability of organic phase change material (O-PCMs) is the key to retain the thermodynamic equilibrium of the external envelope materials and assist in lowering the temperature variations in a building through time. The charging and discharging processes of phase adjusted material are shown in Figure 2.8.

The impact of the insulation degree of a phase adjusted building envelope on the air-conditioning and heating power needs were examined by Venegas *et al.* (2018). In regard to the cooling power needs, the impact of the padding thickness is evident where the occupants situated in a warmer area show that the cooling needs are lower with the increase of insulation level. The energy saved in the walls throughout the warmer as well as cooler days was likewise analysed by Venegas *et al.* (2018). The result of the insulation level is much more evident in residences situated in warmer locations, specifically throughout summer. The consolidation of phase adjusted materials as an external envelope has a rising effect in the quantity of heat energy absorbed and released throughout the day, respectively. Venegas *et al.* (2018) concluded that a phase change material with a moderately reduced adjusted temperature level is better for cooling down functions.

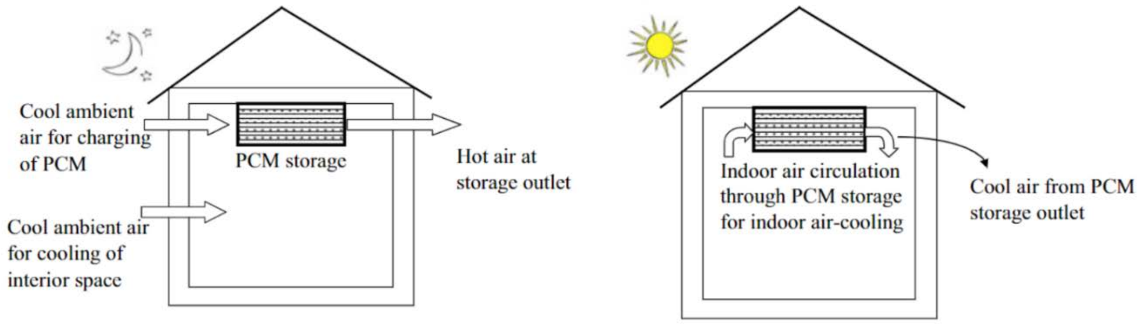


Figure 2.8 Charging and discharging processes using PCM (Waqas and Din 2013).

The integration of phase adjusted materials is an efficient means to decrease the indoor temperature level changes, heating and cooling loads. Phase adjusted product combined in the wall surface is advantageous for the decrease of room temperature level and supports fluctuated air movement in buildings. Choice of dual-layer phase adjusted materials with two separate liquifying temperature levels can offer a drop of temperature level in an indoor space throughout the year (Kumar *et al.*, 2019). Reddy *et al.* (2017) resolved the problems of insufficient solidification and impact on air-conditioning using selective one layer of phase adjusted materials that deliver in the decrease of thermal load. The outcomes reveal that the phase adjusted material structure lowers the intake of heat properly via envelopes throughout the full year in the range of 21% to 32%. Phase adjusted material included in the exterior wall in a building reveals much better efficiency in contrast to the same material used to the indoor wall surface areas, due to much less energy conversation capability from solidification of the material in a warm climate (Lei *et al.*, 2016). Hussein (2019) recommended a decrease strategy of cooling loads as well as power consumption in buildings. These methods were applied with the help of simulation software in a building's wall surfaces, roofing systems, and glazing systems. In his study, a basic structure design was associated with 16 various other cases that integrated the reactive cooling methods. The outcomes reveal that a mixture of phase adjusted insulation and dual glazing can considerably decrease the cooling load requirement in an indoor space.

Panayiotou *et al.* (2016) attained the power cost savings of roughly 22% to 29% via enhancement of phase adjusted envelope material in a reference test cell judge against the base trial cell with no insulation. The outcomes of the optimum phase adjusted material was examined by means of Life Cycle Cost (LCC) analysis method.

The outcomes of the evaluation exhibited that the PCM location externally had an extended repayment duration of 15 years, whereas the repayment period is decreased to 7.5 years when such envelope system includes insulation. Lira-Oliver and Vilchis-Martínez (2017) determined the application of organic phase adjusted material in the exterior building surface as a passive measure to ensure the interior comfort over one year. The authors indicated that the execution of organic phase adjusted material with a mix temperature level of 25 ºC in combination with ventilated concrete leads to the greatest variety of hours the interior temperature levels endured within the human comfort limit.

2.5.4 PV Integrated Building System

Photovoltaics (PV) is a sophisticated method of creating electrical power on a website, straight from the sunlight, without worrying about power supply or ecological damage. There is an expanding agreement that dispersed solar systems that provide electrical energy at the factor of usage will certainly gain extensive commercialisation. Rate of incorporation of photovoltaics in the building, where the photovoltaic components come to be an indispensable component of the building, is expanding worldwide. A photovoltaics integrated building system is made up of integrating photovoltaics modules to the building structure, like the roofing or even the exterior. A photovoltaics integrated building system may offer savings in electricity expenses and materials, reduce utilisation of traditional fuel to produce power and emission of ozone-depleting gases. While almost all photovoltaics integrated building systems have been interfaced utilising the readily accessible energy grid, such a system may likewise be utilised in standalone systems. Among the advantages of photovoltaics integrated building methods that are grid-tied is that using a utility coverage that is combined, the storage process is free. It is also 100 per cent infinite and efficient in power. Figure 2.9 represents the broader categories of BIPV Products.

There are two fundamental photovoltaic technologies. Dense crystal items integrate solar cells made from crystalline silicon as polycrystalline or single wafers and send approximately 10 to 12 W/m² of PV energy. Film products include slim films of PV substance set on a metallic substrate; otherwise, a glass superstrate utilising production technique that is vacuum-deposition and very comparable to those utilised in the covering of glass. Currently, profitable thin 1 m substances provide approximately 4 to 5 W/m² of PV range region. Lightweight film technology holds the promise of reduced prices due to conditions for elements and energy in their creation compared to goods that are thick crystal.

Figure 2.9 Categories of BIPV products (Alim *et al.*, 2019).

The PV components offer the double feature of structure skin, replacing conventional exterior products as well as electricity production in building. Advantages of energy production at the place of usage include savings in cost associated with distribution and transmission of energy. The option is economically more viable to the customer due to savings in electricity bills for not consuming additional energy during the peak hour. Additionally, renewable energy resources decrease the requirements on utility generators that are conventional, reducing the emissions of gases that relate to climate change. Since the costs of their construction materials may reduce the cost, they ought to be considered concerning lifecycle price. Factors to consider for BIPV systems need to consist of the space's usage as well as electric energy consumption, its place and alignment, the ideal structure, even security codes, and the appropriate energy problems as well as expenses.

The study by Elghamry *et al.* (2018) evaluated two uses of PV as an external envelope as well as installing the solar cell on the roof. The results reveal that the PV in the roof covering obtaining the energy produced complied with the PV in the west direction. The active place in vertical exterior for conserving energy, improve thermal relaxation and decrease lights lots is PV in wall surface centre. The results show that the maximum power usage within the centre occurs when the home window is at the wall surface centre as well as the PV insides. Olivieri *et al.* (2014) indicated that a PV integrated building system provides an encouraging state with present multimodal systems and the general power equilibrium of the building. Photovoltaics with semi-transparent elements in a building heavily influences the power need considering that it affects the heating, cooling, lighting and the regional electrical power generation network. To review the international power efficiency of the BIPV aspects, an original power equilibrium index was formulated. The outcomes demonstrate that the power ranges between 18% and 59% for façade openings that are intermediate and big.

Building structure, where the photovoltaic panel is incorporated, has a substantial influence on the quantity of transfer of heat via the external surface. It can impact the interior temperature levels and comfort of the occupants, considering that the exterior surface transforms the thermal equilibrium of the envelope system. It is found that a PV integrated building surface enhances the interior environmental temperature level through 4 ^{o}C, once contrasted towards the construction of identical dimension with no solar cell incorporated (Ekoe a Akata *et al.* 2015). Evola and Margani (2016) conducted a parametric evaluation by altering the orientation, the number of floorings, as well as taking into consideration various modern technologies in photovoltaic industries. The outcomes reveal that the preliminary financial investment can be paid off within around nine years if taking into consideration the present financial rewards as well as a half own-consumption price for the electrical energy created by the photovoltaic components.

Much better PV performances, reduced rates and also greater own-consumption prices can improve the financial viability, which might create a considerable effect in the retrofitting process of the existing multilevel property. By making use of advanced photovoltaic products as in roof coverings as well as in facades, Building-Integrated Photovoltaic (BIPV) systems can provide a vital certainty for attaining a longstanding environmental emission goal. Aguacil *et al.* (2017) compared two case studies on stereotypical property structures which consist of the layout of various renovation circumstances incorporating passive and BIPV techniques. The primary outcome offers superior photovoltaic integrated retrofitting techniques that is crucial for attaining carbon non-partisanship.

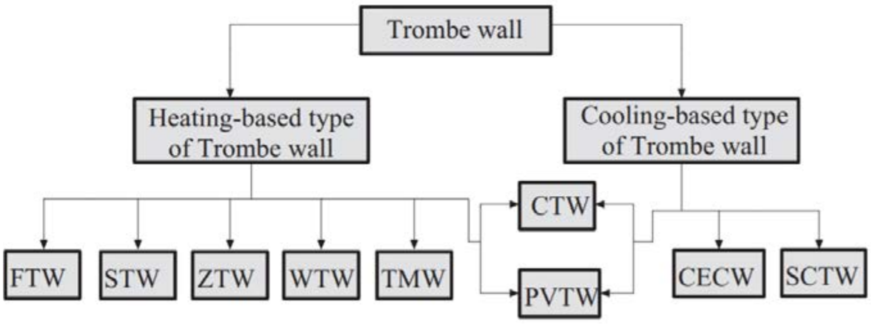
The study by Zhang *et al*. (2018) evaluated two situations: PV on the roof and on the building envelopes. The results reveal that the PV in the roof covering obtained the energy produced in compliance with the PV at the west direction. The active place in vertical exterior for conserving energy, improve thermal relaxation and also decrease lights lots is PV in wall surface centre. The results show that the maximum power usage within the centre occurs when the home window is at the wall surface centre as well as the PV insides. Costanzo *et al.* (2018) talked about an approach that showed for a collection of 20 buildings that the BIPV system can obtain a yearly renewable energy power portion of 23%, in accordance with the eco-friendly resource policy aim at 20% in Turkey. Numerically contrasted requirement along with supply information at per hour time activity discloses that only some power demand could be satisfied by building integrated photovoltaic, so there is a requirement for an ideal coordinating method to improve control of the environment friendly power opportunity.

Inspired by the present obstacles as well as false impressions that hold back an extensive combination of BIPV, Aguacil *et al.* (2019) intended in bringing new understanding as well as a versatile and extensive approach to notify decisions regarding this modern technology. Concentrating on the building layout, the researchers offer a method to choose BIPV surface areas throughout the retrofitting procedure based on a compromise for their own consumption of the building. Positive results for fixing a renovation project in the context of this approach could help engineers to repartition surfaces at the envelope and also size the setup accordingly. Results demonstrate that researchers should take a selection of irradiation approaches to opt for the surfaces, notably within buildings using a higher percentage of façade compared to just the roof based installation of the solar cell. Ziasistani and Fazelpour (2019) reported that the power efficiency of Double Skin Façade, PV as well as PCM depends extremely on geographical and weather conditions. To additionally enhance the power efficiency of Double Skin Façade (DSF), such surfaces can be integrated with photovoltaics (PV) and phase change products. In this respect, the power efficiency of DSF is examined in three situations under six unique weather condition in Iran. It was discovered that photovoltaic integrated building glazing could offer a great deal to meet the energy requirement.

2.5.5 Trombe Wall

Because of power situation and ecological issues, decreasing the need for power usages as well as the usage of non-renewable fuel sources are essential challenges. One of the most affordable strategies of utilising solar power is a Trombe wall (TW) system. A TW system is able to achieve interior thermal comfort with no additional mechanical support to fulfil the heating and cooling requisites. A Trombe wall surface system has been promoted as a result of its one-of-a-kind functions, such as straightforward execution geometry and no ongoing cost associated with the functionality of the system. The standard Trombe wall surface has the unpreventable downsides of independent feature to reduce the thermal resistance. Gradually, adjustments have to be made for Trombe walls to enhance effectiveness. Based upon this significant role of these walls, Trombe walls are categorised into two types: a heating-centred and a cooling-centred Trombe wall (Figure 2.10).

Lin *et al.* (2019) revealed that the typical thermal effectiveness of the PV integrated TW system was 65% greater than that of the usual TW system during hours of daylight. Considering the interior air temperature and exterior surface heat of the external envelope, the interior thermal comfort using a PV integrated TW system was practically the same as that of the usual TW system. The ordinary forecasted PMV comfort value for two systems were 0.05 as well as -0.36, specifically. Easy solar advancements, such as the Trombe wall surface, can add to the reduction of the home heating power requirement and also if appropriately run, they can furthermore impact the summer behaviour of the building. The integrity and performance of the recommended alternatives were confirmed by Bevilacqua (2019) in comfortable atmospheres where the Trombe reduced home heating needs by approximately 71% and lowered the air-conditioning power requirement by 36%. In a cold atmosphere, home heating expense savings were 18% with an air-conditioning power usage decline of around 42%.



Heating - based Trombe wall configurations :
- Classic Trombe wall (CTW)
- Cmposite Trombe wall or Trombe–Michel wall (TMW)
- Water Trombe wall (WTW)
- Zigzag Trombe wall (ZTW)
- Solar trans-wall (STW)
- Fluidized Trombe wall (FTW)
- Photovoltaic Trombe wall (PVTW)

Cooling - based Trombe wall configurations :
- Ceramic evaporative cooing wall (CECW)
- Classic Trombe wall (CTW) and photovoltaic Trombe wall (PVTW) for cooling operation mode
- Solar chimney Trombe Wall(SCTW).

Figure 2.10 Trombe wall categories.

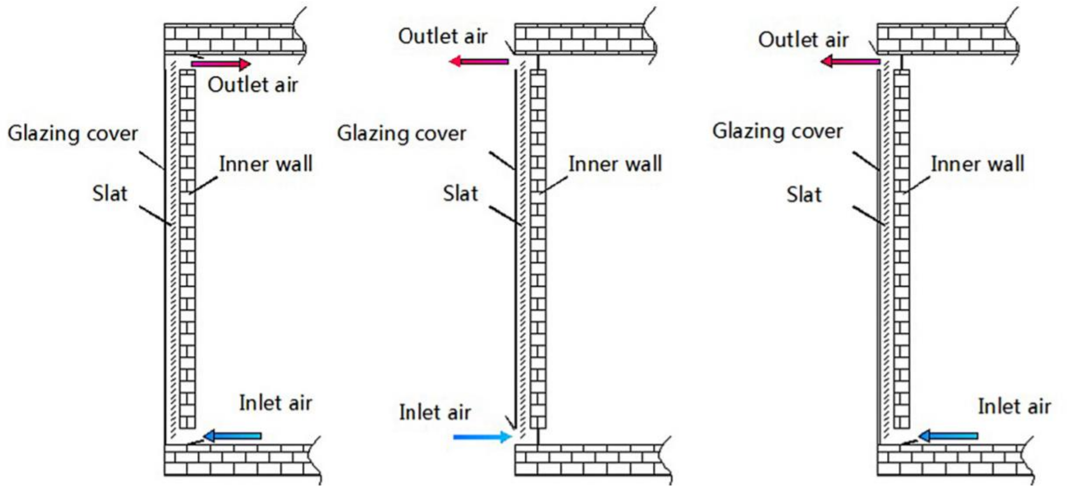


Figure 2.11Trombe wall in area heat up approach; outdoor flow approach and cross exposure to air approach respectively (Hong *et al.* 2019).

Hong *et al.* (2019) proposed adjustment on the Trombe wall system to run under three methods (Figure 2.10); specifically, reheating method, cross air circulation method and outdoors air circulation method. In the outdoors air circulation mode, the slat screen supplies the required shadowing aimed at the Trombe wall. The circulation of air determined by solar heat assists in ridding the temperature from the envelope in cases when it becomes too hot. In the cross-air circulation setting, the flow of air propelled by the solar power would improve the usual airflow throughout the winter.

Hong *et al.* (2019) executed CFD evaluation to recognise the airflow and warmth through the Trombe wall surface under cross airflow setting as well as outdoors circulation setting. The results provide inputs to developing energy constraint of the building in the peak season. The evaluation reported that the air-conditioning power expense with a Trombe wall surface plus Venetian blind is 5% to 6% less compared to the standard Trombe wall surface. More room among the slat, internal partition surface and bigger slat angle could boost the physical convective air circulation and also decrease the indoor temperature and solar radiative warmth gain via the outside wall surface.

2.5.6 Cavity Wall

Advantages of aerated exteriors on lowering thermal loads of structures have been inspected in several research investigations. Envelope structures are the main variables to the power use connected to warming up or cooling down in a building. There were a number of initiatives to boost the effectiveness of envelope systems by integrating simple air-conditioning approaches to reduce cooling load as well as protect proper interior thermal comfort. Particularly, Alaidroos and Krarti (2016) explain a mathematical modelling technique to assess the efficiency of the recommended reactive cooling system to remove heat in dry and hot environments.

Alaidroos and Krarti (2016) showed that the mathematical design could precisely anticipate the outlet air temperature levels and indoor air humidity accomplished by an aerated cavity wall (Figure 2.12) with an evaporative cooling system used to condition the building air in dry and hot environments.

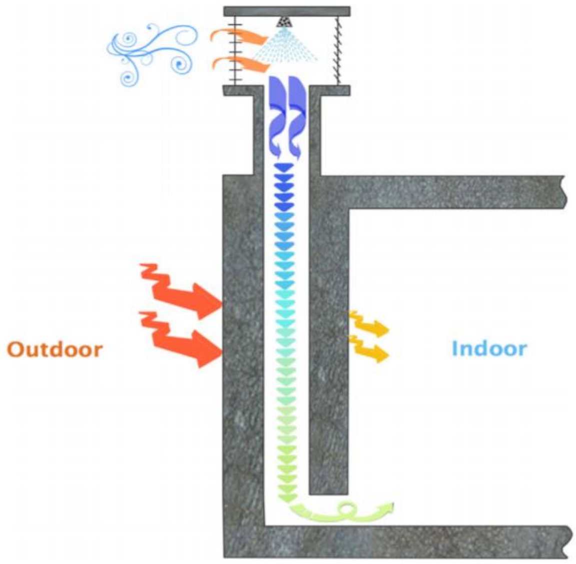


Figure 2.12 Standard representation of the aerated cavity wall with evaporator (Alaidroos and Krarti, 2016).

The results recommend that the aerated wall surface with an evaporator can considerably reduce outdoor air temperature level. Importantly, the system had the ability to decrease the temperature by 20 ºC. Furthermore, the outcomes of an evaluation attained making use of the proved mathematical resolution propose that there is a substantially reduced ability in the transfer of heat via cavity wall surfaces while providing proper supply air temperature in protecting interior thermal benefit. The requirements of numerous quality labels recommending the insulation procedure are evaluated utilising an outline proposed by Rovers *et al.* (2017). The outcomes show that none of the requirements deals with all elements of the insulation procedure. There is a requirement for a new quality label that conquers the imperfections of the existing requirements determined in the research study task by Rovers *et al.* (2017).

Langmans *et al.* (2017) introduced a common air leak pathway near the stiff insulation boards in cavity walls for the envelope system in a building. The air circulation resistances have been determined in laboratory conditions. The acquired outcomes are utilised as key specifications in a streamlined air circulation design in examining the effect of workmanship on thermal effectiveness. The drying out functioning of the air hollows after the exterior siding stays unknown. Typically, a quadrangular unicellular hollow is presumed to streamline examining the hygrothermal effectiveness of an exterior siding system. On reviewing the intricate setup of air cavities made up of several cavity cells, Yang *et al.* (2019) established a numerical design based on the circuit representation principle to determine the circulation rate of air within the multicellular void at the back and external siding with regard to the air differential stress plus the air circulation resistance.

Jin *et al.* (2014) established a model using phase adjusted thermal shield (PCM TS), and its thermal efficiency was examined in three various places. The results disclosed that the top changes of heat flux decreased by 11% contrasted to a wall surface without a PCM TS, once the guard was positioned in the inner position alongside the inner face plaster wallboard in the enclosure surface. The phase adjusted thermal guard created little influence on the changes of heat flux when it was placed 50 per cent technique between the restricting surface of the interior of the wall surface. Virtually no outcome was put alongside the indoor face of the external layer of the wall surface.

2.6 HIGH-PERFORMANCE BUILDING HVAC SYSTEMS

The term A/C describes the three disciplines of Home Heating, Ventilating, and Air-Conditioning. Controls determine correctly how A/C systems function to satisfy the comfort objectives, safety, and cost-efficient procedure. The use of high-performance cooling and heating equipment can lead to significant power, emissions, and cost savings. Each A/C self-control has specific style requirements as well as each has possibilities for power financial savings. Ventilation systems deliver conditioned air to occupied areas.

2.6.1 Constant and Variable Air Volume Systems

A Constant Air Volume (CAV) system delivers a continuous rate of air while differing the temperature level of the supply air. If a CAV system serves more than one zone, the supply air is cooled at the main area to fulfil the requirement of the region with the greatest need. CAV systems with reheat are ineffective since they use up energy to cool air that will be heated up again. CAV is extensively used as a more accessible system and results in lower installation costs than a variable system. The limitation with the system is that it is not adaptive if, for instance, the temperature level in the zone increases, then the system does not react to it.

Variable Air Volume (VAV) method differs the air quantity provided to a zone while maintaining a constant supply air temperature level. VAV systems, nevertheless, can have issues ensuring consistent area temperature level at low airflow rates. Low-flow air diffusers in VAV systems assist in preserving consistent air circulation in an area at low airflows. Passive small circulation diffusers are developed to blend the supply air with the space air efficiently at low flow. Fan-powered VAV terminal systems offer another approach to enhance air circulation at low load conditions. These systems integrate the advantages of a VAV system by decreasing leading fan energy and reheat energy, with the benefits of a CAV system, by preserving excellent airflow.

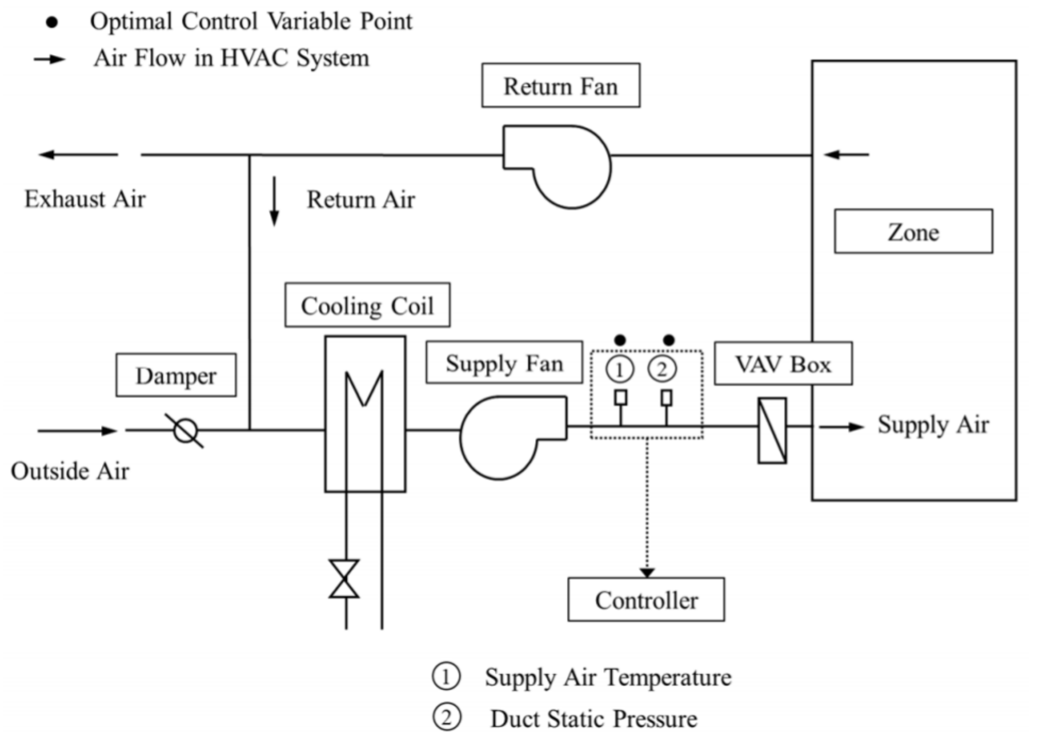


Figure 2.13 Common variable air volume (VAV) air-conditioning system (Seong *et al.* 2019).

The efficacy of cooling systems in a building can be affected due to elements such as temperature level, the humidity of the outdoor air, operation modes and patterns etc. To carry out effective operations and successfully manage a building's cooling method, the heating and cooling system needs to be run and managed by ideal control variables (settings) that represent the modifications in load use according to the external environment. Ideally, such optimum operation and control can be executed without extra expenses for upgrading the system. These local controls have an impact on indoor convenience and energy usage in the system. Regional controls in a VAV system have generally been carried out utilising controllers from conventional control techniques such as setpoint reset, proportional and predictive control. Seong *et al.* (2019) established an instantaneous optimum controller for a VAV system (Figure 2.13) utilising genetic algorithm.

The chosen variables for the controller are the supply air temperature as well as the pressure value in the air duct to supply optimal control for a VAV system. Making use of the recommended optimum variables in the controller, the general power use of the building was reduced approximately 6% in comparison to common settings. Lee and Jeong (2019) compared a Dedicated Outdoor Air System (DOAS) through a VAV system relating to the air quality in the indoor space and energy efficacy. The end results suggested that when the air quantity is substantial, the circulation of air is not ideal in the VAV system, such as in summer. The Dedicated Outdoor Air System, however, provides the outside air steadily. With respect to annual power consumption, a DOAS has taken in about 40% much less power than a VAV system.

2.6.2 Variable Refrigerant Volume and Flow Systems

To examine the energy efficacy of a Variable Refrigerant Volume (VRV) method, a new simulation module is established through simulation and experiment by Zhou *et al.* (2018). The distinctions between experimental and simulation for the total usage of energy for cooling and total power usage are shown to be within 25% and 28%. The coefficient of performance (COP) and part load ratio (PLR) of the VRF system are analysed with the typical variation of COP 6% and PLR 18%. Therefore, it can be concluded from the experimentation that the efficacy of a Variable Refrigerant Flow system at partial load setting is superior.

The debates on the energy-saving capacity of VRF method against other HVAC methods in an office complex even now remain present. Zhang *et al.* (2019) recently investigated the feasibility of a VRF system in office settings. To examine the impact of several uses in the power efficiency of a VRF system, a power usage profile was developed as well as calibrated against actual power usage of a VRF system. The owners' use adds substantially to the power efficiency of VRF systems, which have to be thought about in contrast with various other A/C systems.

2.6.3 Cooled Beams

Cooled beams supply useful cooling to an occupied location by making use of cooled water streaming through modular beams set up to a space ceiling. Cooled beams direct cold space air with the help of cooled water coils exposed to the air. Cooled beams can be categorised into passive and active systems. Previous research studies disclose that dynamic cooled down systems can accomplish much more considerable practical air-conditioning compared to a traditional a/c system. As the coil cools down the area air, the enhanced thickness makes a resistance pressure which produces the bulk of air to descend below the air beam. Kim *et al.* (2014) discussed a mix of the a/c systems with passive cooling option and considered cooled beams as a potential retrofitting option where a base case HVAC system is single duct VAV system. The retrofit with minimum adjustments consists of three settings. The retrofit alternative reported an overall energy cost saving between 8% to 24% in dry environment zones.

Murakami *et al*. (2015) established a unique A/C system with passively cooled beams set up in a suspended ceiling. Full-scale experiments were performed in a test room created to imitate a workplace interior zone. The research revealed that there was no considerable difference in this thermal setting between this chamber and also a surrounding chamber with ceiling panels. The existing technique of tests for ranking passively cooled beams restricts the efficiency evaluation. Nelson *et al.* (2016) experimented with a test area where the temperature is controlled with a passively cooled beam to identify the result of temperature sources on the conditioning capability of the cooled beam. They exposed the substantial influence of the heat source location. Shan and Rim (2018) carried out a parametric analysis to analyse the ventilation and air-conditioning efficiency using a computational fluid dynamics (CFD) model. The outcomes reveal that comfort and airflow efficacy of combined cooled beam and displacement ventilation systems differ with the cooling results. The researchers advised that a fairly high cooling result of a passively cooled beam incorporated with a reduced supply air temperature may disrupt thermal stratification of airflow as well as increasing rate of air draft.

Kim *et al*. (2018) accomplished two full-blown researches to map the effectiveness of passively cooled beam. The outcomes were utilised to establish a regression formula to anticipate the overall chilling capability and surface temperature of the cooled area, considering the cooled beam arrangements. It remained uncovered that the common technique of preparing for the full-blown air-conditioning capability of a passively cooled beam from particular lab examination or companies' sales brochures may significantly skip the system functioning outcome in a multiunit arrangement.

Kim *et al.* (2019) proposed a passively cooled beam designed based on full-blown experiments. The design utilised a system module to represent the radiative and convective impacts of the passively cooled beams. To study the cost savings associated with energy and indoor comfort, four various cooled beam setups, integrated with a VAV system, were considered utilising a full-size office building assumed to locate in multiple weather zones in the United States. The outcomes revealed that utilising a devoted outside air ventilation intended for the passively cooled beams, the refrigeration system might produce substantial energy cost savings.

2.6.4 Ground Source Heat Pump

Ground Source Heat Pump (GSHP) has to turn out to be popular lately for both space cooling applications. Compared to the standard A/C system, Ground Sourced Heat Pumps are extra appealing because usage of GSHP impacts in a substantial decrease in the usage of produced electrical power and reduces CO_2 emission from thermally operated power plants (Zhu *et al.*, 2014; Kharseh *et al.*, 2015; Sivasakthivel *et al.*, 2015; Sivasakthivel *et al.,* 2017). The enactment of the GSHP system depends on the Ground-coupled heat changer loop which links in among the GSHP and the earth. Similarly, Ground-coupled heat exchangers are the single, most costly elements of GSHP systems (Kharseh *et al.*, 2015; Sivasakthivel *et al.*, 2015). Sivasakthivel *et al.* (2017) evaluated heat exchangers by emphasising its impacts on ground configurations, floor temperatures, heating extraction and retention rate as well as its efficacy. Outcomes derived from the study reveal that the typical efficiency is high in the chilling method of operation in both the heat exchangers. Boukli *et al.* (2019) recently presented how the configuration of a GSHP coupled with solar collectors could meet the power needs of a residence positioned in Algeria as well as examining the viability of a GSHP paired with solar batteries as an alternative to fossil-fuel power. Results suggest that the contribution of the GSHP coupled with solar thermal collection may please 87% of a house's existing power consumption. A distinct pre-handling system for fresh air that eventually takes advantage of the power to precool as well as preheat fresh air is recommended by Lyu *et al.* (2019) to decrease the power usage for fresh air handling. The results expose the proportions of accumulated capacity to heat transfer using an air pre-handling method to the yearly accumulated overall air-conditioning load from 35% to 45% in the tropical area. The research study considered that the fresh air pre-handling system with geothermal power is uncommon in the warm summer as well as a comfortable winter location.

2.7 NET POSITIVE ENERGY BUILDING

As an outcome of advances in building and construction innovations, eco-friendly energy systems developing net absolute zero energy building have proven to be more practical. While the precise meanings for Net Total Zero Energy building differ, the core idea is to decrease energy requirements and promote sustainable energy systems that satisfy these minimised energy requirements. A broader classification recommends four methods in which the same could be implemented: Zero Net Site Energy, Zero Net Energy Costs, Zero Net Source Energy, and Zero Net Energy Emissions. The enhancement of new variables in the evaluation, for instance, occupants' behaviours, can utilise some understandings into the choice of the variation between anticipated and authentic energy efficacy.

Fotopoulou *et al.* (2018) highlighted the energy and examined the conserving capacity of the façade enhancement on an existing and low energy building in various weather settings. Specifically, a selected house was examined and modelled to recognise the building's energy consumption pattern and identify overhauling propositions to achieve almost net positive energy building. Models of these numerous theories led to matching various energy efficacy, from lacking efficiency in as-built circumstance, up to almost no extra source energy need, using the selected technical retrofitting option in particular weather context. Ballarini *et al.* (2019) informed a zero net energy building that was constructed with a purpose to study in a laboratory environment and also determined the power needs, renewable resource conversion, interior ecological top quality and various other facets of efficiencies in a functional setting. Consequently, the everyday power equilibrium is recommended to confirm the impact of solar energy as well as electric storage on actual power usage by the building. Ultimately, a numerical model was developed to carry out the energy simulations and undertake the comparative study.

Ascione *et al.* (2016) offered a brief analysis of present Net Zero Energy frameworks in a Mediterranean environment, by explaining the primary qualities of the exterior envelope, power systems for indoor air control and also renewable power resources. The exterior facade as well as the dynamics behaviour of selected retrofitting solution, allow the user to reduce the overheating hazard throughout the summer season and decrease the AC cooling load demand. The outcomes have been used to create and adjust a mathematical model to contrast it with the present energy demand and the supply energy on-site. Ascione *et al.* (2019) proposed an optimisation technique to attend to the energy pattern of the external envelope. The genetic algorithm-based optimisation technique carried out a Pareto optimisation with two excellent services. The Net Zero Energy building, which decreases core energy usages; and the cost-optimal option, decrease overall cost related to energy. These options supply the ideal methods for personal and public stakeholders, respectively. Considering the energy structure and environmental need for the future economy with low carbon technologies, Bazzocchi *et al.* (2019) determined and enhanced these elements by increasing the energy efficiency and decreasing energy intake. The research study was highlighted via the degree of sensitivity evaluation to find out which components most influence the power use with respect to topological layout accepted as reference point considering the environmental zones. Outcomes discussed that the air flow needs is the aspect that influences the power requirement for air-conditioning.

2.8 ASSESSMENT OF BUILDING ENERGY PERFORMANCE

Energy analysis techniques for the examination of mechanical systems in indoor space can be determined as an Inverted technique, Forward technique, and Hybrid technique (Krarti 2016). The inverted models are easier to produce than the Forward modelling principles. In the forward strategy, the power forecasts are dependent on the actual summary of the building systems, such as geometrical representation, area, building information, types of mechanical systems etc. The majority of the existing comprehensive energy simulation tools such as IESVE, Vasari, eQuest, Sefaira, EnergyPlus, ESP-r, Ploysun, DesignBuilder, Doe-2 as well as Trnsys follow the conventional Forward modelling technique. Inverted Modelling emphasised that the energy evaluation version identifies depictive parameters in building systems such as cooling load, coefficient of performance, baseload, and so on by utilising accessible power usage, schedule of the usages and additional appropriate system efficiency-related information. The versatility of Reverse Modelling technique is generally restricted by the articulation of the depictive building evaluation criteria as well as the correctness of the efficiency information of the building systems. The Inverted Modelling technique depends on regression evaluation to determine the performance parameters of the building (Krarti 2016).

2.8.1 Modelling Principles

Energy modelling techniques are utilised to catch the dynamic practices of energy systems. Hence, evaluation instruments can use Stable State or Dynamic State modelling strategies. As a whole, the steady-state designs are made use of to evaluate yearly building energy and power efficiency. Dynamic State modelling strategies may be required to examine the short-term impacts of building energy and power systems.

Frequently made use of energy evaluation tools are Ratio Centred Techniques, Inverse Approaches, as well as Forward Approaches by Krarti (2016). Ratio Centred approach is an analysis method before the auditing takes place. Inverted methods use both constant state and dynamic designing techniques that depend upon obtainable building efficiency information to acknowledge a collection of specifications. Inverted modelling methods are important to enhance structure power efficiency by recognising breakdowns, by providing cost quotes of anticipated financial benefit from the retrofits. Forward modelling techniques typically need physical summaries of building systems to determine energy end uses and to forecast any monetary cost savings sustained from the actions of energy conservation. Current energy evaluation tools which utilise Forward modelling method follow SteadyState approaches and dynamic approaches.

SteadyState Modelling:

In SteadyState modelling, Bin techniques are comparable to the Variable Degreeday approach, which count on Bin environment information to approximate overall building's energy intake to bring out a range of power assessment. Constant state inverted designs are appropriate for forecasting long-term building power usage. Some initial work for short-term thermal designs was brought out by presenting the technique, and the routine heat circulation design to identify the overall comparable temperature level differential for a building.

Dynamic State Modelling

Dynamic state models are developed towards estimating energy transmission among numerous processes in building. System simulation packages using proactive methods carried out effectively to approximate the effects of thermal inertia as an outcome of energy storage area in building exterior surface and/or systems. These simulation tools differ depending on their ability to perform the standard simulation functions, location, constructing envelopes, daylighting and solar, multi-zone and single-zone airflow, sustainable resource systems, electrical systems and devices, mechanical ventilation and air-conditioning systems, emissions, financial savings, environment information, and running timetable. The considerable benefit of lively inverted methods is the capability to design models that depend upon numerous neutral specifications. These variations need good consumer interaction and the data related to the available systems in the building. Dynamic models are advised to make up short-term impacts on building power usage that triggers momentary temperature level modifications throughout warm-up or cold-off durations of a building (Krarati, 2017).

2.8.2 Progresses in Building Energy Modelling

Computer system simulation for the building has become affordable and possible in research with the rapid advancement of computer systems along with the vital progression of numerical calculation methods. Simulation techniques consider a series of components of the building, for example, the efficiency of the ventilation process, the entire thermal load of the building, lighting, daylighting, building construction information, indoor acoustic details, overall energy usages etc. (Wang and Zhai, 2016). Cornaro *et al.* (2016) show how a particular calibration of the vibrant design utilising just internal temperature level counting can conquer this issue. The research study reported that the style might be utilised in the future to look at many repair work services by not simply connecting to the envelope along with the HVAC plant and its use. To assist decision-making, establishing simulation is typically made use of in the late design and retrofitting stages; nevertheless, its application is still restricted in the early stages in which design choices have a substantial impact on building performance. The initial incorporation of modelling tool deals with numerous difficulties that consider lengthy modelling time, quick change of the model, contrasting prerequisites, input uncertainties, and considerable irregularity in the available information (Østergård *et al.* 2016).

Choi (2017) reported the examination of findings of six building performance simulation programs. Based upon findings, the author established options for conversion of each program to other simulation tools. The information used for the analyses was collected from 15 home, and 180 simulation runs in two building modes: as-built and code compliance. The analytical review of the gathered information exposed that heating energy usage index conversion solutions were more robust than those of the cooling energy usage index. Considering that developing energy efficiency consistently produces disparities, depending on the simulation tools embraced, the result of this research assists in building efficiency professionals to comprehend the approximated energy efficiency of one tool. Dodoo *et al.* (2017) studied the consequence of underlying modelling assumptions on simulation of energy balances in two selected properties, including a building in its present condition with retrofitting measures. The results advised that the impact of location on heating operation in the building is rather little in a retrofitted building.

The energy analysis principles detailed by Krarti (2017) is focused on modelling and examination of structure envelope parts and their effect on thermal loads for heating and cooling systems under short-term and steady-state conditions. These modelling approaches are then used to establish forward and inverted designs, and simulation tools utilised to create, run, and retrofit structure energy systems. ASHRAE Standard 14 provided the constant of the variance of the root mean square error (RMSE) as requirements by which the resemblance between the target and building energy simulation design values can be determined. In this regard, Hong *et al.* (2017) proposed an automated calibration design for approaching the minimum Coefficient of Variation utilising the building energy simulation and optimisation algorithm. The authors offered the structure as follow: (i) gathering the target details; (ii) facility of the simulation of building energy design; (iii) calibration of the simulation of energy; (iv) setting the usage variables and unbiased functions; and (v) advancement of the automated calibration design utilising optimisation algorithm.

Tian *et al.* (2018) supplied an extensive evaluation of the open literature on inspirations, techniques and applications of linking stratified airflow simulation to establishing energy simulation in a building. Contemporary types of co-simulation are usually selected for energy effectiveness evaluation and control research studies. Empirical recognition of over one simulation tool has rarely been done in the literature. Nageler *et al.* (2018) provided a thorough contrast of one-dimensional energy simulation versus three dimensional CFD simulation. It was concluded that regardless of the generalisations in the one-dimensional simulation, the typical outcome is fairly exact.

The advancement of Urban-Scale Energy Modelling (USEM) is presently the objective of numerous research teams all over the world due to the amplified attention in examining the effect of building system performance in overcrowded cities. Sola (2018) targeted at examining the present methods while categorising those as per the core capabilities of the methods. The research study likewise exposed the easily offered means for performing new simulation techniques in Urban-Scale Energy Modelling that may decrease the time needed for modelling and enhance consistency of the results using recognised and calibrated modelling algorithm.

Improving building energy efficiency has been a significant tool for making sure energy supply in the climate change policies (Pernigotto et al. 2020, Suplee, 2020, Kim and Clayton, 2020, Kalluri et al., 2020). The energy index can be calculated easily by integrating traditional energy usage, modelling, and public repositories with specific measurements. The index remains expandable as new data becomes accessible, meaning that when new data becomes usable, it can be modified (Suplee, 2020). Building energy efficiency measurement technology has been a modern model that plays a major role in rising global energy demand and greenhouse gas emissions (Pernigotto et al. 2020). There is a worldwide explosion of different frameworks for construction evaluation and benchmarking. Researchers considered multiple factors that determine the success of energy-efficient building (Kalluri et al., 2020, Mafimisebi et. Al., 2020, Mohelníková et al., 2020, Murano et al. 2020, (Elsharkawy and Zahiri. 2020)). Many of those study analysed the relationship and connectedness between some of the variables in terms of the efficiency of buildings.

2.9 CONCLUSIONS

Literatures relevant to the usage of energy by building systems and thermal effectiveness assessment related to the multi-storey building has been studied. Techniques of energy-saving with alternative cooling and efficient envelope were analysed to identify one of the most feasible and optimum conserving methods together with improved thermodynamic performance.

Historically, the technology individuals adopted to make themselves comfortable made little or no change in the use of fossil energy. Modern convenience options included main heating and cooling usage power in difficult ways. These modifications significantly boost the range of environments we can inhabit pleasantly.

They additionally indicate we might live in buildings that would certainly not be habitable without using substantial quantities of energy to ensure human comfort. The ability to be comfortable is not straightforward; the processes presumes dependable accessibility to power as well as the modern technologies that use it. At the same time, the accelerating pace of environment modification and the danger of quick energy price surges, suggest we can no longer count on using inexpensive, fossil-fuel energy to make buildings habitable. We should create buildings systems to reduce their reliance on the power they use to remain habitable. Properly calculated building systems can confirm comfort for much of the year, making usage of small amounts of energy by the cautious use of thermal mass and other passive techniques.

It may be stated in those mentioned above that as a trend responding to the demand for energy conservation and sustainable building environments, thermal comfort research, which is capable of responding to the requirements, remains at an early stage. As a result of construction requirements and this varied climate, diversity is shown by global investigations concentrating on thermal comfort concepts and research procedures. Meanwhile, the occupants play a significant part in the interaction between the atmosphere that is sustainable. More focused investigations, which embrace the challenges of the changing climate, are crucial to better understanding the future adaptability of the occupants. Using suitable energy performance methods might enhance the power and thermal effectiveness of buildings. Numerous techniques are, nevertheless, provided to enhance the energy performance of structures. Envelope systems (i.e. walls, roofing system covering and house windows) end up being outstanding aspects of decreasing the power intake and consequently enhancing the energy effectiveness of structures.

Excessive HVAC use in tropical or tropical climate contributes considerably to greenhouse gas discharges. Even the Federal Government's commitment to zero emissions creates an obstacle which most of us have to adopt if we want to help tackle the climate catastrophe. The retrofitting strategies have a chance to develop infrastructure that will truly deliver the zero-energy utilisation and carbon emission in the long term. To attain zero energy consumption on sites that are constrained, we need to perform numerous challenging functions such as switching to options such as using renewable production and sourcing equipment with better energy efficacy as well as develop optimised operating strategies to meet the energy and comfort requirements. The path to Net Zero Energy buildings needs boundaries, and we could attain true Net Zero Energy building using technologies that are disruptive to dissolve. The current study evaluates the performance of various alternative building envelopes and low energy cooling methods to determine the best performing envelop and cooling method to enhance the energy efficacy and human comfort in buildings in a subtropical climate in Australia.

Chapter 3: Energy Assessment of Building Systems

3.1 INTRODUCTION

Assessment of building mechanical systems are needed to determine in what way energy is utilised within a building and recognise energy cost-saving opportunities. Month-to-month energy usage information was utilised to evaluate the impacts of weather discrepancy on energy usage. This chapter of the thesis intends to examine the power consumption profile through an exploration of the historic energy usages information and review the consumption pattern of an office. This chapter also features the findings of the information gathered throughout the auditing of the selected case study building and efficiency associated with the recording of the indoor climate specifications.

3.2 ASSESSMENT OF THE BUILDING SYSTEMS

Power usage in an administrative complex is influenced by the insulation type of the exterior surface, HVAC functional effectiveness, rate of the outdoor air intake, illumination type and relative performance, and other functional and preservation activities performed by the facility management on a periodic basis. Moreover, building mechanical systems and overall layout and thermal zones also have an immense influence on the quantity of energy usage of the building. The chapter intends to explore monetary advantage through lowered expense on on-site energy usage, minimise expenses through optimisation in operational parameters, enhance the usage of AC plant and eventually decrease operational CO_2 emissions by capitalising on the preservation and administration on-site energy consumption at CQUniversity, Rockhampton.

A power management program can be targeted in decreasing the power expense while providing superior quality, comfortable air supply as well as decreasing harmful environmental impacts. According to AS/NZ Standard 3598, there are two mains. The ASHRAE Handbook (2019) identifies audit via Walk-through evaluation, on-site survey, and an in-depth evaluation where major investment is essential to secure the evaluated savings. Walk-through evaluation offers a preliminary view of prospective cost savings by the evaluation of a power price, effectiveness of energy expenses as well as a short survey of the building (ASHRAE, 2019).

Criterion specifications based on AS/NZ Standard 3598 (2000) have complied throughout the auditing and evaluation process of the study. The standard includes airflow and ventilation system, AC system, illumination, office equipment and other appliances in the space. According to the criterion, the intensity of assessment has three phases. Phase one reviews the general usage of energy at the facility. Phase two studies the statement of costs as well as possible savings. Phase three supplies an elaborated evaluation of usages of energy, potential energy savings as well as the expense of attaining those cost savings. The energy assessment process undertaken as a part of this study offers a comprehensive scenario of the facility to recognise the possibilities of power savings. Level 2 review needs a comprehensive evaluation of the building systems to establish power usage accounts. The first phase in the whole process is to accumulate most of the readily available details about the energy systems as well as the power usage profile. The usage records were evaluated to recognise the typical power usage profile, maximum energy needs in a typical week (summer/winter), weather condition, and potential cost savings. Cyclical energy usage and suitable power efficiency indication have been assessed in recognising the prospective decrease in power usage. As a component of the review, reviewing was done continually with power measuring devices and information loggers to provide crucial info on the overall efficiency of the energy-consuming equipment. Energy efficiency signs were configured to warrant future retrofitting measures. Continual power tracking allows an overview of power uses as well as its relevant prices within facilities. Both recurring and also historical power usage along with the relevant expenses, were recorded.

3.3 POWER USAGES TREND AND EVALUATION

Throughout the on-site evaluation, significant power-consuming components were identified as the mechanical airflow and AC system along with lighting systems. Electricity is a significant source of power on-site and represents 98% of complete energy expenses. The various other power sources include natural gas and diesel, which are about 0.2% and 1.8% respectively. Physically the campus can be split into three subdivisions – Accommodation Zone, Educational Precinct, and Southside Extensions. Each zone has its individual power supply from the power distribution company. The Educational Precinct is a significant energy customer and makes up 89% of overall electrical power consumption. The overall power usage of the Educational zone was 7 GWh at the cost of around $600,000 per year. An audit research was undertaken to evaluate locations of unwarranted use as well as potential improvement procedures to manage the growth of electrical power consumption.

3.3.1 Average Energy Consumption Scenario

The analysis of average exterior air temperature and consumed energy displayed that there is a considerable association amongst electrical energy intake and the equivalent weather condition information, especially exterior temperature. In Figure 3.1, the regression factor R^2 of 0.91 shows a robust relationship amongst the quantity of power usage and the outside environment. Average power consumption was estimated considering a direct line that corresponds with the lowest intake utilising sequential regular monthly power intake records for successive months versus typical atmospheric temperature. In this assessment, electrical energy need and intake from the grid reveal distinctive seasonal variants for the reference location. The single biggest power end usage, specifically mechanical fresh air flow management and cooling is weather condition reliant. The average energy usages were 55K kWh monthly. The consumption profile is fairly consistent on a month by month basis seasonally adjusted.

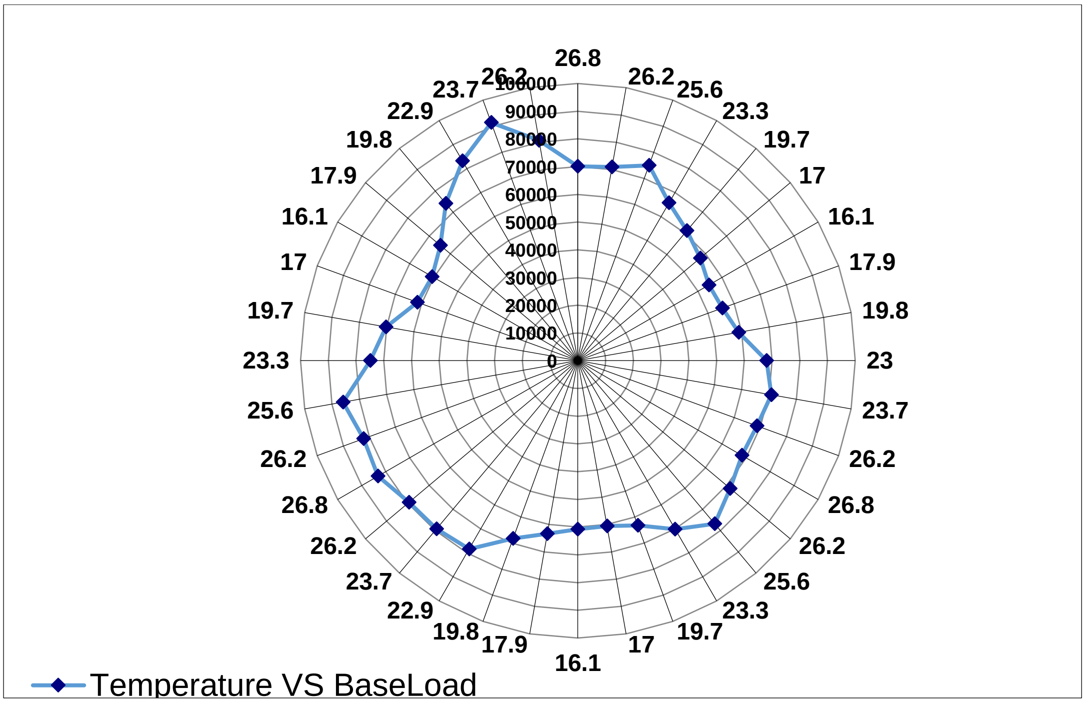


Figure 3.1 Monthly average outside air temperature vs monthly consumed energy (kWh) for the Educational Precinct.

3.3.2 Yearly Energy Consumption

As shown in Figure 3.2, overall electrical power usage grew by 2.1% per year continuously in a typical year, whereas the complete energy expense increased by 8% on a yearly basis. Energy intake rose 2.1% in the year 2015, and the power price enhanced 8.2% related to 2014 (Figure 3. 5). Monthly power intake in every month either lowered or boosted depending on the variation in the relative moisture and outdoor temperature (Figure 3.3 and 3.4). It appears that December and March both observed the variance in power usages with respect to the external temperature. Total power usage increased in March although outdoor air temperature lowered compared to previous months the opposite phenomena is observed in December. It can happen from the beginning of the sessions in the Education block with numerous students and employees returning to the Education Precinct at the beginning of this session. Many employees are on annual leave in December.

The pattern power intake pattern was equivalent for many years. The greatest possible energy need remained in March, and relatively fewer usages were observed in July (Figure 3.4). In general, the consumption was higher in the summer month of December, although peak power demand was not substantial due to the vacation duration. The pattern in power use during non-peak time is comparable for the consecutive three years where the greatest possible power requirement remained during the summer months in December and January, and the least cost need remained in the July-August period (Figure 3.4). Power requirement during non-peak likewise complied with the seasonal variant among the months observed. Differences in energy consumption costs throughout the years is steady and also complies with the direct rise of 8% (typically).

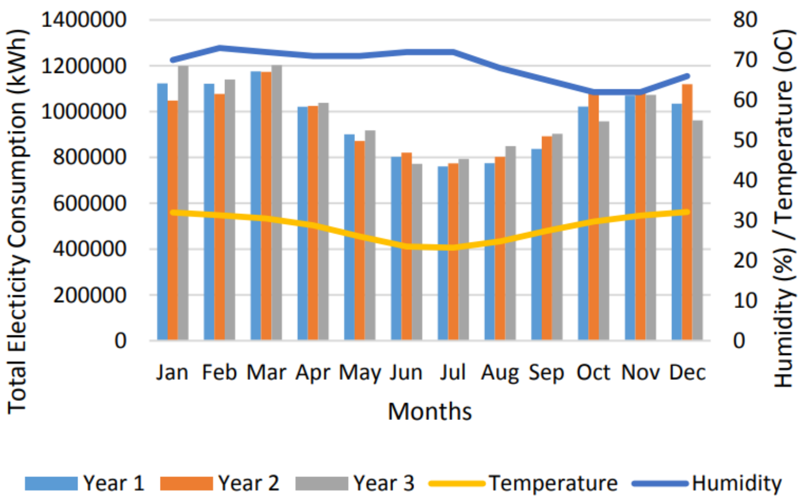


Figure 3.2 Overall average monthly electrical energy usage.

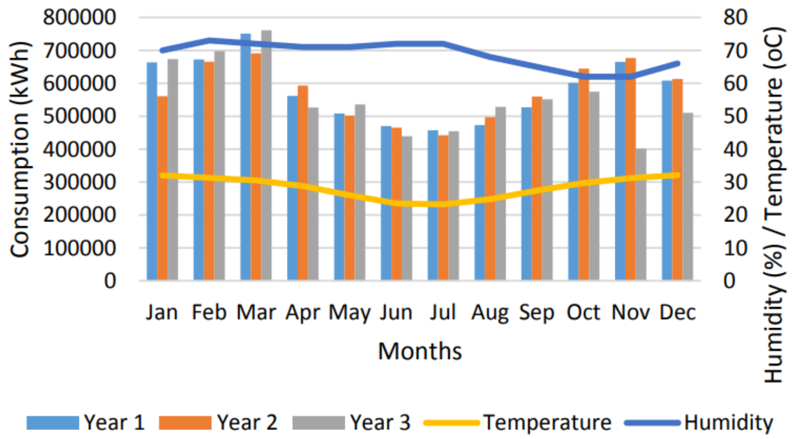


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Figure 3.3 Overall average monthly peak electrical energy usage.

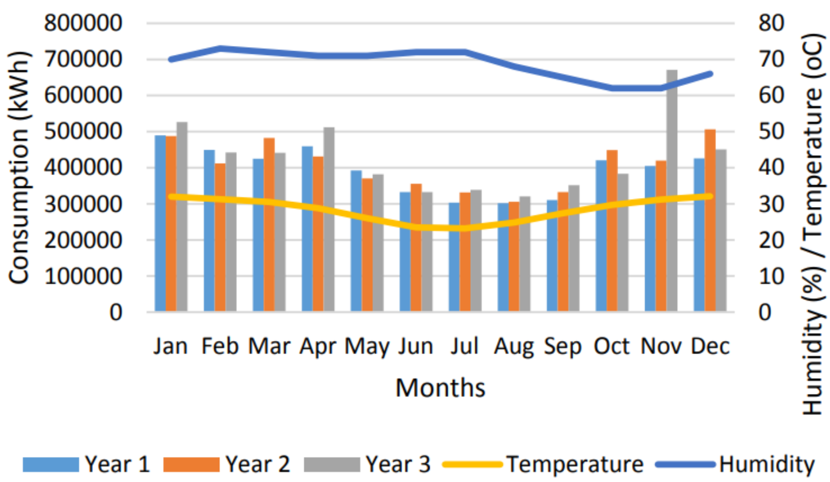


Figure 3.4 Overall average monthly non-peak electrical energy usage.

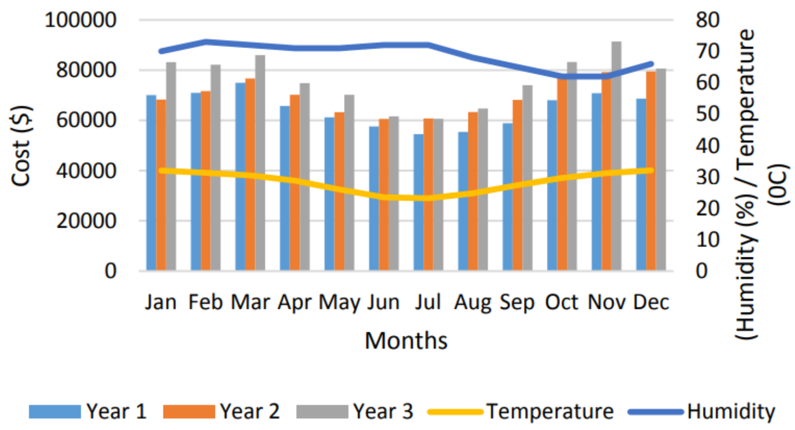


Figure 3.5 Overall average monthly energy usage cost.

3.4 SELECTED BUILDING

A representative building case was considered in this study to evaluate various end-user intake and impacting elements in the systems. The significant power-consuming equipment in the case study 1 building structure is the AC system, ventilation and associated mechanical systems, illumination system and plug loads. As per the AS 3598 (2000) auditing procedure, the case study building's operational performance data for three years have been examined. The building is located in Rockhampton, which is part of the CQ region. The overall structure contains three floors which are all fully air-conditioned throughout the day. Each level of the building has an accessible flooring layout, as revealed in Figures 3.6 to 3.8.

The thermal loads in the indoor space consist of lighting, plug loads, heat gain from people and computer systems that add to the general requirements for the cooling load calculation. Typical plug loads discovered in the structure consist of desktop computer systems, screens, copiers, projectors etc. The building is occupied all days except the public holidays. People density differs by location.

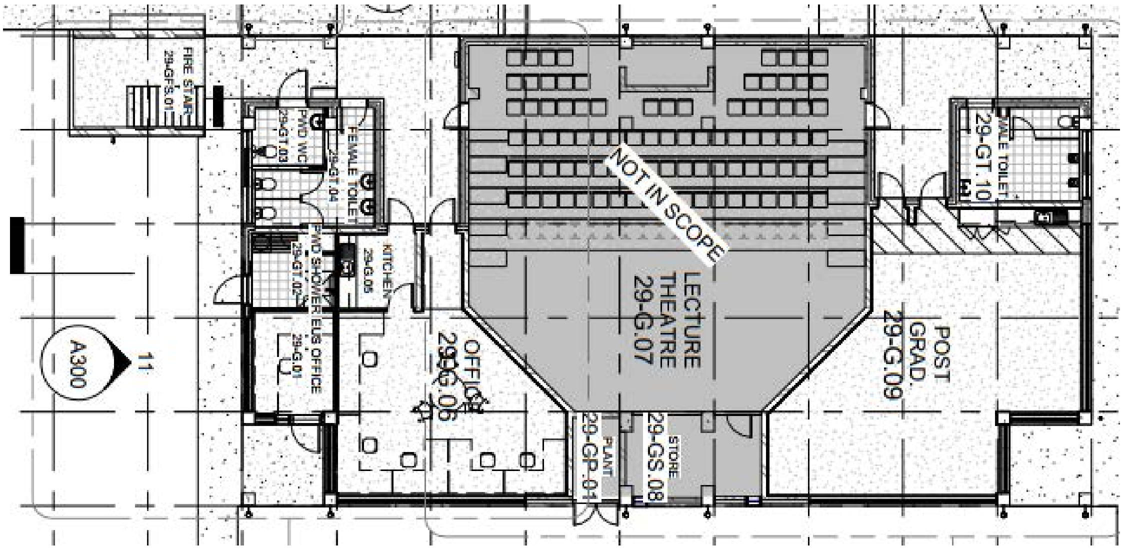


Figure 3.6 Plan view of the ground floor

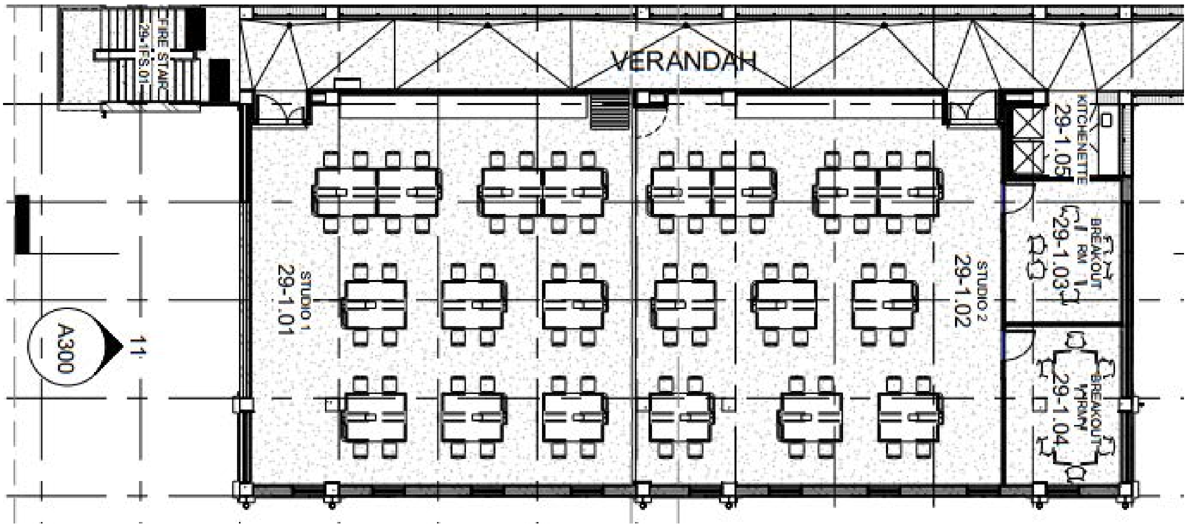


Figure 3.7 Plan view of the first floor.

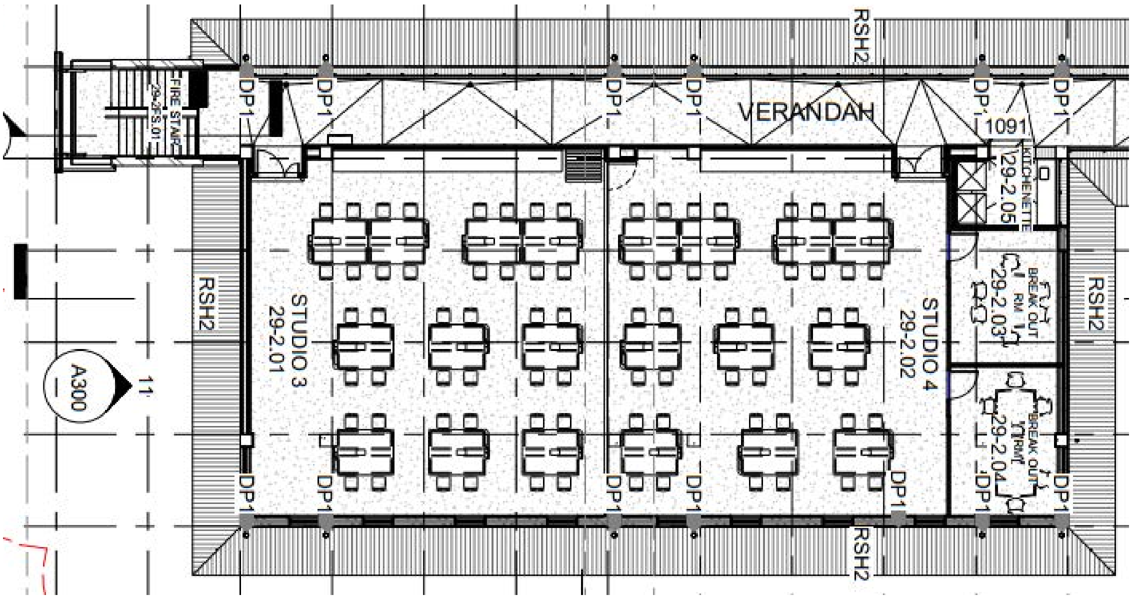


Figure 3.8 Plan view of the second floor.

3.4.1 Data Collection

General information on the selected building was collected to gain a total impression of the genuine energy behaviour of the structure. The information mostly comprised basic structure such as dimensions of the building, loads from internal elements, external envelope, and energy systems consisting of the HVAC systems. The building control system is also a considerable source of information for developing operating information. Information on geometrical setup, construction footprint, construction shell, building products, internal loads throughout occupied hours (workers, workplace devices, illumination systems etc.), and running timetables of HVAC equipment are collected for evaluating the overall efficiency of the building mechanical systems. Some of that information appropriate to the base case design is noted in Table 3.1 and 3.2

Table 3.1 Details of the building

Building Class: Class 5	Walls: Brick Plaster
Building type: Office	Roof Ceiling: Concrete and Plaster Board
Verification Method used: JV2	Floor: Concrete slab with carpet
Building Code Australia Climate Zone: 2	Floor Width: 34 m
Front Orientation: NE	Floor Length: 74 m
Total Height: 16 m	Outside Air Rate: 10 litre/s/person
No. of Floors: 3	Glaze Type: Single, clear float ¼ inch with blinds
Occupancy: 1 person per 10m2	Inside room temperature 23oC
Windows Width: 1.5 m	Window Height 1.5 m

Table 3.2 System operating details

Equipment	Type	Power Density (w/m^2)	Schedule
Lighting	Fluorescent	15	08:00-midnight (in few areas 24 hrs)
Office Equipment	Standard	15	08:00-17:00
Cooling	Air-Cooled	40	08:00-17:00 (in few areas 24 hrs)
Ventilation	Standard	5	08:00-17:00

3.4.2 Indoor Environment

Temperature level and humidity were recorded for both summer and winter utilising HOBO data logger. The data collected at various areas of the thermal zone revealed that the indoor air temperature was fairly consistent due to similar activity and population cohort. The typical air temperature variation on a daily basis is revealed in the graph 3.9, which was plotted in the HOBOware software. The temperature level differs between 23 ºC to 24 ºC with little variation in some durations, as shown in Figure 3.9. Temperature and relative humidity sensing units were set up to keep track of the occupied area environment conditions for the structure, checking information at 30-minute intervals as displayed in Fig 3.9 and 3.10. The indoor humidity level differs from 54% to 78% throughout the determined duration (Figure 3.10). Illumination strength was likewise determined and recorded as 340 lumen/m2(Figure 3.11).

3.4.3 Breakdown of Energy Usages

The considerable problem in establishing the classification of various users of energy energy measuring devices for sub-systems. The energy usage sub-systems were divided into two categories to dominate this difficulty. It was specified with lighting, workplace devices and other devices etc. and this category is not dependent on the climatic condition. The second category was energy usage for cooling that is reliant on the climatic condition. Both the categories of consumption profile show a specific similar trend. The typical day-to-day trend of the energy system was produced depending on the data collected that validates the schedules received from the facilities manager. The data also exposed the enhancements in power usages that could be made.

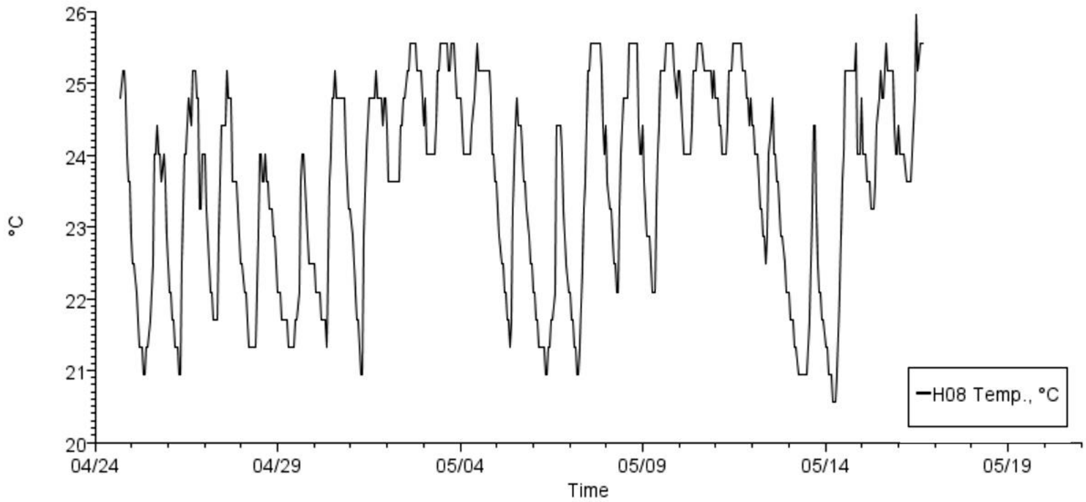


Figure 3.9 Recorded temperature profile (as extracted from the datalogger using HOBOware).

Figure 3.12 indicates the day-to-day energy demand and intake profiles which states that the usages increase from 8 am when the AC plants and lighting operation begins for the day. The peak energy usages are observed from 11 am to 4 pm. The power usages reduced gradually depending on the load condition. There are some computer systems, devices and associated AC units that run on a continuous basis and as such the base power load is justifiable. The air-conditioning units are primarily responsible for peak energy demand that occurred between 12 pm to 4 pm.

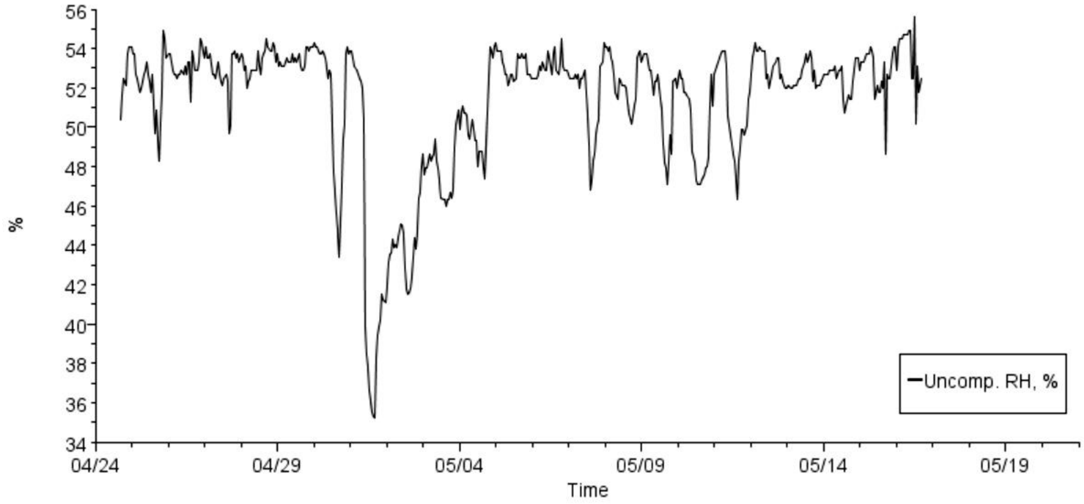


Figure 3.10 Recorded humidity profile (as extracted from the datalogger using HOBOware).

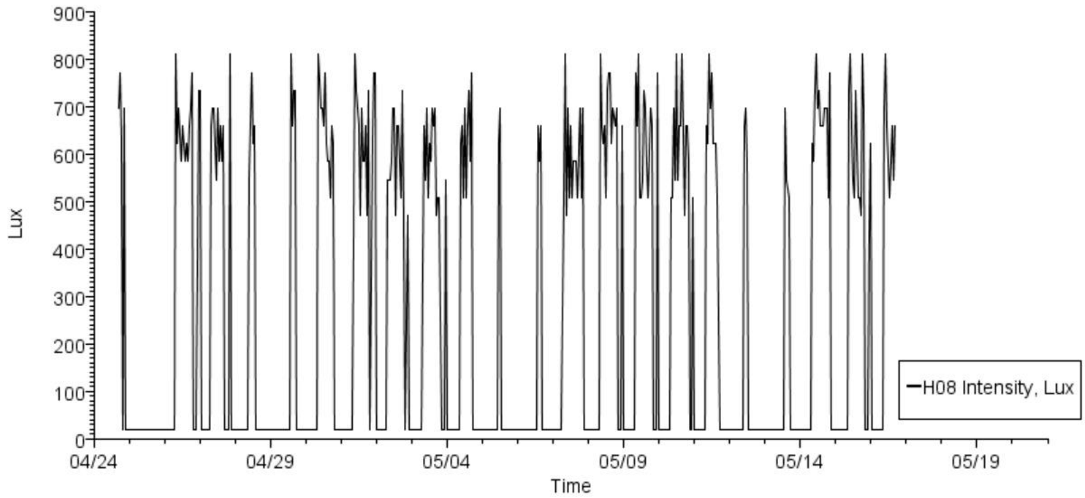


Figure 3.11 Recorded lighting intensity value (as extracted from the datalogger using HOBOware)

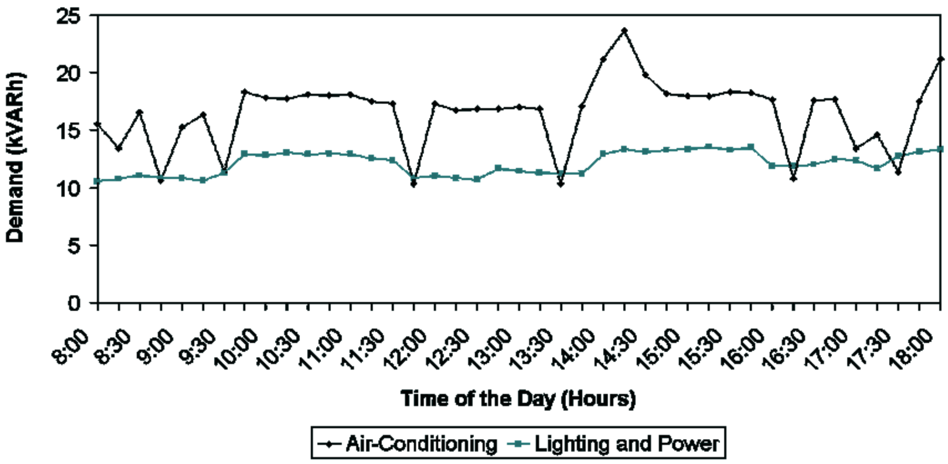


Figure 3.12: Hourly distribution of energy demand load.

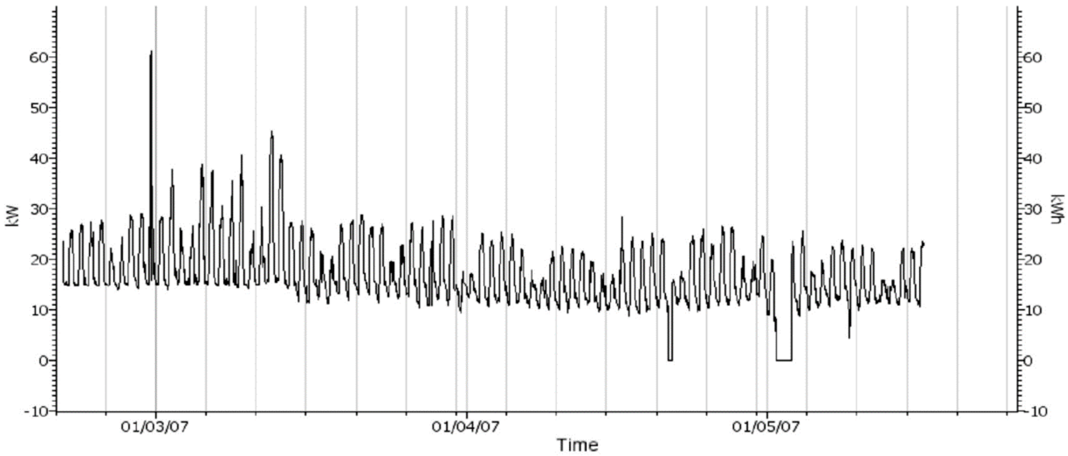


Figure 3.13: Chiller power demand and electricity consumption profile. (as extracted from the datalogger using HOBOware)

Hourly measured data was utilised to create normal everyday energy need and intake profiles of the Chiller (Figure 3.13). These accounts were necessary to determine the power use profile. The identification of this profile will help optimise the power usages pattern of the chillers involved in the cooling processes. Keeping track of the energy data over a period of time also helps to recommend the period when the power demand is high at this facility. The graph in Figure 3.14 suggests the continual operational mode of the AC unit all day and night. Information from 12 months was investigated to establish the total efficiency of the building system. The process also assists in scrutinising the sub-systems within the building. Complete power use records supplied vital data on the power use of the systems and sub-systems.

Additionally, several air-handling units were in operational mode throughout the weekend to eliminate excessive CO_2 which is harmful to the occupants. Some computer systems and a few other devices were in operational mode during the weekend. Chillers' power usages were reduced throughout the non-working day due to a reduction in the internal load. The account of power usage shows that power intake differs in various periods of the day. The phenomenon is predominantly influenced by external temperature level and people occupied within the building space.

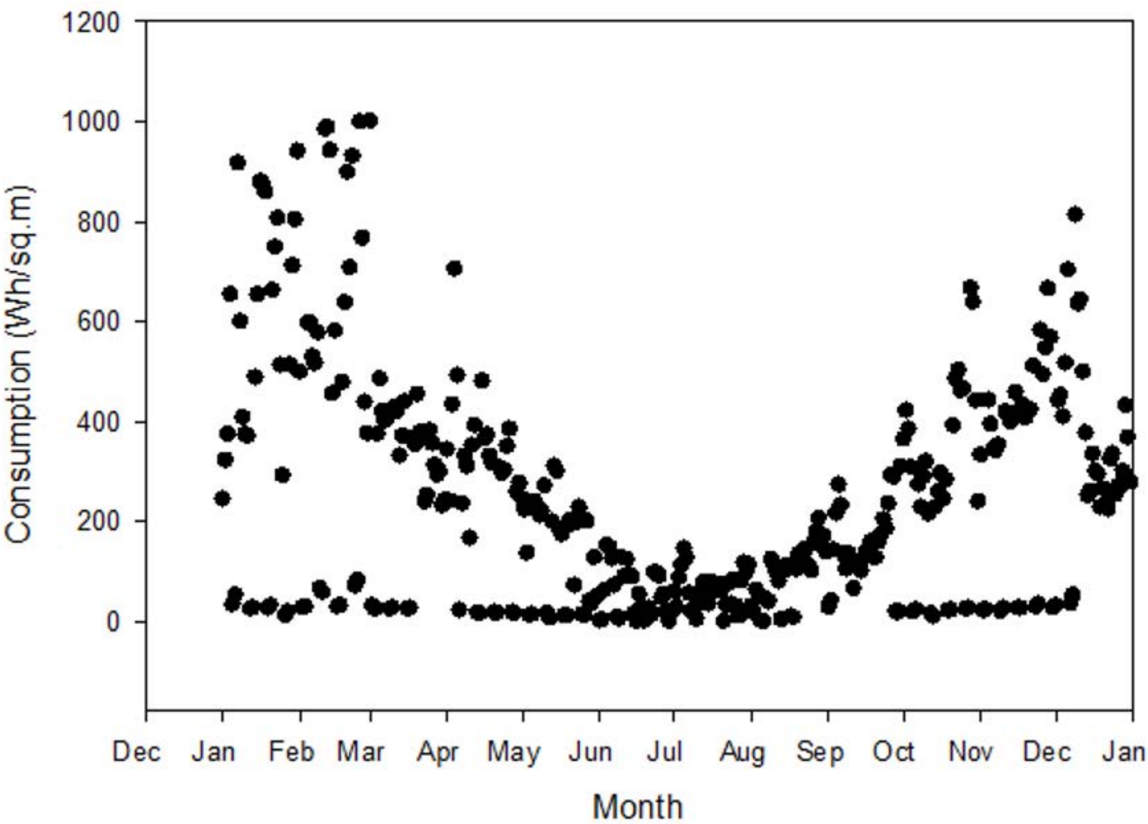


Figure 3.14: HVAC electricity usage pattern.

Based on the energy consumption profile, it is clear that power usage by non-weather associated elements of the building systems (lights, equipment, etc.) was lower compared to the weather associated element of the building systems (HVAC etc.). Power intake for cooling was greater throughout summer and reasonably reduced in winter, which highly correlated to the hot and humid nature of the external environment. From the power usages profile, it is clear that the Chiller systems are a constant user of power along with various air-handling units. On top of that are the lighting system and workplace tools usage responsible for the remaining amount of power usage.

3.5 RESULTS FROM THE ENERGY INSPECTION

Studies suggest that an illustration of mass power usage by itself will not be adequate for the efficient administration of power usages at the facility. Therefore, the trend of building power usage should be examined on a user to user basis essential throughout the facility. Presently, accumulating the power usage data, power and analysis of the power usage data are utilised to estimate the energy efficacy of the system and categorise problems in functional tasks. Nevertheless, numerous alternatives are readily accessible to enhance the power efficiency of the building system.

3.5.1 Illumination Systems

As specified in the earlier section, peak load demand accounts showed simply the basic power usages profile of the Educational Precinct. Further in-depth assessment of the energy system, as well as the operational methods, need to be looked at for other systems. This assessment recognised significant power utilising devices at the facility, including AC units, ventilation system, illumination system and other workplace and educational accessories. The illumination system is calculated to stand approximately 30% of the full power usage of the Educational Precinct. The majority of interior spaces are decorated with incandescent lights with a capacitor to improve the quality of power. For outside, high-stress salt or high-stress mercury lights are utilised. In various areas, some lights near window locations could have been turned off through the daylight hours, however insufficient changing or automated control of illumination are located to be triggering waste.

Interior lights in empty spaces are left on constantly. Personnel is permitted to access some laboratories and workplaces after hours. Some lights are kept on when the trainees and group leave the space from time to time. Some lights, specifically those put outside, were unpleasant and dirty, which eventually reduces the lighting output. A number of the walkways had their passages and balconies illuminated all the time. Illumination systems are missing manual power control buttons. As a result, many of them remained in an operational mode based on the schedule provided in BMS. The bulk of the lighting system and the AC units in the study area stay in operational mode till the security locks up locations. Many lights in the lawn and park run on from 6 pm to 6 am and need rearrangement to suit summer and winter variations.

3.5.2 HVAC Systems

The heating, cooling and ventilation system, with its involved subsystems such as pumps, air handling units, chillers are the biggest user of energy. The overall power usage tread is roughly representing 50% of the average energy consumption by the facility as per the metered data. The AC units are constant air volume type (CAV) system. The installed AC systems are intended to provide adequate cooling effects to all the occupants. There were some incorrect thermal zones for circulation of air inside the building noted.

Building AC units are running in part load condition in good period time during the day. Some AC systems are discovered to be in running mode when those places are empty. When the air-conditioner was running, some entry gates and windowpanes were found to be accessible in some areas. Students and Staff are enabled to go into some labs as well as workplaces after hours, and AC units in the study area keep in operational mode. Some AC units are located in vacant offices in running mode. When the AC units were running, windows were discovered to remain open in certain spaces. The air-conditioning units are left on when people left the space after the activities.

3.5.3 Recommendations

The central purpose of this investigation is to assess the current building systems and identify the retrofitting options that will ensure the energy and monetary saving over the life span of the facility. Off-peak tasks generally increase running hours of power systems. Rearranging of the off-peak hour activities can fit preferential closure of building operations other than ventilation systems.

Recording of the indoor temperature degree at numerous locations recommends that sensors on comfort measurement are weak to adjust and respond based on the environmental condition. Rearranging sensors to treat promptly as well as relocating the sensors in return duct will undoubtedly give far enhanced regulator of the AC units. Sensor setups could be transformed in favour of modification where required. Further investigation with start-up times as well as pre-cooling strategies is needed to recognise to ensure sufficient benefit levels for the people in the space.

Reducing cooling throughout the occupancy schedule is helpful in cutting the power consumption in the building; however, it needs to be conducted based on ensuring that people’s comfort is not sacrificed. By minimising the condensation temperature, by increasing cold water supply temperature in the chiller according to specification from the manufacturer as well as mounting an evaporative cooling cycle to get cost-free cooling operation, chiller efficiency may be improved.

3.6 CONCLUSIONS

In this section, the detailed analysis is rationalised to measure the influences of significant weather parameters on the yearly power use profile of the facility. The evaluation is performed based upon the historical information received from the entire power usage profile of the Education precinct. The effects of numerous useful uses of buildings are spoken about. Effects of amendments in the practical use of the facility have been described. Changes in operational control strategies will have a further positive impact to reduce the power usage, which is also highlighted in the discussion.

The findings of the assessment and recorded data for a considerable amount of time will be essential resources to evaluate the parameters influencing the performance of mechanical systems in buildings as well as to lower the energy usage in those systems and subsystems. Contrasted to the year 1, it was found that the yearly power cost is raised 7.9% with the complete increase in the use of the power of 1.9% in year 3. The financial savings out of the review process depends on the application of the recommendations of the assessment. The research recommends that the additional power usage to overcome the harsh effect of extreme outdoor environment can be minimized by enhanced control methods of the HVAC system. The outcome of this study will certainly aid to boost power effectiveness of the building system, which is an important element to sync with the Government's strategy to provide long term environmental benefit and sustainability for the people. The findings of this chapter will be adopted to establish the base case model for analysis and validation of the model that will eventually be used for retrofitting of HVAC and envelope system in the latter part of the thesis.

Chapter 4: Building Energy Modelling and Simulation

4.1 INTRODUCTION

In this section of the thesis, the focus is on the development of a base case model, undertaking a detailed performance evaluation of the selected case study reference building system and validating the outcome of simulation results for further retrofitting studies for better performance and better resilience in a future climate change scenario. The features of computerised energy efficacy investigation in the building system are to examine the attributes of the building systems and determine the energy usage profile in those systems. The influence of operational parameters of the building sub-systems on the overall efficacy of the systems is also examined.

4.2 SIMULATION PRINCIPLE

EnergyPlus (EP) is primarily a simulation algorithm that conducts an investigation of the systems in building depending on the equilibrium principles of heat and mass of the overall systems. The algorithm uses a Forecaster Corrector based methodology with access to integrated systems configurable by users as well as streamlined access to multi-zone air movement platform for comfort analysis. EP has three conventional elements – the main simulation portal, a simulation module for the equilibrium of heat and mass, and a system simulation component (EnergyPlus, 2019). Making use of EP, internal load calculated on a per hour basis is forwarded to the simulation module of the building systems components at a similar time. The software, DesignBuilder (DB) is expanded on the principles of EnergyPlus set of rules used for the performance simulation of the building systems and is adopted in this study to undertake the modelling of the efficacy of building systems for a retrofitting study.

In EnergyPlus, systems simulation manager governs the interaction between the heat and mass equilibrium module and numerous AC components, for instance, air-handling unit, coolant pumps etc. The EnergyPlus incorporated simulation manager deals with the surface area, and also heat and mass equilibrium module and function as a medium among the equilibrium module and the simulation module. In EnergyPlus software, area temperature level is determined with an estimation of a third-order differential equation. The energy equilibrium of air is offered by (EnergyPlus, 2018):

$$C_Z \frac{dT_z}{dt} = \sum_{i=1}^{N_{sl}} Q_i + \sum_{i=1}^{N_{surfaces}} h_i A_i \left(T_{si} - T_z\right) + \sum_{i=1}^{N_{zones}} m_i c_p \left(T_{zi} - T_z\right) + m_{\inf} c_p \left(T_{\inf} - T_z\right) + Q_{sys} \tag{4.1}$$

$C_Z \frac{dT_z}{dt}$ = Rate of energy storage in air

$\sum_{i=1}^{N_{sl}} Q_i$ = Sum of internal convection loads from people, computers etc.

$\sum_{i=1}^{N_{surfaces}} h_i A_i \left(T_{si} - T_z\right)$ = Convection heat transfer from zone surfaces

$\sum_{i=1}^{N_{zones}} m_i c_p \left(T_{zi} - T_z\right)$ = Heat transfer due to inter-zone air mixing

$m_{\inf} c_p \left(T_{\inf} - T_z\right)$ = Heat transfer due to infiltration

$Q_{sys} = m_s c_p \left(T_s - T_z\right)$ = Air system output

The heat and mass equilibrium module replicate the equilibrium of heat among the outside and inside the atmosphere and accounts for the associations between heat balance limit conditions, conduction, radiation, and convection transfer impacts. After the module of heat and mass equilibrium completes the reproduction of the process, it connects the simulation manager of building systems and revises the air temperature of the specific zone. This module also manages the system simulation of mechanical and electrical components of the building system. The combined simulation module's capability maintains the link with the waterside and airside components of HVAC plant operation.

To guarantee computations are precise, representative of Australian conditions, and are equivalent throughout various kinds of real estate, the software protocol needs all NatHERS recognised software application tools to satisfy stringent efficiency requirements and requirements for variables consisting of (but not restricted to) regional environment and weather condition, thermal resistance and capacitance of building products, window glazing, occupancy patterns (consisting of internal heat loads, times and behaviour), window coverings, thermostat settings (temperature levels at which synthetic heating/cooling is no longer needed to accomplish thermal convenience, noting this differs depending upon environment zone), shadowing/overshadowing by surrounding building and functions, building size etc.

In this chapter, a computer-based performance simulation of the reference building system has been established using the DesignBuilder simulation platform, and the outcome of the simulation results was validated using the measured data as a part of the auditing process. The air conditioning, ventilation and the illumination systems electricity consumption data that were collected for the energy analysis were adopted to develop the base case model and performance analysis of building simulation for summer and winter. The aspects that influence establishing power effectiveness and thermal ease of the citizens have been acknowledged. The elements of the building systems responsible for impacting energy effectiveness of the system and thermal comfortability of the occupants have been recognised as a part of the modelling and simulation process.

4.3 LOCAL WEATHER

Rockhampton weather is classified as tropical. Rockhampton's typical yearly rainfall is a little over 80 cm (BOM, 2018). Rain standards recommend a special summer and winter season, with the peak summer period usually from November to February and the winter period from May to September. Typically, the summer season is from December to February, and also winter is from June to August. Figure 4.1 and Figure 4.2 reveal the outside comfort in Rockhampton utilising the annual fluctuation of temperature and humidity. Figure 4.3 maps the radiation data to reveal the strength of solar radiation on an annual basis for Rockhampton. Figure 4.4 reveals the association of dry-bulb temperature and humidity distribution points and other relevant information to identify the comfort zone limit for the selected location.

Overlaid impression on the chart represents various methods for comfortability reliant upon ASHRAE 55 (2017). The severe warm summertime week was considered from February 3rd to 9th, and closest ideal summertime peak temperature was considered as 38.5 ºC. The selected summer week considered the typical local temperature as 25.9 ºC. The coldest winter period was identified as August 17th to 23rd with the local minimum temperature level of 5.1 ºC as presented in Figure 4.5. The typical temperature level is 17 ºC in the wintertime. Figure 4.6 represents the monthly average of relative humidity for Rockhampton. Figures 4.7, 4.8 and 4.9 show a summarised representation of a whole year's hourly typical temperature levels, daylight, sunrise, sunset with twilight. The length of the day in Rockhampton differs throughout the year. The briefest day is on 22nd June and the lengthiest day is 22nd December in the historical weather dataset.

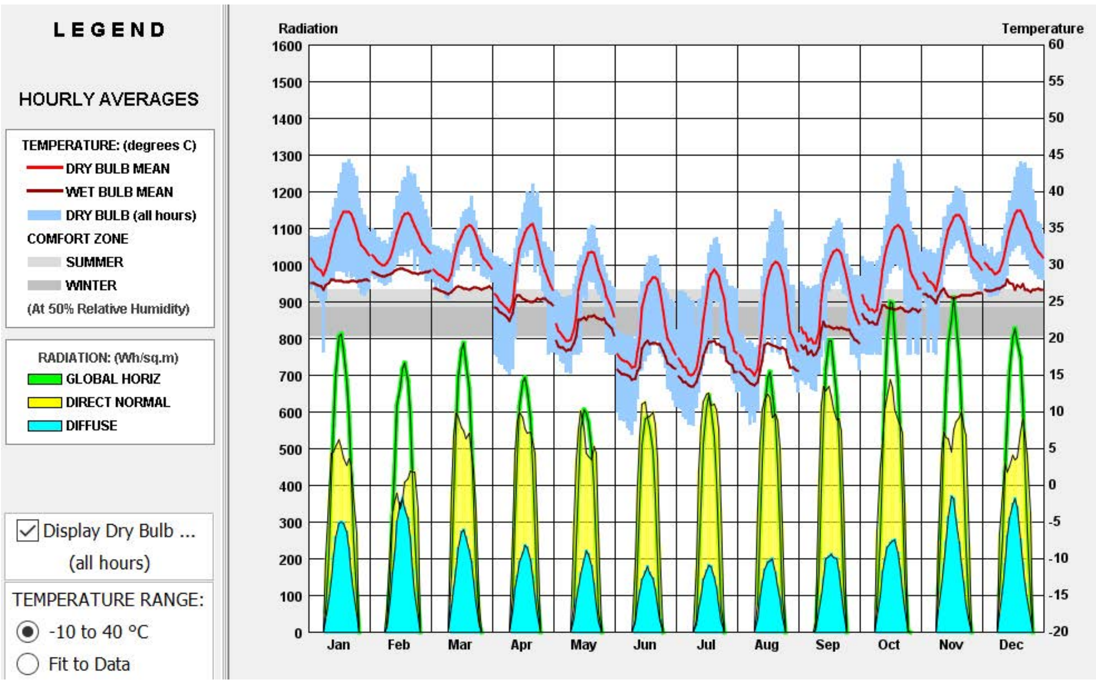


Figure 4.1 Monthly diurnal average of Rockhampton.

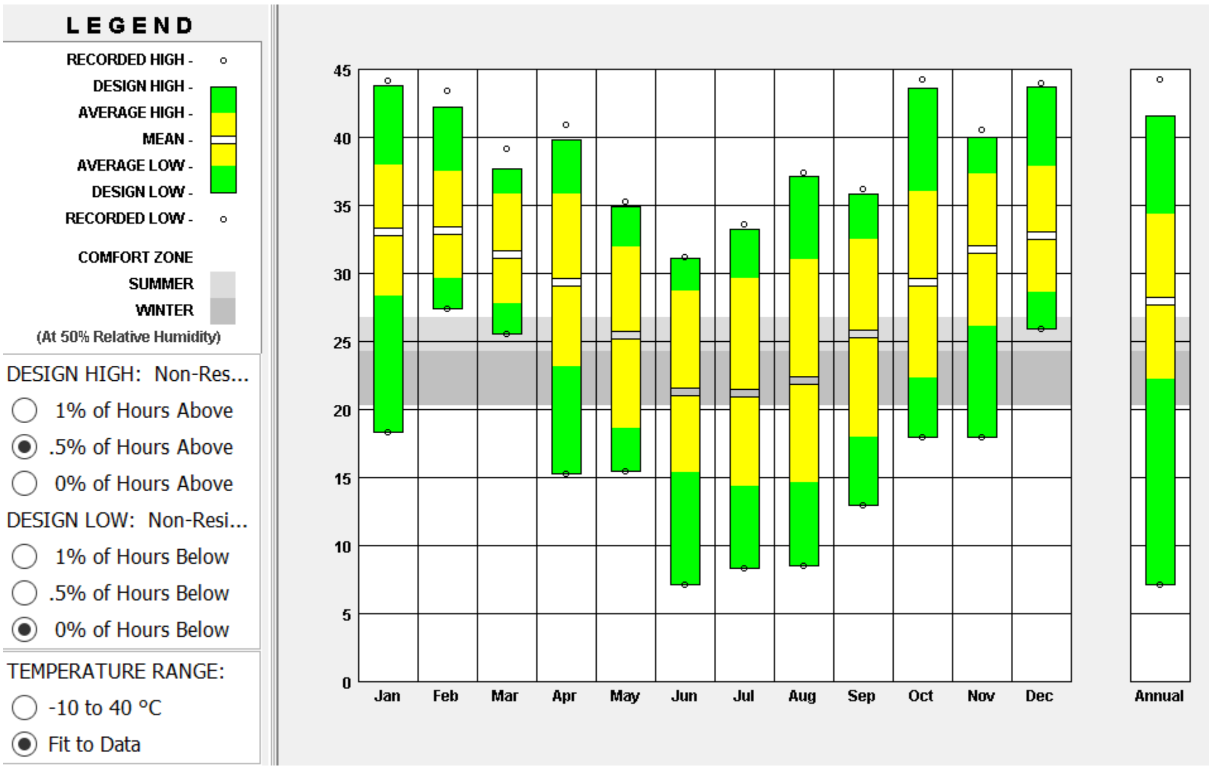


Figure 4.2 Monthly distribution of yearly range of temperatures

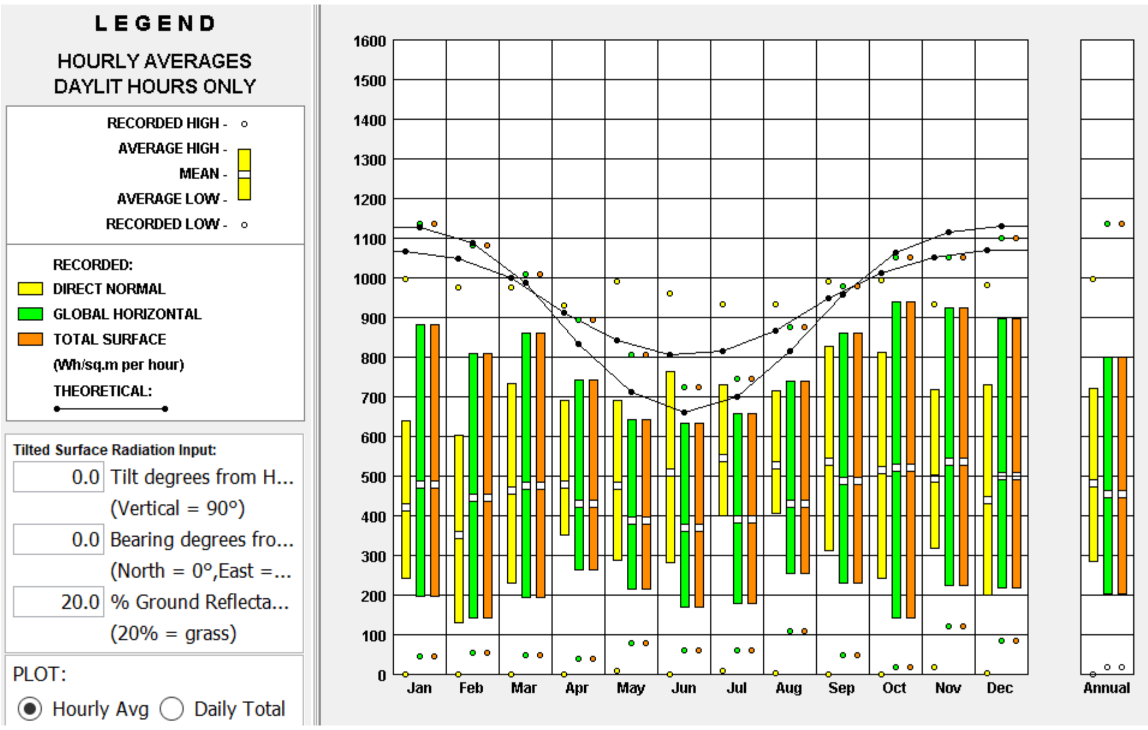


Figure 4.3 Monthly distribution of yearly range of Solar Radiation.

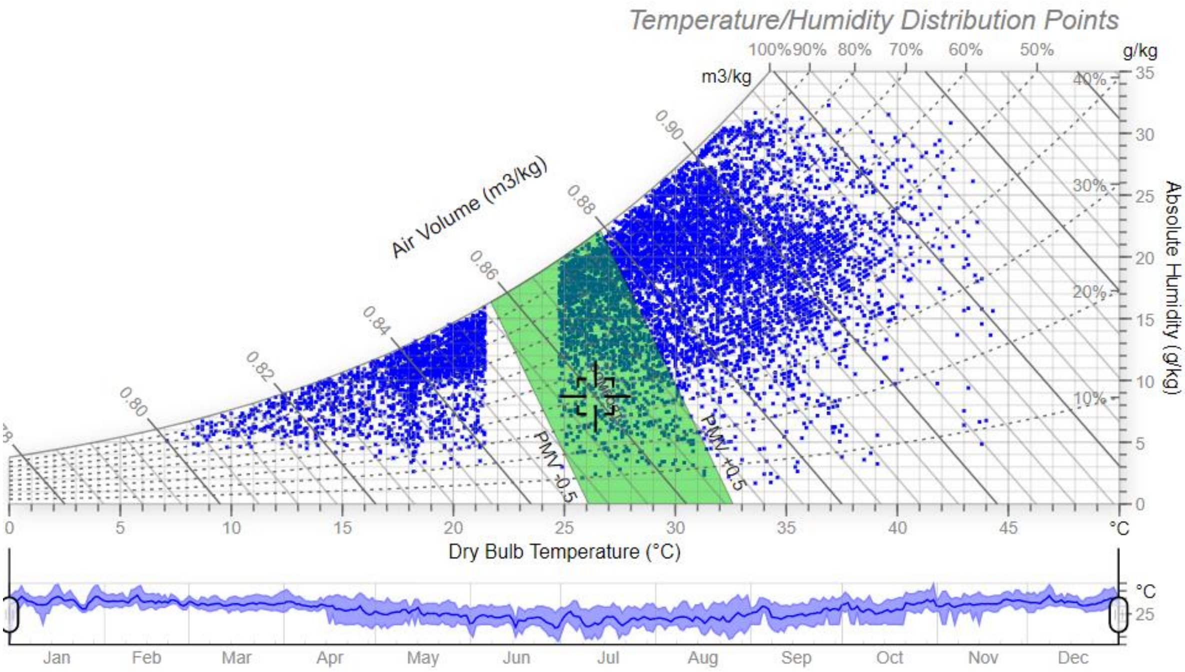


Figure 4.4 Representation of Rockhampton hourly weather data and comfort zone on the psychometric chart.

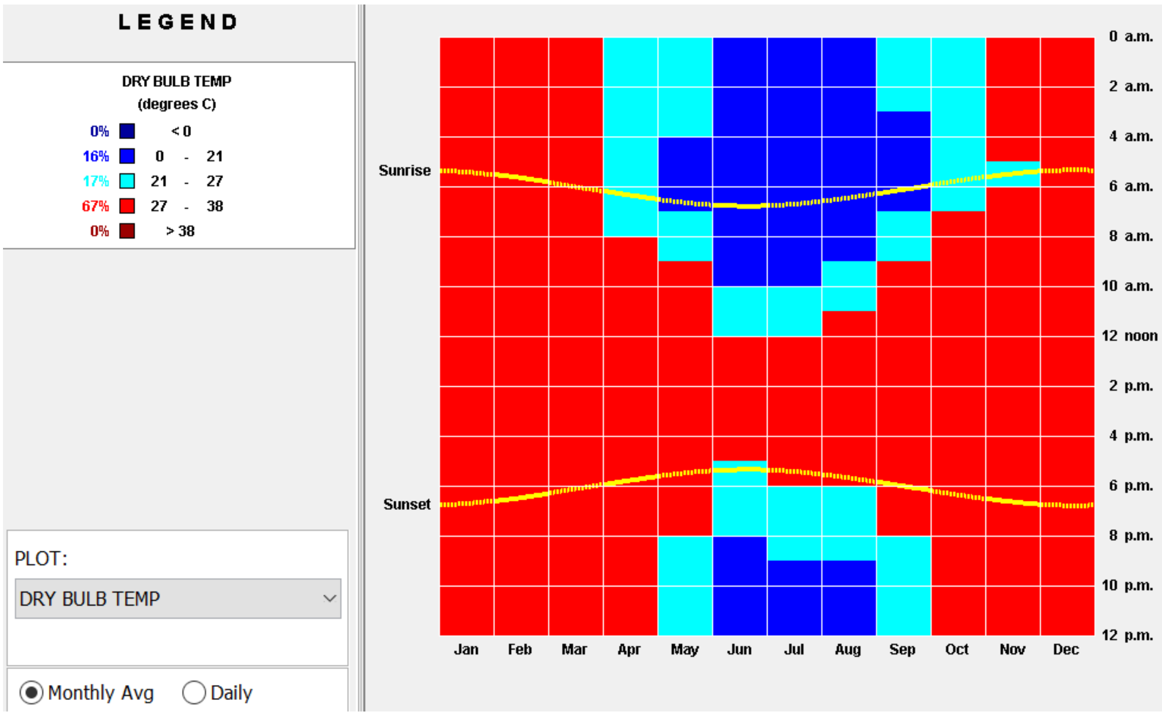


Figure 4.5 Monthly average of external air temperature for Rockhampton.

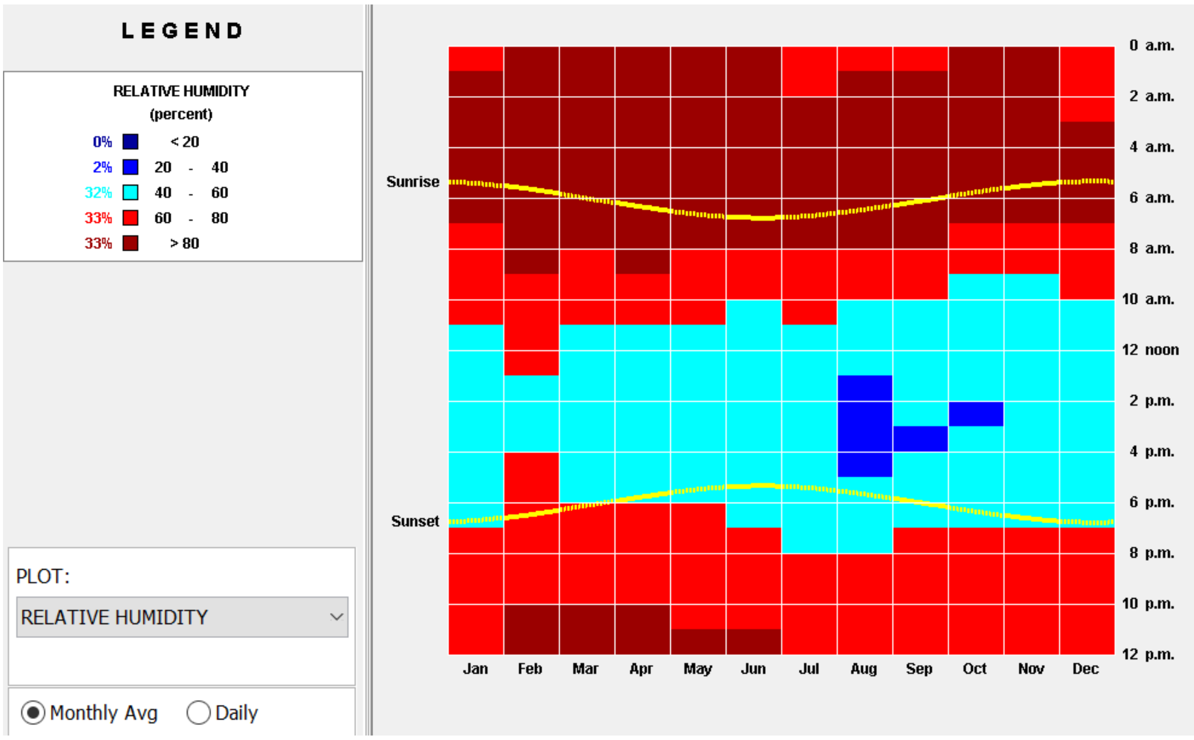


Figure 4.6 Monthly average of relative humidity for Rockhampton.

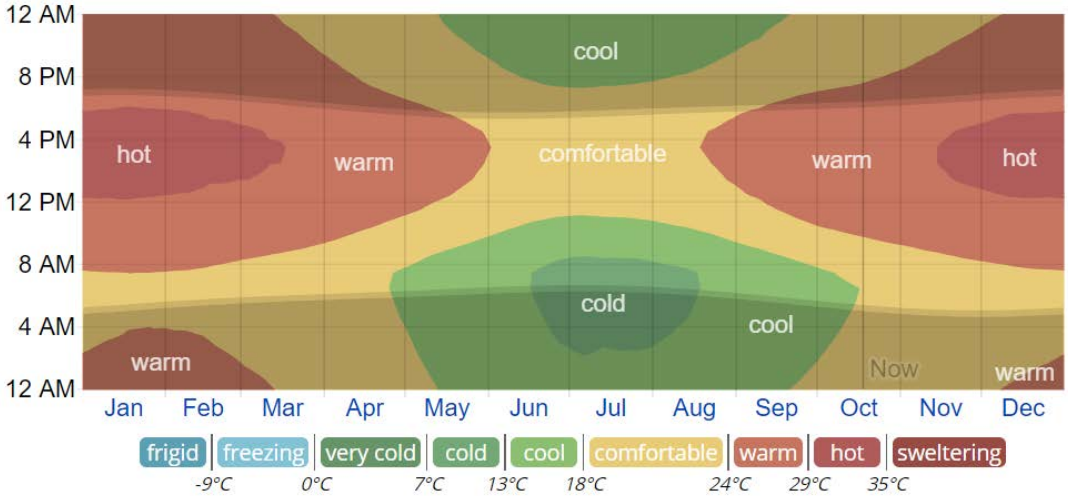


Figure 4.7 Average hourly temperature for Rockhampton.

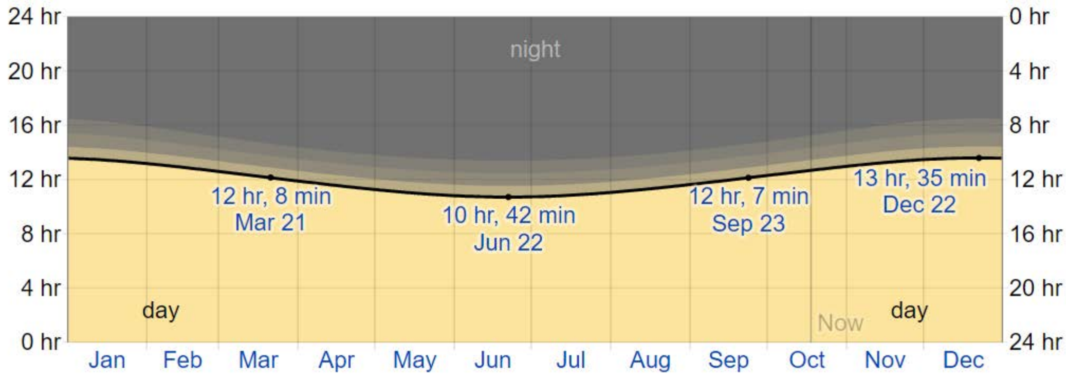


Figure 4.8 Hours of daylight and twilight.

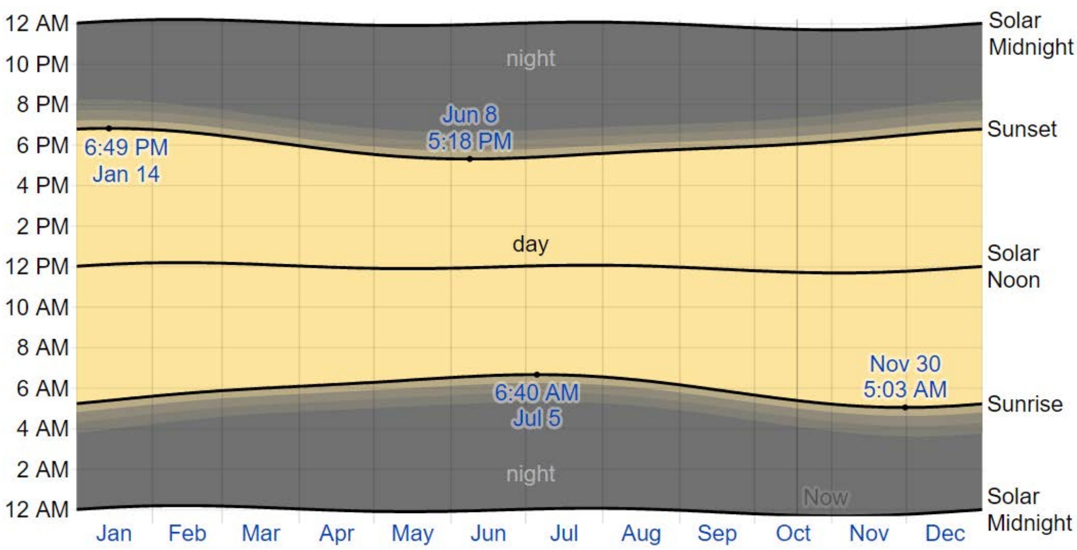


Figure 4.9 Sunrise and sunset with twilight.

It appears from the weather data analysis that Rockhampton suffers from a severe cyclical disparity in the humidity level. Figure 4.10 represents the portion of time invested at different moisture content levels, classified by the dew point temperature. The comfort level could be portrayed based on the information of the dew point. Reduced dew factors offer a dry sensation, and higher dew factors offer a wet sensation, which is unlike temperature, which generally varies significantly between evening as well as day. Dew factor often tends to modify more progressively, whereas the evening may experience a lower temperature.

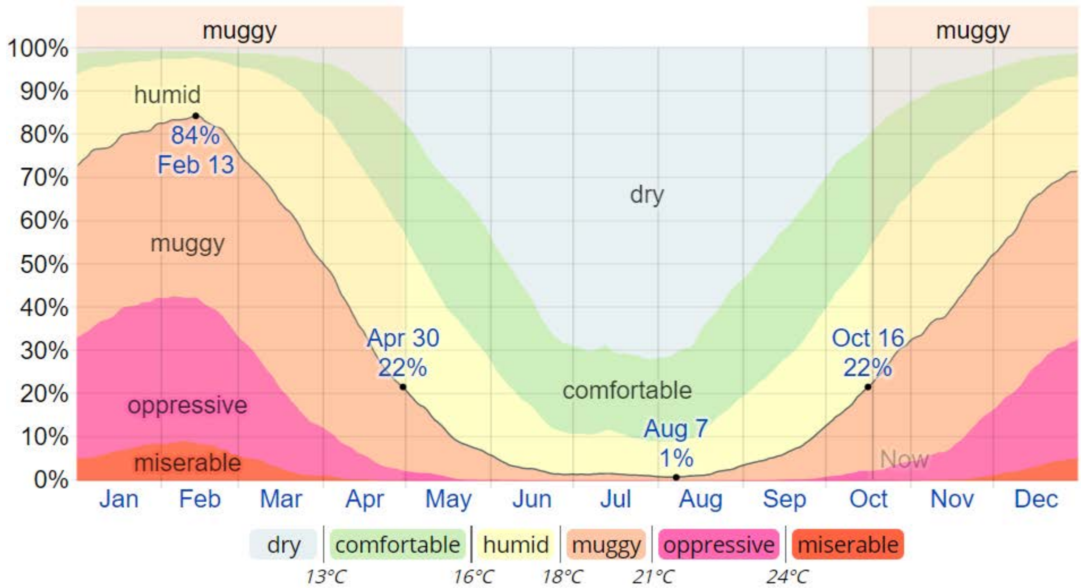


Figure 4.10 Humidity comfort levels.

The Rockhampton climate condition was collected in EnergyPlus EPW format depending on the data received from the Australian National House Energy Rating Scheme (NatHERS). The data in epw format is used in the simulations. HVAC load computations utilise easy worst-case winter season and summer style information from a NatHERS complied weather file. HVAC estimations are completed by considering a sinusoidal curvature through optimum matching and summer season average temperature levels. Figures reveal a generic picture of Rockhampton's weather pattern for the summertime and wintertime. The information consists of outdoor wet-bulb and dry-bulb air temperature, humidity level and heat gain etc. Generic geographical area and weather condition for the selected location are listed in the following section.

Category		Input to simulation engine
Name	:	Rockhampton Airport, Australia
Source	:	ASHRAE/IWEC
Climatic Region	:	4A
Latitude (deg)	:	23.38
Longitude (deg)	:	150.47
Elevation	:	14m
Site orientation	:	3450
Standard Pressure	:	101.2kPa
Start of winter	:	April
End of winter	:	September
Start of summer	:	October
End of summer	:	March

4.4 BUILDING INFORMATION

The selected building is located in Rockhampton, a regional town in Queensland. The building has three levels and fully air-conditioned during the operating hours of the day. The selected building has a common structure made with concrete in lightweight aggregate coated wall surfaces and 10 mm ceiling ceramic tiles. The information used for constructing the model includes, but is not limited to, the structural records, regional environment information, occupancy rate, internal consistent heat sources, component data of air-conditioning and lighting systems. Information and specifications that were not readily available and critical to the modelling are presumed according to building code. A summary of the description of the selected building is included in Table 4.1. The shading effect due to a nearby high-rise building is also considered using the component block features.

4.4.1 Details of HVAC Systems

A number of air-handling units fully serve the three levels of the building. Some of them are independent, and some of them are connected with each other. The air-handling device is composed of a cooling loop, air filter as well as air follower. Treated air by the system is ducted to particular locations. The full path is insulated to protect the heat dissipated from the system. Diffusers from the ceiling are supplied from the wall on the side. Air-handling systems are used to form a wall surface area. Every system has a separate damper, and the arrangements are evaluated with its ability to supply the required air quantity. The air supply is controlled using a time control switch. Each system is managed using a switchable terminal located in each of the thermal zones for after-hours' usages.

4.5 DEVELOPMENT OF THE MODEL

This software-based model considers per hour environmental and operational information to calculate the yearly power usages, and it is performed by first developing the 3D geometric model of the facility. The developed model will help find the values to the heat circulation profile via the external envelope. The effectiveness of the HVAC systems, airflow management related components, lights, and moisture contents could also be tested. Each floor was separated into the designated space layout utilising DB software to comply with the building processes as specified in Siemens control building management system. The power usage in keeping the air-conditioning area temperature level within the comfort limit can be used for evaluating the influence of various thermal effectiveness.

Table 4.1 The features of the modelled building

Building type	:	Office
Size	:	3 storied, nearly rectangular shaped plans with entrance on the ground floor.
Operating Schedule	:	8:00 to 18:00 [5 days/week]
Walls	:	Double Brick Plaster
Roof Ceiling	:	Concrete and Plasterboard
Floor	:	Concrete slab with carpet
Internal Partition	:	Lightweight 2 X 25 mm gypsum plasterboard with 100 mm cavity
Component Block	:	Lightweight concrete block
Thermal Mass Construction	:	130 mm concrete slab
Metabolic Factor	:	0.9
Winter Clothing Insulation	:	1.00 Clo (1 Clo = 0.155 m^2°C/W)
Summer Clothing Insulation	:	0.5 Clo (1 Clo = 0.155 m^2°C/W)
Front Orientation	:	NE
No of Floors	:	4
Windows Width	:	1.5 m
Windows Height	:	1.5 m
Glazing Type	:	Single glazed, clear float ¼ inch with blinds
Occupancy	:	1 person per 10m^2
Outside Air Rate	:	10L/s/person
Lighting Target Luminance	:	320 lux
Infiltration	:	0.3 ach (air change per hour)
Window Shading	:	Blind with high reflective slats
Local Shading Type	:	Overhang and side fins
Lighting Type	:	Compact fluorescent
Lighting Power Density	:	18 W/m^2
Equipment Power Density	:	15 W/m^2
Cooling Type:	:	Air Cooled
Cooling Power Density	:	40 W/m^2
Ventilation Power Density	:	5 W/m^2

The building layout is considered and zoned in a way that the consequences of the variation due to indoor and outdoor environmental parameters can be locally regulated. It is an essential process to offer an ideal comfortable atmosphere noting the temperature level, moisture contents in the indoor space. The effectiveness of the building envelope affects the transmission, radiation or convection-based heat transfer capability of the indoor space with the outer atmosphere. The energy use in providing the required cooling set point temperature within the comfort level could be considered for analysing the impact of different thermal efficiency.

The skeleton of the model has five steps. There are Site, Structure, Zone, Area, and Exterior area information. Blocks in the building are standard geometric forms which are adapted to construct a three-dimensional design that is analogous to constructing an actual design using blocks. Elemental blocks are included around the building structure to establish the zones that won't be served by the building system. The elemental blocks also act as shading structures that do not count in the cooling load calculation and are not a component of the real building. In Figure 4.11, the external covering of the building in the model is comprised of elements, for instance, wall surfaces, floor pieces and roof coverings, and are separated inside to configure the thermal zones of the building systems.

Two-dimensional format of building CAD geometry is introduced into the DesignBuilder model platform for the blocks to be traced back as well as reconstruct the modelled space with divider panels. Initially, the model was developed in WCS and then revolved 340 degrees to match the Azimuth angle depending on the physical orientation of the building. Modelled illustration of the structure is displayed in Figure 4.11. The partition panels of the location limit thermal areas and were designed as per the locations specified in the BMS portal and are shown in Figures 4.12 to 4.14. The algorithm uses the thermal qualities of the buildings for every wall surface area, floor, roofing system, divider panel etc. in each area along with the thermal mass calculated in the whole building simulations.

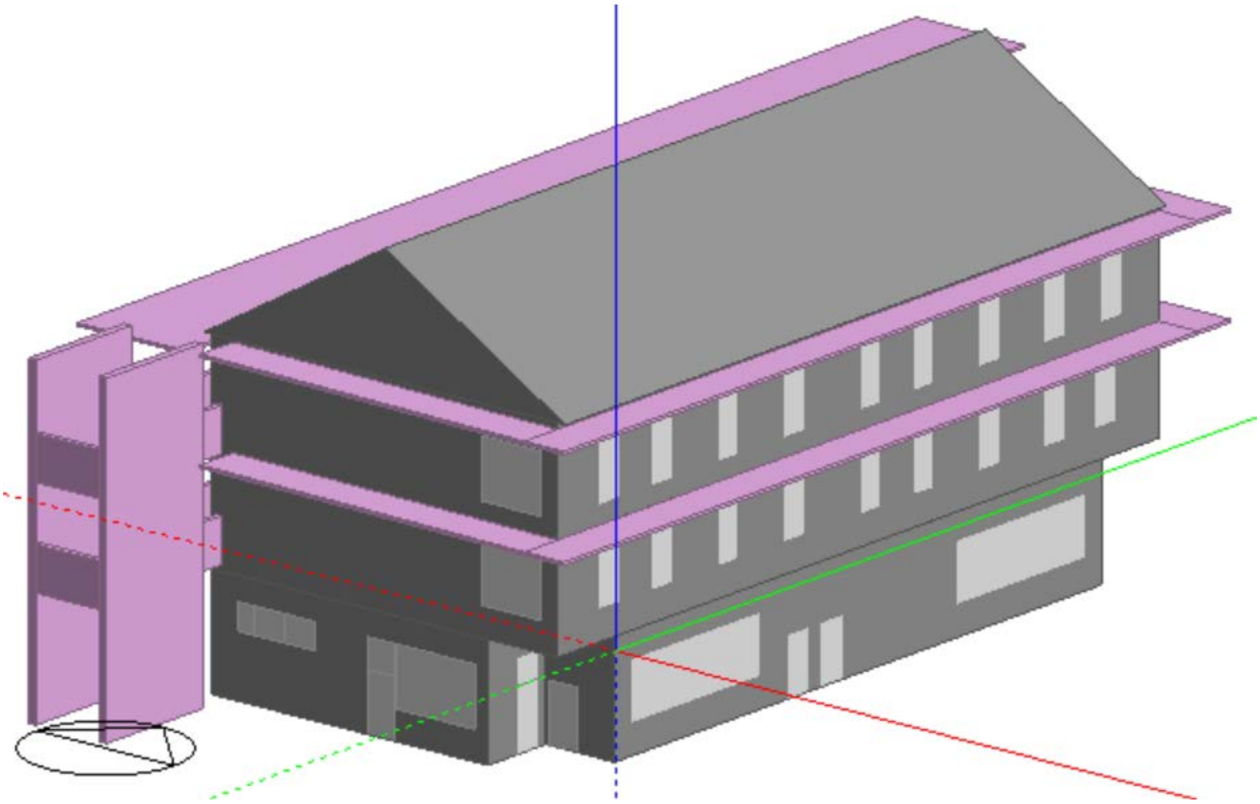


Figure 4.11 Geometric representation of the building.

4.6 OVERALL APPROACH IN MODELLING AND SIMULATION

The attributes presented in the narrative of the building are the main factors considered when forming the physical model in the software. In DesignBuilder, the time steps assigned in the simulation are the time steps required for the thermal network to be resolved. When the heating and cooling section of the simulation starts, it utilises the fundamental time action as its maximum yet after that can lower the time action, as needed, to obtain the remedy. Per hour information (for instance, outside surroundings as revealed by climate data) is inserted to the time steps section assigned to the zone. The combination of temperature value and cooling loads represent the optimum distinction between the subsequent variants before a converged resolution is derived. Depending on the cooling loads and /or zone setpoint temperature criteria are met, a convergence of the synchronised heat equilibrium is contacted for the HVAC services. Both resistances function in a similar way; one resistance examines the temperature levels, and the other resistance examines the relevant cooling loads. On completion of the first iteration, the algorithm measures up the highest warmth felt in the indoor space along with the incoming ideal temperature received on or after the prior time slot. The information then conveyed to the 2nd check-up, if the existing simulation value, as well as the previous time values, are within the limit assigned for the zone. A comparable contrast is highlighted along with the cooling load. The simulation has passed the third, fourth and subsequent inspection if each of them is actually within the approved limit. The process remains in the loop up while waiting for the remaining examinations to complete.

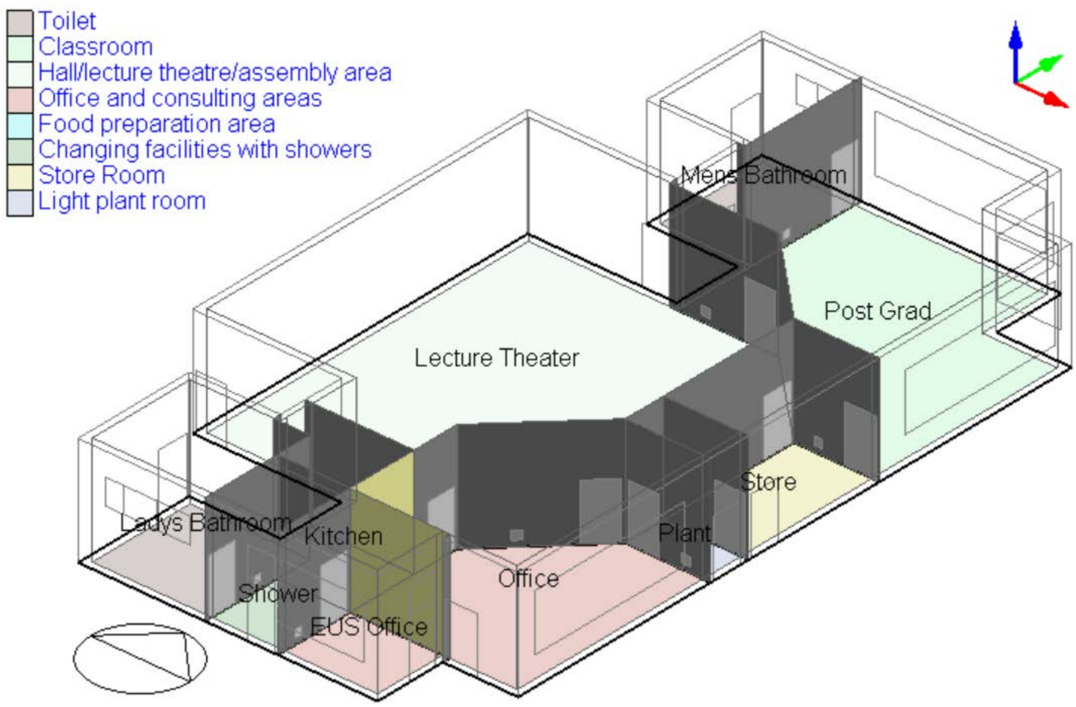


Figure 4.12 Representation of the thermal modelling zones (ground floor).

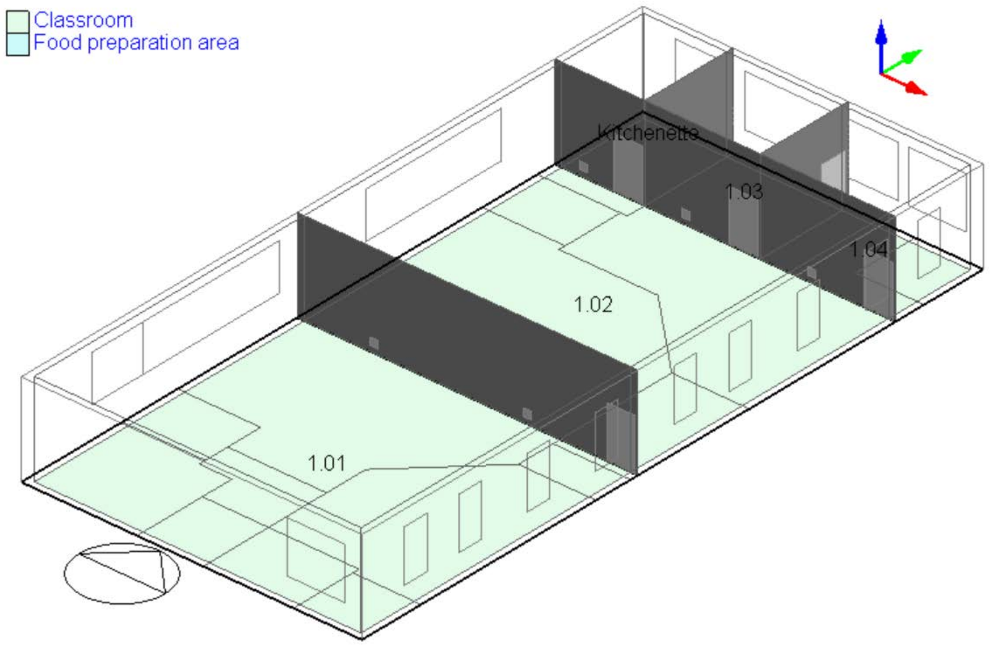


Figure 4.13 Representation of the thermal modelling zones (first floor)

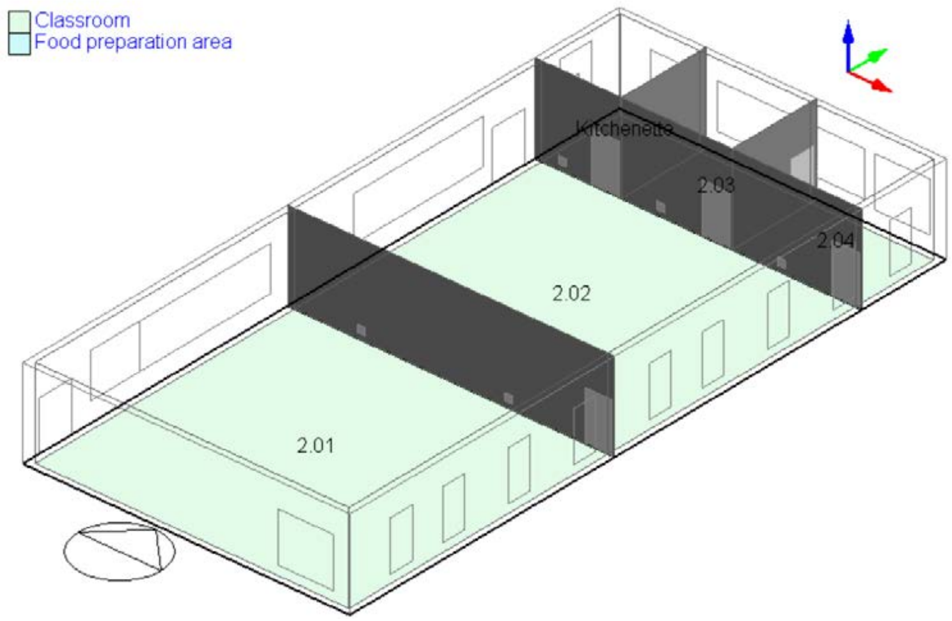


Figure 4.14 Representation of the thermal modelling zones (second floor)

4.7 DESIGN CALCULATION FOR AIR CONDITIONING UNITS

The design to identify the cooling and heating capacity estimations utilise the severest winter month and summer month data from the historical weather record. EnergyPlus algorithm assumes that the indoor warmth in a thermal block is totally blended and consistent throughout the block. The environment details used in both summer and winter months are the highest and lowest outdoor atmospheric temperature, outdoor saturation temperature, wind velocity, air pressure, direct solar average and diffusive solar radiation tec.

Figure 4.15 represents a summary of the weather data used in this study. The computations were accomplished to calculate the dimension and capacity of heating and cooling devices needed to fulfil the cooling and heating requirements of severest winter months and summer months likely to occur in the selected location. The estimated capacity of the air conditioning system was performed by positioning a sinusoid mathematical curve along with the highest temperature for both day and night available in the historical weather data. The day-to-day temperature value needed for the computation of the cooling load was attempted depending on the minimal and optimal temperature in the historical weather record. It additionally presumes the highest warmth level delays the greatest sunlight altitude through three hours. Surface heat reduction information defines comfort transmission from the territory to the inner structural components. Central space heating system estimates predicted warmth reduction of each place at continual condition without solar heat gain taking into consideration of extreme wintertime weather condition of the selected region.

The heating requirement is determined depending on the overall total heat loss of the indoor space. The loss phenomena happen through the surface area of instance, walls, ceilings, and floors. Estimation of heating requirements forecasts the heat energy reduction in the precinct of the establishment without any addition of solar radiation. The calculation was performed depending on the extreme season weather record. The cooling estimation was based upon streamlined sinusoidal worst-case summer month.

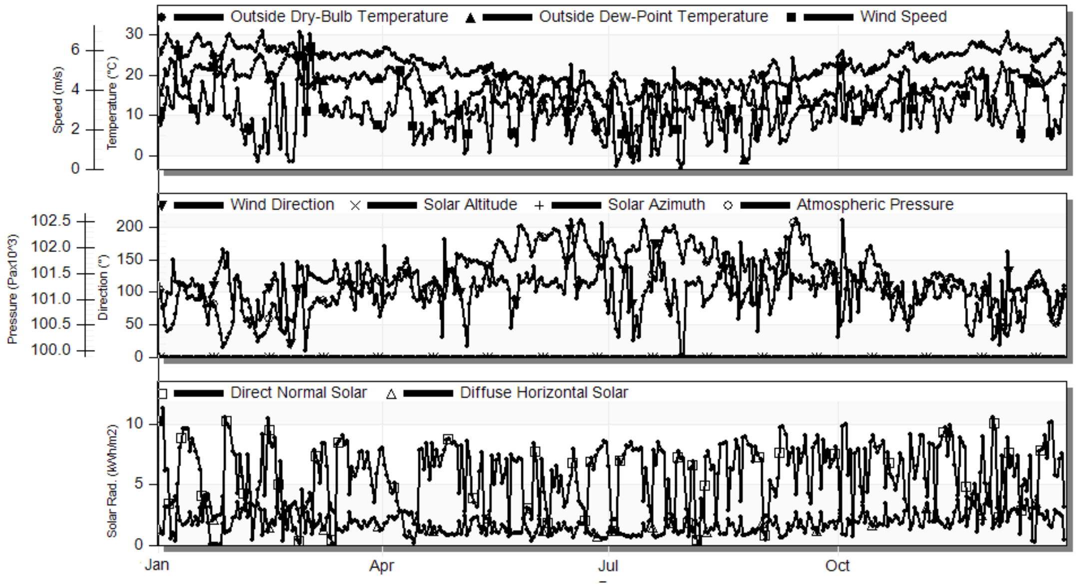


Figure 4.15 Summary of the weather in Rockhampton

The Estimation of heating design is displayed in Figure 4.16 and highlights heat gain and losses throughout the building envelope and sensible heating values. The cooling estimation details are displayed in Figure 4.17. Heat gain and losses due to office equipment, lights, and external building facade are shown in Figures 4.18 and 4.19. The solutions show that the interior setpoint temperature of 23 ºC is maintained in the thermal zones by using the HVAC systems of the building that also represent the conformity of the zonal air temperature satisfying the comfort criterion.

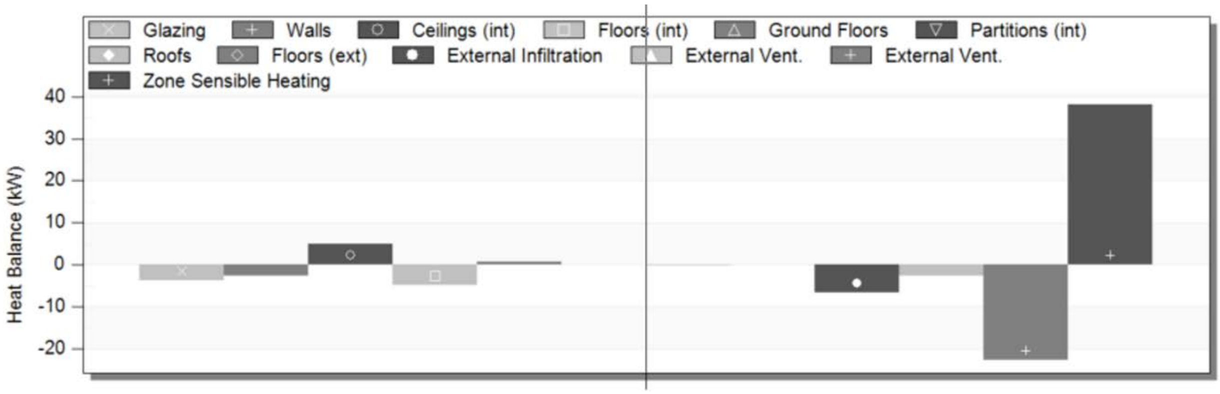


Figure 4.16 Summary of the heat balance

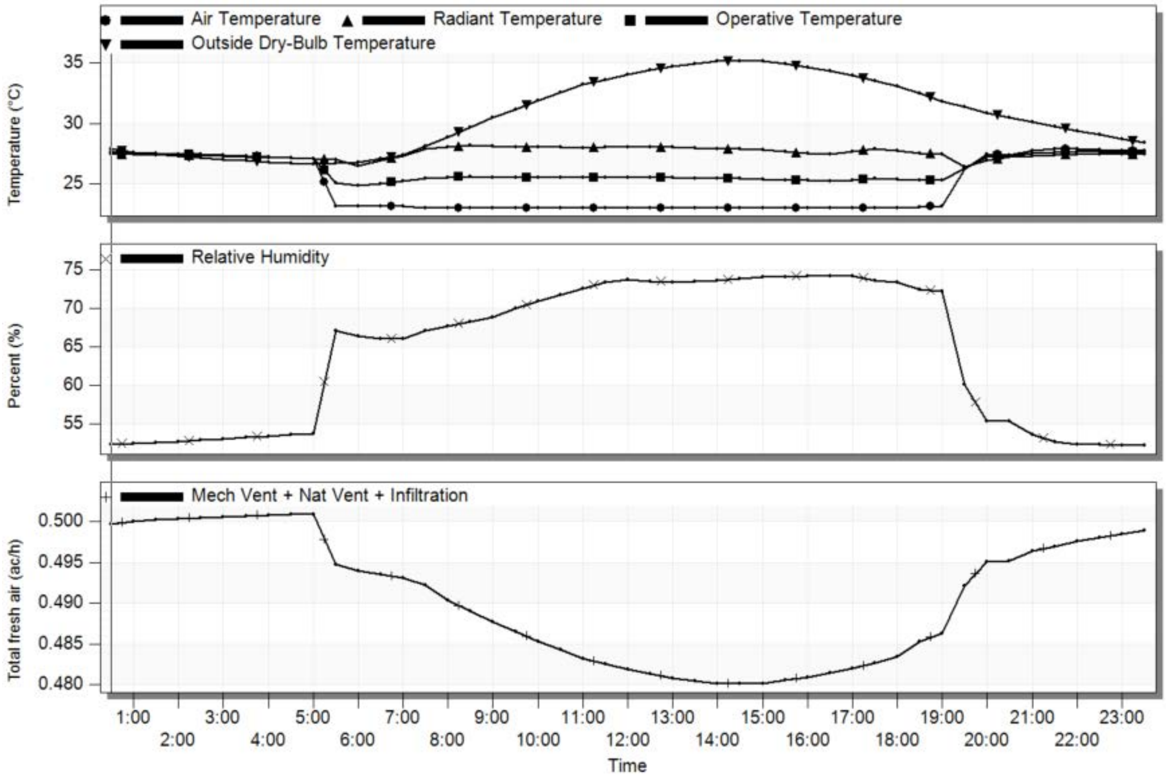


Figure 4.17 Outline of cooling design estimate.

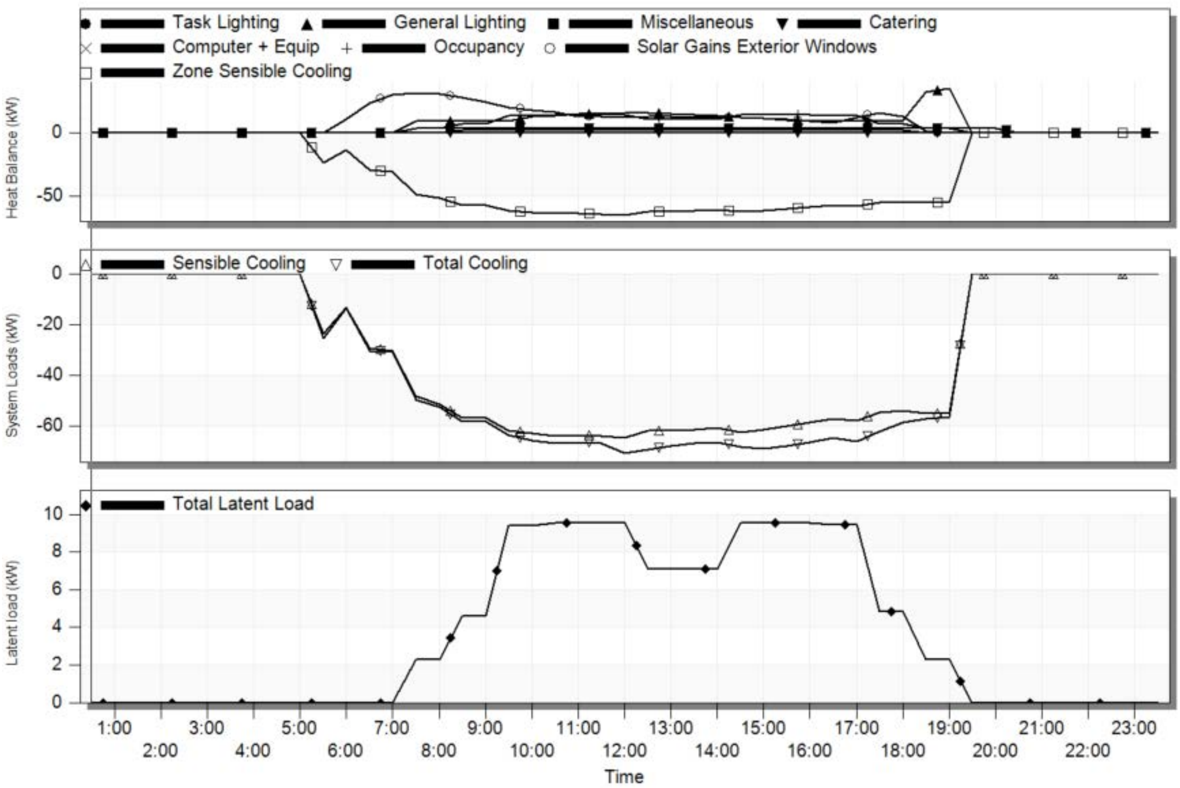


Figure 4.18 Heat gain and losses in cooling estimate.

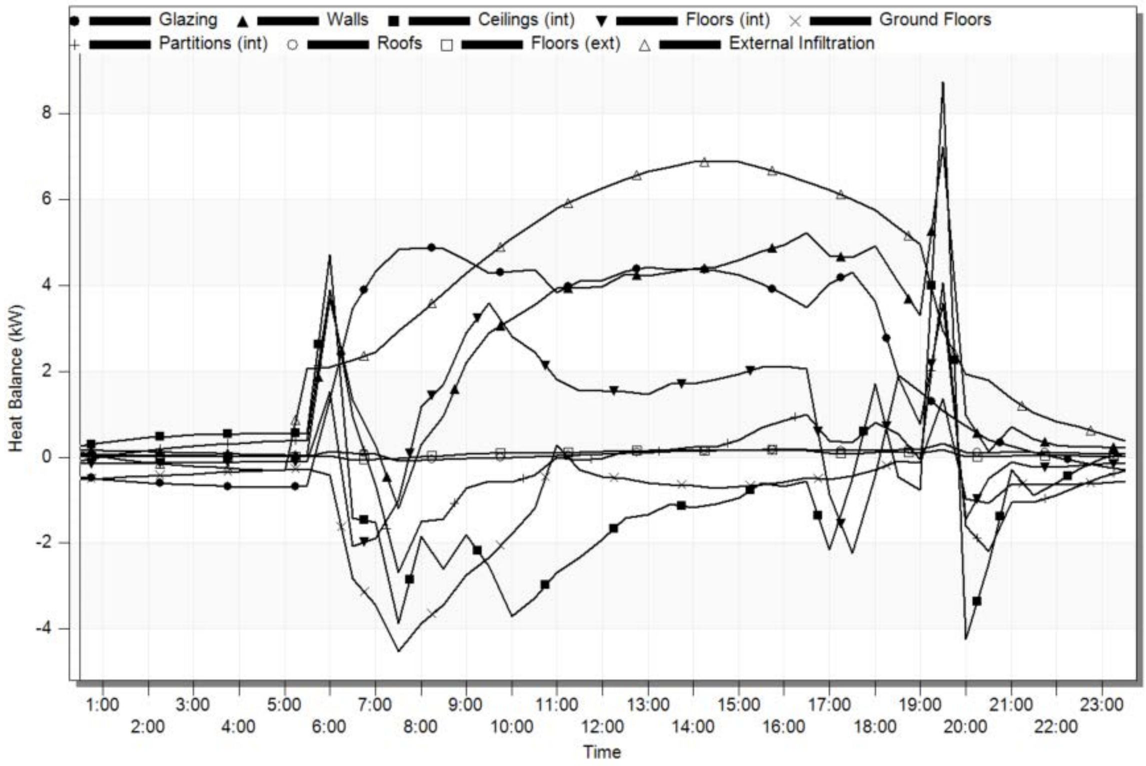


Figure 4.19 Heat balance via ventilation and envelope in cooling design.

4.8 INTERNAL HEAT GAIN

The internal heat gains occur from occupancy, computer, office tools, light gains and so on. The operational schedule is outlined according to the beginning and end time of a weekday seasonally adjusted. From time to time, the cooling load profile for a single zone is taken as a standard for a particular block and even for the whole building. When describing inner load for comfort calculation using the algorithm; building dimension, ventilation technique and daylighting are additionally quantified. The HVAC methods are specified utilising equipment summaries interface, which is translated to EnergyPlus for detailed analysis. The HVAC equipment capability of a single thermal zone is calculated based on the cooling and heating estimations performed in the previous phase. For this instance, the occupied routine setup made use of internal gains and/or AC units by specifying the component specifications. In the simulation, the space usages schedule is managed through the setup option for each of the area. The heat increases due to metabolic change in the area and is enhanced based on the occupancy and activity specified in the model. The electrical illuminations in the functional place are organised depending on the schedule of the usual daytime. When lighting up management is switched on, luminosity levels are computed based on the defined activity schedule during the course of the simulation.

In the simulation, luminosity is calculated for as high as two areas in every block. Luminosity related variables were provided wherever needed by the lightings. When illumination level is amended, a specific sensing unit observer the daytime lighting by the sensing unit area that is considered the centre of the area and controls the lighting in the zone. Figure 4.20 and Figure 4.21 represent heat gain in indoor space in a typical week during summertime and wintertime in the case study building.

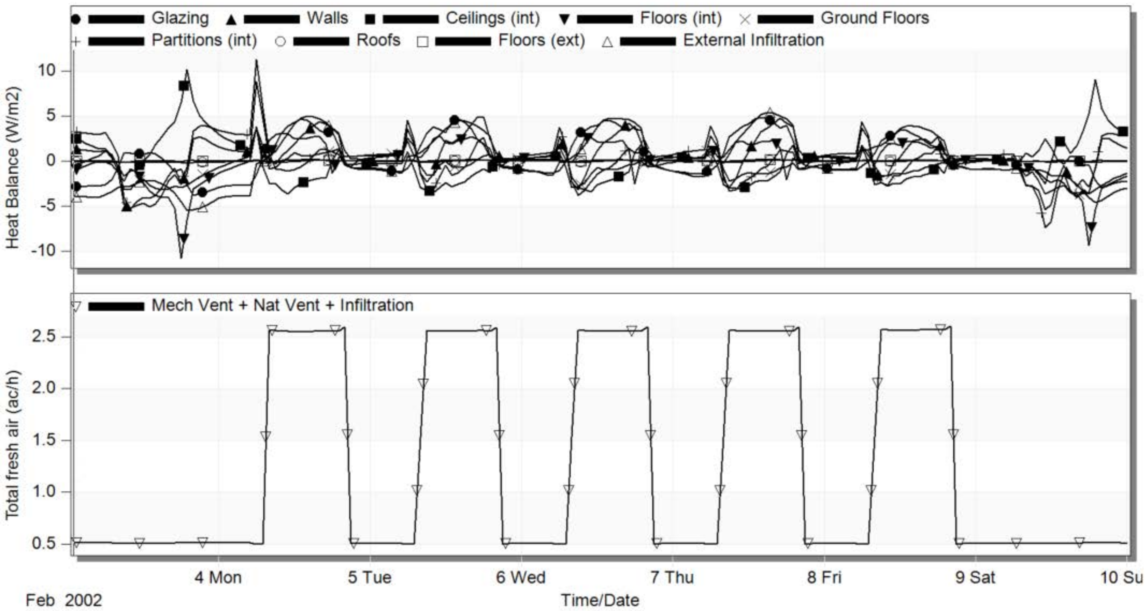


Figure 4.20 Indoor heat balance during the summer representative week.

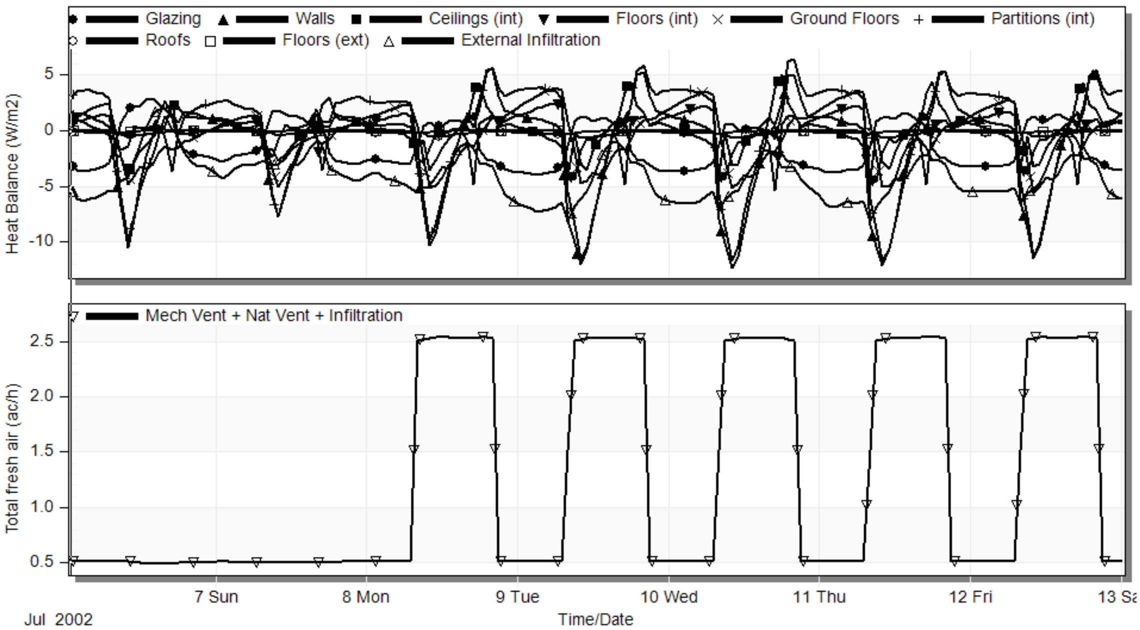


Figure 4.21 Indoor heat balance during the winter representative week.

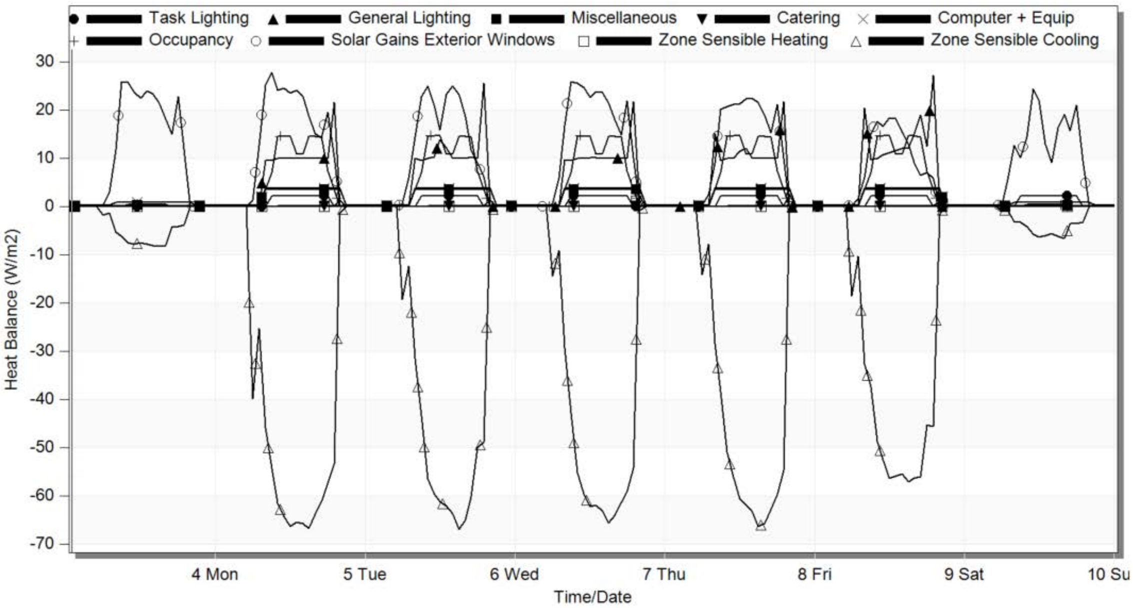


Figure 4.22 Indoor heat balance and cooling load in the representative summer week

The positionings of illuminance sensing units are examined individually in every block to acquire precise outcomes. In the simulation, if the requirement is to ensure required luminosity in one location, there is no control in place for the area. If another lightings region is set up in an area, the second illumination area is designated individually, and the portion of the region dealt with lighting requirement accordingly. The heat gains in the indoor area as a result of lighting, tenancy, transmitted solar warmth, computer system and other workplace devices are revealed on a per hour basis in Figures 4.22 and 4.23 for the representative winter and summer week. The highest possible gain results from the solar radiation during summer and winter. The next big heat gains are from the individuals in the space and the office equipment, lighting etc.

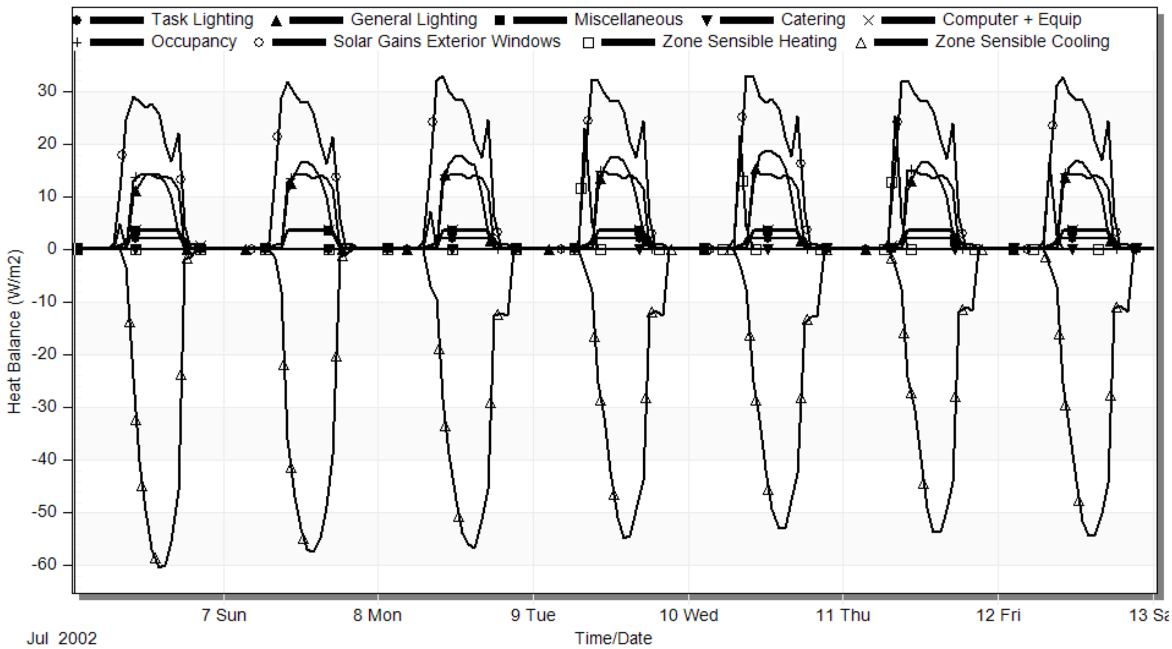


Figure 4.23 Indoor heat balance and cooling load in the representative winter week.

The air-conditioner need throughout the day continues to be the same along with an exemption at the beginning of the day. Simulation outcomes demonstrate that the cooling energy demand is nearly one-third in cold weather in contrast to summer months. Inner heat gain during the start of the day and late at night is almost minimal. The heat gain via building envelope and ventilation in both the winter and summer representative period are shown in the graph. These results reveal the losses of heat due to varnishing, wall surfaces, roof coverings, and external infiltration relevant to the air change per hour to the zone. The similar phenomenon is also observed due to interior floor covering as well as outdoor. The maximum heat energy deficits and acquires are from windows and fresh air intake within the zone.

4.9 ANALYSIS OF COMFORT

The space utilisation statistics indicate the variety of individuals and the occupied hours. This information remains expended in addition to the metabolic value to regulate the heat gain in the occupied space. In this study, a regular workday timetable is used to regulate interior gains and/or AC systems throughout the year. The busy times are controlled by a timetable when the selection is made in the building management system. The rate of metabolic change (either increased or decreased) in every single zone in the simulation is based on the activity. The simulation produces a complete record of indoor environmental condition and comfort level. Figures 4.24 and 4.25 show details of the interior temperature, moisture, people comfort index in winter and summer. It is very well-defined from the images that the temperature and humidity level take part in a significant role in maintaining comfort in the indoor space.

The temperature stayed within 23 °C, and the humidity was within 75% during summer. The discomfort values stay almost zero in wintertime and virtually insignificant in the summertime. In this study, the existing interior comfort parameters and indoor thermal comfort are evaluated. The comfort values are evaluated against the set criteria specified in the literature and are in agreement with the reported values in the comfort standard from ASHRAE. Additional thermal comfort indices were measured, Fanger PMV is found to be within ±0.5 range. Pierce PMV ET and Pierce SET values are a little over ±0.5 range; however, the value is below 1.0, which is not very warm.

4.10 ENERGY PERFORMANCE

The compact AC system information is applied for conducting the modelling and performance simulation of the mechanical systems assigned at the block and zone level. A unitary multi-zone system is adopted in the system at the building level and allowed to operate as per the schedule. The thermal performance simulation was performed according to the comprehensive details inputted from the building manual. A constant volume DX system within a unitary multi-zone system was configured within the building. In the simulation, the main cooling and heating operations are performed by utilising relevant cooling coils and air-handling units for individual areas as per the thermal zone formed in the model. The circulation of air is maintained ensuring that the minimum ventilation rate is maintained (DesignBuilder, 2018).

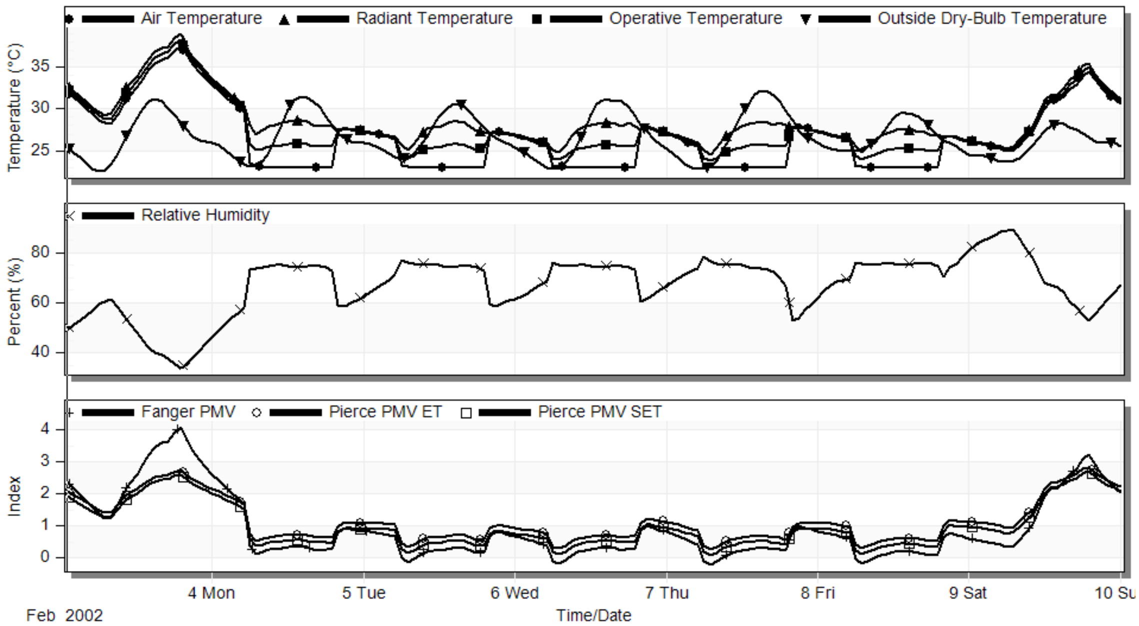


Figure 4.24 Outline of the simulated comfort in summer week.

The thermostat is positioned in the zone and block and defined using thermostatic command zone for the constant volume DX system in the simulation. The temperature positioning is developed in a region as though it indicates the temperature level for the entire property; otherwise, some areas are likely to appear incorrectly overrated or underrated. Only one 'unitary multi-zone device' is outlined for all the areas, which is a member of the central unit. The thermostat placement is established in a zone as though it shows depictive warmth for the entire building; or else some area will certainly come to be over/under heated/cooled. In this simulation, only a constant volume DX system is assigned at the building, which is extended to the server the multizonal thermal area as specified in the building layout.

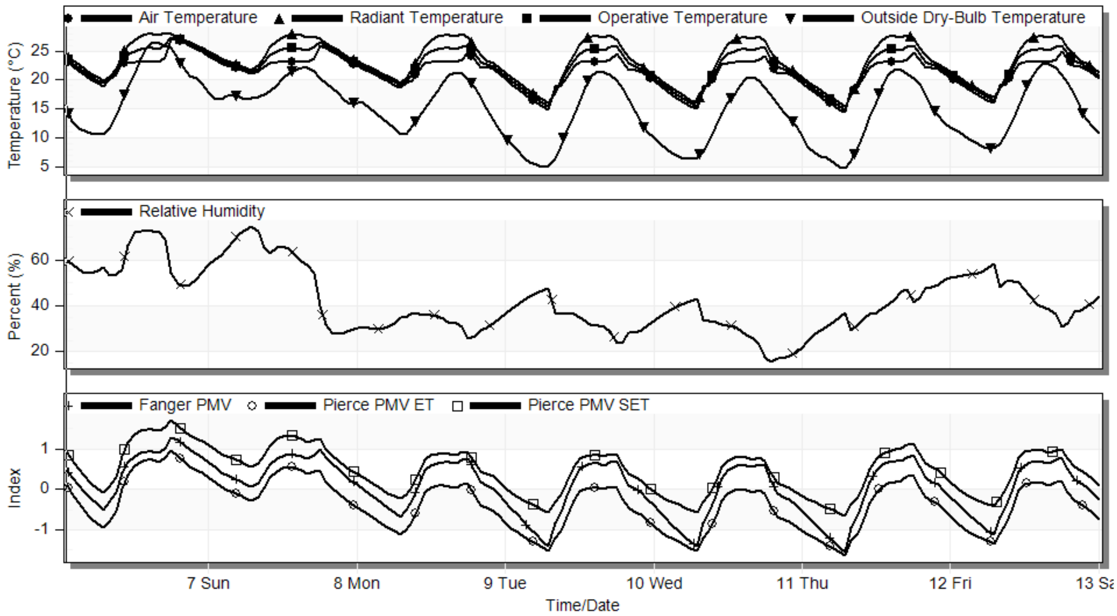


Figure 4.25 Outline of the simulated comfort in winter week.

The air-conditioning capability is determined by design through the outcome of the cooling estimate performed in the previous stage of the simulation. The Coefficient of Performance of the Chiller is utilised to determine the power consumption demanded to comply with the cooling requirement. It works with the overall effectiveness of the chiller, taking into account all systems and sub-systems associated with the appropriate operation of the chillers. Chiller Coefficient of Performance was assigned in the system so that it is reflected in the whole building simulation process. The heat loss through the circulation of chilled water is accounted for and repurposed to improve the air-conditioning before the estimation of chiller energy usage is performed.

The whole building simulation to calculate the energy performance was executed depending on the per hour historical weather station composite data for Rockhampton. Building systems efficiency for the whole year (with greater attention on the selected summertime and wintertime) was reviewed to inspect the overall performance of building systems. The outcome of the simulation helps to understand the overall operational method of the HVAC and other systems and the impact of the weather on those systems as shown in Figures 4.26 to 4.29. No considerable occupancy and inner heat gain was noticed in the building during vacation and weekends.

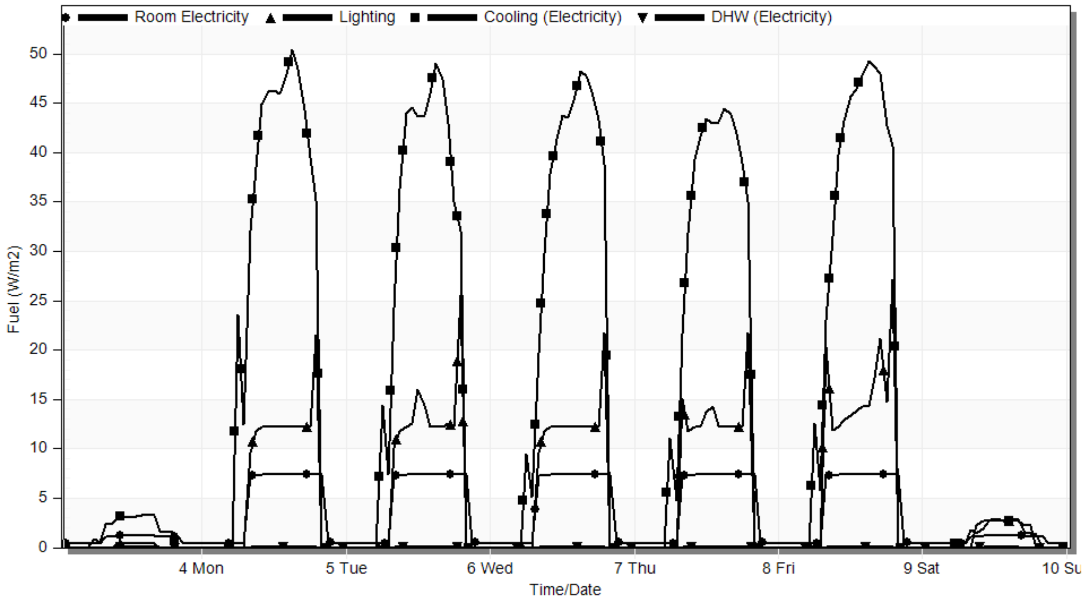


Figure 4.26 Electrical energy usage breakdown in a summer week.

Figures 4.26 and 4.27 represent the electricity consumption for cooling, lighting, plug load and hot water supply in both summer and winter months. The most significant air-conditioning energy demand is in summer at the beginning of the day, which varies between 45 to 53 Wh/sqm. The energy demand is considerably less during the winter week, which will change between 22 to 44 Wh/sqm. The trend is generally consistent throughout the year. By means of the curve fitting technique, it is likely to calculate the standardised energy utilisation profile on a regular basis.

The simulation results suggest that the everyday electricity intake of the building differs from 65 Wh/sqm to 76 Wh/sqm in summer and from 46 Wh/sqm to 64 Wh/sqm in winter as shown in Figures 4.28 and 4.29. Due to the interior heat increase and outside air temperature, it is generally comparable to the property cooling demand. When the exterior temperature level is high, it can always be determined that the power usage climbs throughout the summer season months (December to February). During the course of winter, the usage is reasonably decreased, and the variant of electrical power intake follows and can be recognised generally to interior comfort increase by lights, office devices and people.

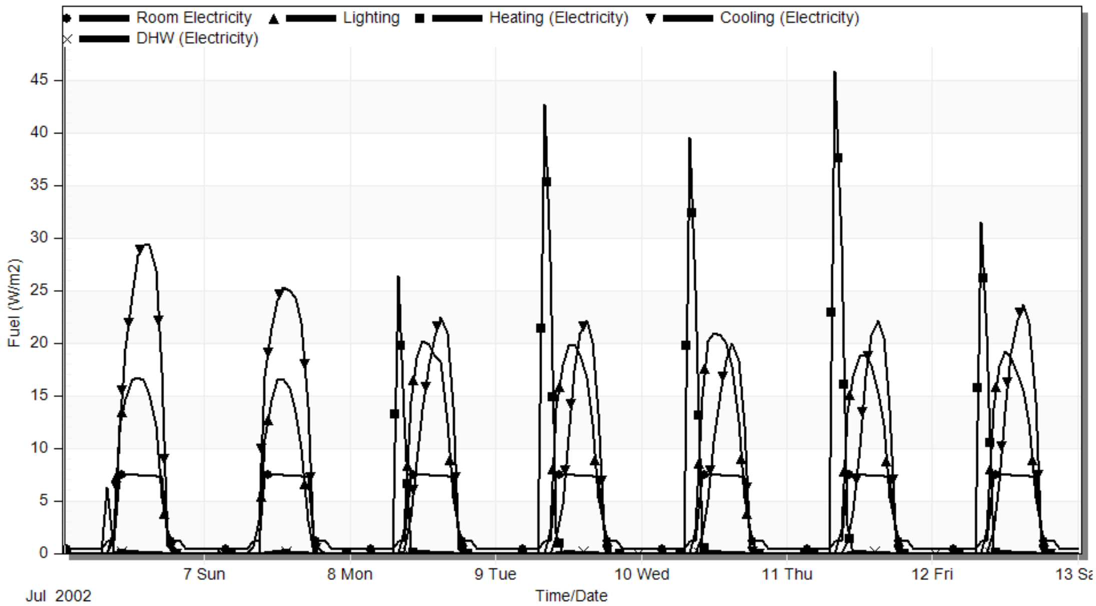


Figure 4.27 Electrical energy usage breakdown in a winter week.

4.11 RESULTS VALIDATION

The results derived from the modelling of the building system is validated following the summary of validation processes of building energy simulation results suggested in the ASHRAE Handbook of Fundamentals (2019). The handbook recommended the evaluation method to define modelling errors for financial cost savings confirmation (IPMVP, 2012; ASHRAE, 2012). Depending on the standards, the processes stated in Figure 4.30 complied to validate the outcome of modelling and simulation derived using DesignBuilder and Energy Plus simulation engine.

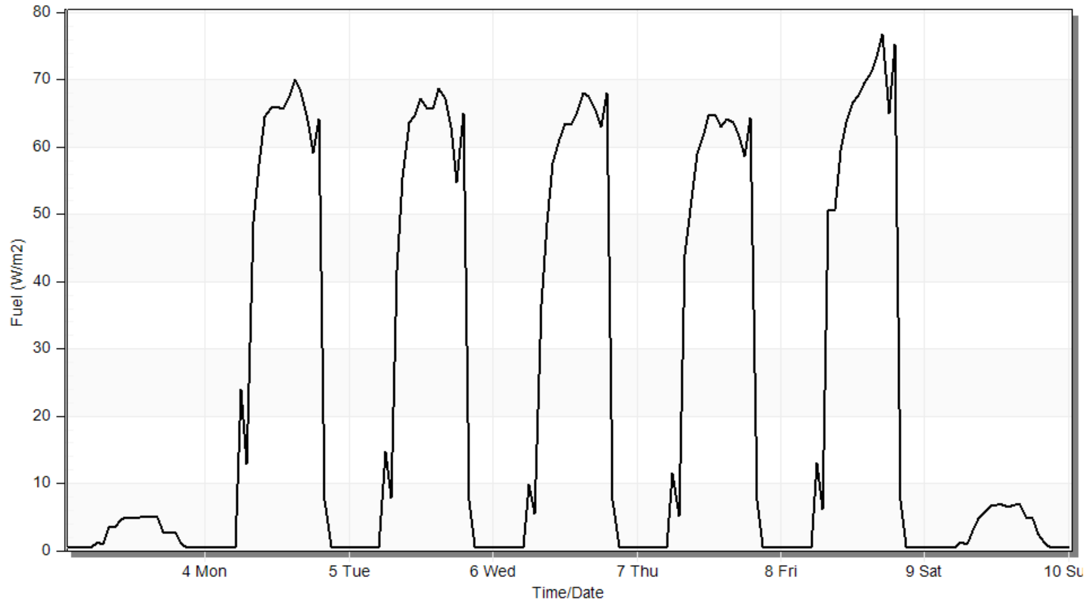


Figure 4.28 Hourly total electrical energy usage in summer

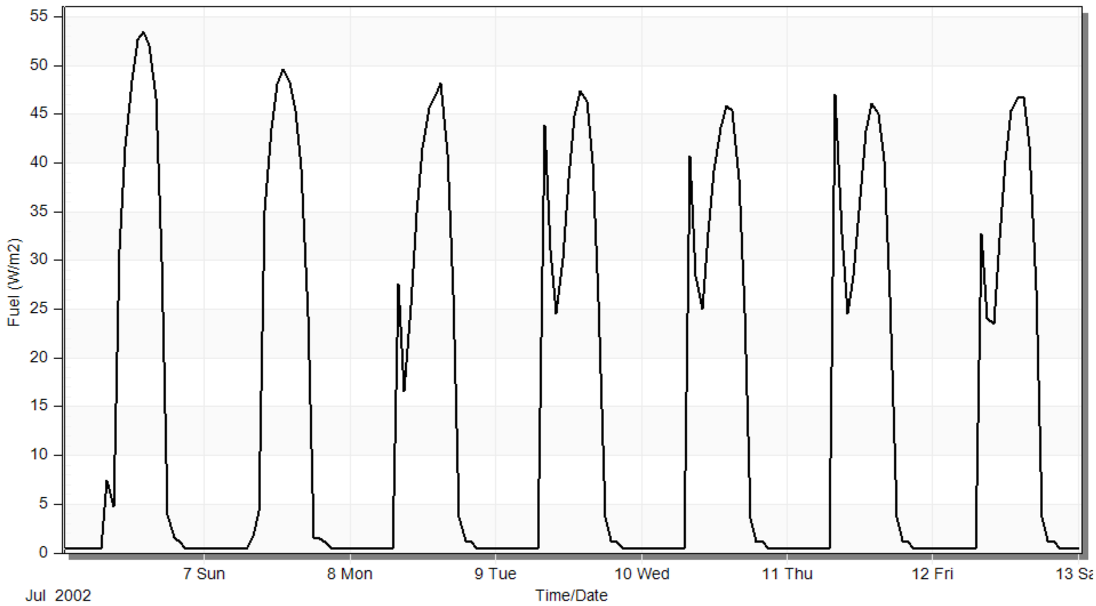


Figure 4.29 Hourly total electrical energy usage in winter week

Official independent evaluation throughout the development processes as well as based on the published results for analytical, empirical and comparative approaches verified the mathematical formula of EP. The key focus is on a comparative and systematic evaluation of the results. Relative examination of simple protocols has been fulfilled by making use of the ASHRAE Handbook of Fundamentals (2019) for the selected building. EP outcomes are contrasted against reference records for a wide array of programs supplied with ASHRAE Standard 140. The evaluation demonstrated that Energy Plus shows an excellent agreement along with other simulation programs including DesignBuilder, BLAST, TRNSYS, DOE -2, ESP etc. The latest edition of EnergyPlus results has matched a range of air-conditioning specifications as pointed out in a diagnosis strategy. The ability of EnergyPlus to compute cooling loads, applicable power intake etc. agreed within 1% of the analytical outcomes (Energy Plus Documentation, 2019).

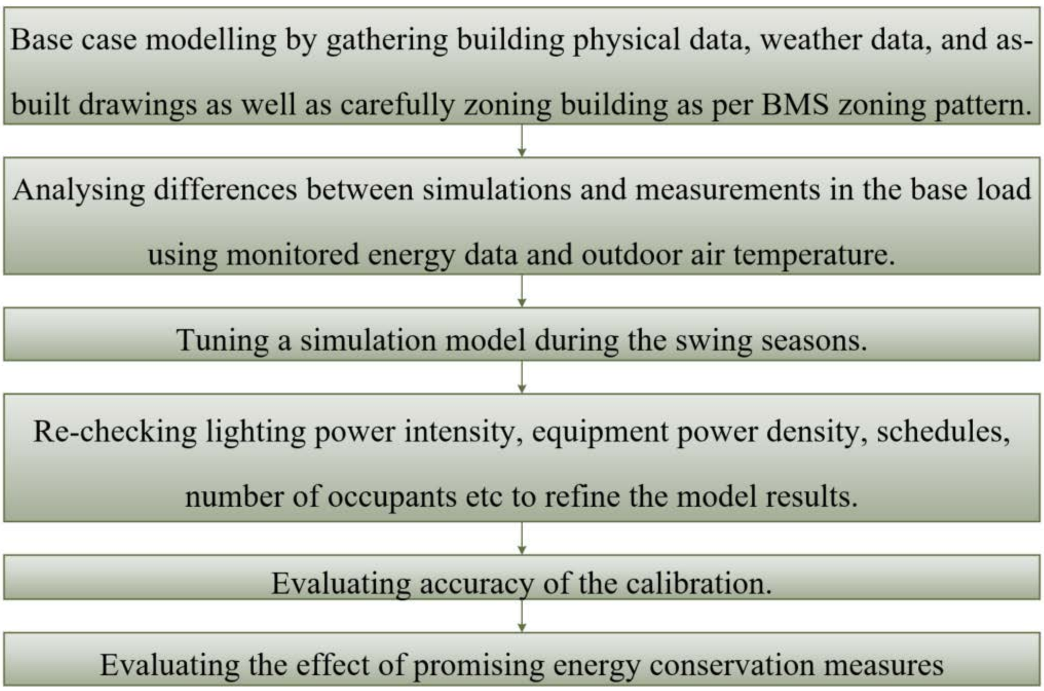


Figure 4.30 Calibration process of the modelled results.

The credibility of the findings of computational analysis hinges on the superiority of the algorithm adopted, simplification and assumptions made in the process. The outcome of the simulation of human comfort in the indoor space is composed of air temperature, humidity, as well as the comfort index. HOBO H8 are utilised to record the indoor air temperature and relative humidity in the designated airconditioned area of the building. The recorded data confirm the accurateness of the simulation results, consisting of the control specification and interior temperature. To validate the building performance simulation base model, temperature and moisture data were obtained from the data logger, and power usage was collected from the smart meters This information includes dry-bulb atmospheric temperature, humidity, and power intake by various systems and sub-systems.

From the temperature records, a sample day hourly data was considered to compare to the 24hr day simulation results. The measure and simulated temperature values in summer are recorded in Figure 4.31. The results show that the system consistently maintains 23 ºC temperature throughout the zone, which a good testimony of the simulation algorithms' ability to model the actual comfort condition of the space. The result is objectively constant in the occupied space throughout the summer season. The modelled profile of the temperature shows that the indoor air temperature is comparatively above average at the beginning of the day since inadequate ventilation maintained throughout the non-operational period of the AC system. Comparison of the results shows that the model predicted temperature profile continues in a comparable trend to the logged data of the temperature in summer and winter.

The air temperature is not fairly consistent with the setpoint temperature at the start of the day during the winter season due to the large internal and external temperature difference (Figure 4.32). The temperature is alleviated slowly while the heating system and internal gains started to function later in the day. The differences between the simulated and measured temperature are around 5.5% for summer and winter days, which is statistically very significant. The simulated and measured temperature values are in good agreement between 12:00 pm and 5:00 pm. The temperature profile produced by the model varied slightly with the measured value during the morning due for the elevated heat intake from the internal sources at the beginning of the day. The variance is decreased progressively once the HVAC system commencements in the morning.

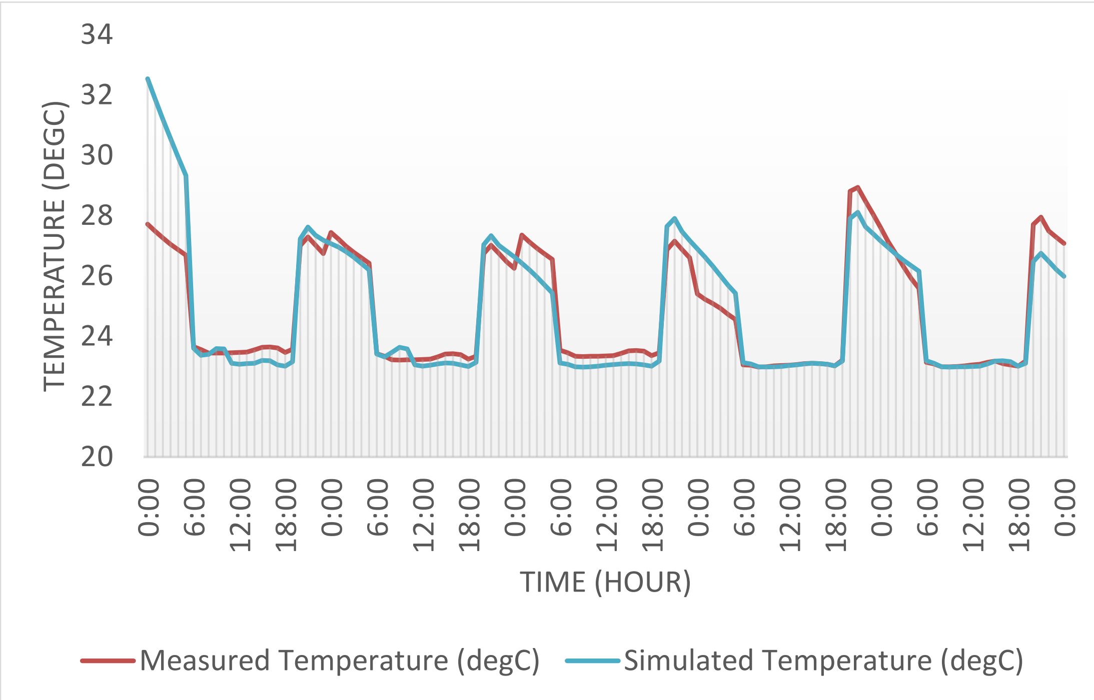


Figure 4.31 Difference of modelled and logged temperature summary in summer.

Indoor relative humidity data is recorded using a HOBO data logger with accuracy around ± 5% and is capable of logging data between +5 ºC and +50 ºC. In Figures 4.33 and 4.34 present comparative value of simulated humidity value and recorded humidity values for both summer and winter are shown. The average humidity level varies between 50% and 85% during summer and between 32% and 65% during the winter. The differences amongst modelled and logged values in working hours are the highest at 9% in the summertime and a maximum of 11% in wintertime. Considering the precision of the humidity sensor, the recorded humidity values show a reasonable agreement with the simulated humidity level for the simulated thermal zones.

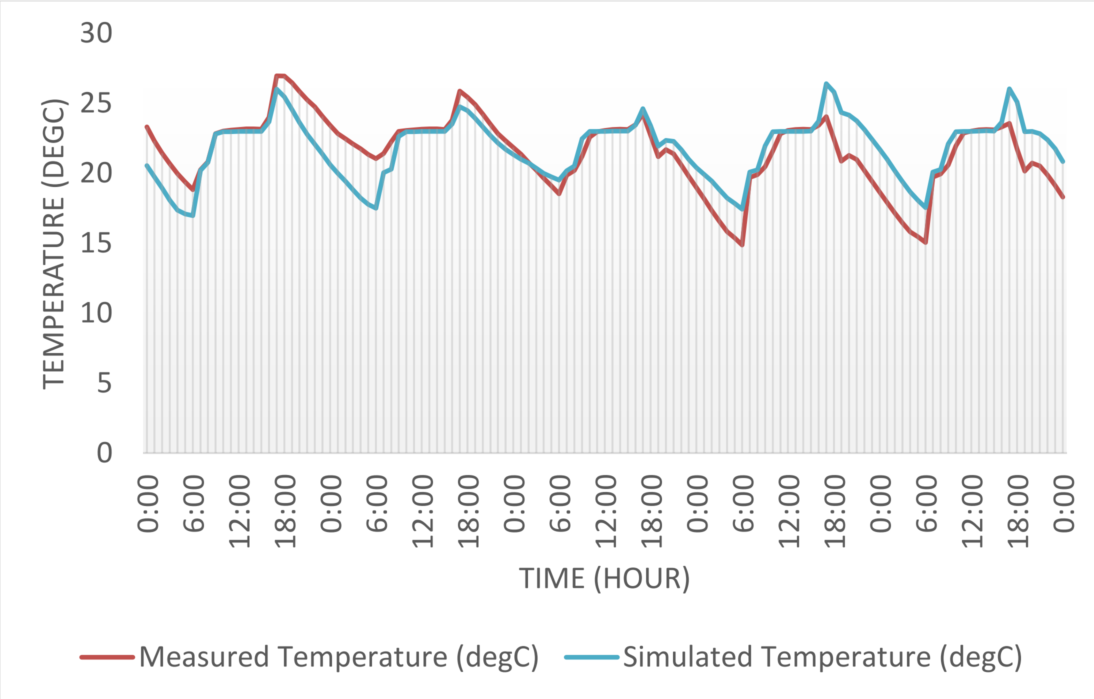


Figure 4.32 Difference of modelled and logged temperature summary in winter

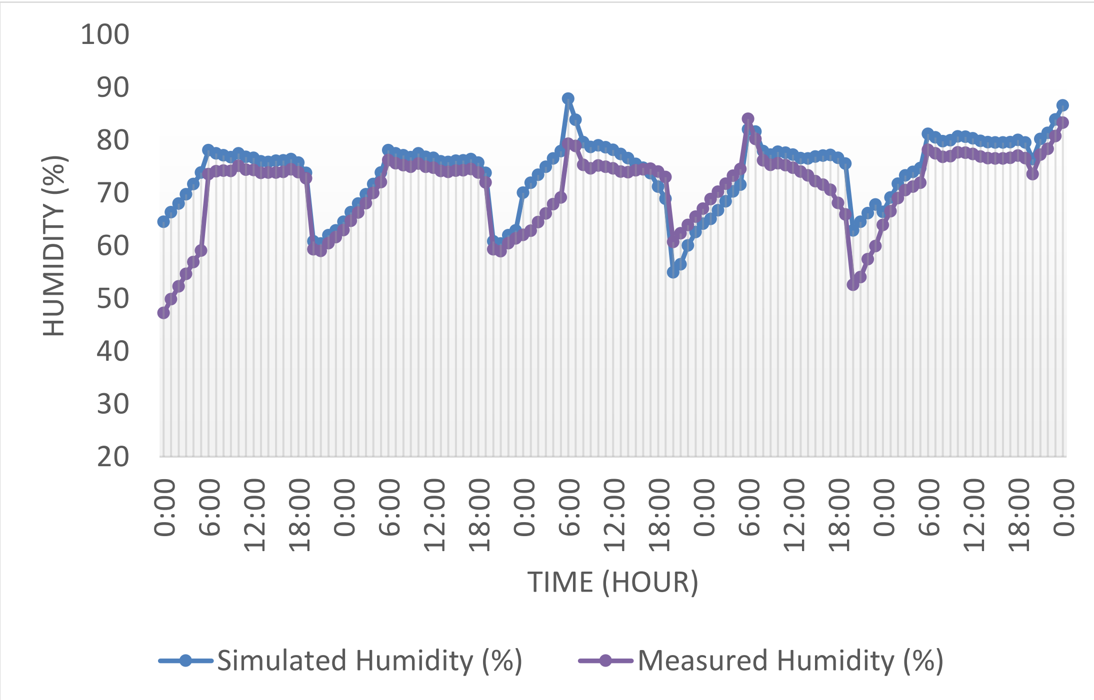


Figure 4.33 Difference of modelled and logged relative humidity in summer

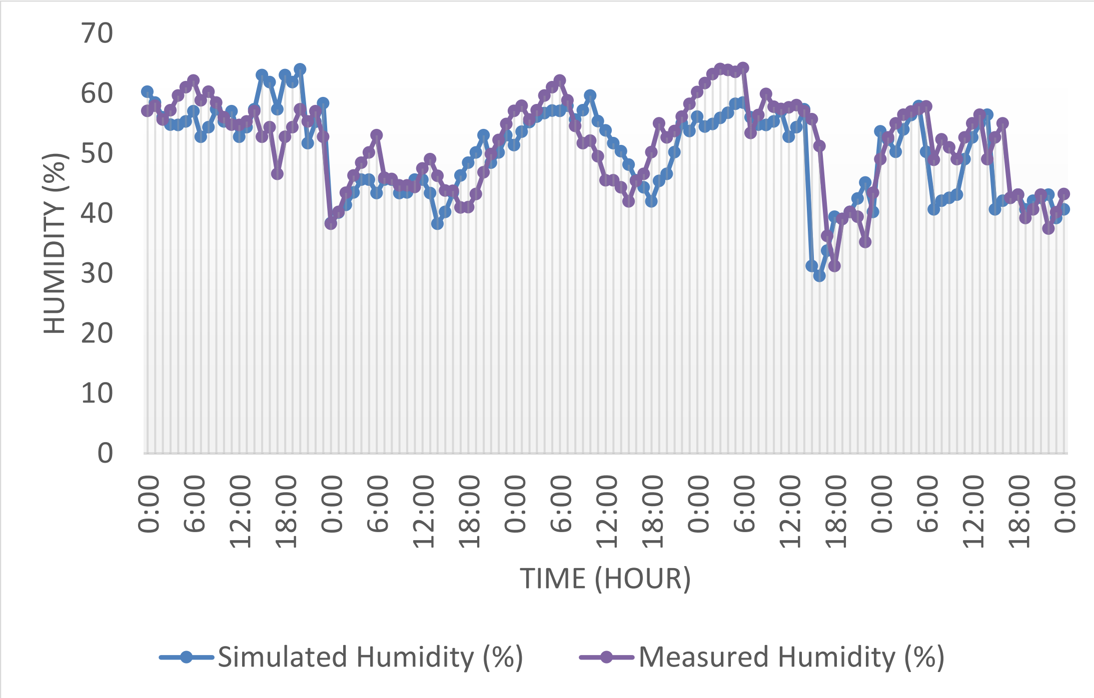


Figure 4.34 Difference of modelled and logged relative humidity in winter

The overall electrical power intake was determined by summarising the power usages data by numerous systems and sub-systems. This information is required to compare the simulated power usage data with the on-site measured value. A representative single week measure data is considered to contrast with the simulated power usage data. Since the HVAC system does not operate in many areas of the building during the weekend, the comparison is performed based on the data collected and simulated during the weekends. In Figure 4.35, the simulated electricity usages data by the cooling system are compared with the recorded energy data during the weekdays in summer and winter periods. The difference between simulation and measured data were found to be within 8% to 10%, as shown in Figures 4.35 and 4.36. The differences noted between the simulated and measured electricity energy consumption data for cooling operation during weekdays are because the chillers are fairly outdated, and there is visible air leakage in some of the thermal zones. However, the simulated and measured graph both follow a similar pattern, which is very convincing. The substitute power consumption trend of the chillers were around 9% of the logged data based on the load conditions and atmospheric state.

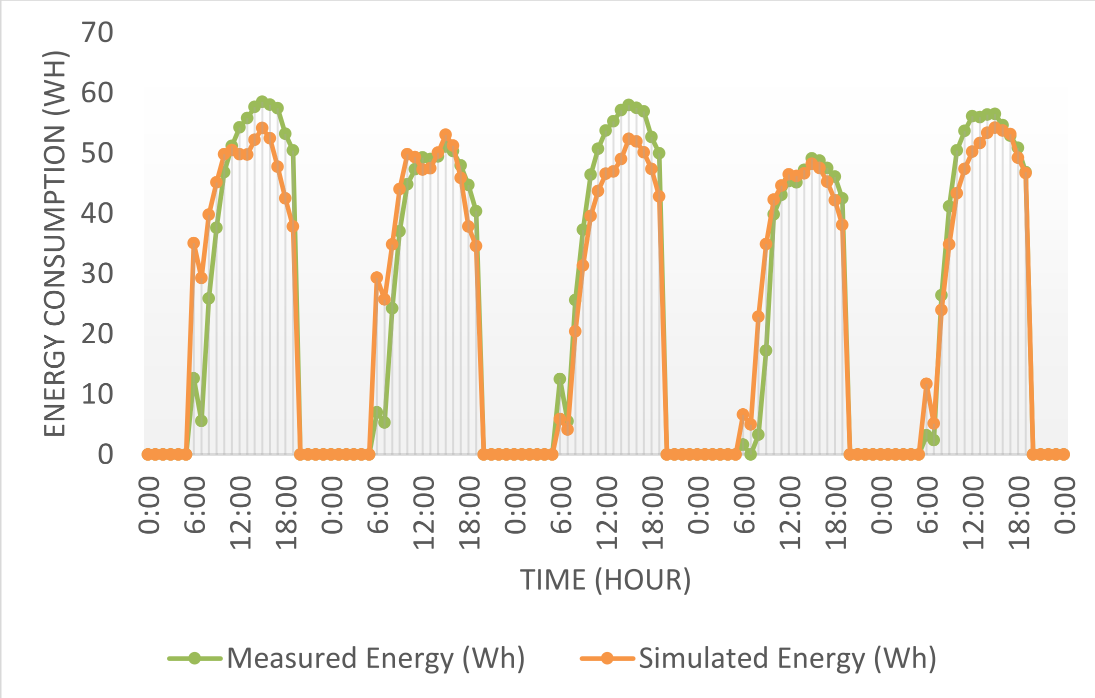


Figure 4.35 Difference of modelled and logged average daily cooling energy consumption in summer

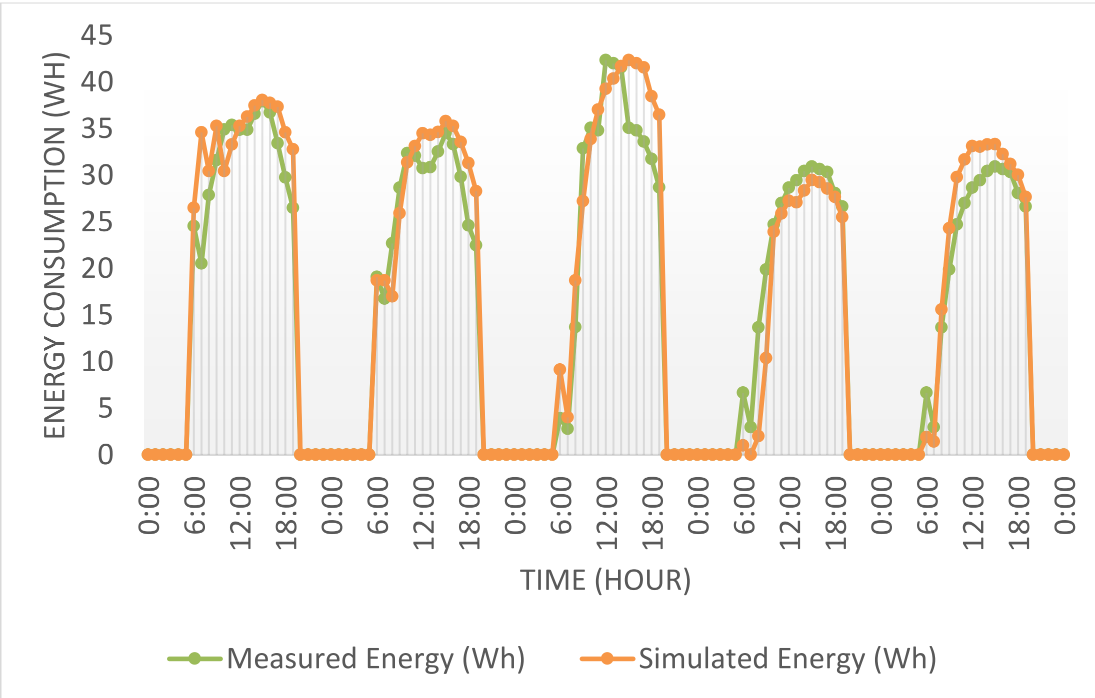


Figure 4.36 Difference of modelled and logged average daily cooling energy consumption in winter

4.12 CONCLUSIONS

The efficacy of the energy system for the selected building for summer and winter season is studied and modelled using EnergyPlus algorithm and simulated in the Designbuilder platform for rapid evaluation using high-performance computing facility. The outcomes consist of overall energy performance, energy performance breakdown of different building systems, internal heat gain, internal comfort profile, cooling load requirements etc. The results were also validated against the measured data for the selected duration. The procedures utilised in the entire evaluation helps to minimise unpredictability about developing simulation-based studies. To minimise the unpredictability of the simulations data, the outcome of the developed models are compared with the measured end usages data as well as recent climate information. Parameters that alter throughout the year, such as irregular use, efficiency deterioration of the equipment over a period of time, etc., are challenging to account for in the simulation.

The simulated outcomes sufficiently concur with the measured information. Little distinctions between calculated and recorded information are expected to inconsistencies among real and modelled climate condition information, variation in operational details and physical buildings, which were anticipated. Various other factors are assumptions as a result of simplification in procedures, as well as system collision because of coding run-time error. This developed model will be utilised on the way to assess the efficiency of selected prospective HVAC techniques and envelope systems in the next two chapters.

Chapter 5: Modelling and Evaluation of Alternative Cooling Techniques

5.1 INTRODUCTION

Modelling on the basis of representative criteria is a profitable strategy in assessing the performance of building mechanical systems as well as the management of numerous retrofit methods of the AC units. When assessing the efficiency of area AC unit, electricity intake and thermal comfort are a matter of evaluation to ensure that the equipment possesses specific features to meet the demand of the local climatic condition. In this chapter, cooling technologies, namely Cooled Beam, (CB), Variable Air Volume (VAV) system, Fan Coil Unit (FCU), Ground Source Heat Pump (GSHP), Heat Pump (PTHP), and Variable Refrigerant Flow (VRF) systems are assessed to avail the benefit of savings opportunities of energy as well as minimising the emission as a result of the cooling process.

5.2 ALTERNATIVE LOW EMISSION COOLING TECHNOLOGIES

The standard simulation design explained in the previous chapter described the functioning state of existing mechanical systems in the selected building. Minimising energy intake in the building system is essential for achieving a sustainable future for us all. So far, there are not many studies available where the various type of comfort indices, reduction of electrical energy consumption and peak energy demand have not been evaluated thoroughly for different AC methods as well as climates. First, the needed details to simulate alternative low emission air-conditioning methods has been recorded and inputted in the simulation software. After that, base case simulation assesses, and various other low emission air-conditioning techniques are contrasted to evaluate the energy efficacy and comfort of a building zone within the building. Ultimately, the operational CO_2 emissions from the power usages in various systems and sub-systems are analysed. The comparative assessment is undertaken depending on the base case settings for the selected case study building. Design and commissioning data were also adopted (where available) in the model as a part of the fine-tuning and verification process of the developed model. The referral structure examined in this research study is about 25 years old. Therefore, this research study considers the existing systems in functional condition for the development of the base case reference scenario to perform the comparative study.

5.3 COOLED BEAM

Cooled Beam systems are typically hybrid air and water systems. Generally, a continuous circulation set temperature forced air system is maintained for satisfying cooling load from the flow of air and internal load in the zone. Occasionally the rate of airflow varied depending on the need of the air circulation, and temperature might be reset by numerous means. Reasonable air-conditioning load could be met by the Cooled Beam passive systems which operate by radiation and natural convection. The actively Cooled Beam systems act as source terminal units for air over the beam AC components. The active system operates by convection only method. The Cooled Beam elements serve as a choice to regular ceiling radiant air-conditioning. This system is not integrated with the building envelope. The heating mode runs separately in this type of system. Generally, particleboards are utilised as the boundary to fulfil space heating demand.

Cooled Beam method is basically dissimilar compared to the traditional AC units as the equipment cool down the people in the room rather than cooling the indoor atmosphere. An entity's sensation of comfort relies on the mix of atmospheric air and radiant temperature and activity in the indoor space. Cooled Beam considers the difference between radiant and air temperature to offer an equilibrium that makes individuals feel comfortable. Radiation represents a big proportion of warm elimination process by Cooled Beam method; therefore, a small temperature variance amongst the air and radiant temperature is sufficiently intended for the system to operate to result in a good thermal indoor environment.

A radiant air-conditioning method operates on a relatively simple principle in a low-temperature range. In the simulation, energy is eliminated from the thermal zone, and people are treated by radiation heat exchange method. Generally, ducts, dampers etc. are not required in this type of system; the exception is the requirement of maintaining indoor air quality. DesignBuilder employs an analysis technique to perform the short-term heat transfer mechanism. The fundamental equation associates numerical change at a single side of a component to a limitless collection of temperature. In EnergyPlus, the Cooled Beam system is modelled as a four-pipeline induction terminal device within the total A/C system where a regular constant air volume solitary duct is placed on the airside, and a Cooled Beam system is placed on the zone devices side. The following mathematical equations are considered in the modelling and simulation of the system. Figure 5.1 represents the details of the Cooled Beam system applied in the simulation.

$$P_{beam} = A \cdot K \cdot \Delta T \tag{5.1}$$

$$K = \alpha \cdot \Delta T^{n1} \cdot v^{n2} \rho \cdot \omega^{n3} \tag{5.2}$$

$$v_{\rho} = (q_{in} / \alpha_0) \cdot \rho_{air} \tag{5.3}$$

$$q_{in} = K_1 \cdot \Delta T_n + K_{in} \cdot q_{pr} \qquad (5.4)$$

Where

P_{beam} = The beam cooling output per unit length in W/m

K = The coil heat transfer coefficient in W/(m^{2}K)

v_ρ = The room air mass flow rate across coil in kg/(m^{2}s)

q_{in} = The room air volumetric flow rate across coil per unit length in m^3/(s-m)

ΔT = the room air–water temperature difference in degC

ω = the water velocity in m/s

q_{pr} = the supply air flow rate per unit length m^3/(s-m)

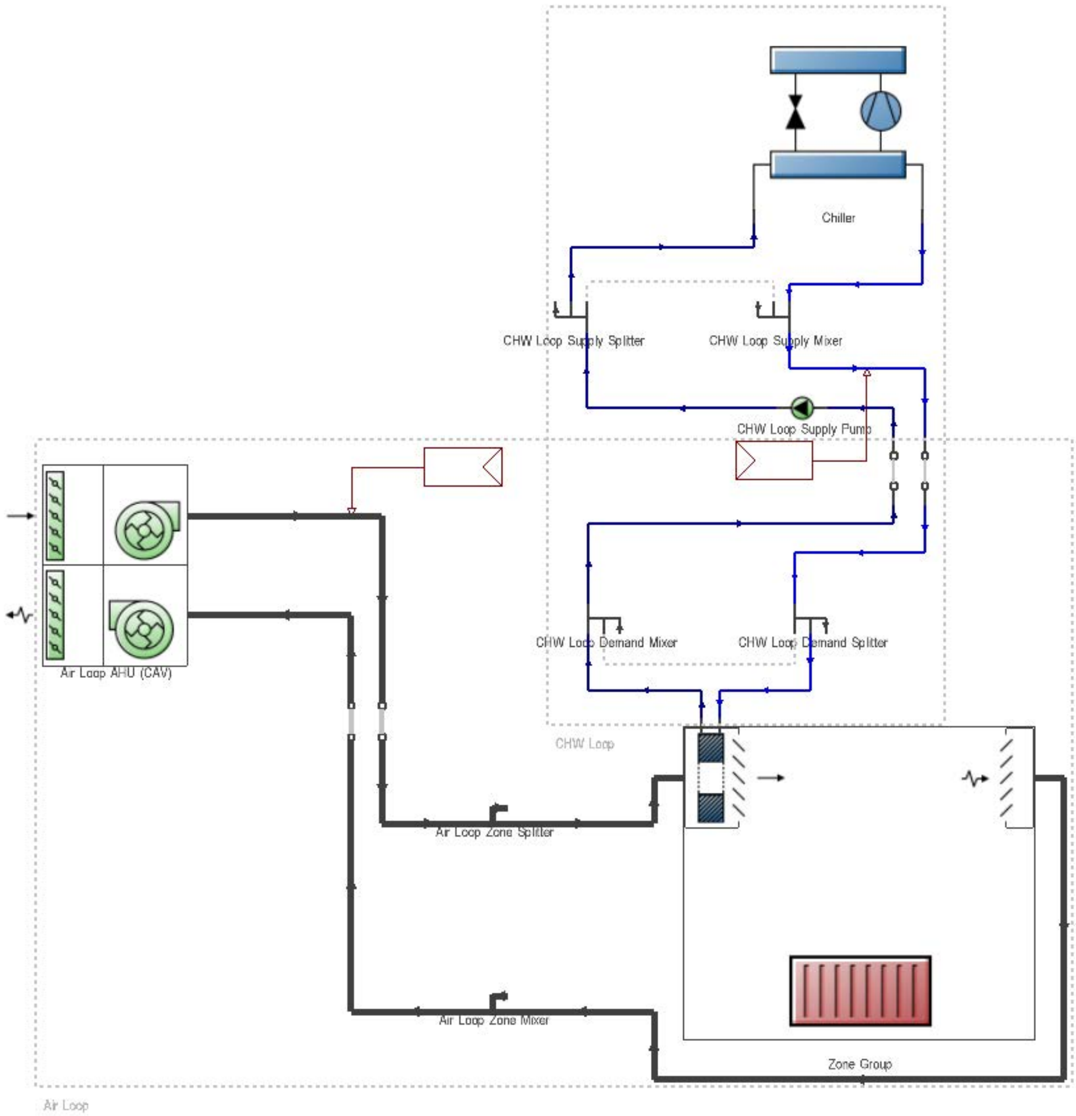


Figure 5.1 Cooled Beam system diagram considered in the simulation

In EnergyPlus, the heat equilibrium is simulated by temporarily closing off the radiant system to identify the reaction of the building system unless there is a nearby source of heat. The radiant system operates based on the schedule specified in the control system. The flow of cooling liquid is enabled to vary at each period, as well as the radiant system is modelled for the defined period.

5.4 PACKAGE TERMINAL HEAT PUMP (PTHP)

The Package Terminal Heat Pump (PTHP) system is composed of an outdoor air blender, DX heating and cooling coils, supply air fan etc. The PTHP collaborates the functioning of the elements and can be modelled as equipment that served the thermal zones. The PTHP is calculated by placing a fan for the air supply amongst the outside blender of air and the direct expansion cooling coil. The PTHP works on its own assigned thermal zone as well as is managed by a sensor situated in the relevant area. The pump works by fulfilling the area conditions for cooling as directed by the sensor scheduling. The design computes the necessary partial load proportion for the heat pump. The cooling load requisites are fulfilled by the supply air. The PTHP provides the required cooling to the designated area through the air inlet node for the area.

The PTHP maintain a single area with the use of thermocouple. EnergyPlus executes a heat equilibrium for the zone air to determine if air-conditioning is needed to match with the settings in the sensor. PTHP enactment is later processed with the cooling coils and the fan to air supply runs as defined in the control system. When zonal heat equilibrium along with the heat pump systems calculated zero need for air-conditioning or the system remains to switch off, then the systems stop operating with zero output from the compressor. When the EnergyPlus algorithm considers zonal cooling need or the PTHP schedule indicates an operational plan, the simulation will calculate the average flow of air for the unit to meet the zonal set-point. The simulation allows for these differences in ventilation with the PTHP system. Figure 5.2 represents the system diagram of a PTHP system considered in the simulation. The mathematical relationship to calculate the cooling rate is stated below.

$$Q_{cooling,max} = (m_{SA,full\ load})(h_{out,full\ load} - h_{zone\ air})_{HRmin} \tag{5.5}$$

$$Q_{cooling,min} = (m_{SA,coil\ off})(h_{out,coil\ off} - h_{zone\ air})_{HRmin} \tag{5.6}$$

where

$Q_{cooling,max}$ = maximum sensible cooling rate (W)

$m_{SA,full\ load}$ = supply air mass flow rate at full-load (steady-state) conditions (kg/s)

$h_{out,full\ load}$ = the enthalpy of air exiting at full-load conditions (J/kg)

$h_{zone\ air}$ = the enthalpy of zone (exhaust) air (J/kg)

HR_{min} = the enthalpies evaluated at a constant humidity ratio,

the minimum humidity ratio of the exiting air or the zone (exhaust) air

$Q_{cooling,min}$ = the minimum sensible cooling rate (W)

$m_{SA,coil\ off}$ = the supply air mass flow rate (kg/s)

$hout, coil\ off$ is the enthalpy of air exiting the PTAC with the cooling coil off (J/kg).

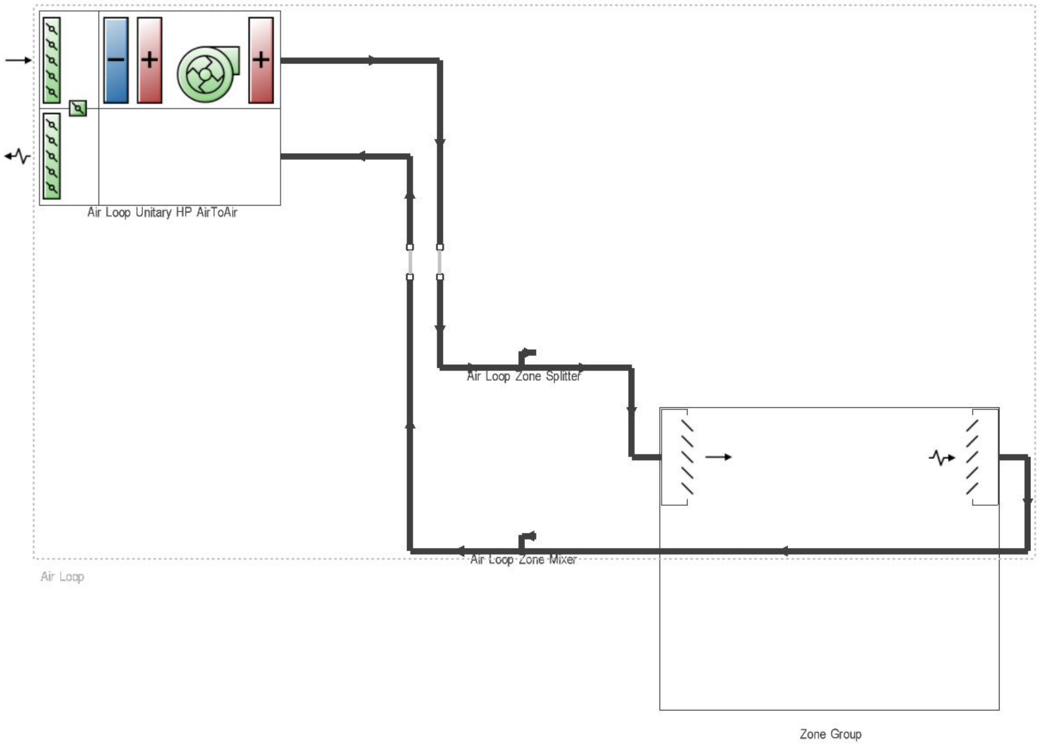


Figure 5.2 PTHP system diagram considered in the simulation.

5.5 VARIABLE REFRIGERANT FLOW (VRF) SYSTEM

The VRF system differs the circulation proportion of refrigerant by making use of compressor(s) with variable speed in the exterior system as well as the expansion valve situated in an individual interior device. The scheme fulfils the air-conditioning need by ensuring the required indoor air temperature in each thermal zone is maintained. The refrigerant stream is maintained as per the cooling loads that use lots of interior systems with differing abilities in conjunction with the large exterior unit which enables the opportunity to maintain control over individual comfort in a different zone at the same time. The system can maintain heating and cooling operation in several zones separately with the recovery of heat from one zone to another zone depending on the zonal set point. This feature of the VRF system offers better operational efficiency during the part-load condition.

Variable refringent flow can be of two types. A heat pump type system is one of the most basic types that could be installed for both cooling and heating the indoor space. However, the limitation of this type of system is that the cooling option could not be performed concurrently. Recovery of a heat type system could organise synchronised HVAC operation to various areas by transporting the heat between the cooling and heating equipment. A VRF air-conditioner system can serve multiple areas and manages through the sensors situated in the thermal zone. The zonal systems run to fulfil the cooling and heating load requirement for each of the thermal zones as established by the operating schedule of the zone. When the pump is not in operational mode to regain the waste heat, the VRF air-conditioner system will run in either air-conditioning or heating setting. The functional method is established by the VRF system considering the thermostat control settings in the respective area. A VRF system cooling setting, the air-conditioning coils can operate where the respective zone requests air-conditioning. When the unit runs in the winter setting, the space heating unit is permitted to operate where the heating need arises in a specific thermal zone. The fans for supplying fresh air will continue to operate if a particular thermal zone requires a continuous flow of air. A representation of the system considered in the simulation is exhibited in Figure 5.3.

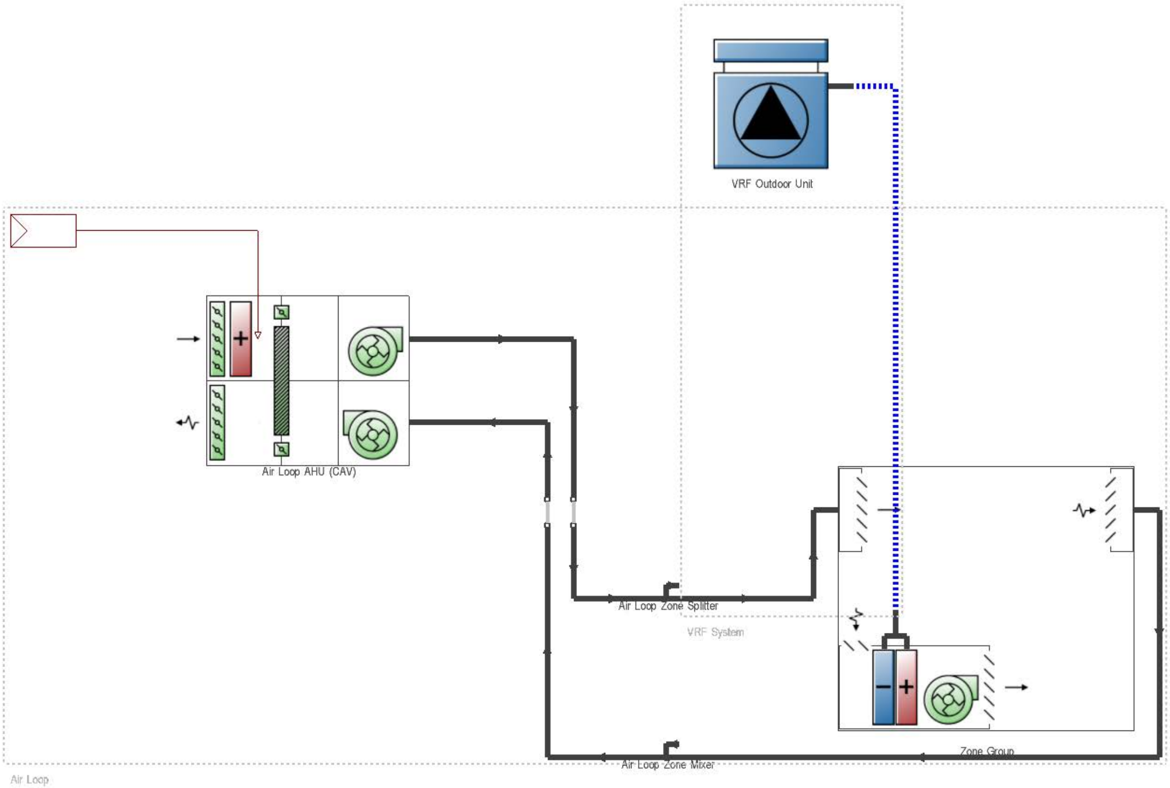


Figure 5.3 Illustration of the VRF system considered in the simulation.

A two-pipe VRF system is the easiest system supplying either heating or cooling down to the busy room though it cannot provide synchronised air-conditioning or home heating on the same system. Three-pipe VRF systems use synchronised heating and air-conditioning on the same system. The technique includes ‘transition’ control systems that draw away the cooling agent gases either to or from the interior device depending on which set of the procedure of the system has been chosen.

5.6 FAN COIL UNIT SYSTEM

In lots of ways, a fan coil system resembles the induction system with four-pipe systems. The terminal units are usually placed either under the window or in a ceiling space from which a variety of supply outlets can be served. Indoor temperature is preserved via a temperature sensor either by controlling the fan speed or by a two-port valve on the system coil. In this study, a fan coil system with 4 pipes is hydronic, considering it can supply cooling as well as heating to an area. It consists of a coil for hot water, a coil for cold water, and a fan unit. The fan is able to supply a constant amount of air; however, it is not able to operate in economiser mode. The fan is a blow-through type that operates with a constant velocity. The flow can be managed by amending the water circulation. The four-pipe fan coil system is designed as a substance containing four sub-components: a heating component, a cooling component, an air blender and a supply air fan. The method is linked to the total air conditioning system by defining the connection for all fluid movement. The parts making up the fan coil are linked with each other appropriately. Figure 5.4 represents a system diagram of the Fan Coil Unit system.

5.7 GROUND SOURCE HEAT PUMP

A GSHP is an excellent method to minimise the power used in air-conditioning and heating while preserving a comfortable environment. A heat pump is not a new cooling method, and many places have installed such a system for energy savings. The pipelines at the back are hot compared to the one within the air-conditioning systems, as these pipes produce the heat eliminated from the interior. Usually, heat progresses from the warmer location to the colder location, yet a heat pump reverses this direction.

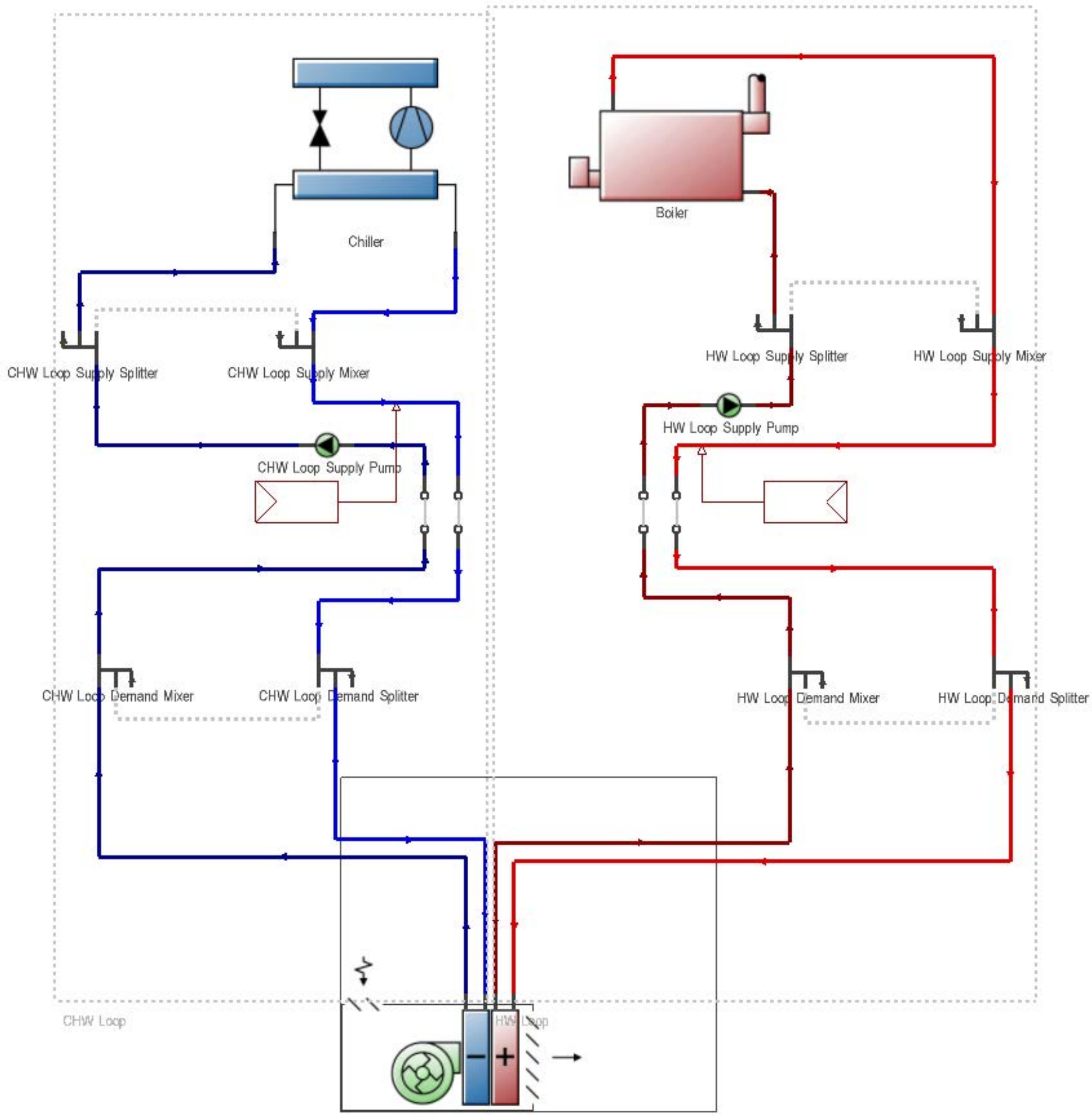


Figure 5.4 Fan Coil Unit system diagram considered in the simulation.

Figure 5.5 represents the system diagram of the Ground Source Heat Pump. A GSHP moves heat amongst the indoor and the ground. They utilise the temperature level a couple of metres below the surface area that is reasonably constant for the entire year, generally 11 ºC to 15 ºC. On a sweltering day, when the atmospheric temperature is quite high, for instance, 39 ºC, and the expected indoor temperature level is 23 ºC, the air-conditioner with a reverse-cycle option will require at least a 16 ºC temperature level variance amongst the condenser and evaporator. However, the ground source warmth pump only needs to provide a temp difference of 3 ºC to 5 ºC. This is much easier to attain and requires less power to supplement the need.

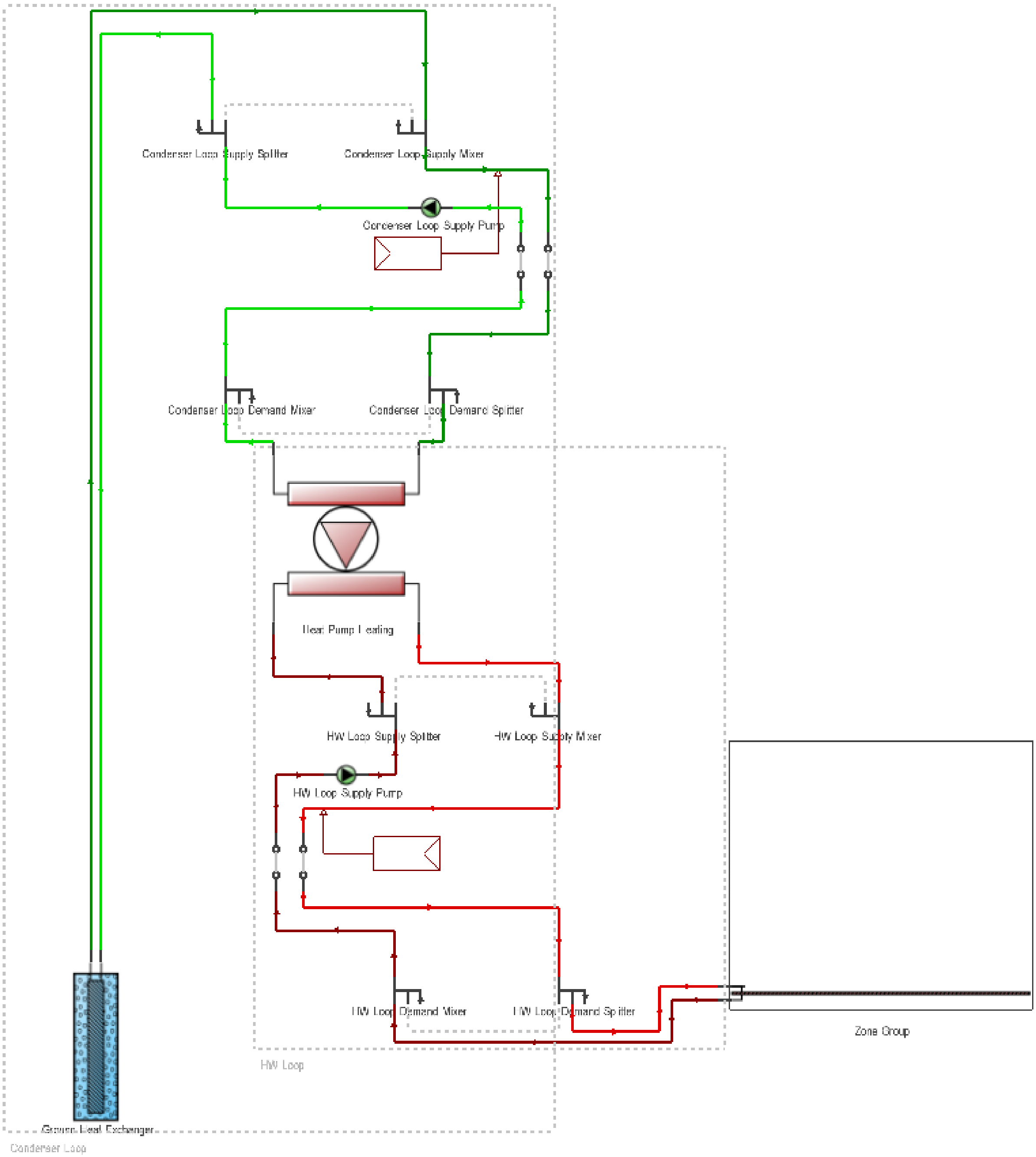


Figure 5.5 Ground Source Heat Pump system diagram considered in the simulation

The Coefficient of Performance determines the efficacy of heat pumps. A GSHP has a COP value higher than 6, which is almost twice that of a standard split system. Nevertheless, a ground-sourced heat pump is not worry-free in terms of installation, usages and maintenance of the system. The knowledge and technology associated with a GSHP are still in the development stage; therefore, use of such a cooling method is mostly restricted to industrial premises. Most of the systems available in the market for quick adaptation are quite big for a residential home in built-up areas. The present models of the ground source heat pumps that are readily available on the market now would be suitable for an apartment facility. They could easily be applied in a business or industrial setting.

5.8 VARIABLE AIR VOLUME SYSTEM

Variable Air Volume (VAV) method differs the air quantity provided to a zone while maintaining a constant supply air temperature level. VAV systems, nevertheless, can have issues ensuring consistent area temperature level at low airflow rates. Low-flow air diffusers in VAV systems assist in preserving consistent air circulation in an area at low airflows. Passive small circulation diffusers are developed to blend the supply air with the space air efficiently at low flow. Fan-powered VAV terminal systems offer another approach to enhance air circulation at low load conditions. These systems integrate the advantages of a VAV system by decreasing leading fan energy and reheat energy, with the benefits of a CAV system, by preserving excellent airflow.

Compared to continuous flow rate, VAV systems have small scale central plant as such possess a great possibility for the saving of operational energy. The air delivered by the fan takes care of the complete instant heat gain, and there is no reheating of the air as in zoned reheat systems. In a design of a VAV system, temperature, humidity control, and energy performance are of principal interest. This method integrates the benefits of the typical double air duct system for superior control with an opportunity to minimise follower power making use of a variable rate follower.

The VAV devices defined in Figure 5.6 are primarily used with air-conditioning system with both heating and cooling ability.

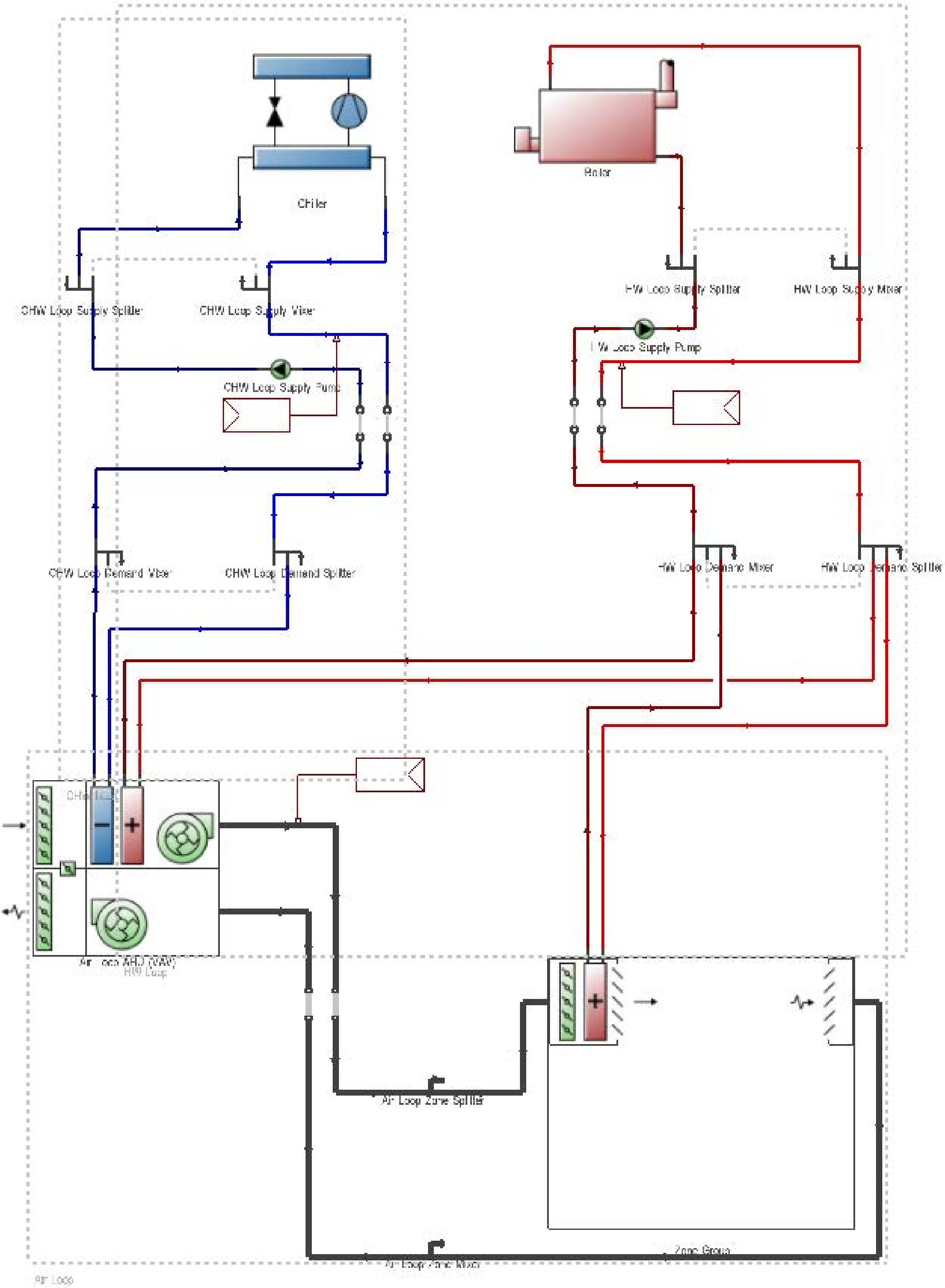


Figure 5.6 VAV with air-cooled chiller

5.9 PERFORMANCE EVALUATION OF ALTERNATIVE LOW EMISSION HVAC SYSTEMS

5.9.1 Cooling Energy Consumption

To reduce the higher thermal load for cooling and to minimise cooling usage and CO_2 emission in the building, the performance of alternative low emission cooling technologies is modelled for the case study building taking into consideration the historical average weather condition. Results from the modelling have revealed that the cooling demand throughout the day continues to be roughly the same with an exception during the beginning of the daytime. Ground Source Heat Pump (GSHP) cooling method, Variable Refrigerant Flow cooling method and Cooled Beam cooling method demonstrated considerably less energy demand compared to the existing cooling method in the building. Reasonable energy-saving was noticed using Variable Air Volume, Fan Coil system and Packaged Terminal Heat pump,

In Figure 5.7, the Ground Source Heat Pump cooling method led to a reduction in cooling energy consumption throughout the summer duration, which was most significant during the peak demand period as it could capitalise on the low-temperature level at the ground, and the system required to run the cooling system to compensate the differences in the temperature. The monthly energy savings profile using the selected cooling methods are very consistent during the summer and winter months. The simulation results show that a Variable Air Volume method can save between 7.7 kWh /m^2/month to 12 kWh /m^2/month during the summer months and 1.5 kWh/ m^2 /month to 4 kWh /m^2 /month cooling energy consumption throughout the winter months. Contrasted to the base case, the Variable Air Volume method offers 12% to 13% energy saving during the summer months and 10% to 13% energy saving during the winter months. Cooled Beam method can save between 7.5 kWh/ m^2/ month to 12.6 kWh/ m^2/ month during the summer months and 1.5 kWh /m^2 / month to 7.2 kWh/ m^2/ month cooling energy consumption during the winter months. Therefore, the Cooled Beam method offers 14% to 16% energy saving during the summer months and 11% to 14% energy saving in winter months against the existing HVAC system in the building.

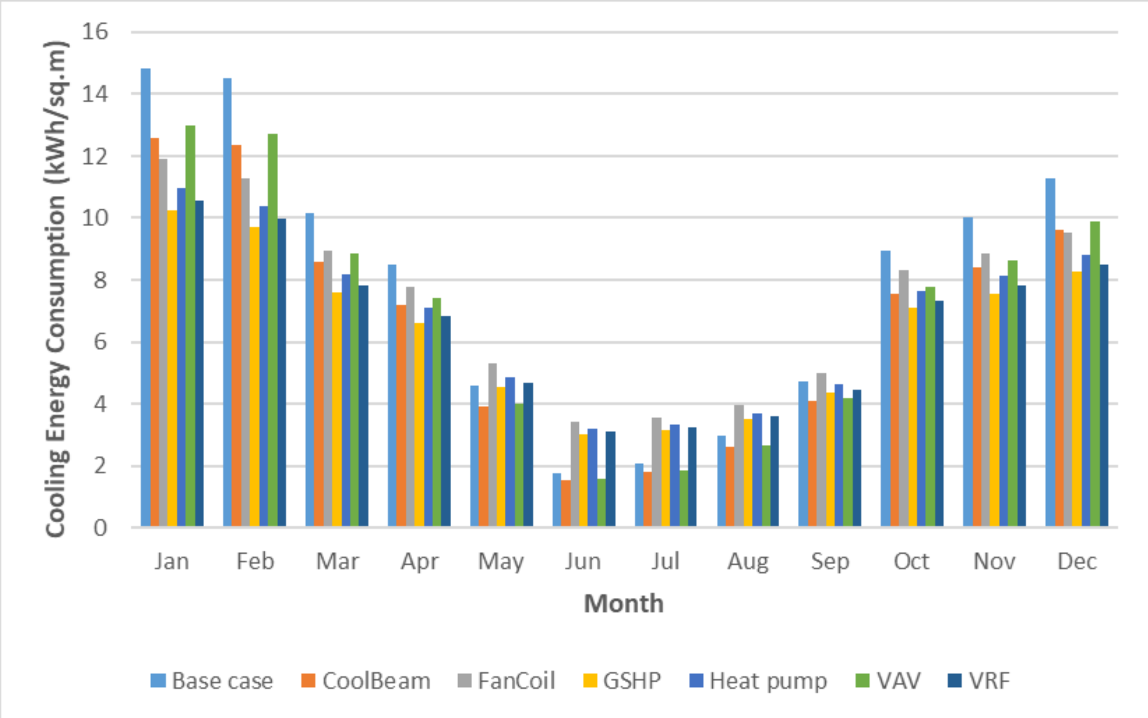


Figure 5.7 Electrical energy consumption using the selective alternative cooling system.

A Fan Coil Unit system extends reasonably convincing energy saving during the summer months of 8.2 kWh /m^2/ month to 11.9 kWh /m^2/ month, which is 11% to 19 % saving of energy with respect to the base case scenario. However, there is no energy saving noticed in the winter months using the Fan Coil Unit. Consumption is higher compared to the existing system during the winter months. A similar trend is observed using the GSHP, VRF and Heat Pump systems. A Ground Source Heat Pump method recommends 7.1 kWh/m^2/month to 10.2 kWh/m^2/month energy saving during the summer months, which is 20% to 30 % energy saving compared to the base case.

Similarly, a Variable Refrigerant Flow method suggests 7.3 kWh /m^2/ month to 10.5 kWh/ m^2/ month energy saving during the summer months, which is 22% to 31% energy saving compared to the base case. A heat pump system presents 7.5 kWh/m^2/month to 10.95 kWh /m^2/ month energy saving during the summer months, which is 14% to 28 % energy saving compared to the base case. There is no considerable energy saving noticed during the winter months using the Ground Source Heat Pump, Variable Refrigerant Flow and heat pump systems. Consumption is greater in comparison to the existing system during the winter months.

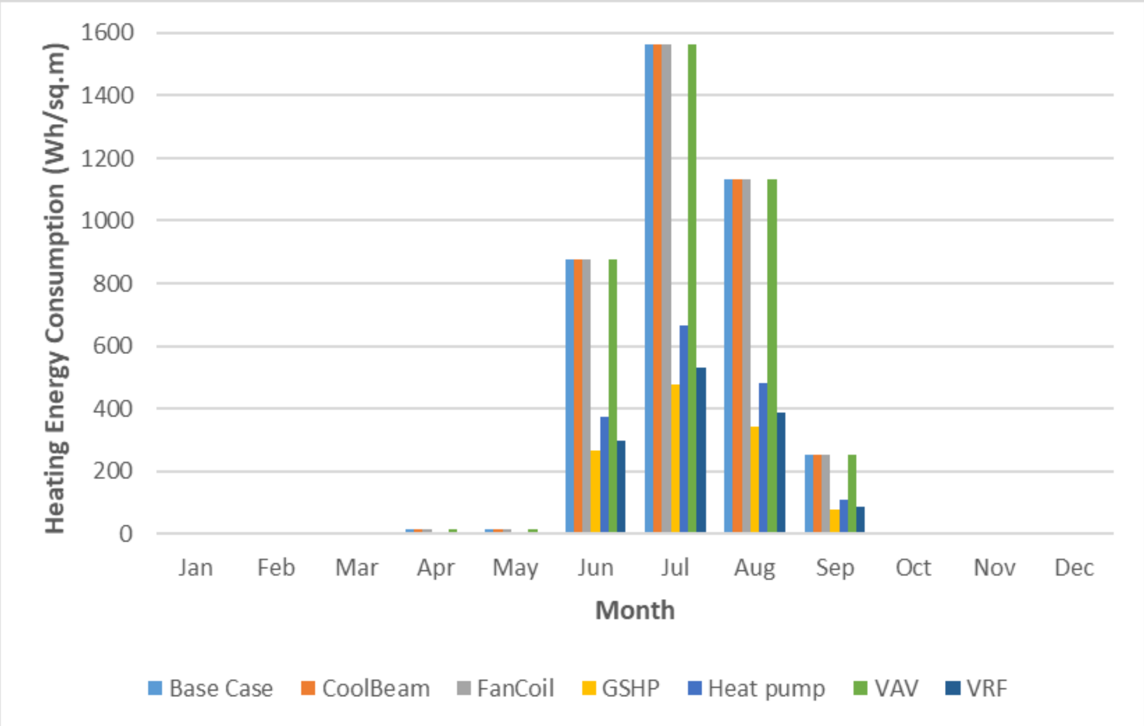


Figure 5.8 Heating energy consumption under a selective alternative cooling system.

Heating is not generally required during the summer months in a tropical climate with exception to the winter months. GSHP and VRF systems reduce the heating energy use in winter months, as explained in Figure 5.8. As mentioned in the preceding section, heating is supplied using a separate mechanism in a Cooled Beam system, and the energy consumption by the process appears to be higher compared to a GSHP and VRF system during the winter month. However, a Cooled Beam method offers overall energy savings when the whole year energy consumption is counted for the method.

5.9.2 Whole Building Energy Consumption

Entire building electrical power use rises during the summer (October to March) when the outside air temperature level is increased compared to the winter months. The base energy consumption from other sources remains almost the same pending the occupancy profile. The variations are mainly due to the change in atmospheric condition and its influence on the efficacy of the HVAC units to deal with the internal heat gain to meet the comfort index during the summer and winter months. During summer (October to March), the expenditure of energy is consistent, and the variant of electric power consumption corresponds to interior heat gain from people, lighting, equipment, ventilation etc. The difference amongst the retrofitted outcomes and the existing scenario is essential since there is a vast possibility for renovation which will improve power efficiency both in summer and winter over some time. The average monthly electricity usage information is calculated and compared to study the variances among the alternative techniques and the existing system for cooling operations. From Figure 5.9, it can be stated that the application of alternate HVAC methods lowers the overall energy intake by the systems. The monthly average energy consumption by the whole building using Cooled Beam method varies from 10.4 kWh/m^2/month to 15. 9 kWh /m^2/ month in winter and 16.9 kWh /m^2/ month to 21.6 kWh /m^2/ month in summer, representing 2.1% to 7.9% energy savings in winter months and 7.5% to 9.5% saving in summer months compared to the base case scenario. A VAV method also offers a similar type of energy savings from 10.5 kWh

/m^2/ month to 16.1 kWh/m^2/month in winter and 16.1 kWh /m^2/ month to 20.7 kWh /m^2/ month in summer, representing 1.8% to 6.4% energy savings in winter months and 6.2% to 7.9% saving in summer months judge against to the base case scenario. Both systems present a better saving of energy throughout the year compared to the existing HVAC systems.

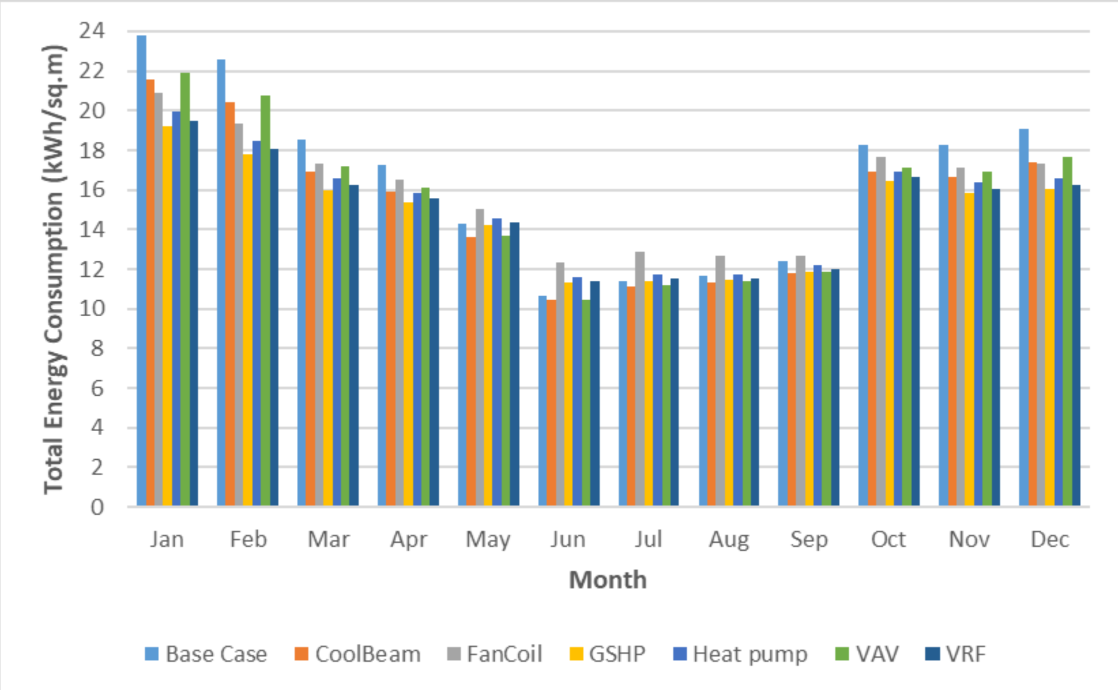


Figure 5.9 Whole building energy consumption under the selective alternative cooling system

On the other hand, GSHP, Fan Coil Unit, VRF and heat pump methods demonstrate significant energy saving potential during the summer months only. The considered VRF system offers 16.7 kWh /m^2/ month to 18 kWh /m^2 /month energy saving, which corresponds to 8% to 20 % energy saving pertaining to the base case during the summer months. Similarly, the selected heat pump system offers 16.9 kWh /m^2 /month to 18.2 kWh /m^2/ month energy saving, which corresponds to 7.2% to 18.3 % energy saving against the base case in summer months. The selected GSHP method offers 16.5 kWh /m^2/ month to 19.2 kWh /m^2/ month energy saving, which corresponds to 9.9 % to 19.3 % energy saving against the base case in the summer months. The selected fan coil system offers 17.6 kWh /m^2/ month to 19.4 kWh /m^2/ month energy saving, which corresponds to 3.5% to 14.2 % energy saving judged against the existing system during the summer months. Although all these methods offer excellent energy saving over the summer months, the methods did not demonstrate any savings at all during the winter months. The Fan Coil Unit, GSHP, heat pump and VRF consumed up to 13.2 %, 6.2%, 8.8% and 7.1% more energy every month during the winter months.

5.9.3 Reduction of CO_2 Emission

Higher energy consumption by the mechanical systems is not essential to better comfort as displayed from the literature. By enabling systems to use a choice of functional method, large amounts of energy can be saved from operational tasks of the HVAC system. Building thermal comfort has currently brought in the HVAC engineers and building scientists worldwide. Considering the importance of changing the nature of the climate and the climbing prices of power, it is progressively crucial to optimise energy usage in general. If efficient technologies are not in use in the building system, mechanical ventilation and air-conditioning systems can trigger many unfavourable results and consume massive quantities of energy over the period. HVAC engineers are trying to determine an efficient air-conditioning system that will suit a particular weather condition and ensure the overall thermal comfortability of the people without consuming massive amounts of energy. The use of electricity for room air-conditioning is expanding quicker than for any kind of various other end-uses in buildings, more than tripling between 1990 and 2016 (Campbell et al., 2018). In the meantime, CO_2 exhausts due to cooling have multiplied threefold since 1990 to 1130 million tonnes (Campbell et al., 2018). Therefore, one of the objectives of this study remained to decrease the operational CO_2 emissions by the cooling systems in a tropical climate without compromising comfort in both winter and summer seasons.

Figure 5.10 shows the total CO_2 discharges triggered by current as well as the selected cooling method each month over one year. In terms of releases, as revealed in Fig 5.10, GSHP is the finest of the different cooling systems and would undoubtedly generate 9.5 % less CO_2 in one year; however, the method does not reduce the CO_2 emissions during the winter months. From Figure 5.10, it can be stated that the application of alternate HVAC methods lowers the overall CO_2 emissions by the systems. The monthly average reduced CO_2 emissions by the whole building using Cooled Beam method vary from 2.1% to 7.9% in winter months and 7.5% to 9.5% in summer months contrasted to the base case scenario. A VAV method also simulates similar reduced CO_2 emissions, which fluctuate from 1.8% to 6.4% per month in winter months and 6.2% to 7.9% per month in summer months. No doubt, both systems compromise reduced CO_2 emissions throughout the year against the existing HVAC systems.

Conversely, GSHP, Fan Coil Unit, VRF and heat pump methods exhibit significantly less CO_2 emissions during the summer months only. The considered VRF system offers approximately 8% to 20% per month reduced CO_2 emissions during the summer months. Similarly, the selected heat pump system suggests 7.2% to 18.3 % per month CO_2 reduction during the summer months. The selected GSHP method offers about 9.9% to 19.3% per month reduced CO_2 emissions in the summer months. The selected fan coil system recommends 3.5% to 14.2 % per month reduced CO_2 emissions compared to the existing system during the summer months. Although all these methods offer an excellent reduction in CO_2 emissions over the summer months, these cooling methods did not demonstrate much CO_2 emissions reduction in winter months. In fact, the CO_2 emissions by the Fan Coil Unit, GSHP, Heat Pump and VRF increased up to 13.2%, 6.2%, 8.8% and 7.1% respectively on a monthly basis during the winter months.

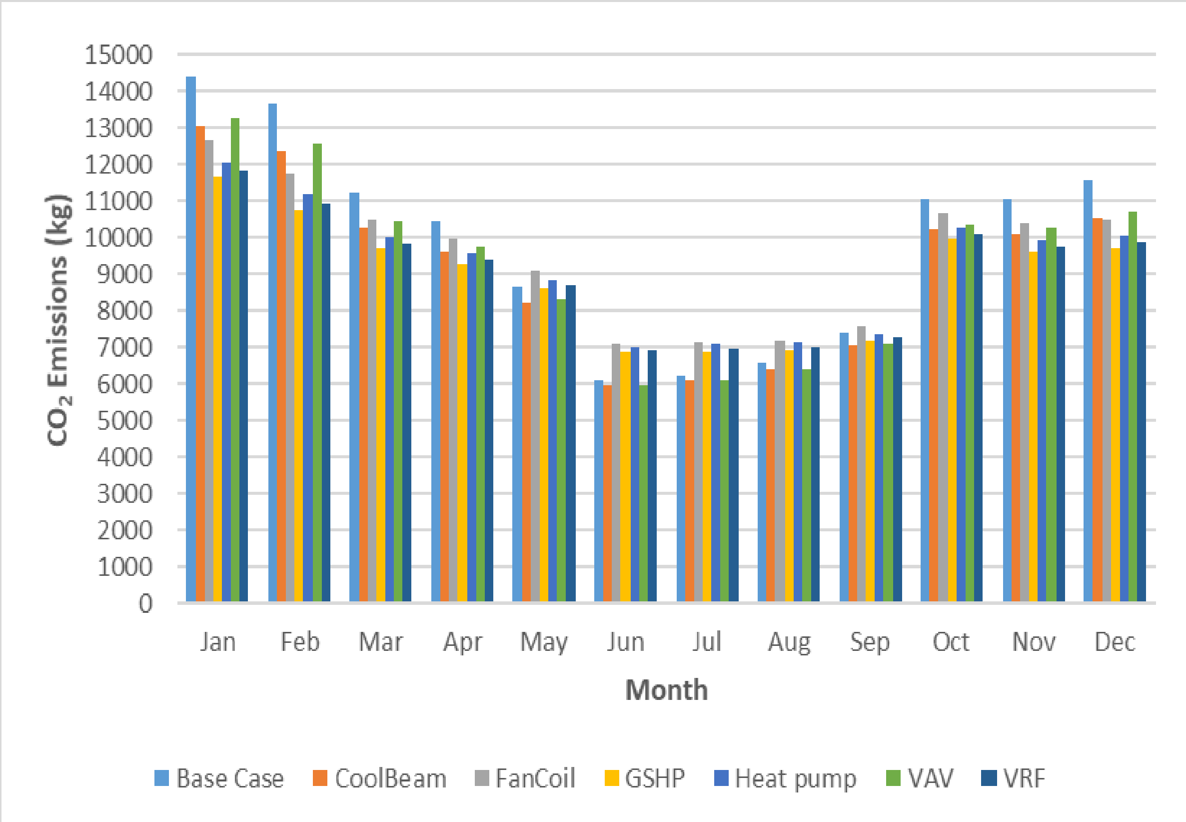


Figure 5.10 CO_2 emission reduction under the selected alternative cooling system.

A comparative analysis of normalised annual cooling energy and total energy consumption concerning the relative CO_2 emissions are shown in Figures 5.11 and 5.12. The current HVAC system of the building consumes 94.8 kWh/m^2/annum. Cooled Beam (CB), Fan Coil Unit (FCU), Ground Source Heat Pump (GSHP), Variable Air Volume (VAV), Variable Refrigerant Flow (VRF) and heat pump (HP) consume 80.2 kWh / m^2, 87.8 kWh / m^2, 75.7 kWh / m^2, 82.5 kWh / m^2, 77.8 kWh / m^2, and 80.8 kWh / m^2 in that order on an annual basis. All the cooling methods observe attractive cooling energy savings against the base case in a tropical climate.

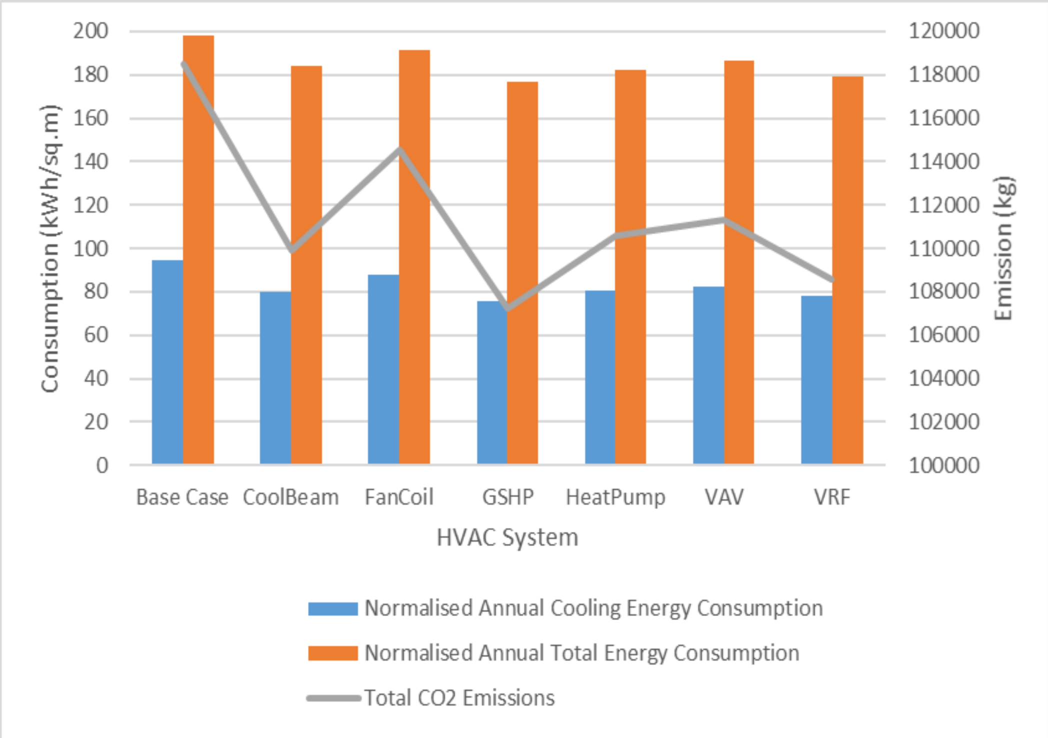


Figure 5.11 Comparison of normalised annual energy consumptions and CO_2 emissions.

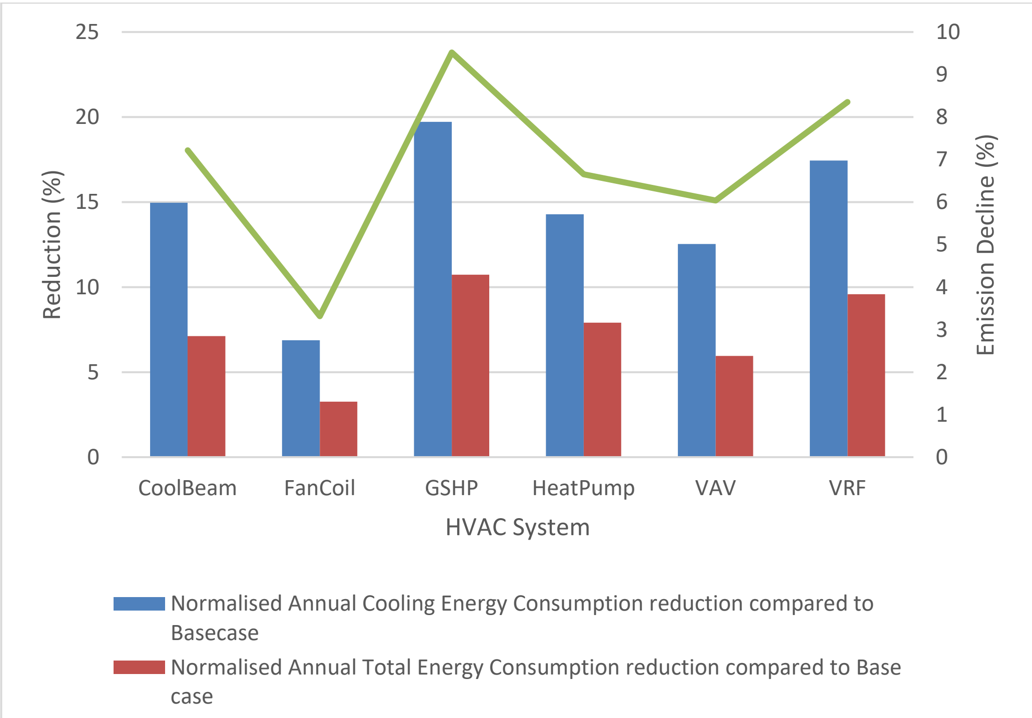


Figure 5.12 Reduction in normalised energy consumptions and CO_2 emissions.

Specifically, CB, FCU, GSHP, HP, VAV and VRF systems exhibit around 14.9%, 6.9%, 19.7%, 14.3%, 12.5%, and 17.4% annual cooling energy saving per year compared to the existing HVAC system which is very suitable for retrofitting purpose. When the total energy consumption by the whole building is counted, a very impressive savings scenario is noted. The total yearly consumption of energy in the entire building using CB, FCU, GSHP, HP, VAV and VRF systems is reduced from 3.3% to 10.7% respectively. In Figure 5.12, CO_2 emissions from the operational cooling energy consumption is also reduced by 7.2%, 3.3%, 9.5%, 6.7%, 6%, 8.4% annually by CB, FCU, GSHP, HP, VAV and VRF systems respectively.

5.10 CONCLUSIONS

The objective of this chapter was to identify alternative cooling methods that will decrease electricity usages and operational CO_2 emissions in a tropical climate in both summer and winter months. When contrasting simulation results of the low emission alternative cooling methods with the existing HVAC system in a selected building situated in tropical weather, a number of cooling methods are identified that offers both energy savings and reduce the operational CO_2 emissions.

As an alternative air-conditioning method, GSHP, VRF and Cooled Beam have a higher capacity for energy savings of up to 20% and up to 9.5% reduction of operational CO_2 emissions contrasted to the base case situation. Therefore, uses of GSHP, VRF, and Cooled Beam headed for tropical areas like Rockhampton are quite suitable for overall energy savings. The usage of alternate air-conditioning methods definitely acts an important function in lowering reliance on air-conditioning methods in an office building. This research uncovers that alternative cooling processes that is able to effectively deploy in buildings found in a tropical climate, that call for excessive electricity usages to maintain comfort.

Chapter 6: Modelling and Analysis of Alternative Envelope Systems

6.1 INTRODUCTION

Assessment of thermodynamic effectiveness of building indoor space considers essential to evaluate and forecast the total comfort of the individuals in the indoor area and to establish the overall efficiency of the building systems responsible for maintaining the comfort. This chapter aims to evaluate the influence of the alternative low emission external envelope enclosure while installing in the buildings in subtropical climate along with other innovative systems, for instance, Biophase change material (Bio-PCM), Building Integrated Photovoltaic (BIPV), Trombe wall, Cavity wall and report the findings of a thermal efficacy of the selected building in the subtropical climate.

6.2 ALTERNATIVE ENVELOP SYSTEMS

Several alternatives envelop system were considered to evaluate in this study. These neoteric envelope systems are technically and ecologically sustainable. The envelop system in the selected building currently made with brick and timber frame. The alternative envelope systems that are studied to characterise the possibility of reducing power usages and improving the comfortability in the indoor space are Bio-Phase Change Material (BioPCM) wall, Trombe wall, Cavity wall, Building Integrated Photovoltaic (BIPV) wall as well as a newly develop envelop system. The new envelop system is externally rendered and internally contains reinforced concrete, polystyrene and plasterboard. The interior walls are constructed from pressed straws made from rice or wheat and are fully decomposable, eco-friendly, as well as free from any chemical compounds, fire and sound resilient. The base case simulation model is developed considering the existing building condition to set up a base case scenario that is engaged in this chapter to undertake the comparative study. This chapter explains the modelling and analysis process followed to model and to simulate energy performance under alternative envelope systems. The impact of each of the envelop system on cooling energy consumption was simulated as well as evaluated to assess yearly power savings for the selected building.

6.3 BASE CASE ENVELOP SYSTEMS

The envelope of the selected building has a concrete slab in the base foundation. The other sections consist of exterior and interior walls with a rooftop structure. The outside wall consists of brick, cavity with air, slim sisalation foil, wooden assembly covered by padding batts and plasterboard. The interior wall is comprised of wooden assembly and plasterboard on all two surfaces. A diagram of the exterior surface is presented in Figure. 6.1.

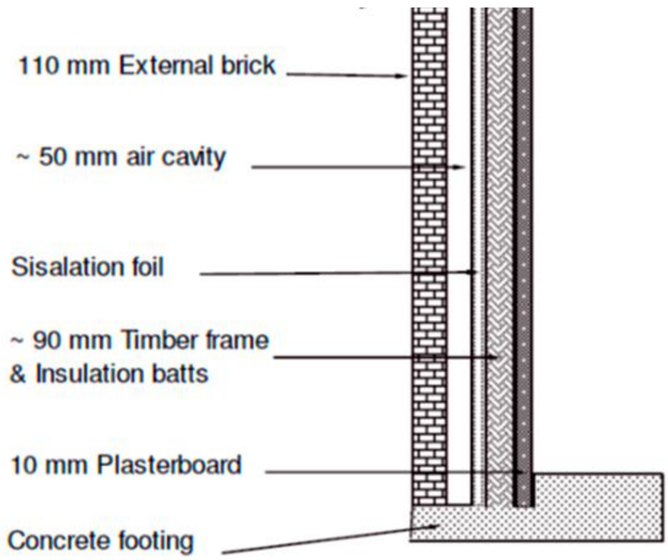


Figure 6.1 Existing building envelop

In Australia, the above traditional style of assembly is even now a forerunner building approach. It is reliable on energy performance in comparison with the building methods before the industrial age. The problem as ends up being much less energy efficient compared to modern-day building and structural techniques. The resource acquirement, phases of the building processes are responsible for considerable CO_2 emission from the processes which leave consideration amount of carbon footprint from the activities. Table 6.1 provides the specification of the existing wall.

Table 6.1 Specification of the existing building envelope

Wall Type	Existing (Base Case)
Number of Layers	5
Materials	Thickness(m)
Outermost Layer	
Brickwork outer	0.11
Air cavity	0.05
Sisalation foil	0.01
Timber frame and insulation batts	0.09
Innermost Layer	
Plasterboard	0.01
Interstitial Condensation	Structure is free of condensation
Surface Condensation	Thermal quality is good. Mould growth unlikely
Cost	$391.98/sq. m
R-value (m^2-K/W)	2.93
U-Value (W/m2-K)	0.341
U-Value Surface to Surface (W/m2-K)	0.362

6.4 NEW ENVELOP SYSTEM

As a part of the comparative study, a new exterior envelope system is evaluated, which is considerably dissimilar from a traditional method. The new envelope is much extra energy effective, fully degradable, cost reliable as well as environmentally friendly compared to a conventional household residence. The new envelope contains concrete structure, rendered exterior walls, concrete, polystyrene and plasterboard from within as well as inner wall surfaces of pressed wheat and rice straws. Table 6.2 represents a comparison of construction details, as well as environmental details for both existing and new building, envelop systems.

Table 6.2 Comparison of existing and new building envelop system

Conventional	New
External Wall Brick vaneer + foil + stud frame (timber or steel) + insulation batts + plasterboard. *Environmental Impact* Greater greenhouse emission & carbon foot Print	*External Wall* Cladding + polyesterine foam + reinforced Concrete + polyesterine foam + plasterboard) *Environmental Impact* All fully recyclable & high energy efficient, less greenhouse emission & carbon foot print, long Life, less wastage, flyash (by product of burning Coal) can be used in concrete mix
Internal Wall Plaster board + stud frame + plaster board *Environmental Impact* Greater greenhouse emission & carbon foot print	*Internal Wall* compressed wheat & rice straws (waste product) without any chemical compounds) *Environmental Impact* Fully recyclable, no greenhouse emission, no carbon foot print, non toxic
Roof Concrete / terracota tiles / colour bond + truss made of Timber / steel + insulation batts + plaster board *Environmental Impact* Greater greenhouse emission & carbon foot print	*Roof* Suspended concrete slab + polyesterine foam + plaster board *Environmental Impact* All fully recyclable & high energy efficient, less greenhouse emission & carbon foot print, long life, less wastage, flyash (by product of burning coal) can be used in concrete mix

The arrangement of the new envelope system is shown in Figure 6.2. Table 6.3 gives the requirements of the brand-new different exterior envelope.

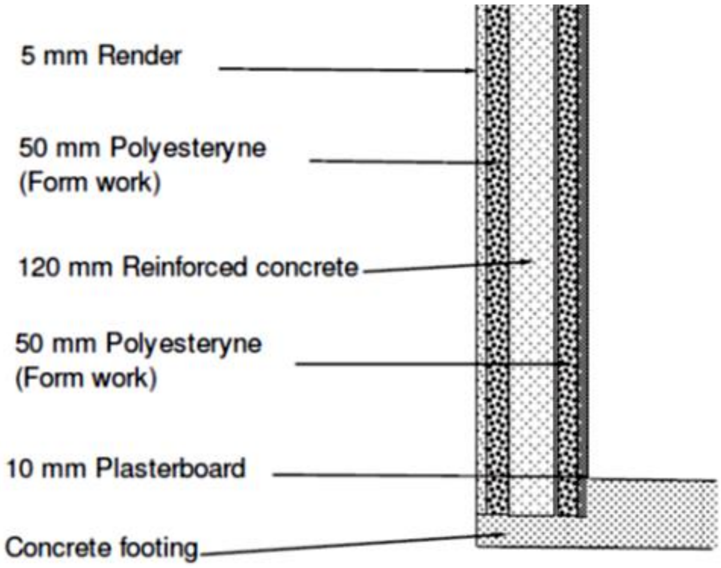
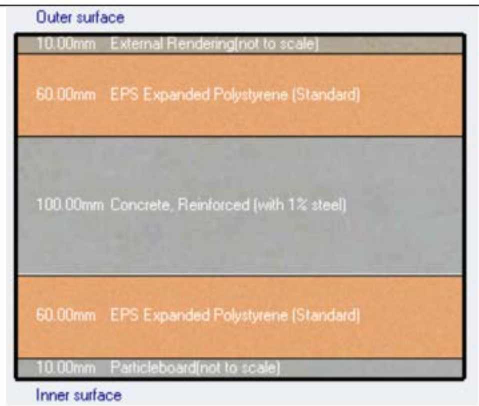


Figure 6.2 Newer way of rearranged building envelop

Table 6.3 Specification of the new alternative building envelope

Wall Type	New Wall
Number of Layers	5
Materials	Thickness(m)
Outermost Later	
External Rendering	0.01
EPS Expanded Polystyrene	0.06
Reinforced Concrete	0.1
EPS Expanded Polystyrene	0.06
Innermost Later	
Particleboard	0.01
Interstitial Condensation	Structure is free of condensation
Surface Condensation	Thermal quality good. Mould growth unlikely
Cost	$428.16/sq. m
R-value (m^2-K/W)	3.305
U-Value (W/m2-K)	0.303
U-Value Surface to Surface (W/m2-K)	0.319
Image	

6.5 BIOPCM

Phase Change Material (PCMs) is generally filled right into plaster, concrete, gypsum board, or other components to enhance the thermal loading of walls, roofs and floorings. Certain PCM products additionally supply floor coverings of pure PCM pouches which could be integrated with the coatings within buildings. By taking advantage of conversation properties of the material from liquid to stable or solid to liquid, PCMs can quickly soak up in big quantities of latent heat. The ability to carry higher latent heat by the PCMs allows the building envelope to adequately increase thermic mass which regulates the interior temperature levels and enhance comfort. By using this excellent phase change property, PCMs could support reducing the requirement of mechanical ventilation and air conditioning requirement in the subtropical climate, switching of the energy demand in the peak hours and strengthening solar power utilisation. The benefit of using a phase-change component in the building envelop is that the enhancement allows the envelope to improve its ability to carry higher specific latent heat which is utilised by the indoor space to regulate the thermal comfortability without much support for an air conditioning unit.

PCM wall structures possess thermal characteristics to deliver better power saving. Nevertheless, additional research concentrating on specific properties as well as behaviours of the materials when exposed to the real-life weather condition is required to ensure that the comfortability is maintained in both summer and winter condition. Jayalath *et al.* (2016) suggested that PCM usages in wall surfaces require to be blended with various other materials to reinforce the total use result. The addition of bio-PCMs can incorporate an environmentally friendly layer to the infrastructure, including mortar or even in concrete, given that they strengthen the building structure and improve thermodynamics efficacy of the building envelope. Application of bio-based

PCMs in building envelop can enhance thermal comfort and better hygro-thermal equilibrium which assist in the moisture control processes. Table 6.4 represents the specification of BioPCM Wall adopted in this study.

Table 6.4 Specification of BioPCM wall

Wall Type	BioPCM Wall
Number of Layers	4
Materials	Thickness(m)
Outermost Layer	
Stucco	0.019
XPS Extruded Polystyrene	0.0897
BioPCM Q23	0.0112
Innermost Layer	
Gypsum Plasterboard	0.013
Interstitial Condensation	The structure is free of condensation
Surface Condensation	Thermal quality is good. Mould growth unlikely
Cost	$143.22/sq. m
R-value (m^2-K/W)	2.93
U-Value (W/m2-K)	0.341
U-Value Surface to Surface (W/m2-K)	0.362
BioPCM Q23 Melting Point (°C)	23
BioPCM Q23 Latent Heat (J/g)	210 – 250
BioPCM Q23 Energy Storage Capacity (kJ/m^2)	400 – 1250
BioPCM Q23 Specific Heat (J/g K)	2.2 – 4.5
BioPCM Q23 Thermal Conductivity (W/mK)	0.15 – 2.5
BioPCM Q23 Relative Density (g/mL)	0.85 – 1.4
BioPCM Q23 Viscosity	Liquid, viscous gel, solid-solid gel
Image	

Several researchers (Kang *et al.,* 2015; Cui *et al.*, 2015; Cellat *et al.*, 2015, Jayalath *et al.* 2016) illustrated that bio-PCM is beneficial as the construction elements, like concrete, since the material strengthens the thermodynamic properties of the elements and could quickly be adopted for enhancing the energy efficacy of the building systems. Moreover, bio-based phase change materials are mentioned as substantially much less combustible than inorganic PCM (Kang *et al.,* 2015). PCM utilised in buildings envelop will typically solidify as well as liquefy within 18 ºC to 30 ºC. These materials usually incorporated with the structural fabric for easier installation and maintenance. This type of materials can absorb, and discharge less than 16 times more thermic power compared to standard insulation which does not possess extended phase-change characteristics. Considering the features, this material is efficient in sustaining thermal functionality over a period of peak demand and comfort during the day time. The bulk of commercially accessible phase change materials are made with wax. Bio-PCM is able to be produced from leftover feedstocks from the agricultural industries, for instance, soybean and is substantially reduced flammability compared to PCM made with non-organic materials.

Sustainability of bio-based products usually is extremely valued. There are 2 key groups of ecological benefits connected to making use of bio-based products. The very first group is connected to product production. CO_2 is trapped in all-natural cells of biomaterials and also, as a result, does not add to the greenhouse outcome. The 2nd team of benefits is connected to the end-of-life of bio-based things. Biodegradability enables green degeneration of things and also a return of chemical substances back to the natural cycles. From the power preservation perspective, façades are obstacles in between insides of building and even the surrounding environment. To conserve energy, it is crucial to minimise the power transfer between the inside as well as the outside building while keeping a favourable and healthy and balanced internal microclimate. BioPCM can achieve the above attribute without any doubt.

The four specifications that are crucial to carrying out the simulation making use of

BioPCM are absorption of solar energy, melting temperature, specific heat, the thickness of PCM materials, and R-value. BioPCM is an encapsulated poly film based fatty-acid which is considered as an organic PCM commercially developed by Phase Change Energy Solutions. The BioPCM type adopted in this study was BioPCM Q23 with the specification is given in Table 6.4. The separate covering blocks craft them perfect for retrofitting. In this research, the optimal shift temperature level of the phase adjusted material was picked depending on the cumulative hrs that sustain the comfort standards of the people with no additional treatment of air circulating in the building. The curve for BioPCM Q23 using Differential Scanning Calorimeter is presented in Figure 6.3. This material is described to hold a latent heat of 210 to 250kJ/ kg, and specific heat of 2.2 to 4.5 kJ /kg K. The melting and freezing temperature of the Q23 BioPCM is 27 ◦C and 23 ◦C respectively (Jayalath *et al.* 2016).

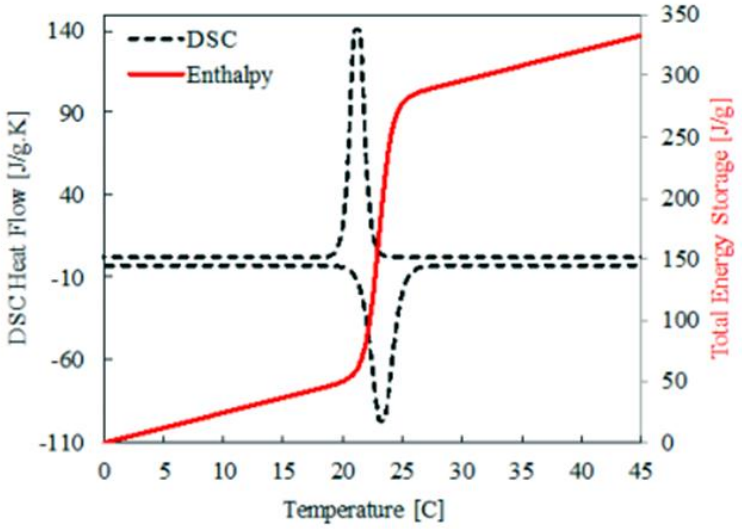


Figure 6.3 Differential scanning calorimeter curve for BioPCM Q23 (Phase Change Energy Solutions, 2019)

6.6 TROMBE WALL

Trombe wall structures can be considered as solar energy tools created for thermal energy storage space and transfer when needed. A Trombe wall includes a solid wall faced with a particular area photovoltaic absorber, air space, as well as glass pane with higher transmissivity. Trombe walls are generally sun faced for maximum visibility. An overhang over the wall structure is used to minimise uncovering in the summertime when the sunlight is higher, and heating is not essential to operate. Spec of Trombe wall envelops utilised for the instance research revealed in Table 6.5.

Table 6.5 Specification of a trombe wall

Wall Type	Trombe Wall
Number of Layers	4
Materials	Thickness(m)
Outermost Layer	
Brickwork outer	0.105
XPS Extruded Polystyrene	0.118
Concrete Block	0.1
Innermost Layer	
Gypsum Plasterboard	0.013
Interstitial Condensation	The structure is free of condensation
Surface Condensation	Thermal quality is good. Mould growth unlikely
Cost	$195.99/sq. m
R-value (m^2-K/W)	3.973
U-Value (W/m^2-K)	0.263
U-Value Surface to Surface (W/m^2-K)	0.263
Image	

This technique gives versatility in stating the several wall structure parameters and makes it possible for the freedom to discover different configurations. A Trombe wall is generally an enclosed zone without exposure to air. The outdoor barrier surface of the Trombe region has a solo or dual-panel opening. Efficiently, the opening deals with most of the structure and possess an elevated transmissivity to make it possible for the highest volume of solar energy changes into the Trombe area. The internal wall structure is typically designed of incredibly bulky brickwork area to absorb solar energy in the inner tier of the wall. The absorbent material has a discerning area with extreme absorptivity as well as reduced emissivity. Most Trombe walls work based on the passive principles could be vacuum-packed off or even sometimes ventilated.

6.7 BUILDING INTEGRATED PHOTOVOLTAIC WALL

Building-integrated photovoltaics (BIPV) are solar elements that are physically incorporated into the building outside wall (Montoro *et al.* 2011). BIPV is a multi-performing innovation, which is not only able to generate electric energy but also functions as a weather and sound barricade. BIPV can create usable heat energy as well as the surface enables the transmission of daylight radically efficient in turning up to about 80% of the photovoltaic radiation right into useful power.

BIPV is an emerging technology and is anticipated as the principal tools for producing energy onsite. The additional advantage of BIPV is its net-zero energy properties given that it could be taken advantage of to deal with the huge roofing system and front view surfaces. For this to be actually performed successfully, the alignment and form of the main surface areas have to be improved. Specification of BIPV envelop used in the modelling is shown in Table 6.6.

6.8 CAVITY WALL

A cavity wall possesses a wall structure with a void inner gap. A cavity wall consists of double brickwork wall surfaces separated through the void inner gap. It could be illustrated as being composed of two levels divided through the void inner gap. A cavity wall includes double brickwork wall structure areas split with deep interior space. The exterior wall surface is made from brick which faces the outdoors of the building structure. The internal wall structure might be built of brickwork systems such as concrete, brick or clay-based, improved concrete. These pair of walls are secured with each other with metal ties or even bonding blocks. The links build up the cavity wall surface. The specification of the cavity wall is provided in Table 6.7.

Table 6.6 Specification of BIPV envelope

Wall Type	Building Integrated Photovoltaic Wall
Number of Layers	4
Materials	Thickness(m)
Outermost Layer	
Brickwork outer	0.1
XPS Extruded Polystyrene	0.0795
Concrete Block	0.1
Innermost Layer	
Gypsum Plasterboard	0.013
Interstitial Condensation	The structure is free of condensation
Surface Condensation	Thermal quality is good. Mould growth unlikely
Cost	$195.99/sq. m
R-value (m^2-K/W)	2.856
U-Value (W/m2-K)	0.35
U-Value Surface to Surface (W/m2-K)	0.372
Image	

Table 6.7 Specification of Cavity wall

Wall Type	Cavity Wall
Number of Layers	6
Materials	Thickness(m)
Outermost Layer	
Brickwork outer leaf	0.105
Mineral wool batt	0.075
Concrete	0.01
Air layer	0.022
EPS	0.02
Innermost Layer	
Plasterboard (wallboard)	0.013
Interstitial Condensation	The structure is free of condensation
Surface Condensation	Thermal quality is good. Mould growth unlikely
Cost	$461.33/sq. m
R-value (m^2-K/W)	3.11
U-Value (W/m2-K)	0.321
U-Value Surface to Surface (W/m2-K)	0.34
Image	

6.9 MODELLING AND SIMULATION APPROACH

An Energy Plus algorithm is a distinctive instrument for evaluating the thermodynamics efficacy of the indoor space in the building. The algorithm is adopted in this study to estimate the ability of the current and alternative environment-friendly envelope system to decrease the cooling requirement during the peak hours and eventually decreasing the energy for cooling usages and operational CO_2 emission. The algorithm applies the computational method to develop the base case scenario and customised to suit the specific modelling conditions for all the chosen alternative envelope system and calculate the energy efficacy of the system. A virtual environment was formed using the algorithm to set the base case (existing) up and validate the model so that the outcome of the model in normalised condition could be adopted for the comparative study. This simulation-based assessment is conducted to explore and quantify the capacity of the selected envelope systems to reduce the cooling requirements in the subtropical climate.

The seasonal differences of thermal equilibriums amongst people and the surrounding atmosphere are studied considering the dynamic weather condition of the place. The set-point temp and metabolic rate are also an important variable in this process. Clarke and Hensen (2015) explained the function of a building system simulation program which can contribute with the development of effective interior environments and overall thermal performance. Thermal comfort is measured to attain and preserve a pleasant condition could be determined by developing a model with the required information and undertaking the simulation of the developed models. The authors presented a procedure through which the impact of individual behaviours could be included right into a current program. The findings recommend that it is actually feasible to calculate the series of scenarios of the indoor environments, to forecast the comfort of residents, to estimate the impacts of tenants' practices on the electricity usage, to design the interior microclimate in subjugated properties as well as to recognize the activities needed to recover their comfort.

The thermal efficiency in a structure is affected by several elements such as outside environment, heat transfer, ventilation rate, indoor heat gains as well as losses via the structural envelop, overall thermal mass, occupancy and so on. Entire building performance simulation is an influential tool since it considers the construction details outer atmosphere, interior environment, ventilation, mechanical and electrical systems to analyse and accomplish much better interior setting. In this research study, several envelopes with remarkable energy effectiveness are tested to minimise the energy consumption and dependence on non-renewable fuel source as well as boost thermal comfortability of the owners in the subtropical climate of Australia. Here, a variety of wall-building envelope systems for the mainstream building are used which are entirely distinctive compared to the existing brick wall.

6.10 RESULTS AND ANALYSIS

Energy simulation of the building carried out for all the chosen envelope systems depending on the specification stated earlier concerning the selected hourly weather data for the location. The overall cooling loads are computed as considering the enthalpy variance in between return air and the supply air for the extant load in the specific zone. Heat gain via exterior ventilation is from the addition of outside air through air supply mechanism in place. Sensible cooling load requirement is calculated considering the amount of outside air included in the zone via the air supply mechanism. Depending on the weather condition, this can be considered as a free air treatment mechanism because of the introduction of relatively cold outside air.

At the time of the external atmospheric air temperature level is boosted in summer compared to the winter months, the energy usages by the building increase in those summer months in between October and March. The base power usage by other systems remains almost the same depending on the occupancy profile. The interior heat gain is due to people, lights, devices, ventilation etc. The distinction in between the retrofitted results and the existing scenario essential because there is a vast scope for renovation, which will better power efficiency both in summer and winter over some time. The average monthly electrical energy use info is calculated using each of the envelop systems as well as the distinctions among the alternative envelope systems and the existing envelope were profiled.

From Figure 6.4, it can be stated that the application of alternate envelope systems lowers the overall cooling energy intake by the mechanical systems. The monthly average electricity consumption for cooling by the whole building using BioPCM envelope varies from 2.1% to 7.3% monthly energy savings in winter months and 1.2% to 1.4% monthly savings of energy in summer months judge against the base case scenario. A BIPV envelope also offers a similar type of energy savings from 2.4% to 6.8% monthly savings of energy usages in winter months and 1% to 1.2% monthly savings of energy in summer months when judged against the base case scenario. Both the alternative envelopes offer better energy saving throughout the year compared to the existing envelope.

Trombe wall, Cavity wall and New envelopes demonstrate reasonable energy-saving potential in few months of the year. The rest of the months all these three envelope systems demand more cooling energy compared to the existing system. Trombe wall recommends 3% to 4 % monthly energy saving judged against the base case in the summer months. Similarly, the new envelope offers 1% to 1.2 % monthly energy saving against the base case in the summer months. A Cavity wall provides around 1 % to 1.2% monthly saving of energy in comparison with the base case during the winter months. Although all these methods offer some savings on the specified period, these envelopes did not demonstrate any savings for the residual months of the year. The Trombe wall and the new envelope consumed up to 13.8 %and 1.2% more energy every month during the winter months, and the cavity wall-based envelope consumed up to 2.9% more monthly cooling energy compared to the existing envelope.

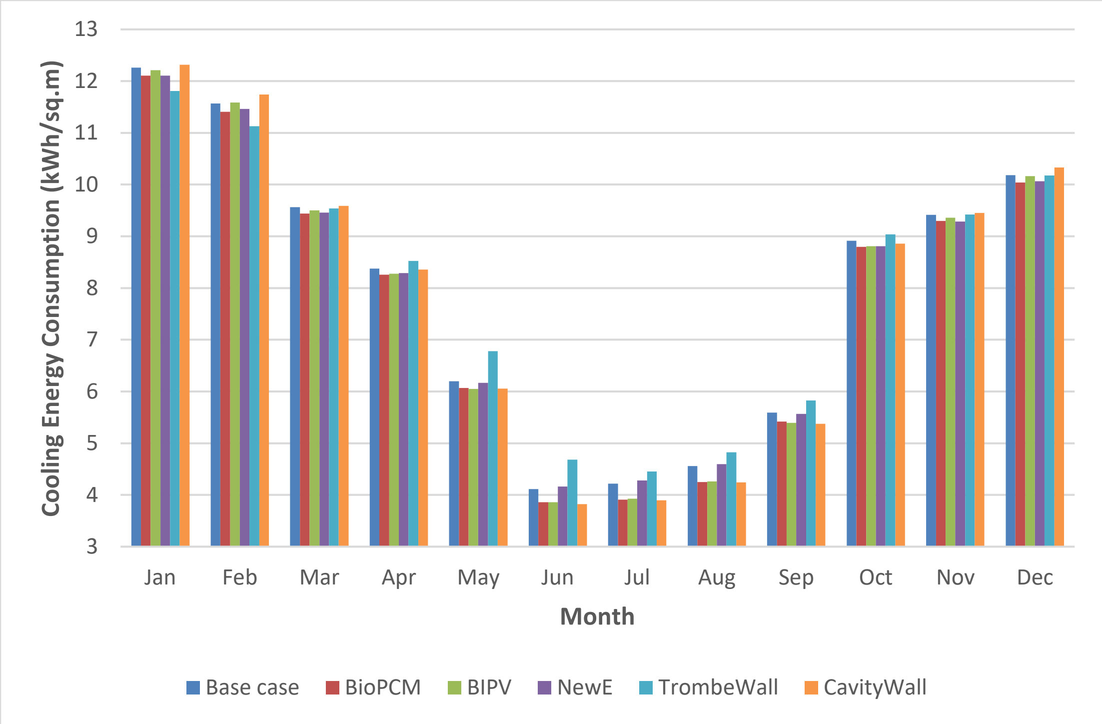


Figure 6.4 Cooling energy consumption profile under alternative envelop systems

Figure 6.5 represents the comparison of normalised monthly overall energy usage in the building under alternative envelop systems. The normalised monthly overall energy usage by the whole building using BioPCM envelope varies from 2.3% to 6.8% monthly energy savings in winter months and average 1% monthly energy savings in summer.

A BIPV envelope also offers an almost similar type of energy savings in both the summer and winter months compared to the base case scenario. Trombe wall recommends 6% to 10 % monthly energy-saving weigh against the base case during the winter months. A Cavity wall offers around 5.3 % to 7.2% monthly energy-saving weigh against the base case during the winter months. Although all these methods provide some energy savings, these envelopes did not demonstrate any savings in the remaining months of the year.

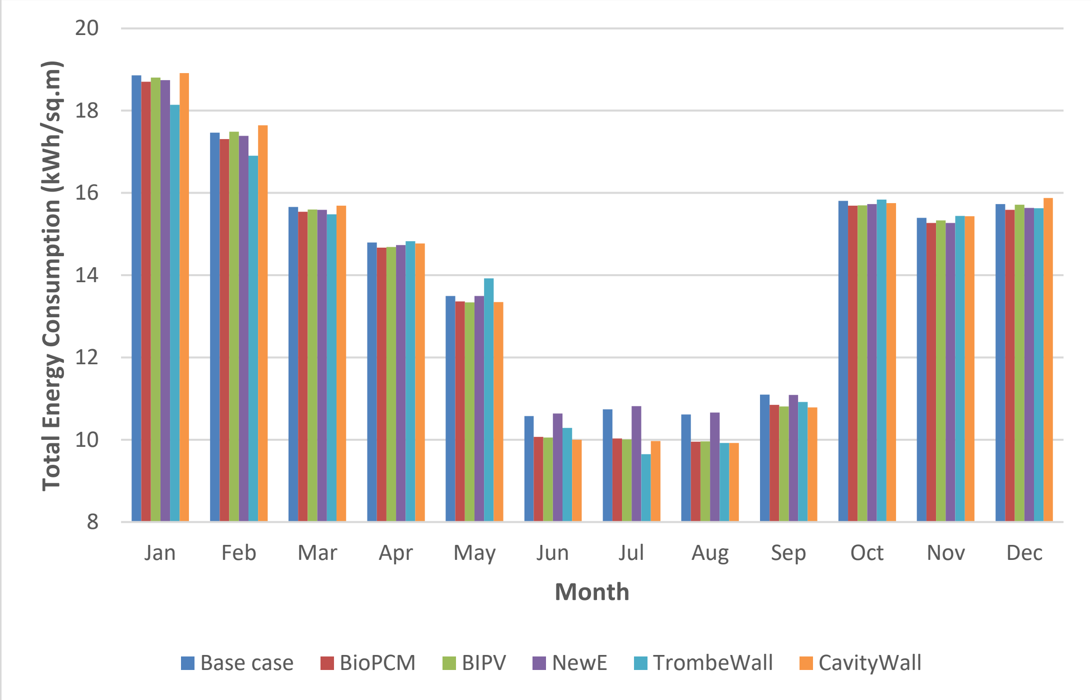


Figure 6.5 Total electricity consumption profile under alternative envelope systems

Figure 6.6 represents the comparison of normalised month-to-month operational CO_2 emission by the operational systems under alternative envelope systems. Since building envelopes play an active role in holding the thermal mass within the indoor space, the envelops systems directly contribute to overall operational CO_2 emission by the building systems. The normalised monthly functional CO_2 release by the entire structure utilising BioPCM envelope varies from 2.3% to 6.8% in winter months as well as ordinary 1% regular monthly power cost savings in summertime contrasted to the existing building. A BIPV envelope additionally supplies almost comparable reduced CO_2 emissions in both summers as well as winter season contrasted to the base case scenario. Trombe wall surface suggests 6% to 10 % monthly reduced CO_2 release compared to the base situation during the winter season months. A Cavity wall provides around 5.3 % to 7.2% reduced CO_2 emission compared to the base case during the winter months. Although all these approaches supply some energy, these envelopes did not demonstrate any savings in the remaining months of the year.

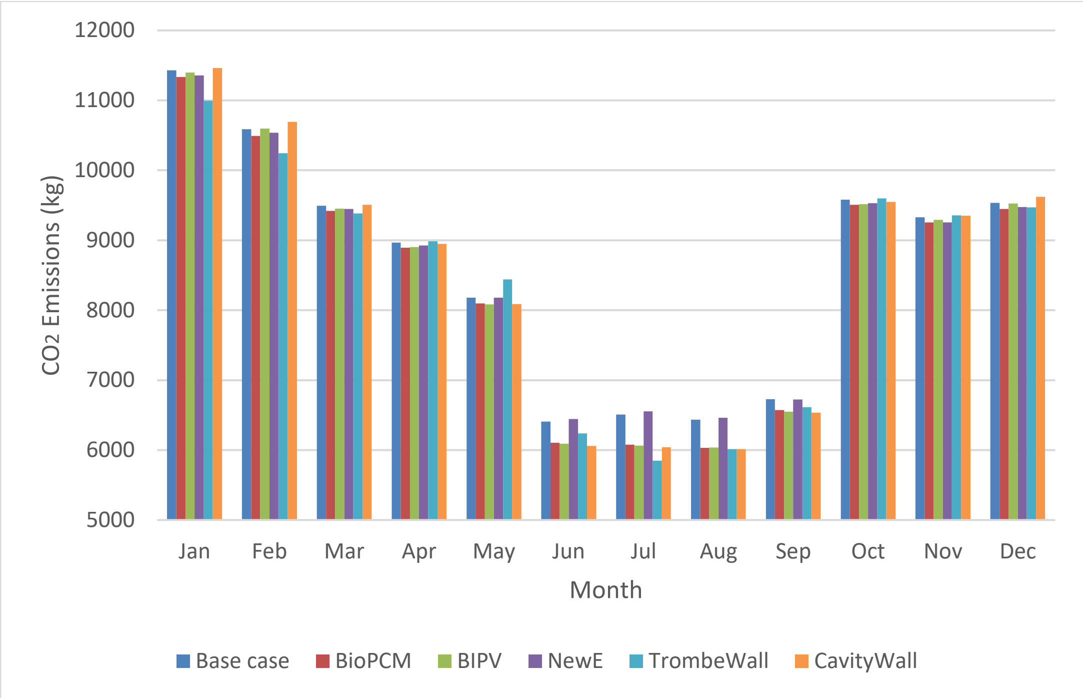


Figure 6.6 Operational CO_2 emission profile under alternative envelope systems

Figure 6.7 and 6.8 represent the sensible and total cooling load under different envelope systems. The monthly sensible and total cooling load saving using BioPCM vary from 1.1 % to 7.9% during the summer and winter months. BIPV wall offers between 1% to 7.8% monthly normalised cooling load reduction in summer and winter months. The sensible and total cooling load reduction is not that visible using a Trombe wall. Insulated Cavity wall offers up to 8.4% reduced sensible and total cooling load reduction during the winter months only. The new envelope system offers a slim reduction in both sensible and total cooling load during the summer months only. Finally, it can be concluded that BioPCM offers 2.4 kW/m^2/annum reduced sensible and complete cooling load judge against the existing building envelope that is the highest compared to all other envelope systems compared. BioPCM also offers an overall 5.9% total energy consumption per year measured up the base case scenario which is also the highest energy usages reduction compared to all other options.

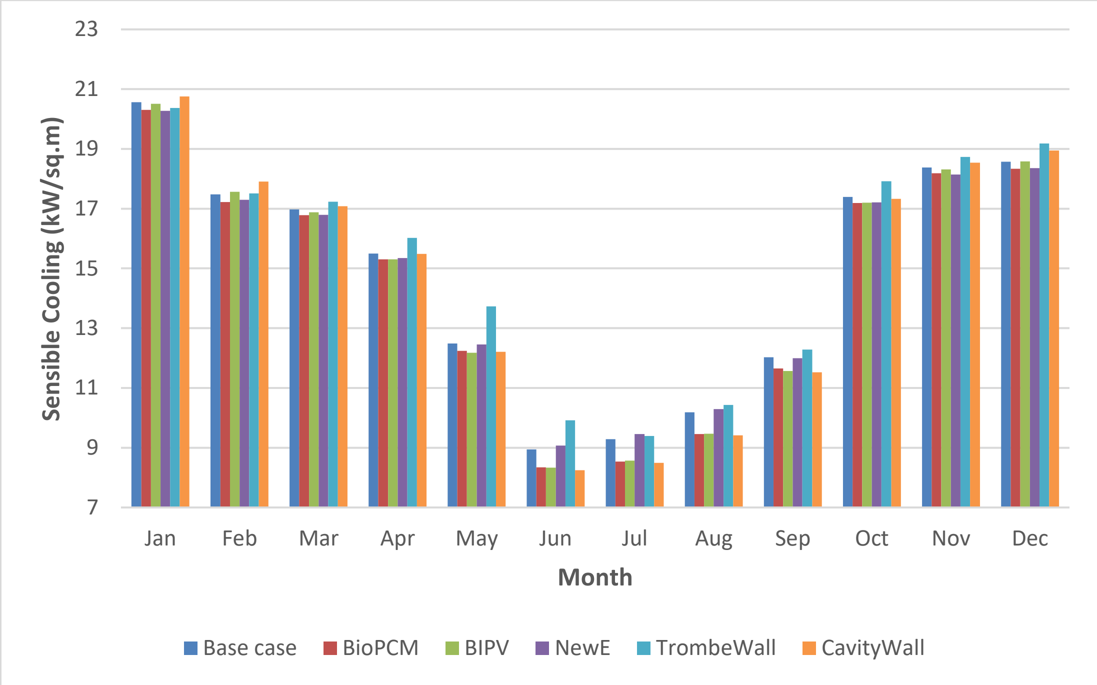


Figure 6.7 Sensible cooling load using alternative envelope systems

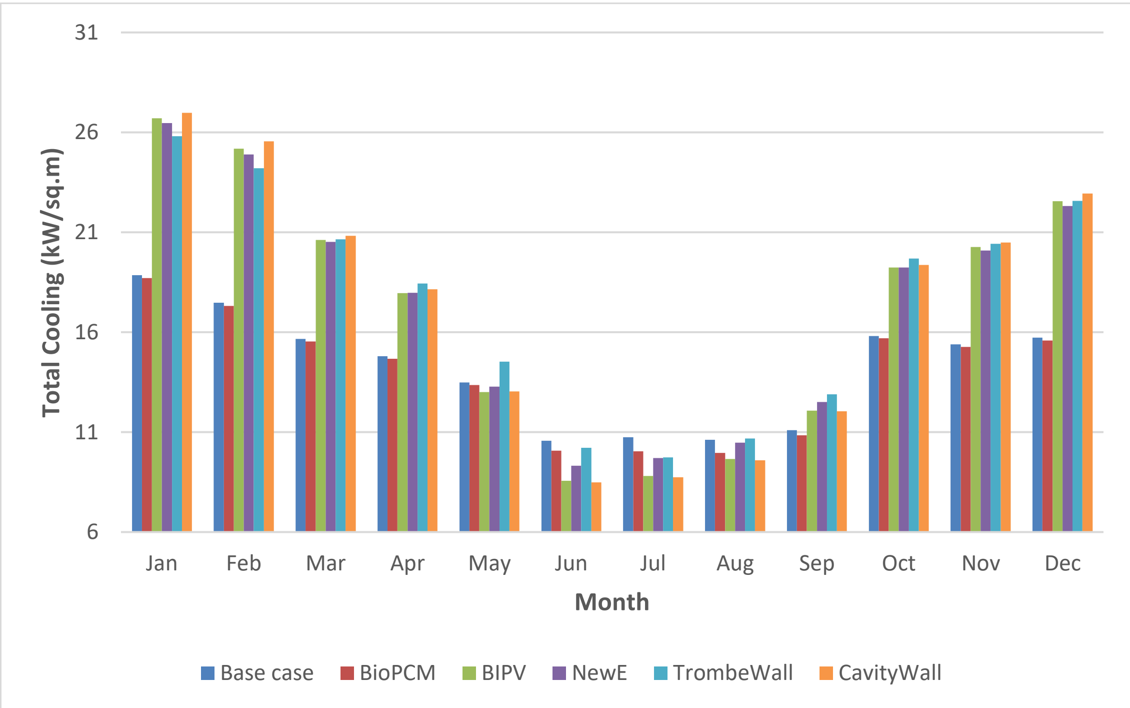


Figure 6.8 Total cooling load using alternative envelope systems

6.11 CONCLUSIONS

The alternative building envelops have an immense capacity to adhere to greater energy savings when considered the existing building and envelope assembly mechanism. The strength of the selected exterior envelopes on reducing the cooling load requirements and the subsequent energy usages are examined. On completion of the assessment, an envelope system utilising BioPCM has a higher possibility for energy savings and peak energy demand to subtropical environment regions like Rockhampton. These envelopes systems can have a crucial function in minimising dependence on HVAC units to meet the comfort requirement. The analysis uncovered that BioPCM based insulation envelope system could be efficiently adopted in building the wall in sub-subtropical Rockhampton and other places with the similar weather condition in Australia. These envelope systems will undoubtedly permit the building to be made faster, flexible to suit the relevant climate as well as will offer a seriously required scientific superiority in transmuting large office spaces to a fresh height. In addition, this appealing low-cost findings could be estimated as a durable technique on the emerging climate transformation problem to reduce long-term consequences.

Chapter 7: Computational Comfort Analysis

7.1 INTRODUCTION

Numerical depictions of the preservation of matter, motion and energy flow in fluids have been adopted to advance, sets of estimation whose resolutions would explain the temperature pressure, the velocity at any location in the fluid for a given limit condition. Unfortunately, these mathematical expressions are very problematical to resolve and need more straightforward statements and numerical solution methods. Calculating these results are a continuing challenge to the speediest of the computers. The core theory of computational fluid dynamics (CFD) is the preservation of properties in the movement of the fluid. This can be studied as a variation of measure in an area equal to flow in/out of the area plus diffusion in/out of the area and creation or deficiency in the space. The performance of building systems can be impressively evaluated by adopting computational fluid dynamics (CFD) technique. This chapter will demonstrate the computational analysis of comfort in the building by applying comfort theories and CFD principles.

7.2 COMPUTATIONAL COMFORT ANALYSIS

There are numerous analyses related to the possible utilisation of the CFD technique in indoor space in relation to the assessment of the impact of airflow within and outside of the building. Sadrizadeh and Holmberg (2015) depicted the diverse air dissemination techniques for a room air conditioning system and evaluated the functioning of unique parameters of the system. Myhren and Holmberg (2008) researched indoor air quality and atmosphere control parameters by the CFD technique. Karimpanah *et al.* (2014) tried four diverse air dispersion frameworks with a cooling load to anticipate air temperature, airspeed, ventilation adequacy and so on and created a unique computational fluid mechanics-based analysis technique Zhai *et al.* 2014 combined various systems in a typical building systems efficacy simulation program along with a CFD program which has resulted in a better airflow prediction method. Storås (2019), Dziedzic, *et al.* 2019, Cuce *et al.* 2019 and Sultanguzin *et al.* 2019 have attempted to consolidate the CFD based performance assessment method with the building energy analysis technique. The significant utilisation of CFD in interior building space is identified with air-conditioning as well as ventilation performance assessment and the forecast of ventilation rate. Mallick and Kumar (2019) applied the execution of K-e model, low Reynolds model and RSM to evaluate indoor airflow pattern within the building space.

CFD module of DesignBuilder has been intended to envisage airflow and temperature dissemination in and around structures utilising indistinguishable strategies from the general CFD software. For predicting airflow pattern and thermal comfortability using traditional CFD software, for instance, Clima 3D, Fluent, Phoenics, etc. require a lot of efforts to define the geometry, boundary conditions and derive the potential outcome. CFD module of DesignBuilder rearranges this procedure tremendously via logically giving the geometry and limit conditions based on the supplied building information modelling specifics. Temperatures and heat stream rate determined by internal assessment deliver the delivery of pressure, velocity of air, and temperature all over the building spaces. This evidence could be expended to calculate the efficacy of different ventilation and AC system and to assess the comfort conditions in the indoor space.

EnergyPlus could be flawlessly used to give limit conditions basically by indicating the time/date of the CFD examination. CFD interface of DesignBuilder empowers virtual CFD investigations from sequentially created principle-based default data.3D CFD matrices are naturally produced from model geometry and limit conditions and can be adjusted to advance arrangement assembly. The CFD algorithm utilises a SIMPLER calculation, which has a place with a standout amongst the most generally utilised groups of CFD arrangement strategies. The disturbance is demonstrated utilising the k-e display. The interface fuses apparatuses to empower a wide scope of limit conditions, for example, supply diffusers, extricates, temperature patches, and so forth to be administrated out to room surfaces. In this study, a building model has been recreated, and comfortability of the tenants have been mimicked utilising computational liquid elements methods.

The comfort temperature has generally been calculated using regression analysis using a procedure that is fully explained in Nicol *et al.* (2012). It expresses the tendency for occupants to familiarise to the settings people usually encounter. Majority of these studies were carried out during the daytime in non-domestic buildings. There is surprisingly little information about night-time thermal comfort (CIBSE, 2013), though it is generally assumed that sleep deficiency from sweatiness in the night-time is the main drive for purchasing an air-conditioner. This trend is particularly problematic in the urban context where there is less air movement, and urban heat island effects are most noticeable after dark. This partnership in between atmosphere and comfort determines the adjustment of the people they normally exposed to in day to day life. It is the underlying relationship between the adaptive thermal comfort model. Note that the link applies irrespective of whether the buildings are mechanically or naturally conditioned, or indeed mixed mode.

While the comfort temperature is not equivalent to the average indoor temperature, the span of temperatures for a given mean indoor operative temperature is in the range of 3–4 K (95% confidence interval). Because each point on the graph is the result of a considerable number of individual comfort assessments (minimum 20), the actual values are statistically reasonably precise. So this is a real range of comfort temperature, not merely an error about a mean. While there are potential sources of error in, for example, the sampling of the buildings and the times of day at which the data were collected, this suggests that the optimum temperature can generally be estimated from the average operative temperature within a degree or two (Chowdhury *et al.* 2018). The indoor neutral temperature is not the same as the indoor mean operative temperature but is somewhat below it in hot conditions and above it in cold conditions. In conditions where there is air movement, the neutral temperatures will be higher. In hot climates, fans are often provided in offices as a matter of course so that the degree of overheating implied by the discrepancy between neutral temperature and operative temperature.

7.3 MODEL DESCRIPTION

The modelled building has a concrete footing for the foundation. Most of the key construction details have remained unchanged, as discussed in the base case scenario in Chapter 4 of this thesis. The outside wall is modified considering the best performing alternative BioPCM envelope made with brickwork, XPS extruded polystyrene, BioPCM Q23, and gypsum plasterboard. The internal wall is comprised of plasterboard on both sides with timber structure. The building consists of three levels, and the conditioned are amended to be served by a Cooled Beam HVAC system as the best suitable system identified in Chapter 5. The base case model developed with the existing settings has been considered to undertake the computation comfort analysis. The model is updated based on the selected alternative low emission Envelope and HVAC system suitable for subtropical climate. An essential first step to carry out CFD analyses is to specify the limit conditions. All the related variables in the formulas require realistic values for the computations in the fluid domain, which are called boundary conditions of the problem statement. The requirements of the boundary conditions for the CFD analysis of the indoor space need the additional zone surface temperature, heat gain, supply diffusers, grille as well as the design settings up representing residents, HVAC systems etc.

7.4 CFD SIMULATION PROCESSES

The software, DesignBuilder, is adopted to assess people comfortability in an academic building located in Rockhampton, Australia. DesignBuilder (DB) Version 6.0.1.019 CFD module was adopted to determine the comfortability of people within the building. DesignBuilder creates a simulated atmosphere where the performance building energy systems are evaluated, and peoples thermal comfort are predicted. The CFD technique is applied that accounts on the governing partial differential equations (PDEs) depending on the energy, momentum and turbulence quantities. The CFD method of the DesignBuilder software considers all the reasonable and available yield designs: shading shapes, vectors and streamlines, which can be comprehended. The grid is arranged to fit the geometry of objects in the model building. The number of cells is 71 x 120 x 38. Here the grid is a distinct illustration of the constant field incidents. The precision and mathematical steadiness of the model depend on the selection of the grid. The mathematical method applied by the CFD module is referred to as a primitive variable method, which includes equation sets representing the conservation of mass and momentum. The momentum equation (Navier-Stokes formulas) has three velocity components and the temperature. The study adopts a k-ε turbulence model and the principle of turbulent kinetic energy. The formulas consist of a collection of paired non-linear partial differential formulas of second order. The theory considers the airflow is an incompressible and steady-state in the air-conditioning system. The leading equations for the general dependent variable, φ, is expressed by the equation 7.1.

$$\frac{\partial}{\partial t}(\rho\phi) + div(\rho u\phi) = div(\Gamma grad\phi) + S \tag{7.1}$$

where

ρ = the density,
Sφ =the source/sink rate per unit volume for the dependent variable φ
Γ φ = the effective exchange coefficient of φ.

The k-ε model, which is an accessible widely utilised turbulence model originated from the RANS (Reynolds Averaged Navier-Stokes) family principles, is adopted in this study. This model requires substituting the instantaneous rate in the Navier-Stokes as well as energy formulas with a mean and swaying element. The derived methods provide surge to supplemental terms as Reynolds stresses and unstable heat flux elements. Reynolds stresses are changed with terms entailing instantaneous rates where molecular viscosities are alternatives to efficient viscosities. A comparable alternative is carried out for the energy equations. The efficient viscosity is the amount of the molecular and turbulence viscosity that is acquired as of the turbulent kinetic energy (DesignBuilder Software, 2019).

Li *et al.* (2009) indicated that the computational technique assumed for a 3D airflow with turbulence which can resolve the core numerical formulas for the variables, for instance, the component of velocities in 3D space, pressure, temperature. Finite volume technique is applied to resolve the equations. In the model, the velocity module for both inlet and outlet flow is checked to confirm that the flow rate has a constant value. DesignBuilder applied a computerised amorphous hybrid mesh surface where a mesh refinement algorithm is allowed to characterise the boundary conditions precisely.

Grids were applied to identify the locations with sizable gradients of the solution variables, for instance air velocity, temperature. Grid refinement applied on the surface of heat sources and in the inlet and outlet regions. The airflow rates and temperatures of the air supply diffusers and jets were set equal to their actual values as the boundary condition. The flow was expected to homogeneously disseminate in all these stream entrance by means of a perpetual upright velocity. The temperature was specified in the model as the temperatures of the internal surfaces. Heat fluxes were considered to signify the tangible quantity of heat produced by the types of heat sources. The concept applied to perform the CFD simulation is shown in Figure 7.1.

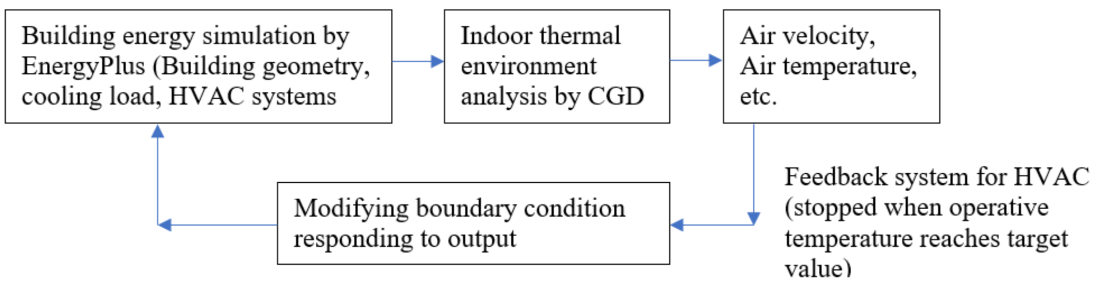


Figure 7.1 CFD Simulation framework for building systems

DesignBuilder CFD works based on the finite volume (FV) technique shown in Figure 7.2. The technique encompasses the service of a collection of PDE formulas explaining the transportation of power, energy and momentum amounts. CFD simulation techniques in building specify the details on air temperature as well as velocities occurring in the rooms with specified limit conditions including environment, heat gain and air conditioning system.

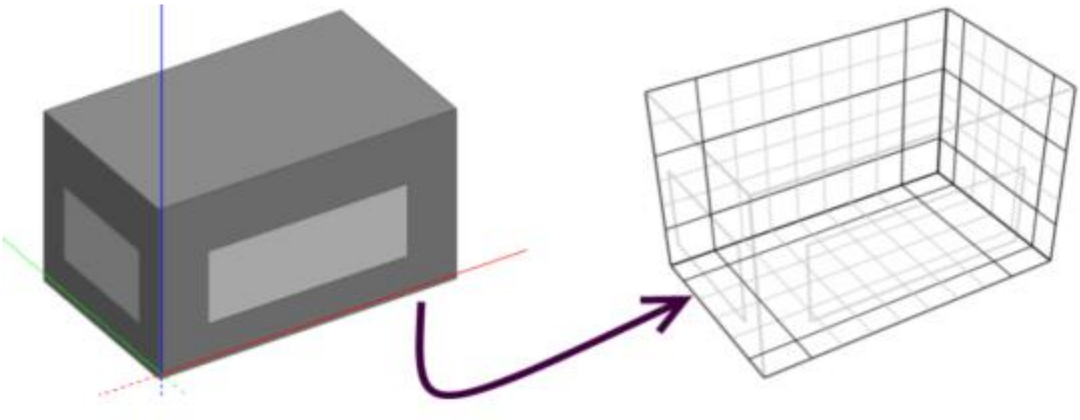


Figure 7.2 Finite volume grid transformation (DesignBuilder Software, 2019)

As indicated in the DesignBuilder Software documentation (2019), at the start of the solution process, PDEs are exchanged to a group of arithmetical formulas. The indoor space in the room is split right into a collection of non-coinciding straight-lined cells situated side by side, which can also be denoted as finite volume grid. Algebraic formulas are established up for all the cells in the grid cell. The entire collection of equations was resolved by following the suggested solution method. The PDEs are composed of a variety of terms including a multiplier or coefficient. The coefficients in the differential equations could include identical variables; consequently, the formulas cannot be resolved using logical techniques. The variant of the PDE is constant. Linear partnerships can resolve the constant nature of these non-linear variables. This process is called discretisation.

The procedure is started by distributing the indoor space into several non-coinciding control volumes jointly referred to as the finite volume grid. The individual control volume is covered by a lattice location where the variable is examined. The PDEs can be discretised throughout the control volumes utilising linear outlines to stand for the variant of the reliant variables in between the grid points. These discretised equations are reorganised to algebraic equations so that can be resolved utilizing standard mathematical methods. The mathematical approaches are iterative whereby the formulas are continuously rearranged until there is no adjustment needed in the variables. The algebraic formulas are formed so that a converged option can usually be achieved utilising the Gauss-Siedel method (DesignBuilder Software, 2019).

Table 7.1 Indoor and outdoor environmental condition in CFD

Design Condition	Minimum	Maximum
Indoor Temperature	22 °C	24 °C
Humidity	45%	50%
Comfort Index	-0.5	0.5
Outdoor Temperature	n/a	36.5 °C
Outdoor wet bulb temperature	n/a	24 °C
Global Solar Radiation	n/a	950 W/m^2

7.5 FINDINGS FROM COMPUTATIONAL COMFORT ANALYSIS

Approximation of cooling and heating load requirements is performed using the weather data for Rockhampton to decide the extent of the cooling and heating equipment necessary to sustain the very coldest and most popular summer and winter situation likely to be in Rockhampton. Energy Plus presumes that airflow temperature inside an area is completely standard. In the Energy Plus algorithm, it is assumed that the air indoor temperature in a thermal block is blended and consistent throughout the block. The environment details used in both summer and winter months are highest and lowest outdoor dry-bulb temperature, outdoor dew point temperature, wind speed, wind direction, atmospheric pressure, direct solar average and diffusive solar radiation tec. Figure 7.3 represents the typical relative humidity and dry bulb temperature profile of the indoor space.

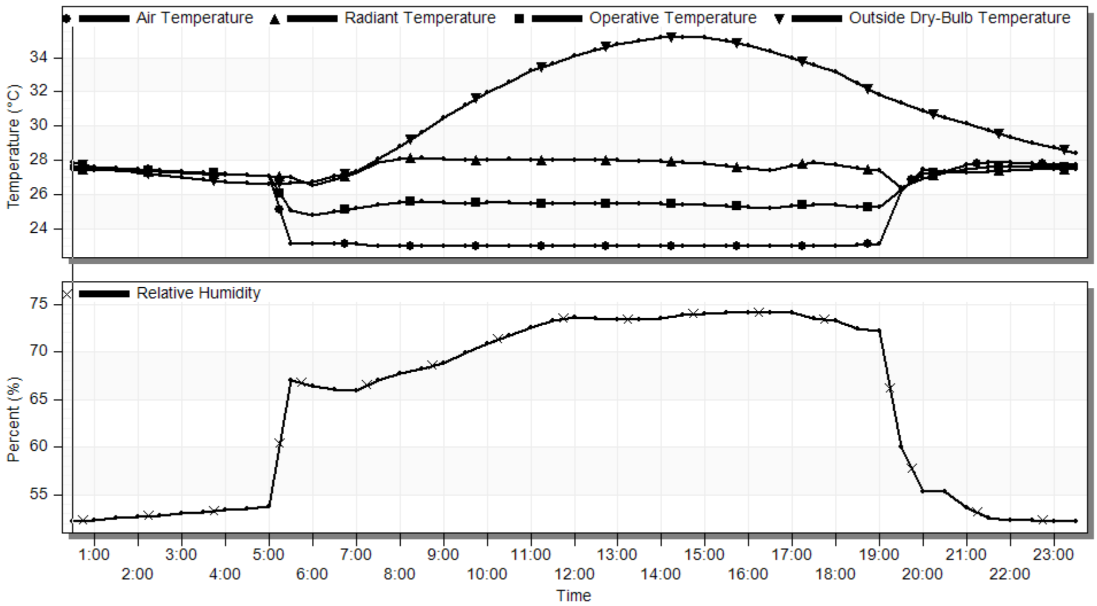


Figure 7.3 Temperature and relative humidity using the base case scenario

The degree of human relaxation and wellbeing is established with the Fanger PMV calculation method for several air conditioning methods and evaluated against the base case in summertime and wintertime. As the operational requirements of the cooling system depend on the usage of the space, the comfort values were simulated based on weekday service hours. Figure 7.4 and 7.5 represent the summer and winter indoor air temperature profile which demonstrate that the setpoint temperature is fairly consistently maintained all through the daytime when the BioPCM and Cooled Beam cooling method is applied respectively. The exception is at the start of the day for both the cases due to non-operating hours of the HVAC system.

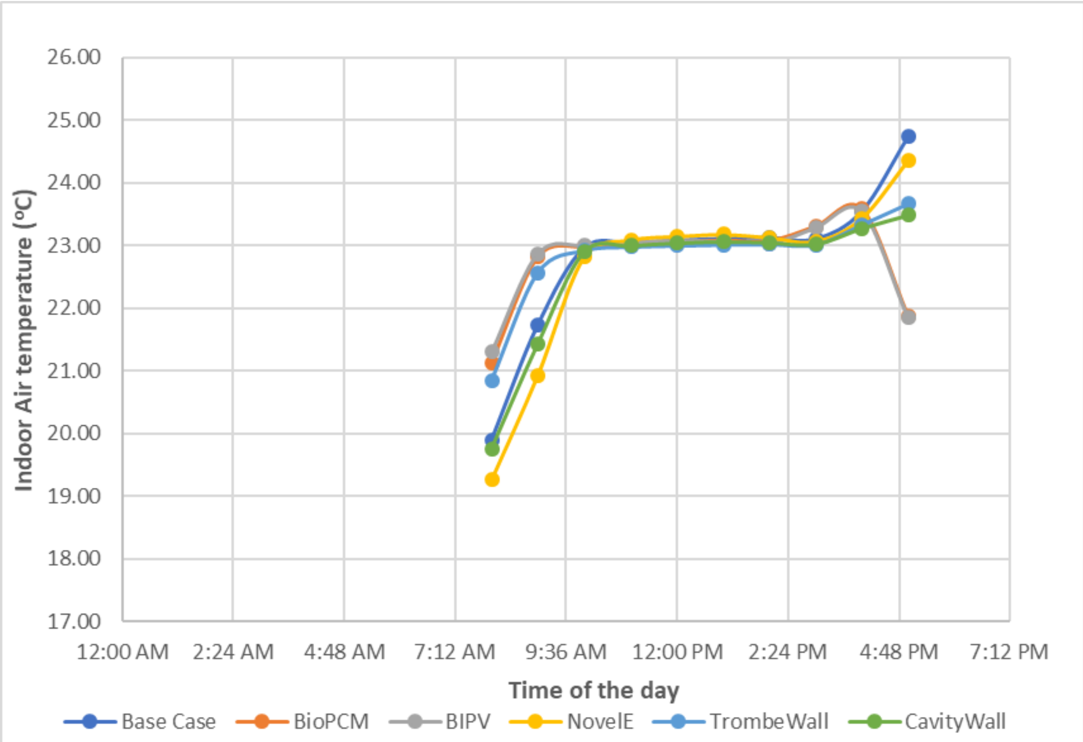


Figure 7.4 Indoor air temperature summary using the alternative envelop systems in summer

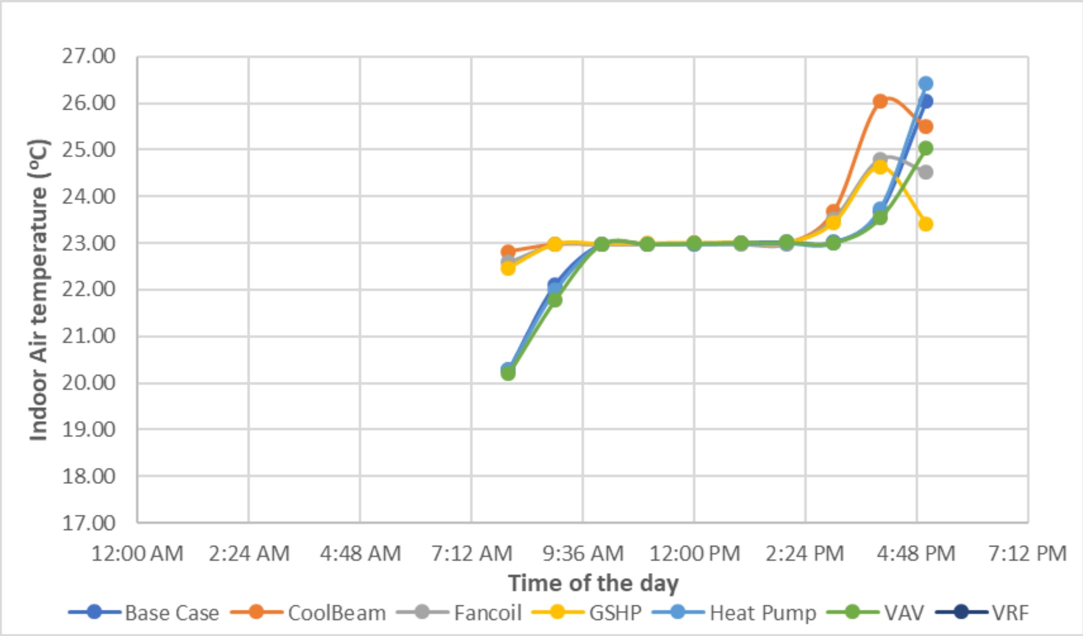


Figure 7.5 Indoor air temperature summary using the alternative HVAC systems in winter

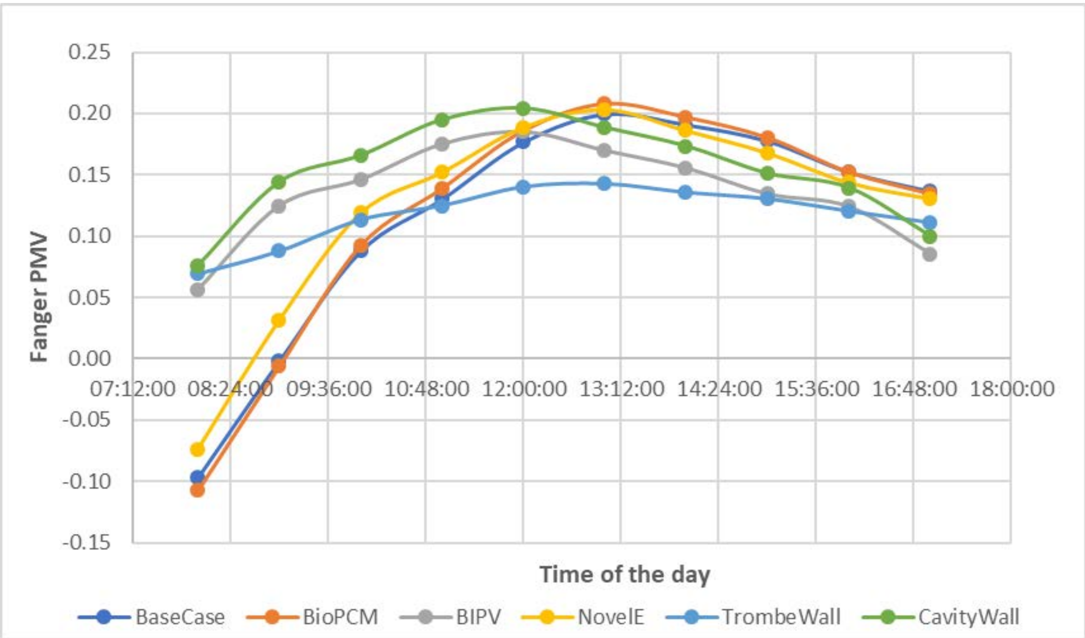


Figure 7.6 Thermal comfort index using the alternative envelope system in summer

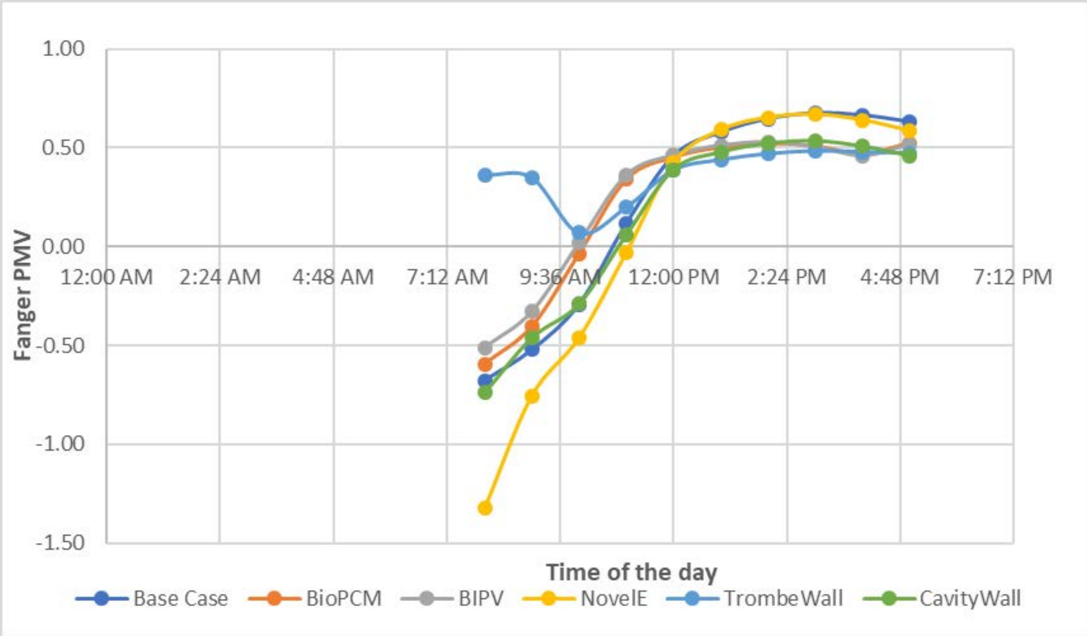


Figure 7.7 Thermal comfort index using the alternative envelope system in winter

Figures 7.6 and 7.7 indicate that the thermal comfort is maintained using all the alternative envelope systems in summer within the desirable range, i.e. PMV value with ±0.5 as per comfort standards discussed in Chapter 2. The trend is not the same in winter using a similar type of envelope system. BioPCM, BIPV, Trombe Wall and Cavity Wall were able to maintain the comfort throughout the day; however, the new envelope system along with the current base envelope was not able to maintain the comfort after the mid-day due to lack of thermal mass.

The comfort is also evaluated using all the selected alternative HVAC systems, and the outcome is demonstrated in Figures 7.8 and 7.9 for summer and winter day. The results indicate that the comfort was maintained within the recommended ±0.5 range throughout the day in summer using all the alternative cooling methods. The comfort profile is not the same in winter months; only cooled beam exhibited the PMV value within the recommended ±0.5 range. Other systems offer slightly higher PMV value compared to the recommended range. The results show that the comfort index was maintained by the Cooled Beam method only during peak energy consumption period from midday onwards. In all circumstances, PMV indicates with Cooled Beam maintained the Finger comfort profile a lot quicker to neutral/comfortable (0.0) in both summertime and wintertime in the tropical climate.

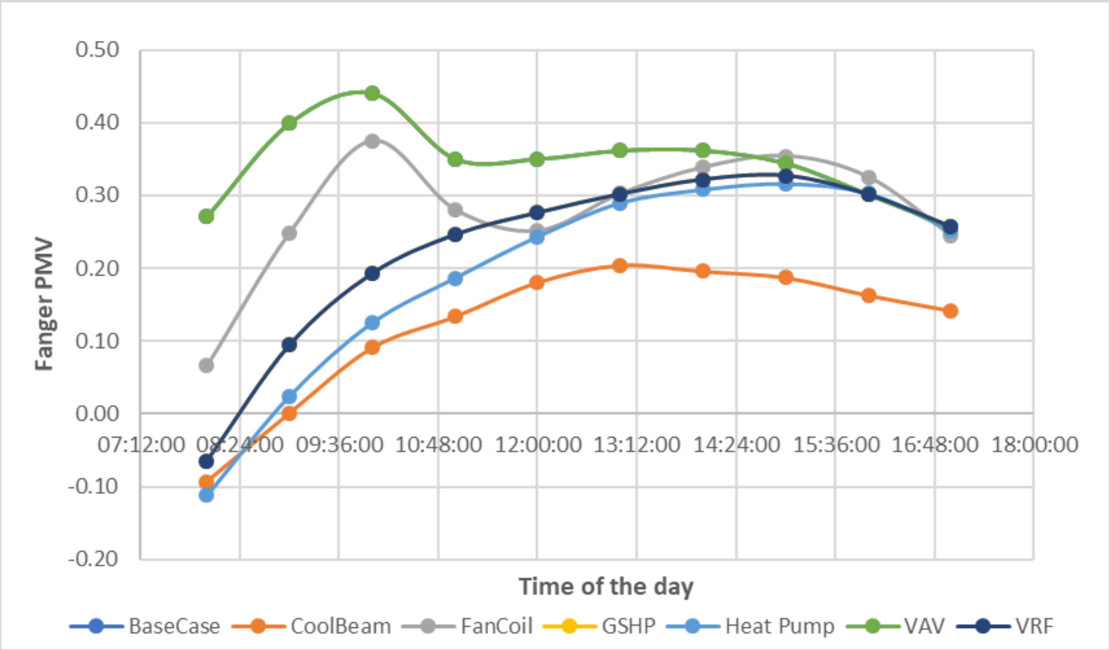


Figure 7.8 Thermal comfort index using the alternative HVAC systems in summer

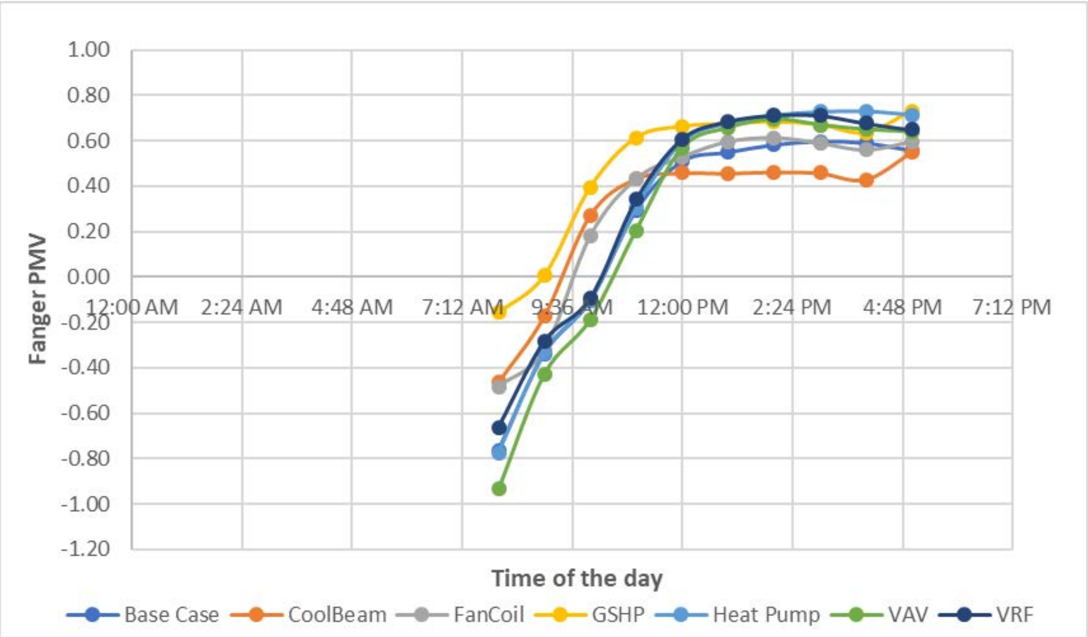


Figure 7.9 Thermal comfort index using the alternative HVAC systems in winter

As shown in Figures 7.6 to 7.9, BioPCM envelop system and Cooled Beam HVAC systems comfortably meet the thermal comfort standard value in both summer and winter months in a subtropical climate. Relating to normal atmospheric pressure, the intake and exhaust pressures were delegated to become zero. The ambient temps were modelled. Velocity data are important pertaining to the illustration of the performance of the building system. Simulation has been completed for a circulation rate of 10 l/s to check into the air stream in the model space.

Figure 7.10 reveals the degree of velocity vectors located within 0.01 metre/second to 0. 07 metres/second with small change within the inlet and outlet area (doors and windows). The pressure value varies from one thermal zone to another thermal zone. The air velocity seems to change steadily to practically uniform move as the flow goes towards the windows and doors. Figure 7.11 exhibits the CFD simulation outcomes of mean operative temperature and average radiant temperature and distributions. To decide the air acceleration and temperature performance had been chosen for determining the comfort level of the occupants. The results demonstrate that indoor CFD simulations employing pressure-inlet boundary conditions provide better forecasts than using velocity-inlet border conditions.

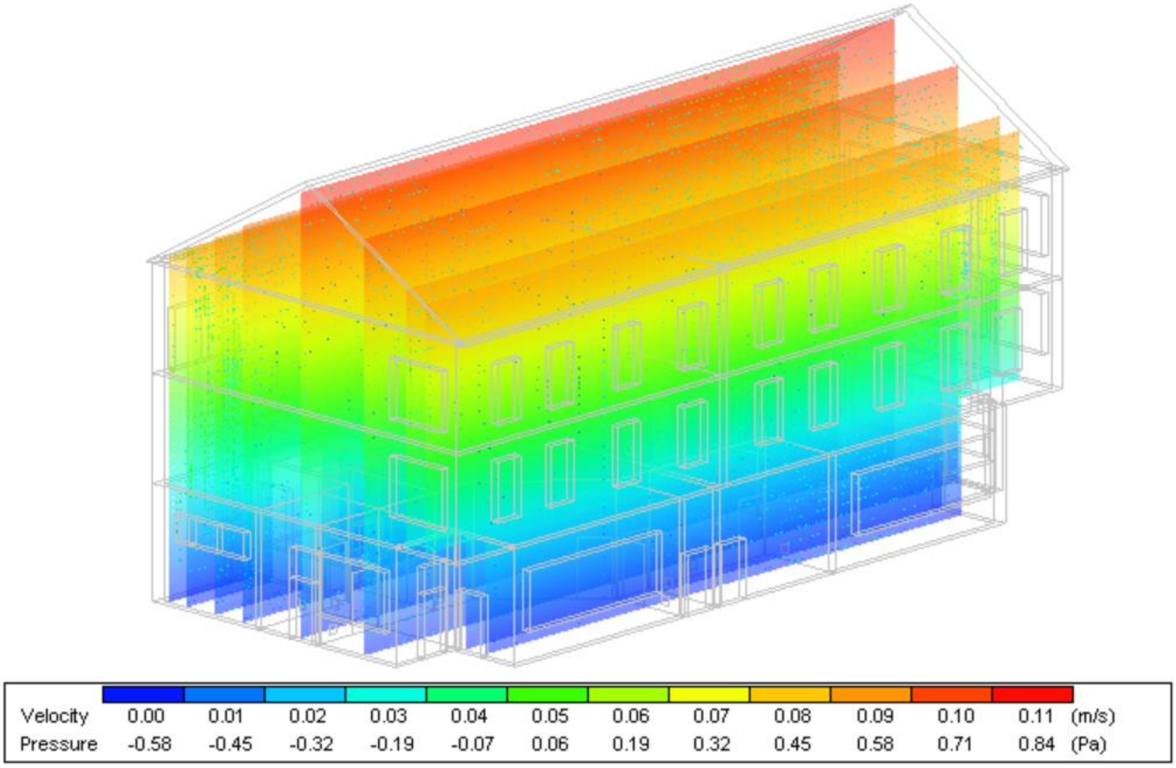


Figure 7.10 Distribution of simulated velocity and pressure values

Figure 7.12 shows the simulated temperatures contours. It could be perceived the temperature vectors are quickly altered to approximately identical flow as the flow goes by throughout the zone. The indoor temperature within the air-conditioned spaces is found within the 23.33ºC range throughout the building. In Figure 7.12., the sole exception is the roof space where the thermal comfort limit is relatively large due to the character of the actions. Figure 7.13 represents that the PPD value was 9.77% and 9.96%, which is within the range of 10% PPD limit suggested in the comfort standard during the office hours in winter and summer days. Figure 7.14 represents that a converged solution with respect to thermal mass, velocity and temperature is achieved after 22K interactions.

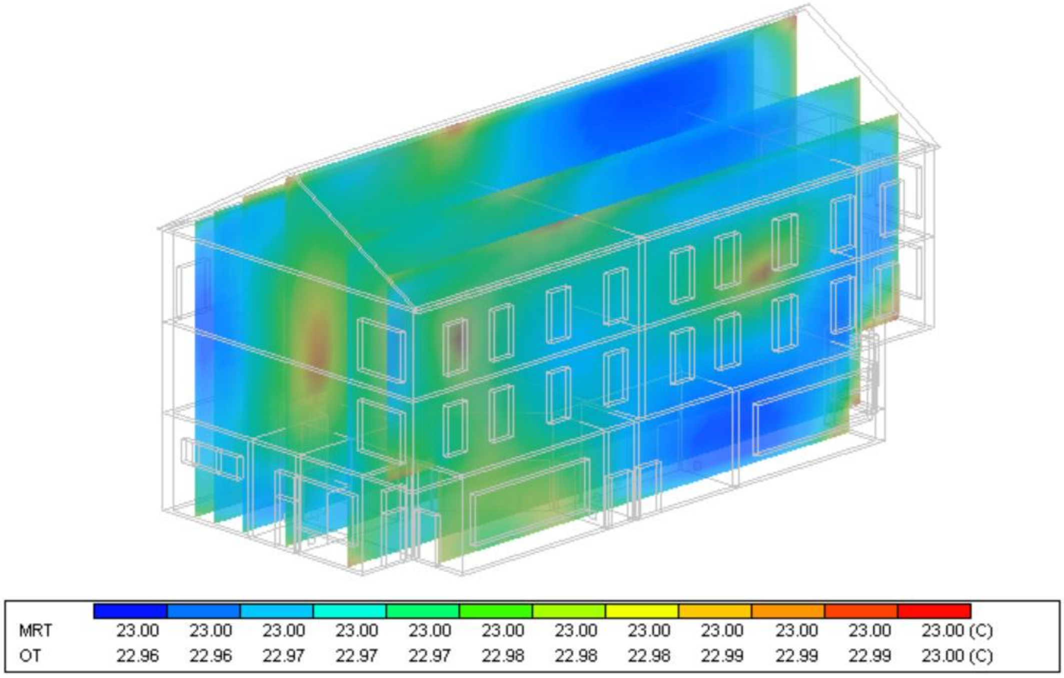


Figure 7.11 Distribution of mean radiant temperature and operative temperature values

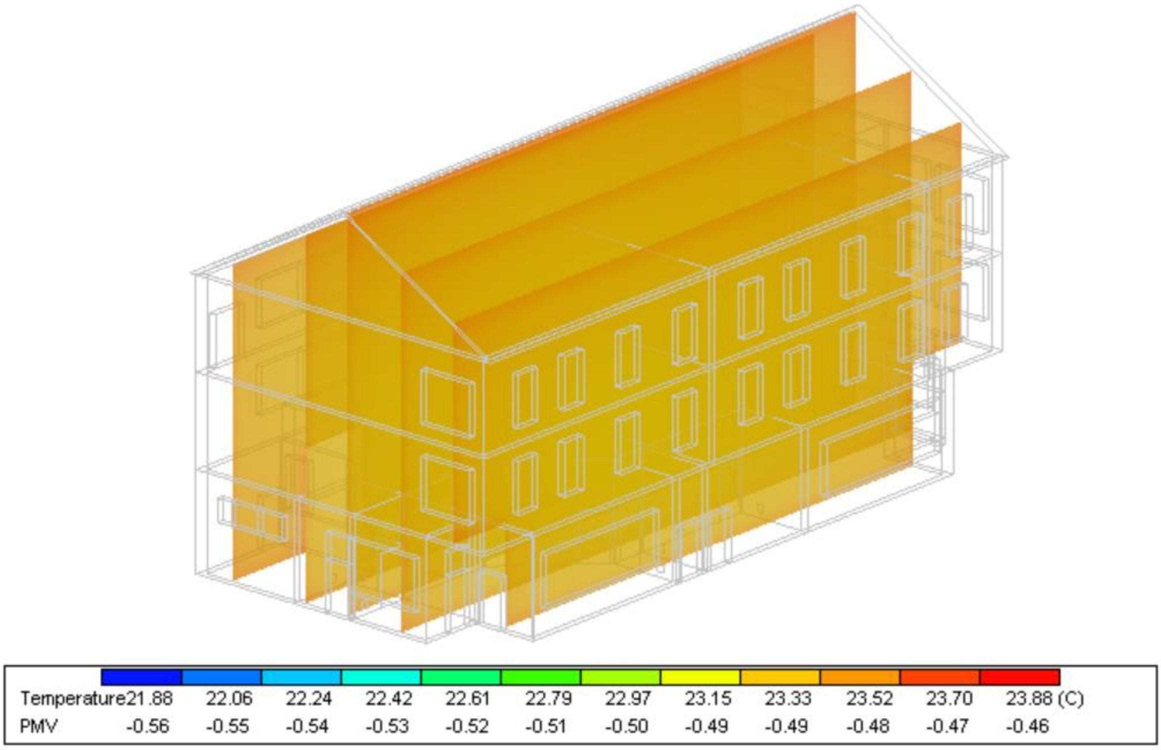


Figure 7.12 Distribution of simulated temperature and PMV values

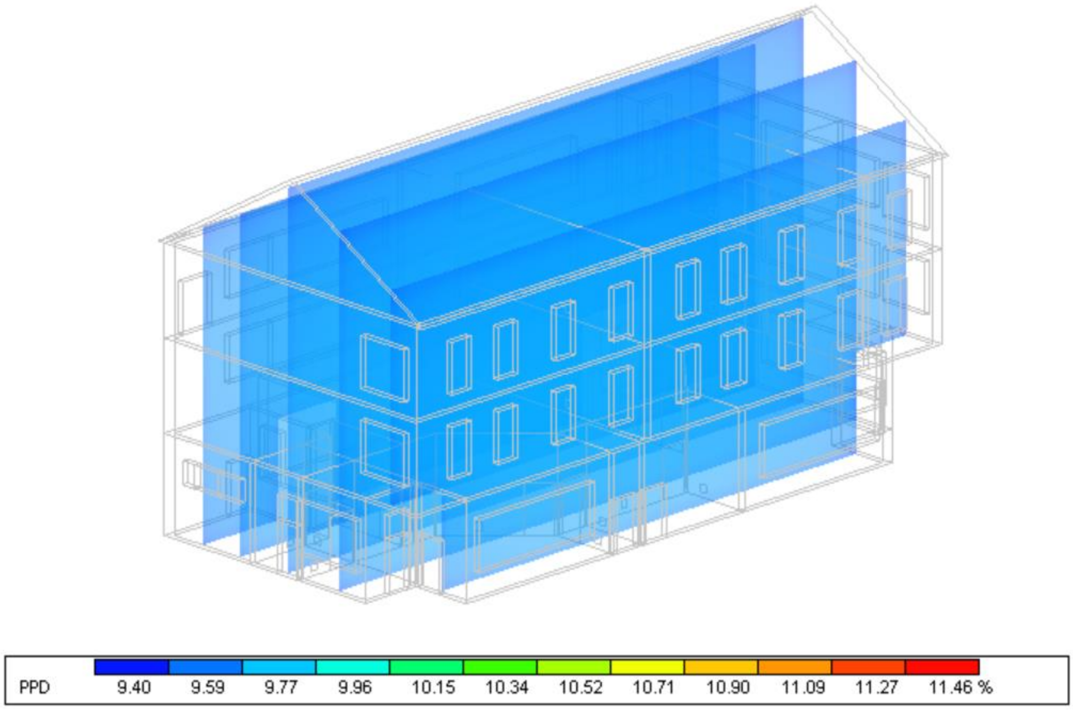


Figure 7.13 Distribution of percent people dissatisfied slices

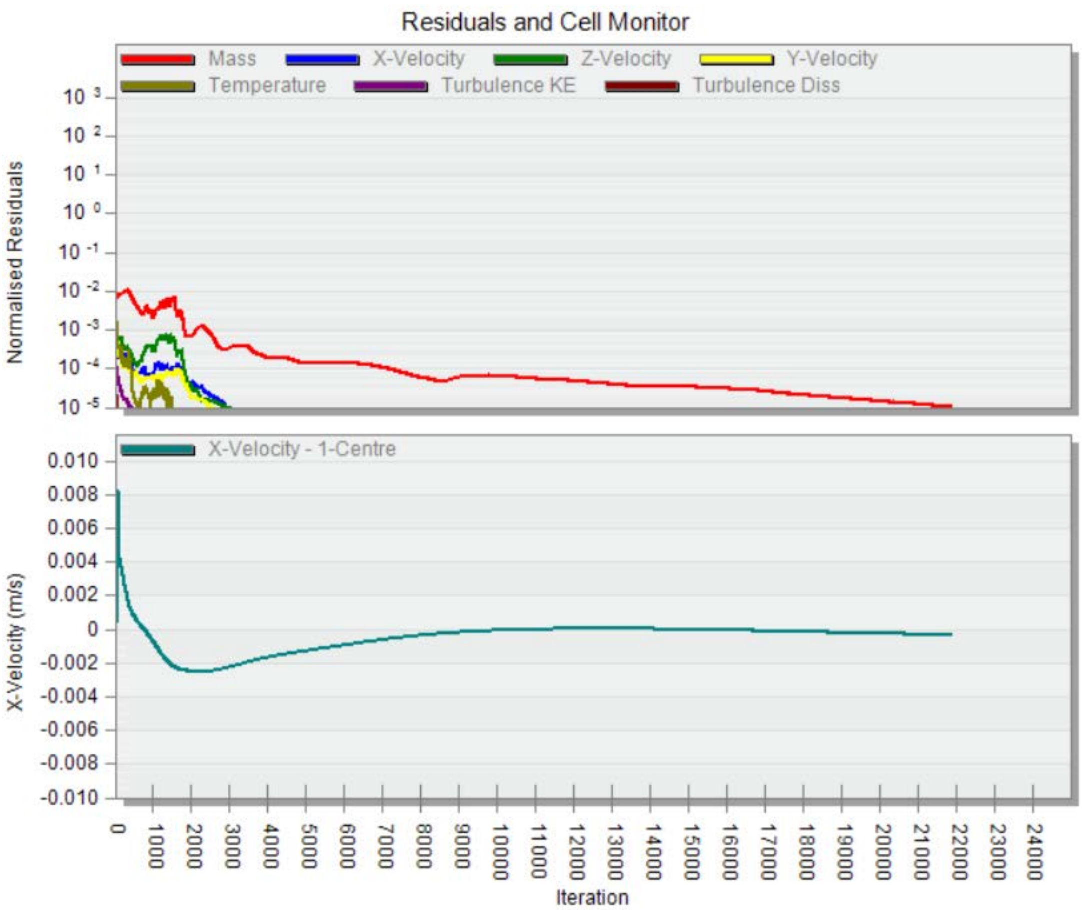


Figure 7.14 CFD converged solution considering mass, velocity, and temperature

In this study, considerable data about indoor environmental settings of the building and occupants' comfort level have already been studied. The temperature level and comfort index values are found constant and managed considerably at the desired comfort level. Throughout the analysis, the present operating schemes in the interior space are examined, and comfort capability of the construction are calculated using the established principles. Thermal comfort index (Fanger PMV) is simulated in nine-stage of thermal point scale, and results are within ±0.5 for the whole period.

CFD simulations can reveal flow conditions that have not been anticipated (which might make it possible to use simpler models that are less expensive to run) and therefore the results need to be carefully examined and compared with results from simpler calculations and experimentally characterised conditions or using engineering judgement. Visualisation of CFD results can appear complex. Complexity must not be confused with the accuracy or reliability of solutions and output. Examining the predicted flow fields using CFD algorithm can confirm anticipated flows and reveal any unusual issues within the space.

7.6 CONCLUSIONS

The thermal CFD simulation model describes in this study combines the newest turbulence modelling technique suitable for airflow modelling technique in the building. The simulation outcomes can give convincing and effective numerical information of the real thermal comfort on the building user. The computational comfort analysis technique is used to analyse building systems performance to assess the indoor thermal environment considering the alternative low emission cooling method, Cooled Beam as well as the alternative envelope system, BioPCM. The simulated results demonstrate the satisfactory uniform temperature distributions noted during the working hours. The outcome of the modelling also exhibits that investigating the human comfort in the indoor space using advanced CFD technique is a useful technique to determine the comfortability of the occupants.

Chapter 8: Optimisation of Building Performance

8.1 INTRODUCTION

Cautious long-lasting choices in the retrofitting of a building system could considerably enhance the thermal efficiency and hence decrease the intake of energy by the building system. Alternative energy preservation steps in building, compliance requirements, and optimisation can be assessed utilising energy, comfort and environmental analysis and cutting-edge decision-making methods. These might vary from streamlined energy analysis approaches for approximate energy usage to in-depth computer simulation combined with strategies to make the required decision to enhance the efficacy of the envelope and to build mechanical systems. This section analyses the potential scenario to help produce the building retrofit options. Unique consideration is committed to the methods utilising genetic algorithm (GA) based multi-criteria optimisation of the retrofitting objectives.

8.2 OPTIMISATION OF BUILDING PERFORMANCE

An optimisation is a method for effectively examining and determining alternative options that would satisfy the essential efficiency goals. The primary distinction from solitary objective optimisation is that a multiple objectives-based optimisation methods has to deal with many facets of the scenario, each representing a compromise between goals. It is a constant procedure of discovery and evaluating services of a provided issue until no improved service could be identified. Resolving the criteria based optimisation issues is a numerically intricate job as such deriving the optimisation results is an extreme time-consuming process. These days, many cutting-edge technological methods and operating strategies are available, intending to enhance the capability of a building and meeting the people comfort requirements of the indoor area. Alanne (2004) presented an approach on how to help find the most sustainable retrofitting actions that will fulfil the demands of the imminent future. The process of decision making during the conceptual phase of design is an iterative process, as shown in Figure 8.1.

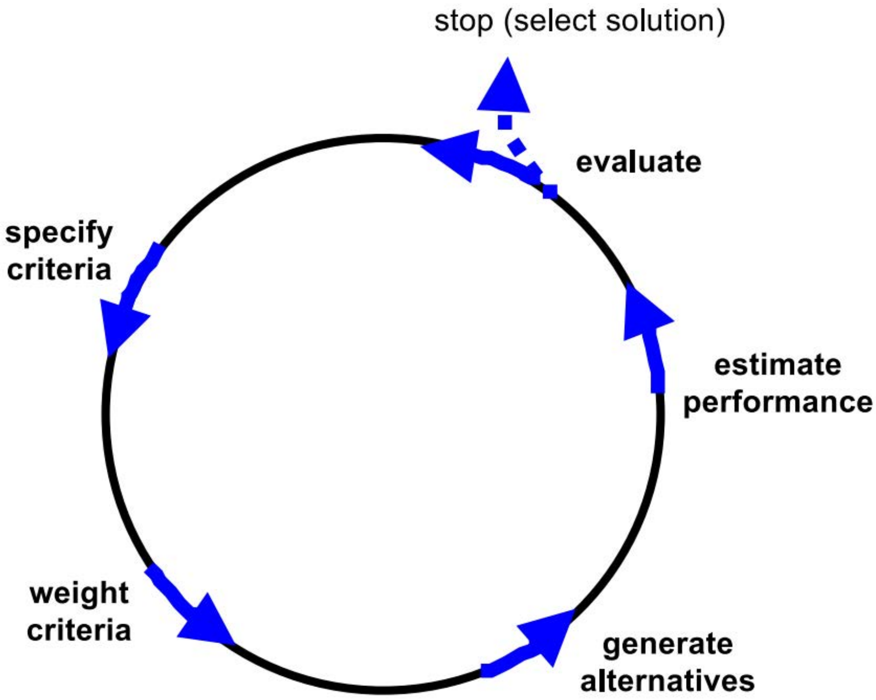


Figure 8.1 The iterative decision support process (Alanne, 2004)

8.3 GENERIC OPTIMISATION APPROACHES

The retrofit goals of building systems can be either qualitative or quantitative. These goals are viable in the sense that it is difficult to enhance all of them concurrently. For this factor, numerous decision-aid techniques have been established for resolving multi-objective based optimisation. The evaluation stage includes the examination of energy conservation measures versus the selected unbiased functions pointed out in the retrofitting strategy of the building. The differentiation and making of a decision in retrofitting analysis can be undertaken using these two primary methods – Multi-criteria Decision Analysis (MCDA) method and Multi-objective Programming (MOP) method (Asadi *et al*., 2013).

In the MCDA method, there are not many alternative options to consider. The primary issue when utilising MCDA strategies is that the user is restricted to a group of pre-described alternative options. The choice of a representative set of options is normally a hard issue, while the last option is greatly impacted by the group of pre-described options. On the other hand, once many options exist, the needed examination and choice procedure might turn out to be exceptionally tough to manage. In the MOP method, the modelling of practical issues normally needs the factor to consider unique axes of examination of the benefits of prospective services. Mathematical designs should clearly attend to these numerous incommensurate and frequently clashing elements of examination as unbiased functions to be enhanced (Asadi *et al.*, 2013). Figure 8.2 represents the categories of optimisation approaches.

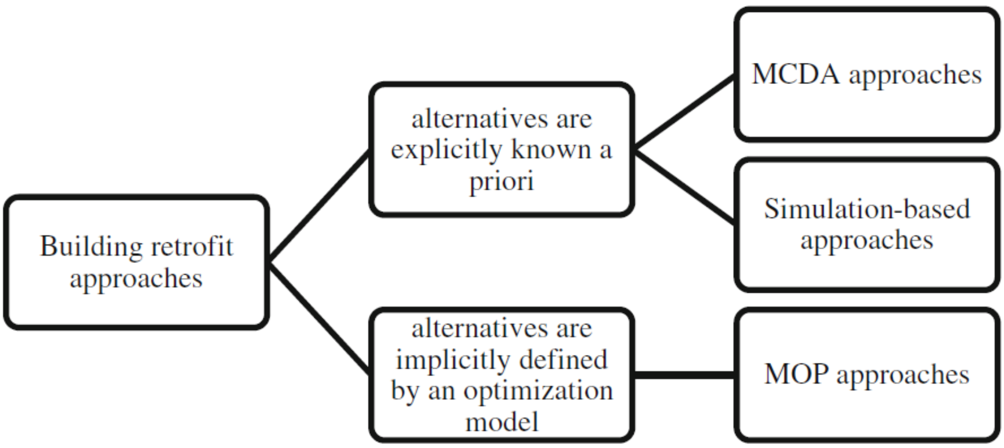


Figure 8.2 Categorisation of methodological approaches (Asadi *et al.,* 2013)

Similarly, a parametric analysis would generally consist of a couple of variables being changed in an organised method to highlight patterns and discover styles with the most beneficial attributes. With parametric analysis, an optimum of three variables is preferably utilised due to the fact that a) the outcomes of more than three measurements to an issue are challenging to picture; and b) the large number of simulations needed with four or more style variables would take too long to finish.

8.4 MAIN CONCEPTS

A multi-objective optimisation issue consists of numerous unbiased functions to be enhanced or decreased, i.e. optimised depending on the optimisation goals. The idea of Pareto supremacy develops as a service for these issues as it allows a contrast of the options. One option will be a Pareto ideal if no other service of the practical area controls it. In this method, a multi-objective optimisation treatment is specified as an exploration for the ideal Pareto options by applying an effective service process (Justesen, 2010). This approach is schematically represented in Figure 8.3.

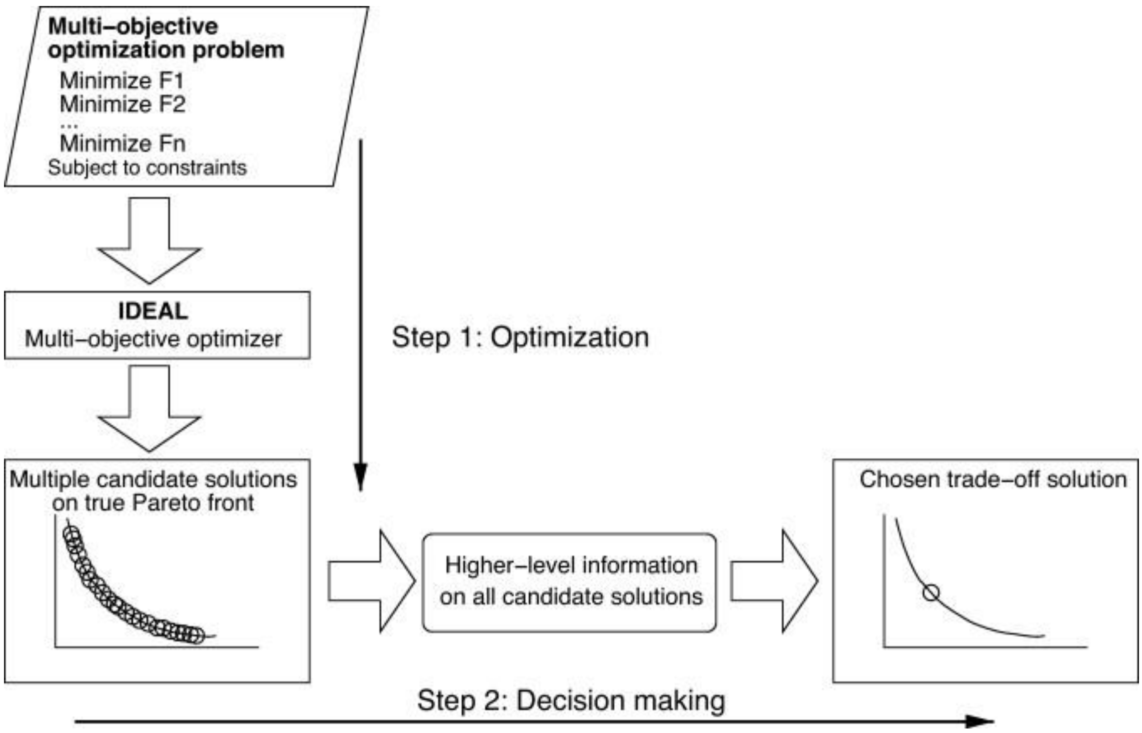


Figure 8.3 Multi-objective optimisation procedure (Justesen, 2010)

8.4.1 Genetic / Evolutionary Algorithms

A conceivable treatment for multi-objective optimisation is using evolutionary algorithms. In evolutionary algorithms, each service is treated as a person of an offered population, where their strength is determined by how it deals with it, either much better or even worse. The immense benefit of Evolutionary Algorithms is the application of a group of options in every cohort rather than a solo option intended for enhancement, which is further effective for locating the ideal Pareto options (Almeida *et al.* 2015). Evolutionary algorithms, utilising systems to maintain the variety of the options, can offer a group of services that characterize the whole unbiased area. Hence, evolutionary algorithms might give various services every time they are utilised (Almeida *et al.* 2015). Figure 8.4 represents a flow chart of the evolutionary algorithm process.

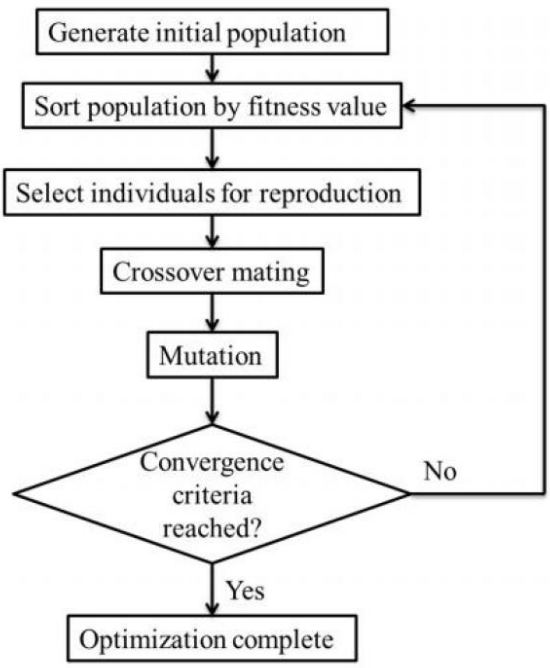


Figure 8.4 Flow chart of the evolutionary algorithms (Goldberg, 2014)

8.4.2 Constraints

The lower and upper constraint margins are used as part of the constraint handling method used by DesignBuilder, which is based on a generic penalty function approach. During a constrained optimisation, each design alternative is tested against any constraints applied, and a penalty is generated based on whether the design is feasible or not, i.e. whether it meets constraint requirements. If the function value is within the feasible range, then no penalty is applied and conversely, if it is outside the feasible range, then a penalty is applied. There is a margin between the feasible and the infeasible regions where a linearly ramped penalty is applied. The upper and lower margins set on the calculation options dialogue are used to define these regions, as shown on the graph in Figure 8.5.

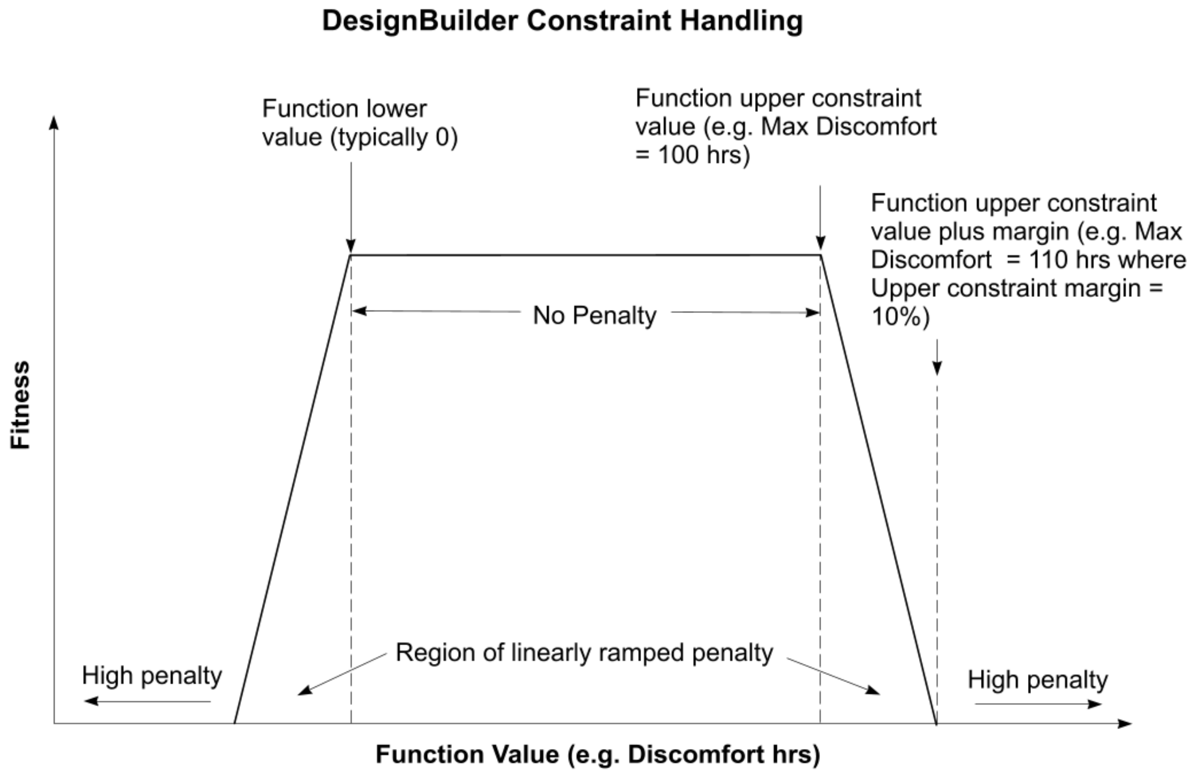


Figure 8.5 DesignBuilder constraint handling (DesignBuilder Software, 2019)

8.5 BUILDING PERFORMANCE OPTIMISATION TOOLS

There are several comprehensive energy system simulation software available such as BLAST, DOE-2, HVAC-SIM+, eQuest, DesignBuilder, EnergyPlus, ESP-r, TRNSYS, and so on. In optimisation function in the DesignBuilder software, the genetic/evolutionary algorithms are utilised to identify the ideal options. When more variables are included, the optimisation function is far more effective than is possible with parametric analysis. In DesignBuilder, approximately ten variables can be included in the analysis with approximately two goals to be achieved in one optimisation simulation. Expense and carbon emission are an often-utilised set of goals in building performance optimisation analyses. An optimisation analysis includes a base style which is to be optimised for expense and carbon emissions with respect to the operational and design variable. In a typical optimisation run of the above-mentioned goal, the combination of least expensive and least carbon emission forms a *Pareto front* that can be considered as an optimum solution to achieve the selected objective. The goals could be utilised in the optimisation of energy effectiveness, indoor comfort and the life cycle expense in addition to the operating cost. The optimisation analysis becomes really time-consuming and computationally extensive when more variables are available to be optimised. Considering that multi-objective optimisation algorithms need numerous models, it becomes difficult to utilise them directly with the simulation software application and hence requires access to high-performance computing facilities for the required optimisation studies.

8.5.1 DesignBuilder optimisation

DesignBuilder adopted a genetic algorithm which was developed based on a Non-dominated Arranging Hereditary Algorithm II (NSGAII) approach, which is extensively utilised as an elitist and quick multi-objective technique offering an excellent adjustment between a satisfactory congregated and a well-dispersed service suites. This algorithm is the most effective in terms of merging and a variety of services. The structure is reasonably basic and therefore needs fewer simulation attempt, and thus fewer run hours compared to many other popular algorithms.

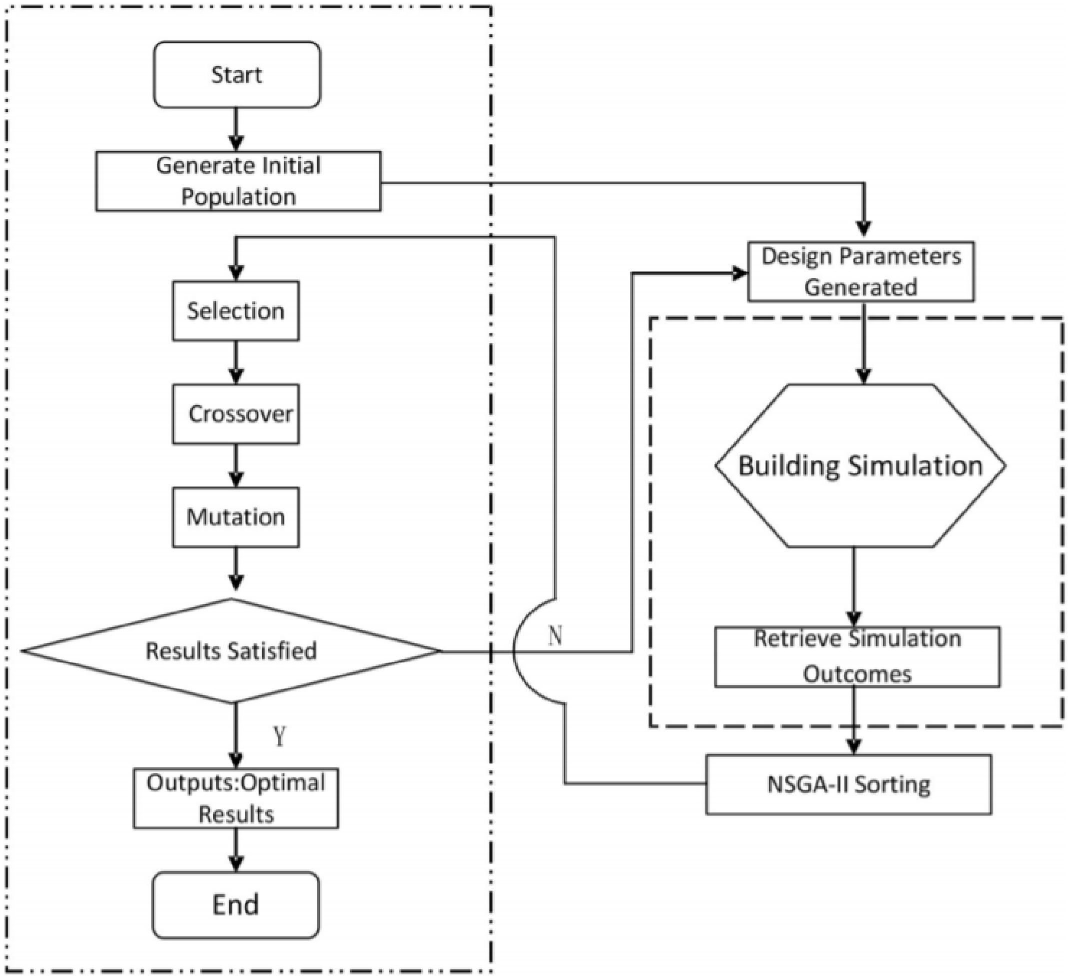


Figure 8.6 Flowchart of the optimisation process following GA (Lin and Yang, 2018)

The NSGAII algorithm operates depending on the principle of classification among the group to categorise them based on the degree of supremacy. In addition, the NSGAII algorithm consists of an essential operator, the Crowding Range. Utilising this method, the algorithm continues iteratively until it reaches the services that make up the Pareto front. Normally, options that are far away (not crowded) from other services are provided with a greater choice in the choice procedure to help produce a varied option set and prevent crowding. The finest option is selected from the existing group and keep in a pool for further processing. The options set is the greatest ranked Pareto non-dominated set from all populations. Figure 8.6 represents a flowchart of the genetic algorithm-based optimisation process.

8.6 OPTIMISATION OF BUILDING SYSTEMS

The optimum variable parameters were obtained from genetic algorithms, and it is recommended to alleviate energy usages and enhance the efficacy of HVAC systems in building infrastructure. The computed ideal parameters were involved in the AC system. In this study, GAs are utilised to evaluate the changes in the determined optimal control variables, which, in turn, were used to operate the designed system. In the past, there were many scenarios where modelling has been utilised in certain methods to enhance the operating performance of the building. However, it is rarely used to enhance the operation of the building through optimisation. The novelty of the study is that it considers the combination of building HVAC systems and envelope system to optimise the heat gain via the envelope, comfort index, cooling energy requirement, operational CO_2 emissions, and optimal total energy usages in the building. Figure 8.7 represents the framework developed and tested in this study to secure the objectives of the study for the present and future climate conditions.

8.6.1 Optimisation Processes in Evolutionary Algorithm

Genetic algorithm is a type of set of rules that is influenced by the Darwinian advancement theory. Darwinism is a theory of biological advancement established by the English biologist Charles Darwin that states that all types of organisms establish and occur through the natural choice of small, acquired variations that increase the person's capability to contend, endure, and replicate. The principle of GAs is straightforward – the process begins with a random set (population) of services, and then consistently assesses the options and chooses better ones for developing new versions till sufficient ideal services have been discovered.

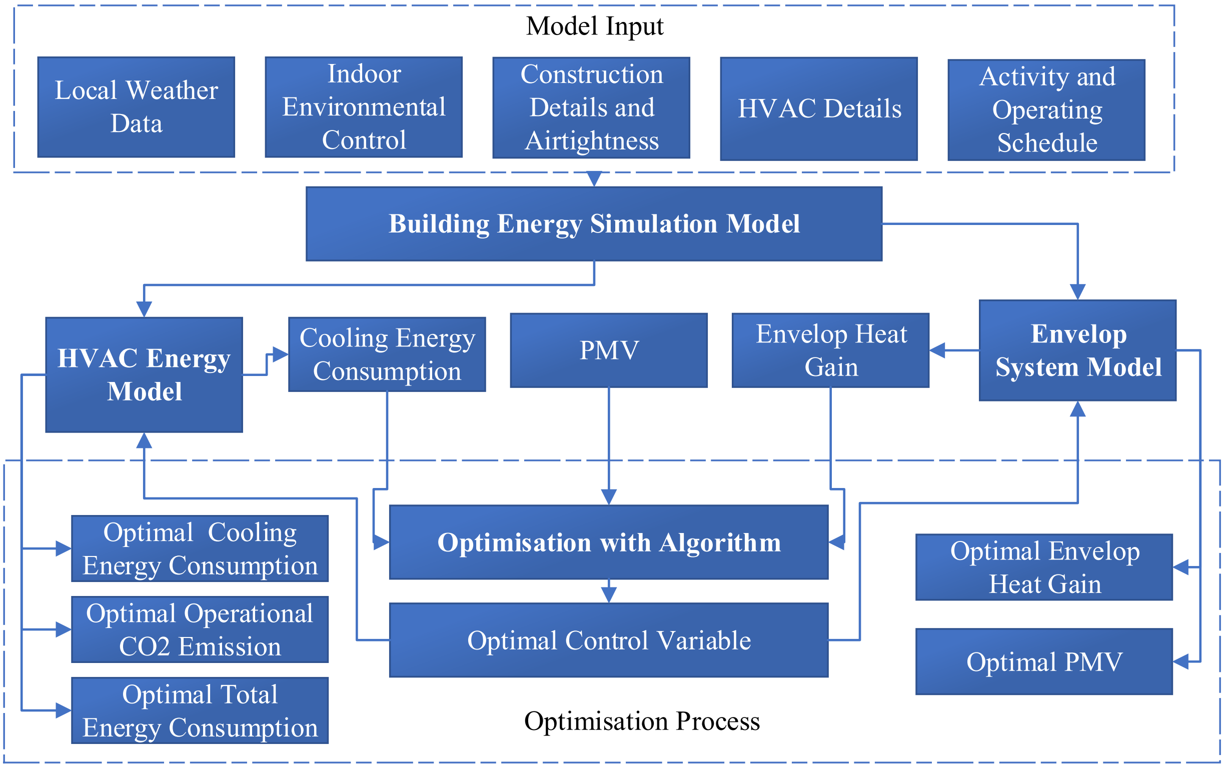


Figure 8.7 Energy and comfort analysis design for building a HVAC and envelope system utilising genetic algorithms.

Considering the merit and difficulties of GA based optimisation, the following stages were developed and followed to identify the prime retrofitted resolutions for the selected building, which is also suitable for any other similar large-scale building with similar optimisation settings:

- Stage 1: Create a model with all consideration and requirements
- Stage 2: Create and run the simulation model
- Stage 3: Evaluate the results from the simulation model to ensure that the outcome meets the correct seasonal operational requirements

- Stage 4: Prepare baseline simulation data
- Stage 5: Compare and evaluate the retrofitting options and impact of seasonal variations
- Stage 6: Define optimisation analysis settings' objectives / goals, constraints and variables
- Stage 7: Conduct multiple optimisation solutions
- Stage 8: Optimisation solution evaluates evolutionary fitness and breeds new generations
- Stage 9: Analyse Pareto optimal solutions

8.7 SETTINGS OF OPTIMISATION

The principal optimisation treatment is the reduction of the functions linked to energy efficiency and comfort. The optimisation job consisted of evaluating the goals and effect of the variables. As referenced above, this research study focuses on examining the conserving energy capacity under existing energy effectiveness requirements for multi-storeyed buildings. Growing usage of low energy cooling innovations in addition to effective building envelopes satisfy the comfort requirement and the adequacy of the innovations to allow for the severe weather. At the same time, it is very important to comprehend that the compromise between energy, carbon, and convenience utilising standard modelling approaches is challenging and time-consuming when considering numerous variables. The goal of this assessment is for multi-objective optimisation strategies to simulate development by natural choice to effectively discover optimal retrofitting techniques when it is too intricate to mimic all possible circumstances. The following objectives were considered in the optimisation:

- Minimise envelope heat gain

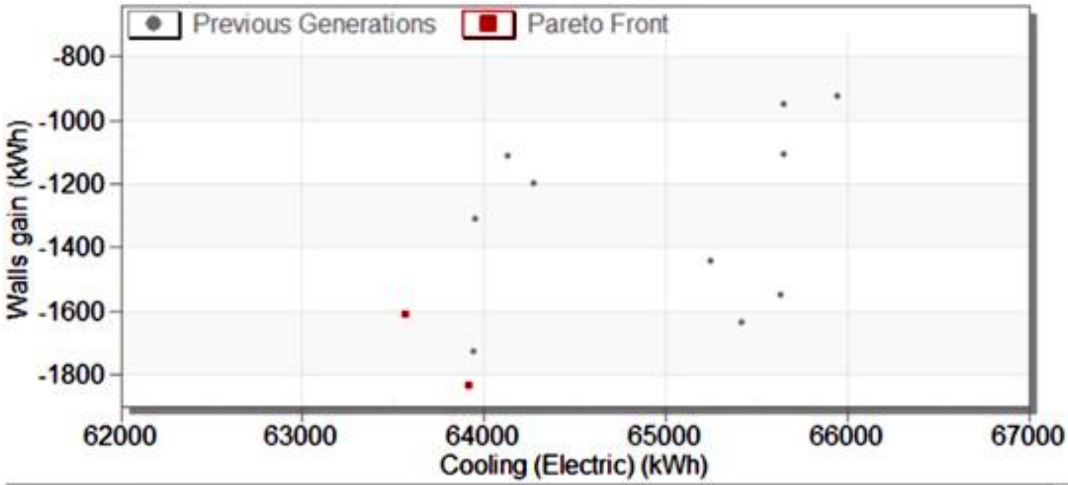
- Minimise discomfort hour
- Minimise cooling energy consumption
- Minimise operational CO_2 emissions
- Minimise total energy consumption

The following variables were considered in the optimisation:

- HVAC Methods: Base Case / Cooled Beam / Fan Coil /Ground Source Heat Pump/heat pump / Variable Air Volume / Variable Refrigerant Flow
- Envelope Systems: Base Case / BioPCM / BIPV / Novel Envelope / Trombe Wall / Cavity Wall
- Comfort level: PMV -0.5 to +0.5

8.8 OUTCOME OF OPTIMISATION STUDY

The population range, transformation rank, and boundary rate are the key criteria that affect the precision and calculation time in a genetic algorithm-based optimisation analysis. As indicated by Lin and Yan (2018), it is important to review the population size because if it is very small in quantity, there is a good chance that the distribution of outcome will be unequal. As a result, the solution could be susceptible to cause early merging. On the other hand, it will be time-consuming if the population size is too large. The crossover and anomaly rates are decided manually and have an immense effect on the universal union. Through refinement, population range, transformation rank and boundary rate are set to be 200, 0.02 and 0.95, respectively. The case study building is optimised to first reduce envelope heat gain that results from the building envelope system, and as such, the cooling energy intake could be reduced to maintain the comfortability in the indoor space. Consequently, optimisation is focused on reducing the discomfort hours, maintaining the required comfort index, and accounting for LCA and operational CO_2 emissions. Enormous outputs representing the Pareto front were created bearing in mind the stated restraints, control variables and goals. Two optimised solutions were recognised as displayed in Figure 8.8, which reveals the Pareto front obtained for the optimised model.



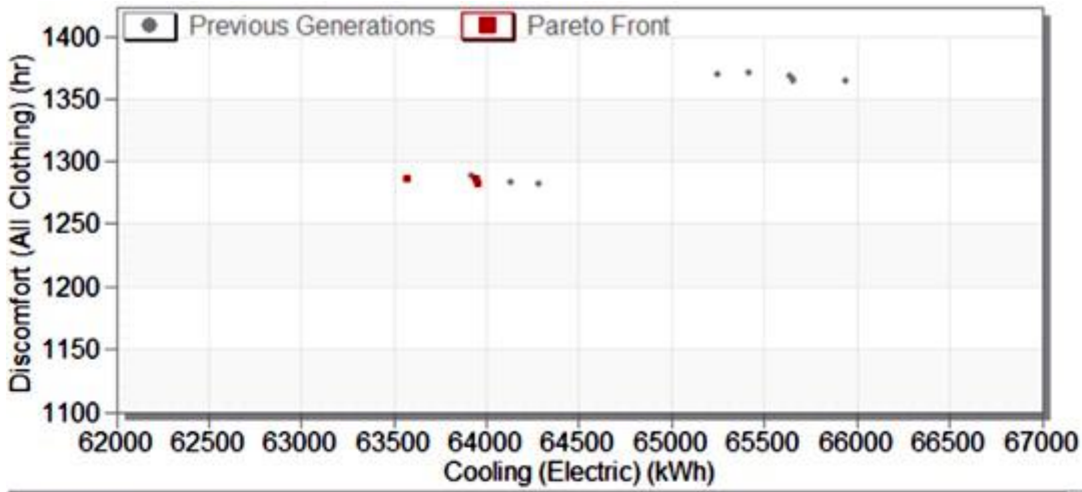
Status

Iteration	Gen...	Stat	Cooling (Ele...	Walls gain (...	CO2 (kg)	LCA (Simple...	HVAC	External Wall	PMV
Optimal Designs									
3	0	Opti...	63571.38	-1613.24	79237.005	3961850.239	Cooled Bea...	BioPCM Exa...	-0.100
0	0	Opti...	63917.08	-1834.46	79601.118	3980055.912	VAV, Dual d...	NoPCM Wal...	-0.500
(none)									
33	2		63571.38	-1613.24	79237.005	3961850.239	Cooled Bea...	BioPCM Exa...	0.200
34	2		63571.38	-1613.24	79237.005	3961850.239	Cooled Bea...	BioPCM Exa...	0.300

Figure 8.8 Optimising cooling energy consumption and heat gain through the wall.

The first iteration of the optimisation with objectives to minimise the cooling energy consumption and minimise heat gain through the wall, Cooled Beam, HVAC method and BioPCM external envelope system provided the best 63571 kWh/annum cooling energy usage as well as 1613 kWh heat gain through the wall. CO_2 emissions were 79237 kg/annum, and PMV value was -0.1, which remained within the acceptable limit of ±0.5. VAV air volume system and the standard wall systems also considered an optimum solution, however, the optimum solution is a rather high energy-consuming unit and the heat gain over the building envelope is rather high compared to the BioPCM.

Figure 8.9 reveals the Pareto front for the optimised model considering the objective function as minimising the cooling energy consumption as well as the discomfort hours. The point that represents the cooling energy performance, operational CO_2 emissions, LCA, PMV of the building is also included. When evaluating the Pareto value of optimal options with cooling energy consumption and discomfort hours, a considerable improvement rises to utilise the Cooled Beam HVAC method and BioPCM products. Cooled Beam HVAC and BioPCM external envelope combination were the standalone optimum combination 63571 kWh/annum cooling energy consumption and 1286 hr of discomfort hours. The other variables produce reasonable values which are consistent with the previous optimised results reported. This is a typical circumstance for all variables considering the optimisation settings. VAV with BIPV envelope systems and Novel envelope systems were also found as a feasible solution; nevertheless, the energy intake increased.

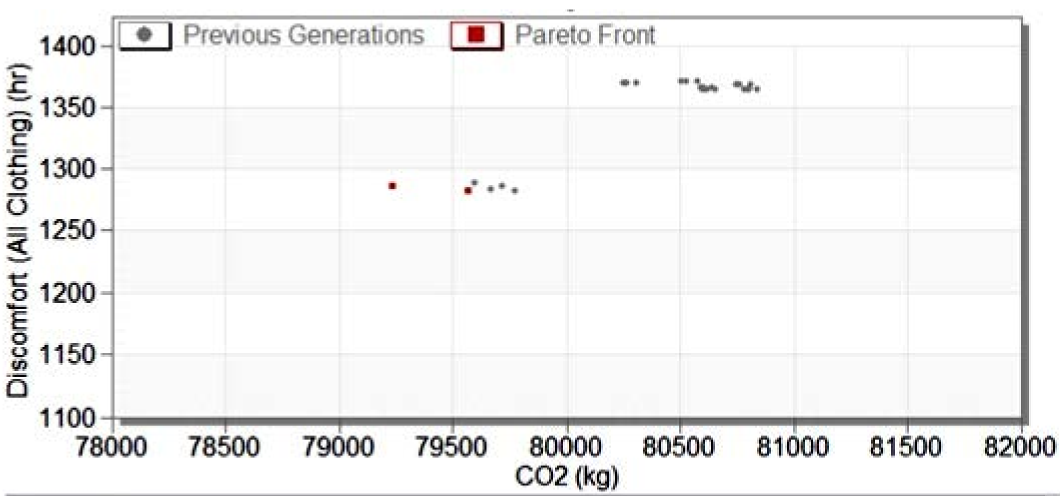


Status

Iteration	Gen...	Stat	Cooling (Ele...	Discomfort (...	CO2 (kg)	LCA (Simple...	HVAC	External Wall	PMV
Optimal Designs									
50	4	Opti...	63571.38	1286.4656	79237.005	3961850.239	Cooled Bea...	BioPCM Exa...	0.000
6	0	Opti...	63943.35	1285.6138	79722.239	3986111.926	VAV, Dual d...	Novel Exter...	0.100
22	1	Opti...	63954.74	1282.5784	79572.949	3978647.473	VAV, Dual d...	Project BIP...	-0.100
(none)									
52	4		63571.38	1286.4656	79237.005	3961850.239	Cooled Bea...	BioPCM Exa...	0.300

Figure 8.9 Optimising cooling energy consumption and discomfort hours.

Figure 8.10 reveals the outcomes of the new optimisation treatment for the selected building model. Outcomes are considerably similar to the originally secured, considering that Pareto fronts are noted for only two sets of solution. The important function that develops from this optimisation treatment in discomfort hours and operational CO_2 emissions combined with Cooled Beam HVAC methods and BioPCM envelope system offered the optimum solution set in conjunction with VAV systems and BIPV envelope systems. The building offers its users appropriate indoor air quality conditions, thus minimising the cooling energy and the discomfort hours. The improvement of the indoor air quality using a VAV system and BIPV will constantly represent a rise in the functional expenses of the building.

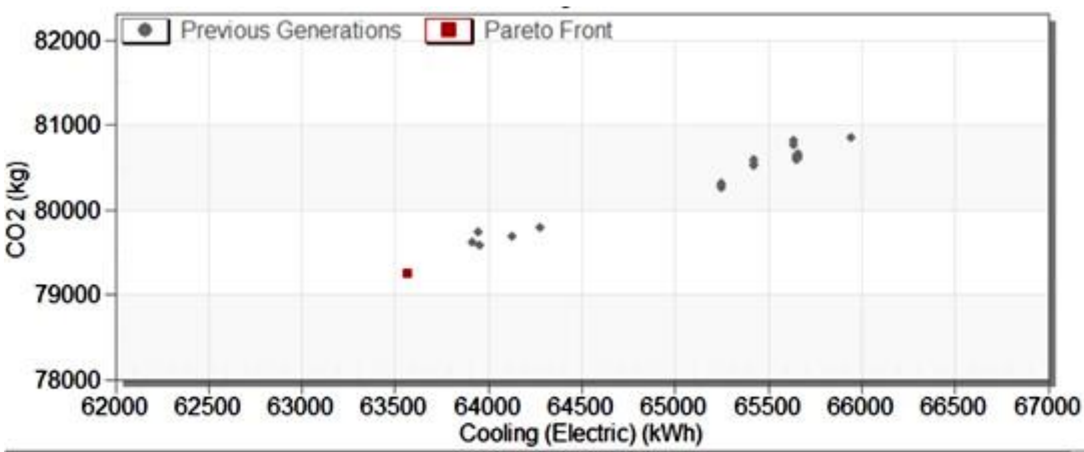


Status

Iteration	Gen...	Status	CO2 (kg)	Discomfort (All...	Total site ener...	Cooling (Electr...	HVAC	External Wall
Optimal Designs								
15	1	Opti...	79237.005	1286.4656	63571.376	3961850.239	Cooled Beams...	BioPCM Exam...
14	1	Opti...	79572.949	1282.5784	63954.737	3978647.473	VAV, Dual du...	Project BIPV ...
(none)								
17	1		79237.005	1286.4656	63571.376	3961850.239	VAV, Dual du...	BioPCM Exam...
19	1		79572.949	1282.5784	63954.737	3978647.473	Cooled Beams...	Project BIPV ...

Figure 8.10 Optimising discomfort hours and CO_2 emissions.

Figure 8.11 displays the outcomes of optimisation of the HVAC and envelope variables with respect to CO_2 emissions and total discomfort hours. The optimisation resulted in one optimum solution. Cooled Beam HVAC and BioPCM external envelope combination were identified as most optimum by counting CO_2 emissions at 79237 kg/annum and 1286 hr of discomfort hours. The outcome was derived considering other optimisation objectives considered in all previous iterations.

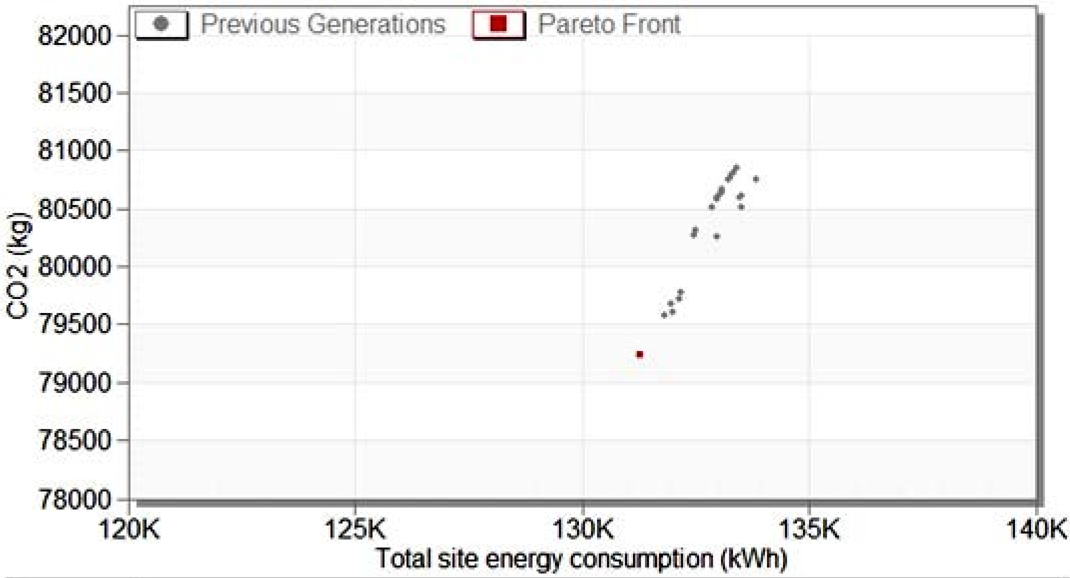


Status

Iteration	Gene...	Status	Cooling (Electr...	CO2 (kg)	Total site ener...	Discomfort (All...	LCA (Simple) (	HVAC	External Wall
Optimal Designs									
14	1	Opti...	63571.38	79237.005	131299.346	1286.466	3961850.239	Cooled Beams...	BioPCM Exam...
(none)									
16	1		63571.38	79237.005	131299.346	1286.466	3961850.239	VAV, Dual du...	BioPCM Exam...
11	1		63917.08	79601.118	132014.293	1288.302	3980055.912	VAV, Dual du...	NoPCM Wall ...
12	1		63917.08	79601.118	132014.293	1288.302	3980055.912	Cooled Beams...	NoPCM Wall ...

Figure 8.11 Optimising discomfort hours and CO_2 emissions.

Figure 8.12 reported the optimised total site energy consumption and CO_2 emissions, which produces only one optimum solution out of all the iterations. The recommended optimum solution reported is Cooled Beam HVAC, and BioPCM external envelope where CO_2 emissions were 76237 kg/annum, and total site energy consumption was recorded as 131299.35 kWh. A thorough investigation of the outcomes exposed that the outcomes are highly reliant on the optimum limitations enforced for the restraints; discomfort hours with 10 per cent. In truth, most of the ideal services represent sensible, useful circumstances.



Status

Iteration	Gener...	Status	HVAC	External Wall	Total site energy...	CO2 (kg)	PMV
Optimal Designs							
17	1	Optim...	Cooled Beams, ...	BioPCM Exampl...	131299.35	79237.005	0.300
(none)							
18	1		Cooled Beams, ...	BioPCM Exampl...	131299.35	79237.005	0.400
34	2		Cooled Beams, ...	BioPCM Exampl...	131299.35	79237.005	0.200
65	4		Cooled Beams, ...	BioPCM Exampl...	131299.35	79237.005	-0.300
66	4		Cooled Beams, ...	BioPCM Exampl...	131299.35	79237.005	-0.100

Figure 8.12 Optimising total site energy consumption and CO_2 emissions

8.9 CONCLUSIONS

When numerous retrofitting options of a building are available, the primary concern is to determine the most consistent option in the long term. Multi-objectives optimisation is a necessary tool to help in justifying the contrast between non-dominated services and evaluate the compromises between those unique building operational elements. The case study on the optimisation of the performance parameter of the academic building demonstrates the targeted objectives are achieved by the developed optimisation framework considering the variables of interest and the constraints in place to confirm the comfortability of the occupants. A couple of scenarios are compared to explore the influences of the variables on the optimum operational models. The results show that both an HVAC system and external envelope of the building are major contributors on a building's energy usages profile plus emissions from the associated processes. It is evident from all the consolidated optimization results that cooled beam HVAC system and BioPCM external wall satisfy all the optimization objectives by maintaining the defined constraints. The annual cooling energy consumption becomes more important when the building has a longer life span. It also demonstrates that the optimal building performance could be achieved by following the developed optimisation framework that helps to eliminate some of the challenges reported by researchers in the past and represent the novelty of the study.

Chapter 9: Impact Assessment of Future Weather Transformation

9.1 INTRODUCTION

This chapter defines approaches to scrutinize the level of tolerance of indoor weather conditions to buildings outdoor envelope and external weather condition. The values of the extreme exogenic environmental variables were taken into consideration to evaluate the building systems on the energy requisite for room cooling and heating in future. The treatments defined in this thesis are not implied to show what is excellent or negative, they are just implied to reveal that how much effect not recognising the future weather condition has on and are trying to recognize interior comfort condition, power usage etc in that change in condition.

9.2 ASSESSMENT OF POTENTIAL FUTURE WEATHER CHANGE

Absence of comfortable indoor environment in intense weather condition can be deadly in a tropical area. A shifting environment and other regular extreme weather events will require the usage of methods that could overcome such an unexpected scenario. One way to overcome such a situation is to have a backup measure that will eventually be of assistance at the time of need. Passive measures such as the use of high performing envelope systems could be considered as a back-up rather than defaults HVAC options for a comparable better outcome. The global scientific area has concentrated significant initiative to define the probable effects of CO_2 discharges from individual actions on the worldwide microclimate. The Intergovernmental Panel on Climate Change (IPCC) released an exclusive report in 2019 that identifies the buildings as an infrastructure category with the most significant CO_2 reduction possibility of any other industrial sector. The possible variation is forecasted yearly mean worldwide temperature level during in the coming era is 2 to 6 ºC (Crawley and Barnaby 2019). The information shown highlighted that some locations would experience much larger month-to-month or hourly adjustments. Strategies have been established to adjust present climate data to show climate modification scenarios (Crawley and Barnaby, 2019).

Belcher *et al.* (2005) proposed the morphing method to create climate data for the future. Crawley (2008) provides an approach for producing predicted 2100 climate sequences. Guan (2009) identifies proposed processes of preparing forthcoming climate information that can be adopted for performance simulation of a building system. Crawley and Lawrie (2015) advised using multiyear performance simulation with the predicted climate condition data rather than single-year forecasted from existing reference years. Nakano *et al.* (2015) developed Urban Weather Condition Generator software to create a scenario for future weather that could be adopted in building performance simulation. Zhu *et al.* (2016) proposed deriving future typical meteorological years from the hourly output of the basic model instead of changing the existing average meteorological year based on future regular monthly data. The morphing technique developed by Belcher *et al.* (2005), was adopted by Jentsch *et al.* (2013) to develop a tool CCWorldWeatherGen and produced weather conditions for the years for 2020, 2050, and 2080 for several cities in the UK. Moazami *et al.* (2017) examined CCWorldWeatherGen and WeatherShift software that can create future weather data and advised to review the resultant data with cautious to guarantee its usefulness. Ladybug Tools (2018) developed Dragonfly which makes it possible for modelling and evaluation of massive environmental phenomena and future environmental change based on the topographic variation by means of Urban Weather

Generator as well as CitySim. The Dragonfly development creates extensive weather parameters, that count on weather information as a preliminary factor to perform relevant investigation (Crawley and Barnaby 2019).

There have been numerous occasions when the temperature exceeded the record of high and low temperatures this year in many regions of Australia. Therefore, the performance of the building system must be reviewed so that potential peak conditions can be evaluated. The processes developed by many researchers to produce synthetic weather data for future consequences may not consider the extreme realistic implications. However, they do weigh quite a lot on the past severe environmental occurrences as well as the general pattern of weather change in the past. Wood & Eames (2017) and Sillmann *et al.* (2017) reviewed the modelling and prediction of short and long duration extreme weather occurrences and suggested to make use of simulated recent climate data or morph information based upon past years.

9.3 PROGRESSES IN PREDICTING FUTURE WEATHER

Present method to forecast the efficacy of the building system depends on historical common weather data. Nonetheless, making use of historical records to anticipate potential performance using expected future weather exposes buildings to considerable dangers. deWilde and Coley (2012) highlighted about excess heating of the indoor space, mismatching capability of building systems to deal with the cooling load and so on. Initiatives to integrate the emerging climate transformation aspect into HVAC system simulation have focussed on concepts, for instance, how to forecast future temperature as well as exactly how to adjust building envelope and mechanical systems to unfamiliar potential environments. Existing studies on adaptation to potential climate change scenario are reviewed in this section. Kershaw and Coley

(2012) matched up morphed weather data with UKCP09 (stochastic) power generator utilising reference weather. The authors reported that the changing procedure systematically produces warmer minimum temperature levels as well as cooler optimal temperature levels for all locations tested, though they clear up that this is most likely as a result of the reality that the UKCP09 producer creates many more reports than the changing method. Typically, morphing creates the specific very same weather condition styles while the stochastic producer makes a distinctive profile for all years. While each kind of records may be utilized for climate improvement research studies, the morphing technique should not be relied on entirely as its ability to predict the maximum temperature level is limited.

Cox *et al.* (2015) suggested a straightforward future weather report generated by relating a climate adjustment foresight based on the difference of temperature approach to an existing traditional year data. Zhu *et al.* (2016) recommended a procedure to create future weather upon morphing, where the review of the environmental indicators is produced by suitable environmental tendency data in China. The authors reported that the lasting environment change possesses sign of both centuries wide (200 years to 600 years), as well as decade wide (40 years to 80 years) periodicity.

9.4 POTENTIAL TREND OF FUTURE WEATHER

There are many options available to access weather data. These data can either be recorded in the weather station at the local site or could be sourced as a typical year. It is not recommended to use a single year climate data or test reference year type data for energy performance simulation because a single year or reference year could not represent the long-term behaviour of the weather condition for a specific location. The acceptable approach by ASHRAE as well as the practising engineers is to use a synthetic year that will represent long term weather pattern and other relevant variables which are able to assess the efficacy of building systems that will be quite a lot nearer to average practical performance. Typical meteorological year utilise this form of strategy by adopting the improved calculation model of solar data and is considered in this study. The chapter discusses the historical average data to produce the typical meteorological year data for the study. In Figure 9.1, the annual median air temperature levels in Australia have warmed up through concerning 1ºC from 1910 (Australian Government, 2019a). The Bureau of Meteorology reported that the temperature has been warming every decade compared to the earlier decade from 1950 onwards, which is also very concerning, as noted in Figure 9.1 (Australian Government, 2019a).

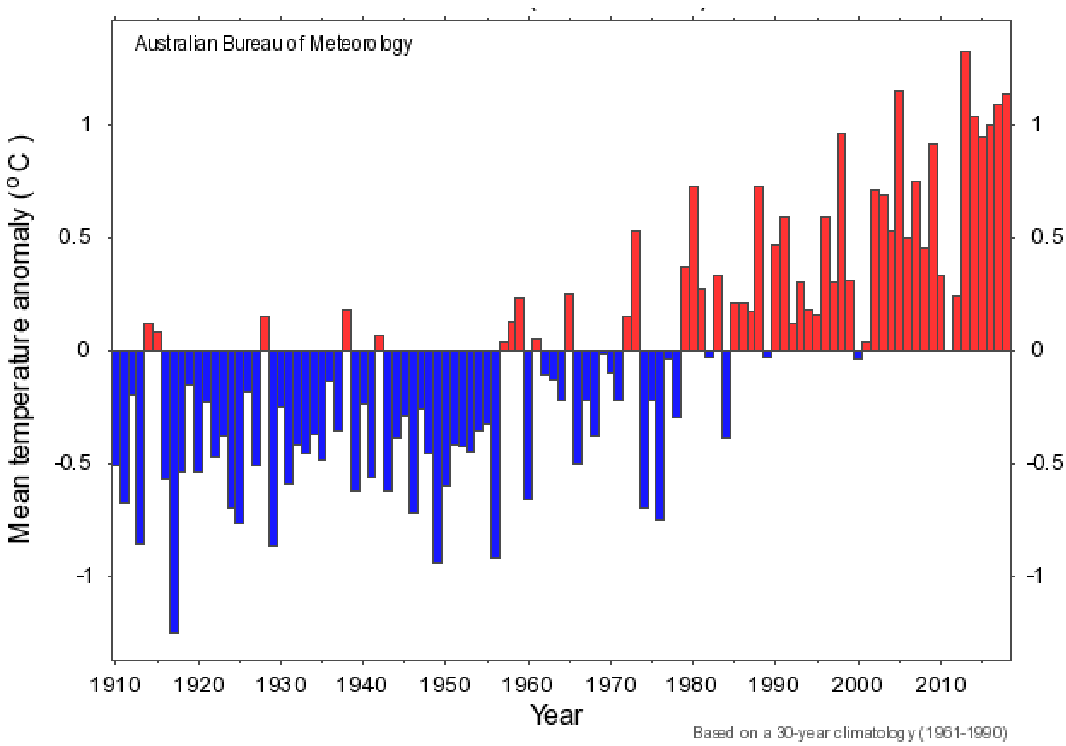


Figure 9.1 Yearly variance of mean air temperature for Australia between 1910-2018 (Australian Government 2019a).

(Note: Available under Creative Commons Attribution Australia Licence http://www.bom.gov.au/climate/change/#tabs=Tracker&tracker=timeseries&tQ=graph%3Dtmean%26area%3Daus%26season%3D0112%26ave_yr%3D0)

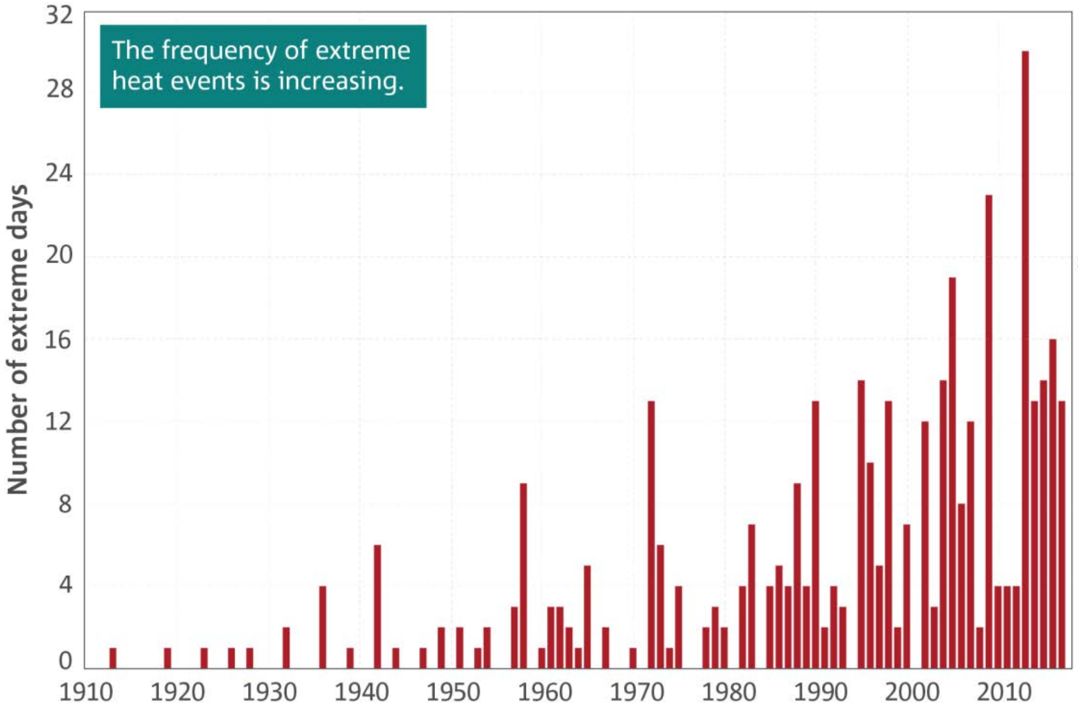


Figure 9.2 The frequency of extreme daylight temperature (over 40 ºC) between 1910-2018 (Australian Government 2019b)

(Note: Available under Creative Commons Attribution Australia Licence http://www.bom.gov.au/state-of-the-climate/australias-changing-climate.shtml

A lot of those warming happened from the 1970s onwards. Based on the weather data, the world's warmest year was 2016, and the years 2015 and 2017 were the same second warmest years around the globe (Australian Government, 2019b). As shown in Figure 9.2, the length, occurrence and strength of extreme summer have intensified throughout Australia since 1970. The year 2013 was Australia's hottest on record with an average temperature level of 1.1 ºC over 1961-1990 average temperature. The occurrence of very hot daylight temperature (over 40 ºC) has been expanding since the 1990s (Australian Government, 2019b).

Therefore, Australia is currently facing the impacts of a transforming climate, precisely adjustments linked with temperature change and intensity of summer weather condition. Scrutiny of the long-term weather data and future projections reveal that these changes from the historic climate are recurring and long-term. This chapter considers potential climate change scenario of a possible increase of the future temperature increase from 0.5 ºC, 1.0 ºC, 1.5 ºC and 2 ºC from the historical average based on IPCC report as well as consider an average increase of temperature in future based on the global climatological database Meteonorm which is adopted by the scientific community for climatological response in building performance simulation. Meteonorm adopts the results of AR4 from IPCC as input in lieu of adopting downscaling extensive methods based on regional climate models to produce the data file. Figures 9.3 and 9.4 show a comparison of a daily average outdoor air temperature of Rockhampton with climate change scenario and the historical average for the whole year.

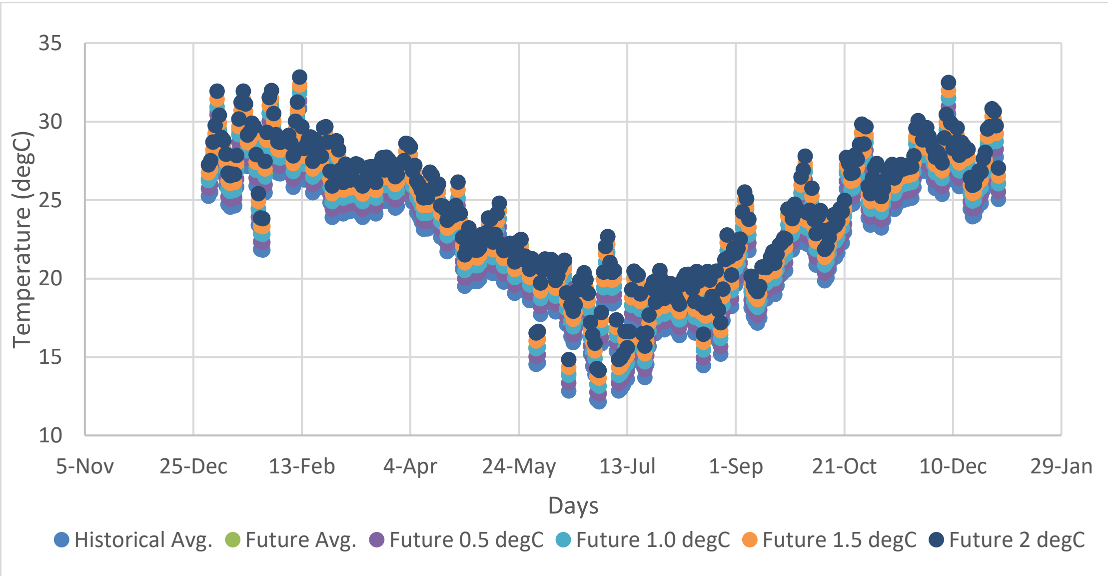


Figure 9.3 Future daily average outdoor temperature considering potential scenarios

Although the Figures illustrate the temperature values for the future prediction, the simulation weather file considered solar radiation, dew point temperature, wind speed and direction, solar altitude and azimuth and atmospheric pressure data. The hourly average weather simulation data provided 38.05 ºC to 40.10 ºC maximum outdoor air temperature and 4.43 °C to 6.5 °C minimum outdoor temperature in different scenarios. The daily average weather simulation data provided 30.81 °C to 32.81. °C maximum outdoor air temperature and 12.14 degC to 14.14 degC minimum outdoor temperature in different scenarios. The monthly weather simulation data provided 26.74 °C to 28.74 °C maximum outdoor air temperature and 16.6 °C to 18.6 °C minimum outdoor temperature in different situations. Table 9.1 and 9.2 represent the historical average monthly external surfaces solar incident (kWh/m^2) and outside surface temperature (°C). The solar incident value varies from 74 kWh/m^2 to 89 kWh/m^2 during the summer months and 45 kWh/m^2 to 67 kWh/m^2 during the winter months. The monthly external surface temperature varies from 30 °C to 32.26 °C during the summer months and 18 °C to 23.94 °C during the winter months.

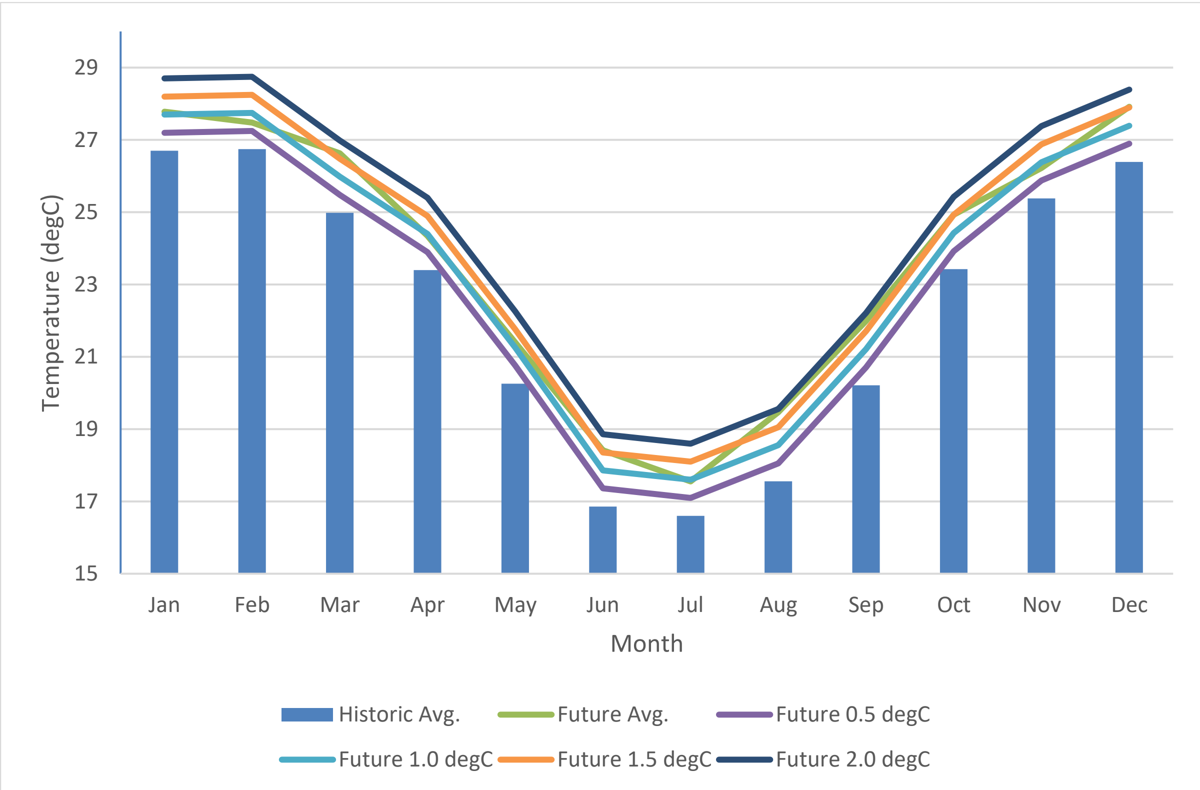
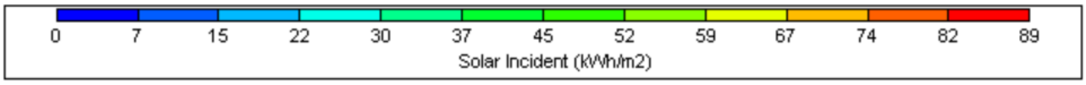


Figure 9.4 Future monthly average temperature considering potential scenarios

Table 9.1 Monthly external surfaces – solar incident (kWh/m^2)



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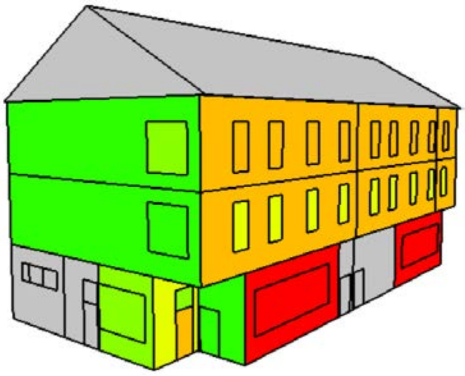

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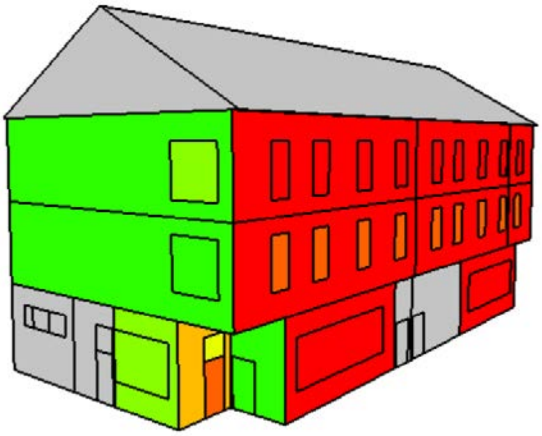

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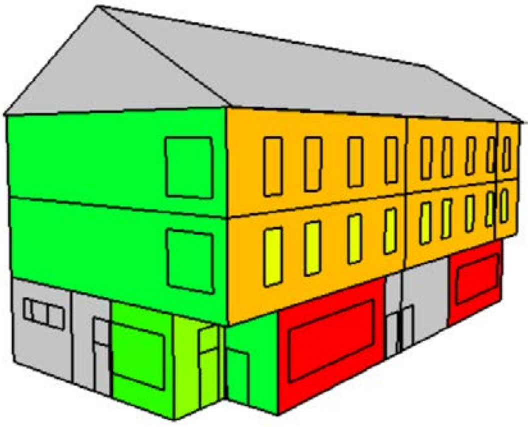

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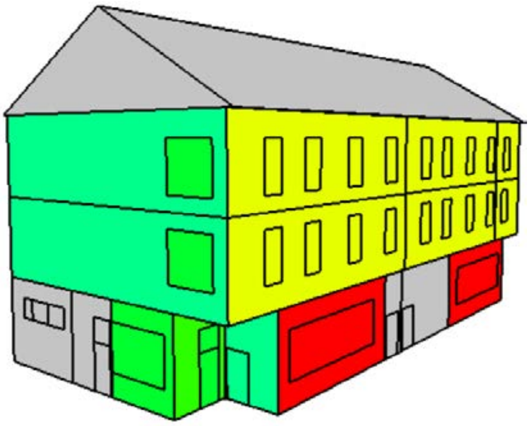

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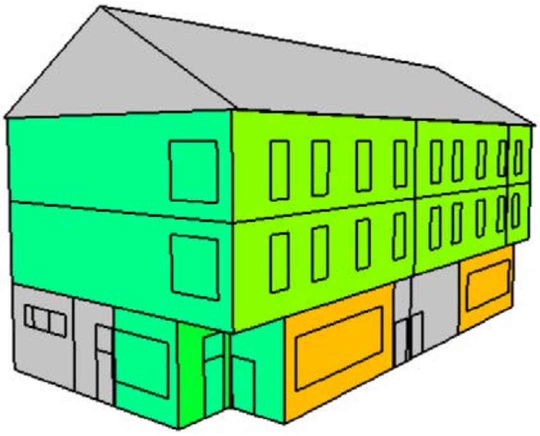
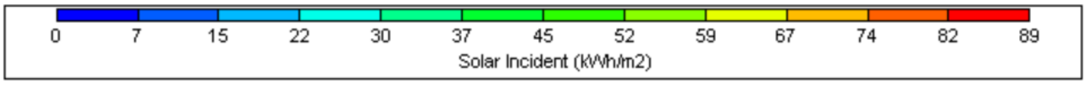


Monthly external surfaces – solar incident (kWh/m^2)



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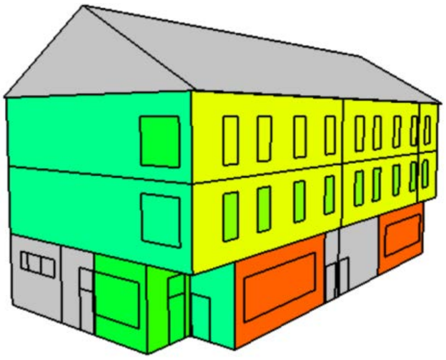

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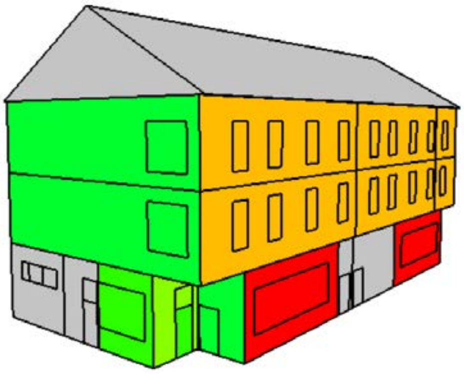

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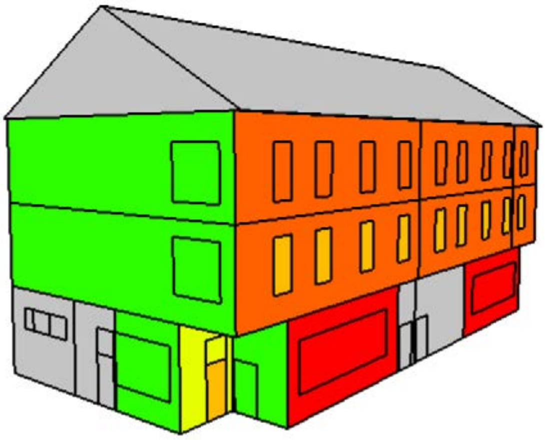

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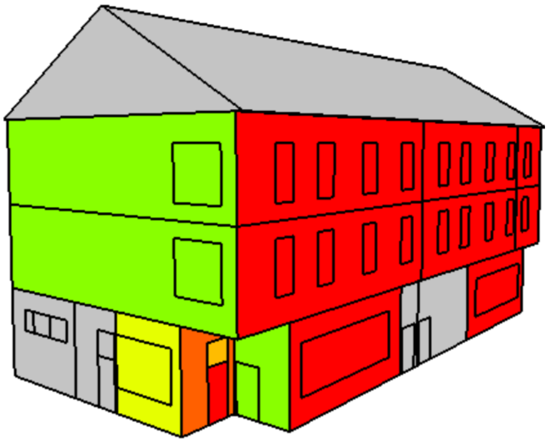

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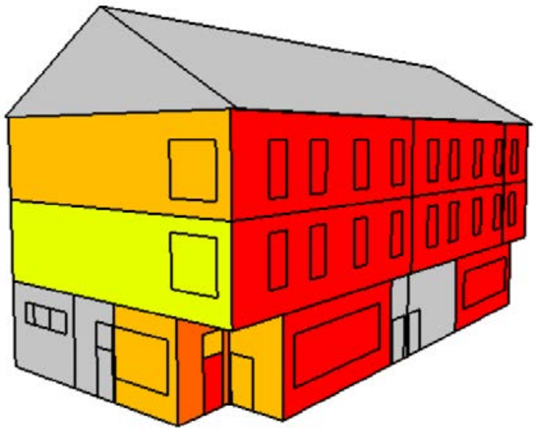
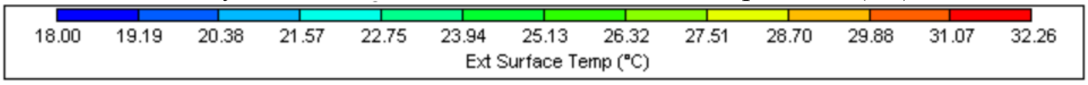


Table 9.2 Monthly external surfaces – outside surface temperature (^{O}C)



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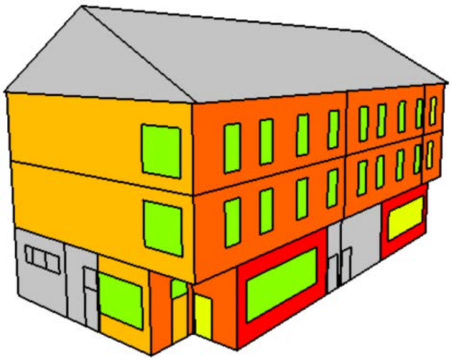

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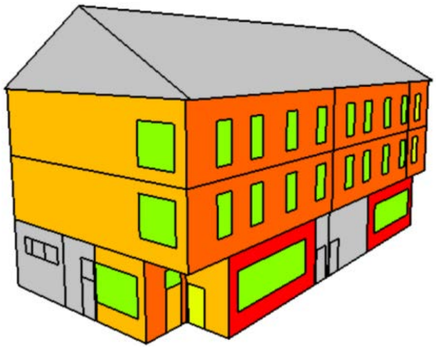

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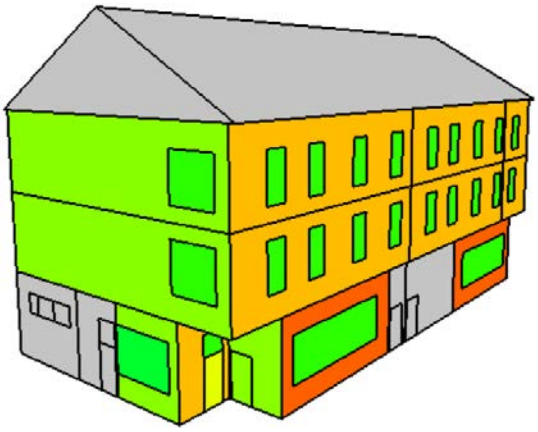

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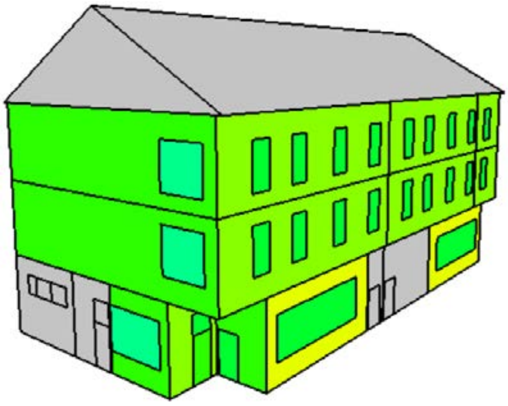

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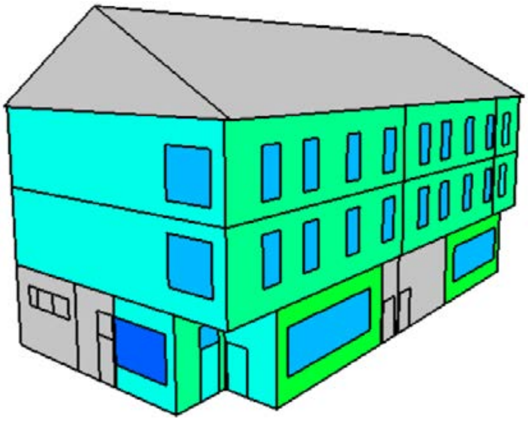

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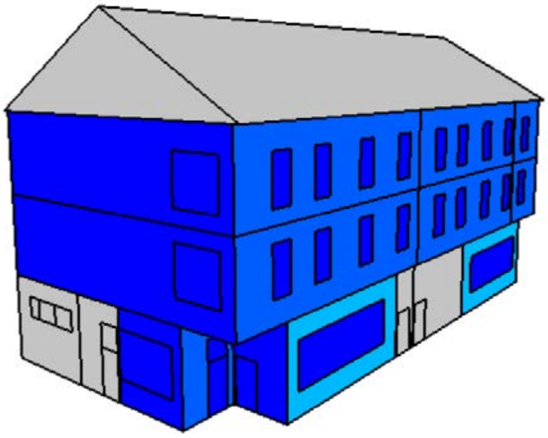
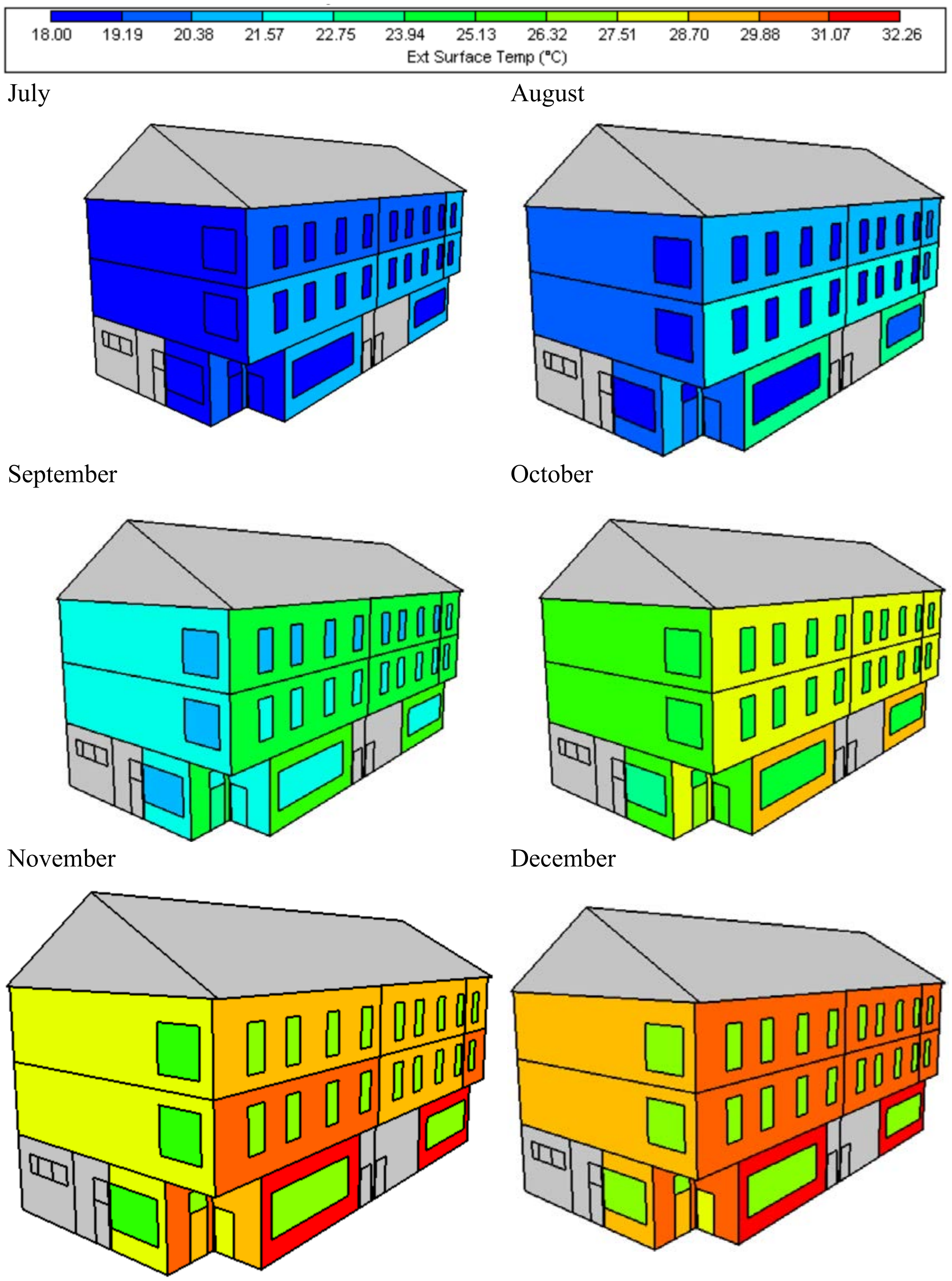


Monthly external surfaces – outside surface temperature (^{O}C)



9.5 COMFORT PROFILE IN FUTURE WEATHER SCENARIO

Figures 9.5 and 9.6 show details of the interior temperature, moisture, people comfort index in wintertime and summertime. The humidity and temperature are within the desired comfort level. The discomfort values are almost none in winter months and even practically insignificant in the summertime. In this study, the existing interior comfort parameters are evaluated, and the comfortability of the space has been calculated. The comfort values are evaluated against the set criteria specified in the literature and are in decent treaty with the reported values in the comfort standard from ASHRAE. Additional thermal comfort indices were measured and found to be effective.

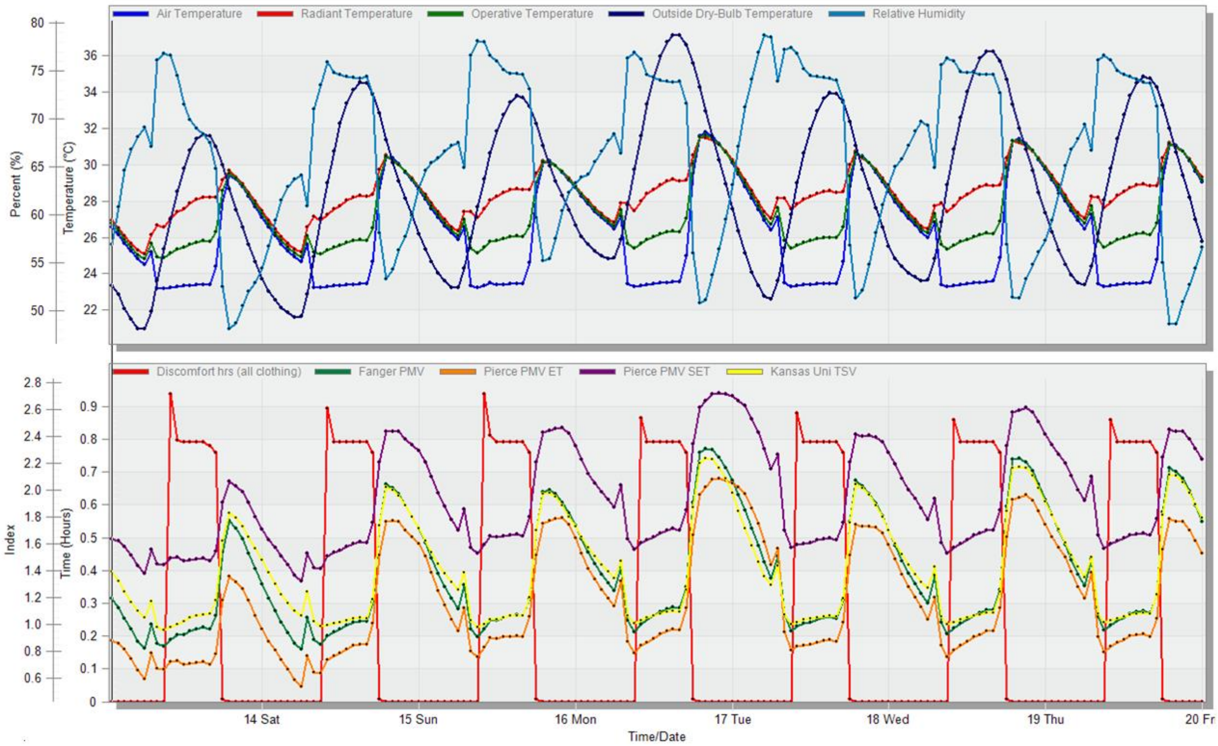


Figure 9.5 Summer comfort profile considering future potential hourly average weather condition

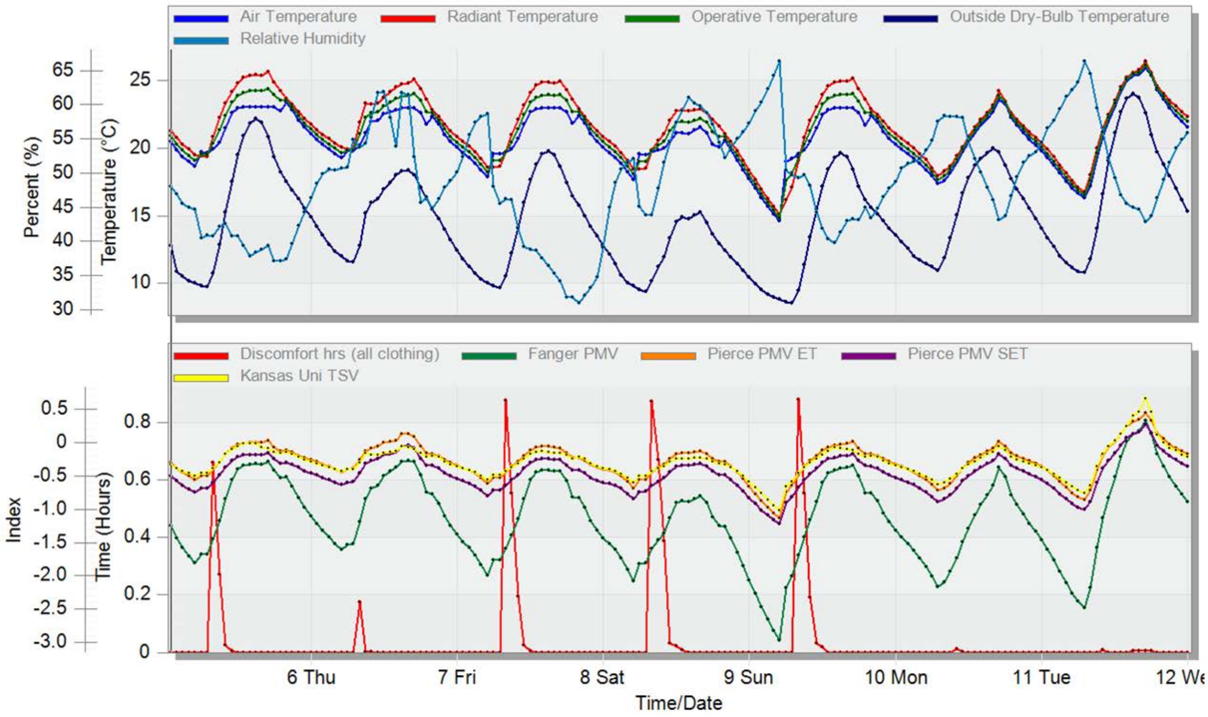


Figure 9.6 Winter comfort profile considering future potential hourly average weather condition

9.6 COMFORT PROFILE IN FUTURE WEATHER SCENARIO

Figures 9.7 to 9.11 compare normalised monthly cooling, heating and total energy consumption, operational CO_2 emission, and cooling demand considering historical average and future potential average weather condition. In figure 9.7, the simulation results show that cooling energy consumption increase from 0.2 kWh /m^2/ month to 1.9 kWh /m^2/ month during the summer months and 0.3 kWh /m^2/ month to 0.85 kWh /m^2/ month during the winter months under future average weather condition. Compared to the historical average, the cooling energy consumption increases from 2.8% to 26.7% during the summer months and 8% to 23.6% during the winter months under future average weather condition. A similar trend observed under 0.5 ºC to 2 ºC increased temperate status in future. Performance simulation of the building system under 0.5 ºC potential temperature increase in future could increase the monthly cooling energy consumption from 4.9% to 7.4% in summer months and

6.2% to 8.8% in winter months. Similarly, 1.0 ºC possible temperature rise in future could surge the monthly cooling energy consumption from 11.2% to15.4% in summer months and 13.8% to 19.1% in winter months. 1.5 ºC likely temperature escalation in future could upsurge the monthly cooling energy consumption from 17.4% to 23.8% in summer months and 21.11% to 29.4% in winter months. And 2.0 ºC potential temperature escalation in future could boost the monthly cooling energy consumption from 23.7% to 32.3in summer months and 28.3% to 39.4% in winter months. Figure 9.8 represents the increase in monthly heating energy consumption, considering historical average and future potential average weather condition during the winter months. Similar to the present situation, there are no heating requirements in the summer seasons. Heating energy is simply needed through the peak wintertime, and demand is proportional to the change in increased external air temperature in the wintertime.

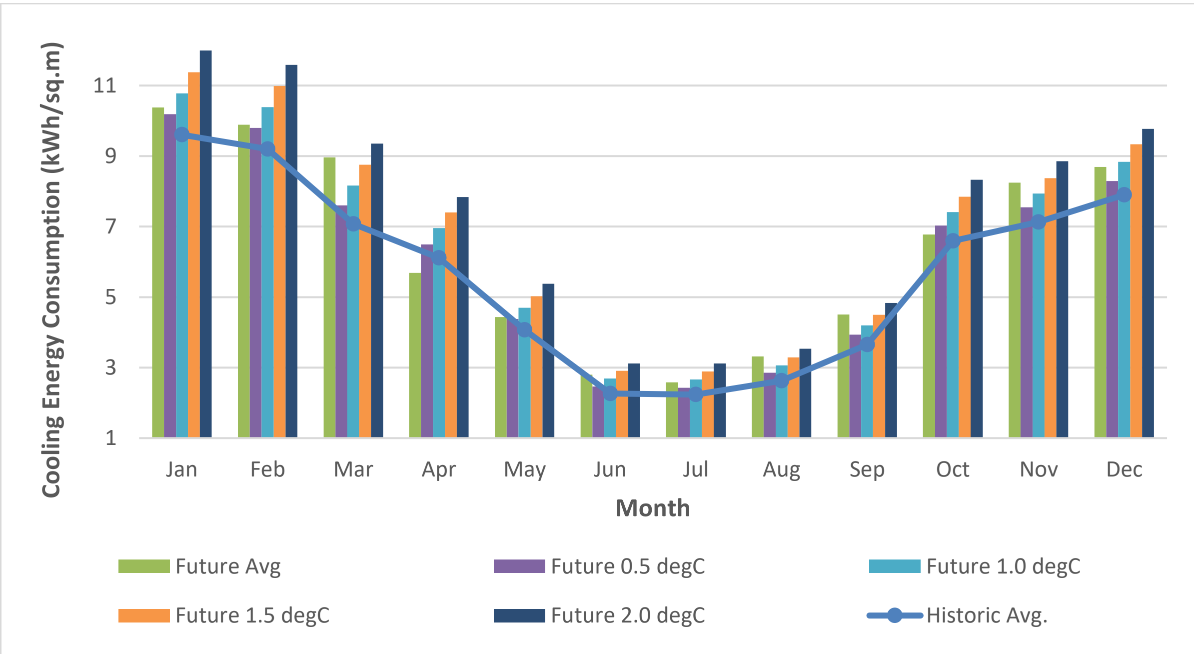


Figure 9.7 Comparison of normalised monthly cooling energy consumption considering historical average and future potential average weather condition

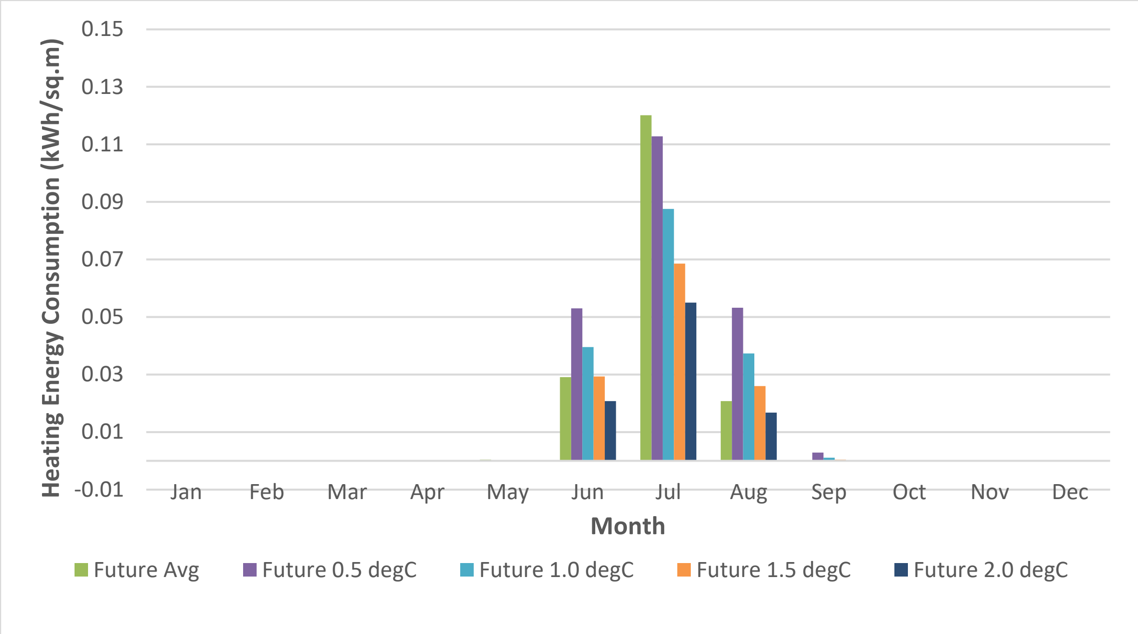


Figure 9.8 Comparison of normalised monthly heating energy consumption considering historical average and future possible average weather condition

In Figure 9.9, the simulation results exhibit that total energy consumption increase from 0.6 kWh /m^2/ month to 2 kWh/m^2/month during the summer months and 0.6 kWh /m^2/ month to 1.28 kWh/m^2/month during the winter months under future average weather condition compared to the historical average. The overall electricity usages increase from 4.6% to 15.6 % during the summer months and 5.6 % to 14.7 % during the winter months under future average weather condition. A similar trend noticed under 0.5 ^{o}C to 2 ^{o}C increased temperate condition in future. Performance simulation of the overall building system under 0.5 ^{o}C potential temperature increase in future could increase the monthly cooling energy consumption from 3% to 4% in summer months and 2.2% to 3.2% in winter months. Similarly, 1.0 ^{o}C possible temperature rise in future could surge the monthly total energy consumption from 6.1.2% to 8.4% in summer months and 5% to 6.8% in winter months. 1.5 ^{o}C likely temperature escalation in future could upsurge the monthly total energy consumption from 9.4% to 13% in summer months and 7.6% to 10.4% in winter months. And 2.0

°C potential temperature escalation in future could boost the monthly total energy consumption from 13.2% to 17.6% in summer months and 10.4% to 14.2% in winter months.

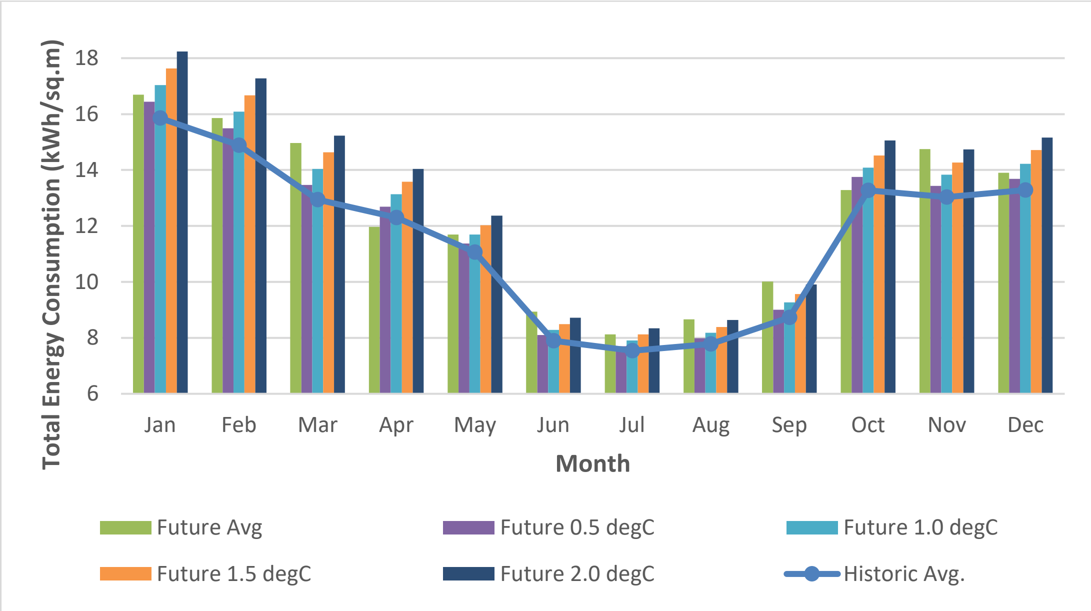


Figure 9.9 Comparison of normalised monthly total energy consumption considering historical average and future potential average weather condition

In Figure 9.10, the simulation outcomes show that the total operational CO_2 emission increases from 4.6% to 15.6 % during the summer months and 5.6 % to 14.7 % during the winter months in future median weather condition. An analogous trend noticed under 0.5 °C to 2 °C increased temperate condition in future. Performance simulation of the overall building system under 0.5 °C potential temperature increase in future could increase the monthly operational CO_2 emission from 3% to 4% in summer months and 2.2% to 3.2% in winter months. Similarly, 1.0 °C possible temperature rise in future could surge the monthly operational CO_2 emission from 6.1.2% to 8.4% in summer months and 5% to 6.8% in winter months. 1.5 °C likely temperature escalation in future could upsurge the monthly operational CO_2 emission from 9.4% to 13% in summer months and 7.6% to 10.4% in winter months. And 2.0

°C potential temperature escalation in future could boost the monthly operational CO_2 emission from 13.2% to 17.6% in summer months and 10.4% to 14.2% in winter months.

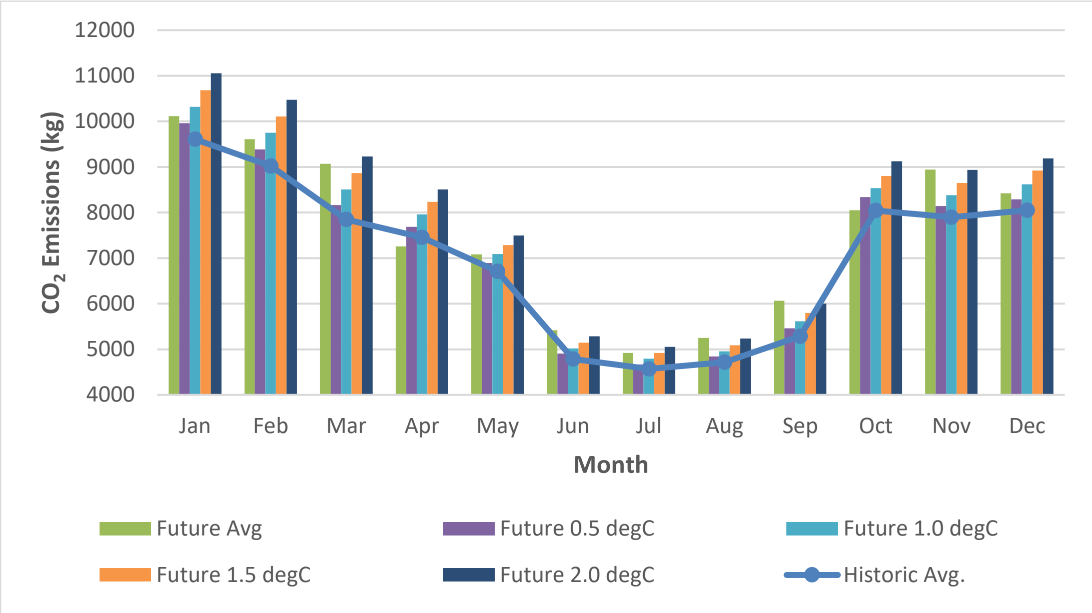


Figure 9.10 Comparison of normalised monthly CO_2 emission considering historic average and future potential average weather condition

In Figure 9.11, the cooling demand increases from 3.2% to 26.9% during the summer months and 8.9% to 24.6% during the winter months under future average weather condition compared to the historical average. A similar trend observed under 0.5 °C to 2 °C increased temperate condition in future. Performance simulation of the building system under 0.5 °C potential temperature increase in future could increase the monthly cooling demand from 4.9% to 7.4% in summer months and 6.2% to 9.1% in winter months. Similarly, 1.0 °C possible temperature rise in future could surge the monthly cooling demand from 11.2% to15.4% in summer months and 13.8% to 19.1% in winter months. 1.5 °C likely temperature escalation in future could upsurge the monthly cooling demand from 17.4% to 23.8% in summer months and 21.11% to 29.4% in winter months. And 2.0 °C potential temperature escalation in future could boost the monthly cooling demand from 23.7% to 32.3in summer months and 28.3% to 39.4% in winter months.

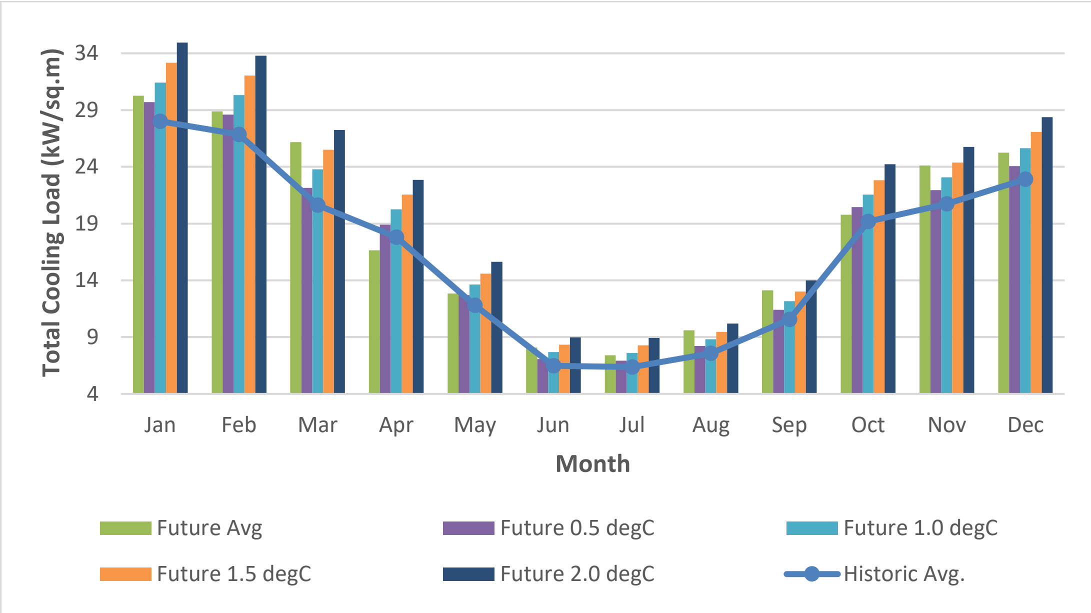


Figure 9.11 Comparison of normalised monthly total cooling load considering historical average and future potential average weather condition

Figure 9.12 explains the association of increased normalised yearly cooling and overall energy consumption, considering future potential average weather conditions. The cooling energy consumption increases around 15.1%, 22.6%, 30.3% and 38.3% respectively on an annual basis due to potential increase in external temperature from 0.5 °C to 2.0 °C and around 20% from future average temperature increase. A similar trend is also observed in term of total energy consumption. The total energy consumption rises 7.2%, 10.6%, 14.3%, 18.1% in that order on an annual basis due to a potential increase in external temperature from 0.5 °C to 2.0 °C and around 11.4% from future average temperature increase. The operational CO_2 emission increases 3.3%, 6.6%, 10.1%, 13.8% respectively on an annual basis due to potential increase in external temperature from 0.5 °C to 2.0 °C and around 7.4% from future average temperature increase.

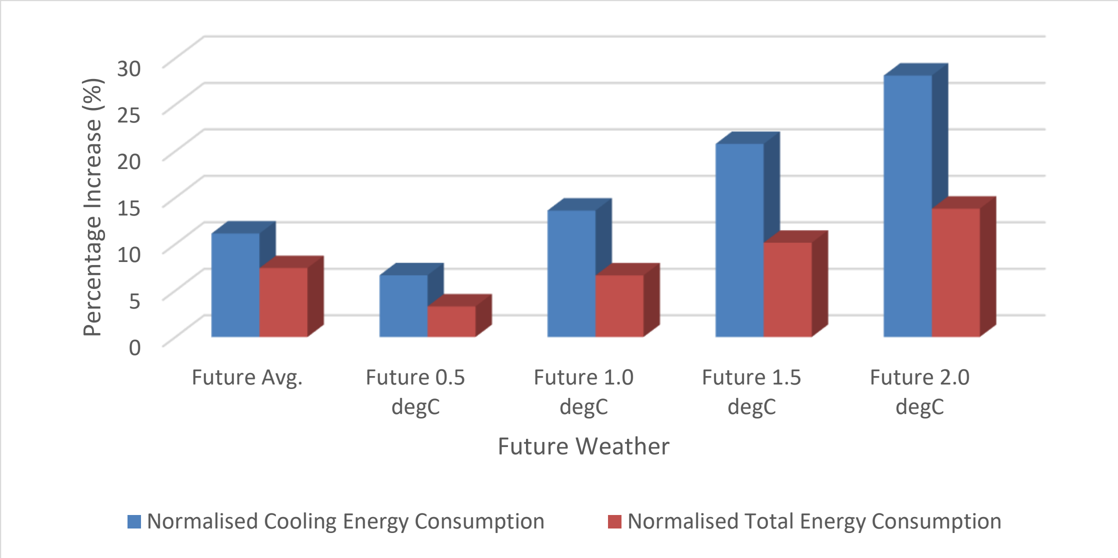
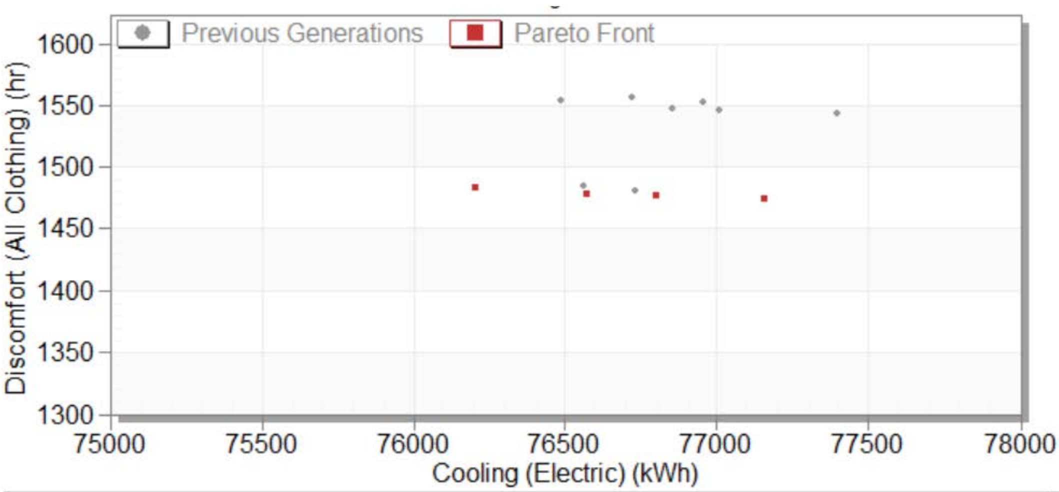


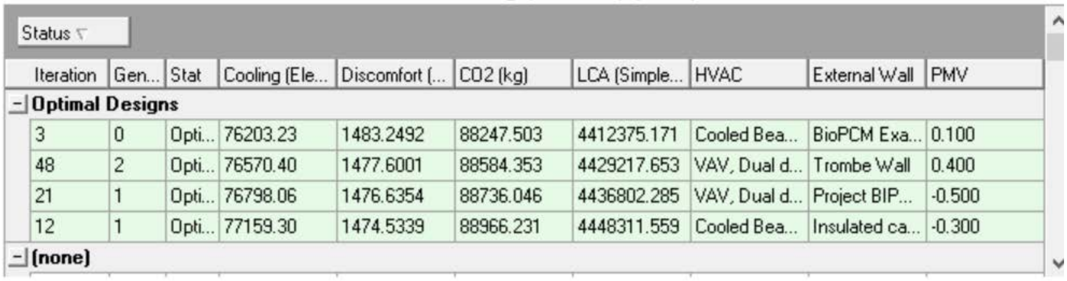
Figure 9.12 Assessment of increased normalised yearly cooling and overall energy consumption considering the future potential average weather condition

Figures 9.13 to 9.17 in the following sections show the optimisation results of cooling yearly energy consumption concerning discomfort hours over the same period considering the feature weather change scenarios derived from the developed model stated in the previous chapters. The only amendment made in the model was the weather data. Five optimised solutions were presented considering the changes in weather in future. From Figure 9.13, The optimisation results against discomfort hrs and cooling energy consumption suggest Cooled Beam and BioPCM as one of the optimised solutions with 76203 kWh/annum cooling energy consumption and 1483 hrs discomfort per year due to potential average future weather condition.

From Figures 9.14.to 9.17, Cooled Beam HVAC and BioPCM external envelop combination was the standalone optimum combination considering that 71203 kWh/annum, 74353 kWh/annum, 80184 kWh/annum, and 85598 kWh/annum cooling energy consumption and 1523 hrs, 1467 hrs, 1568 hrs and 1672 hrs of discomfort hours due to potential increase in external temperature from 0.5 °C to 2.0 °C respectively. The other optimised solutions are also feasible; however, Cooled Beam and BioPCM combination are recommended considering additional optimised discomfort hours, CO_2 releases, PMV values etc.

The other variables produce reasonable values which are consistent with the previous optimised results reported. Figures also reported the optimised LCA and operational CO_2 emission, which provides similar optimum solution out of all the iterations. The recommended optimum solution is Cooled Beam HVAC and BioPCM external envelop in all scenarios because of the overall performance considering the minimum cooling energy consumption, discomfort hours, operational CO_2 emission although a couple of other optimised solutions identified.

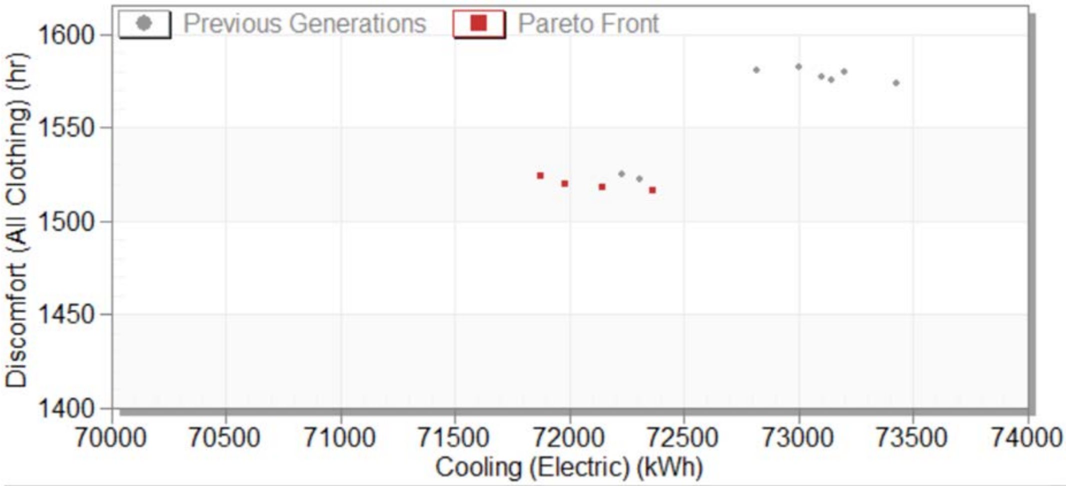




Status

Iteration	Gen...	Stat	Cooling (Ele...	Discomfort (...	CO2 (kg)	LCA (Simple...	HVAC	External Wall	PMV
Optimal Designs									
3	0	Opti...	76203.23	1483.2492	88247.503	4412375.171	Cooled Bea...	BioPCM Exa...	0.100
48	2	Opti...	76570.40	1477.6001	88584.353	4429217.653	VAV, Dual d...	Trombe Wall	0.400
21	1	Opti...	76798.06	1476.6354	88736.046	4436802.285	VAV, Dual d...	Project BIP...	-0.500
12	1	Opti...	77159.30	1474.5339	88966.231	4448311.559	Cooled Bea...	Insulated ca...	-0.300
(none)									

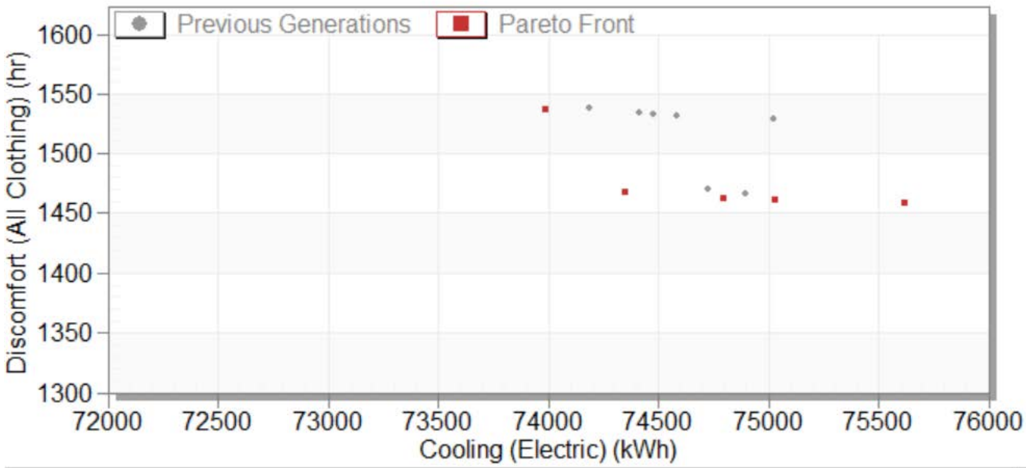
Figure 9.13 Optimizing cooling energy consumption and discomfort hours considering the potential average future weather condition



Status

Iteration	Gen...	Stat	Cooling (Ele...	Discomfort (...	CO2 (kg)	LCA (Simple...	HVAC	External Wall	PMV
Optimal Designs									
14	1	Opti...	71876.17	1523.5671	85609.745	4280487.247	Cooled Bea...	BioPCM Exa...	0.300
38	2	Opti...	71980.47	1519.7567	85820.318	4291015.903	VAV, Dual d...	Trombe Wall	-0.200
4	0	Opti...	72148.86	1517.9626	85928.717	4296435.835	Cooled Bea...	Project BIP...	0.100
5	0	Opti...	72363.64	1516.3265	86062.062	4303103.095	VAV, Dual d...	Insulated ca...	-0.200
(none)									

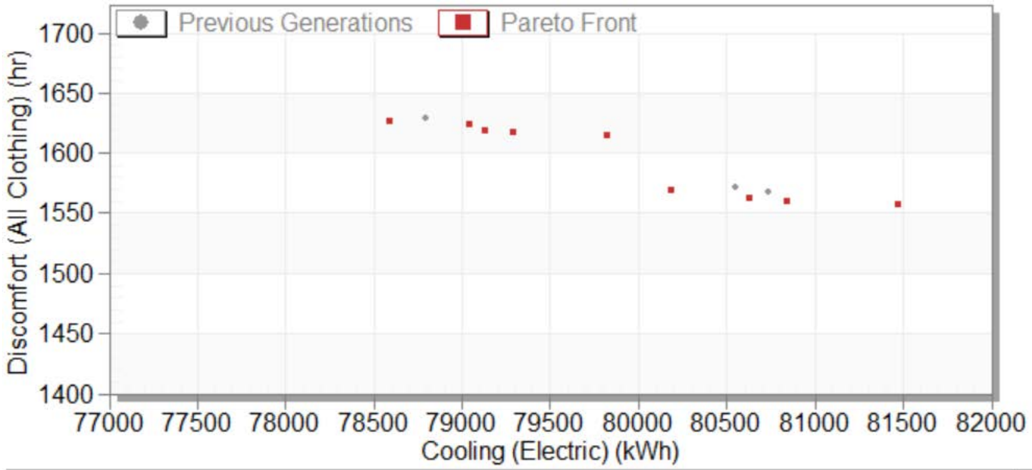
Figure 9.14 Optimizing cooling energy consumption and discomfort hours considering potential 0.5 ºC temperature increase in future



Status

Iteration	Gen...	Stat	Cooling (Ele...	Discomfort (...	CO2 (kg)	LCA (Simple...	HVAC	External Wall	PMV
Optimal Designs									
16	1	Opti...	73990.48	1536.1796	85470.781	4273539.075	GSHP Unita...	BioPCM Exa...	0.300
10	1	Opti...	74353.50	1467.7224	85692.108	4284605.379	Cooled Bea...	BioPCM Exa...	0.000
5	0	Opti...	74797.12	1462.4225	86065.243	4303262.138	Cooled Bea...	Trombe Wall	0.200
11	1	Opti...	75035.38	1460.6141	86214.363	4310718.143	Cooled Bea...	Project BIP...	0.000
13	1	Opti...	75617.61	1458.9254	86571.000	4328550.015	Cooled Bea...	Insulated ca...	0.200

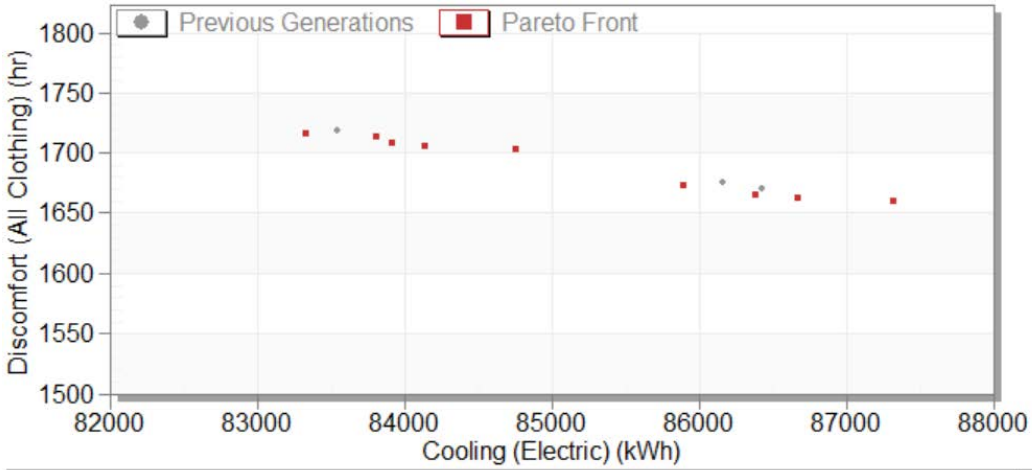
Figure 9.15 Optimizing cooling energy consumption and discomfort hours considering potential 1.0 ºC temperature increase in future



Status

Iteration	Gen...	Stat	Cooling (Ele...	Discomfort (...	CO2 (kg)	LCA (Simple...	HVAC	External Wall	PMV
9	0	Opti...	79825.21	1614.9519	89101.288	4455064.392	VRF (Air-Co...	Insulated ca...	-0.200
10	1	Opti...	80184.73	1568.6807	89198.097	4459904.858	Cooled Bea...	BioPCM Exa...	0.000
58	3	Opti...	80626.08	1562.1006	89574.083	4478704.149	Cooled Bea...	Trombe Wall	0.300
18	1	Opti...	80841.96	1559.9244	89708.839	4485441.932	VAV, Dual d...	Project BIP...	0.500
0	0	Opti...	81470.80	1557.6875	90092.016	4504600.783	VAV, Dual d...	Insulated ca...	-0.300

Figure 9.16 Optimizing cooling energy consumption and discomfort hours considering potential 1.5 ºC temperature increase in future



Status

Iteration	Gen...	Stat	Cooling (Ele...	Discomfort (...	CO2 (kg)	LCA (Simple...	HVAC	External Wall	PMV
4	0	Opti...	85898.84	1672.4109	92639.643	4631982.138	Cooled Bea...	BioPCM Exa...	0.400
54	3	Opti...	86386.38	1664.8653	93046.562	4652328.092	VAV, Dual d...	Trombe Wall	-0.300
21	1	Opti...	86679.67	1662.4759	93227.197	4661359.836	VAV, Dual d...	Project BIP...	-0.300
25	1	Opti...	87322.17	1659.5946	93617.677	4680883.852	VAV, Dual d...	Insulated ca...	0.500
(none)									
34	2		83332.02	1715.7422	91088.911	4554445.532	VRF (Air-Co...	BioPCM Exa...	-0.100

Figure 9.17 Optimizing cooling energy consumption and discomfort hours considering possible 2.0 ºC temperature increase in future

9.7 NET POSITIVE ENERGY BUILDING

As a result of advances in building and innovations in mechanical systems, environment-friendly energy systems establishing net outright zero energy building is ending up being more functional. While the precise meanings for absolutely no energy building differ, the core concept is to reduce energy requirements and promote sustainable energy systems that satisfy these reduced power requirements. A broader classification recommends for techniques in which the same might be carried out: Zero Net Site Energy, Zero Net Energy Costs, Zero Net Source Energy, Zero Net Energy Emissions. The enhancement of new variables in the evaluation, for instance, occupants' behaviours can utilise some understandings right into the choice of the variation in between anticipated as well as authentic energy efficacy.

The stipulations for boosted energy efficacy demands were initiated in the Building Code of Australia (National Construction Code - NCC). The absence of an emission decrease target over time, or a zero net emission target similar to those established by various other nations to mount the application of these procedures, will undoubtedly result in Australia dropping behind the remainder of the globe in regard to the efficacy of its building. Provided the core concept for the zero net energy building interpretation is an equilibrium in between energy need and supply of various form of energy from a renewable source, a positive net energy building might be specified in the following type of a framework in Figure 9.18.

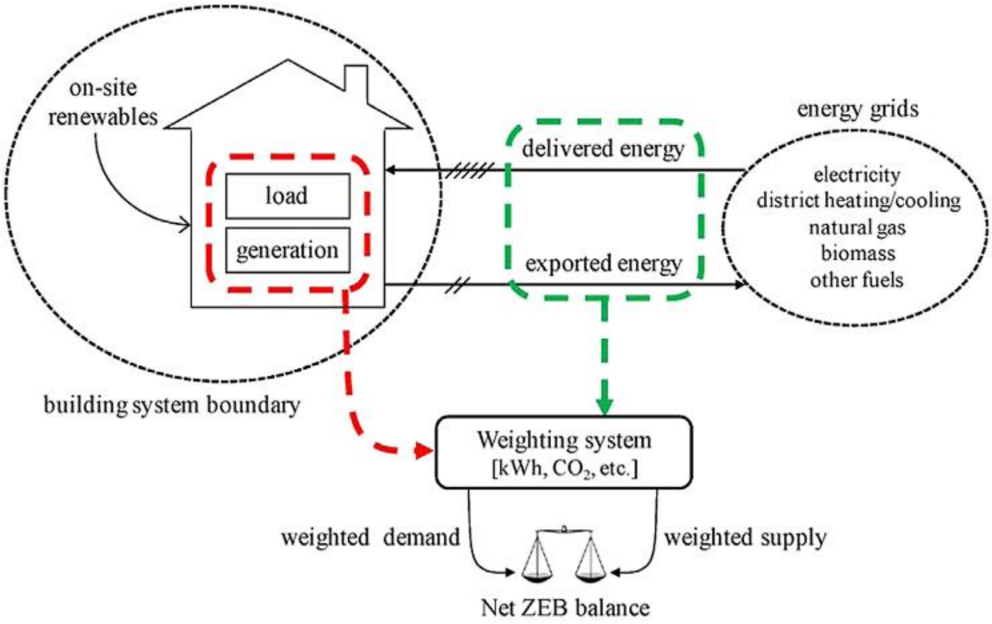


Figure 9.18 A proposed pathway for achieving a balanced zero net energy building (Satori *et al.* 2012)

9.8 INTEGRATION OF PHOTOVOLTAIC (PV) SOLAR SYSTEM

At this stage, Photovoltaic (PV) panels were included in the optimised, developed model by following the steps below.

- Position and size PV panels were included by following the software instructions in the Adding Solar Collectors menu.
- The properties of the PV panel were defined by first navigating to the solar collector object by double-clicking on the graphical object from building level or single-click on the solar collector item in the Navigator.
- The performance and other panel properties were defined on the assembly of the solar collector section.
- The electrical component of the PV system was defined under the Generation section of the Site Electricity Generation.

- Electric load centres were included with the DC bus and Inverter type.

Table 9.3 Outcome of net positive energy building considering the future weather condition

	Electricity (kWh)	Per cent (%)
Fossil fuel-based energy utilisation	0.00	0.00
Photovoltaic Power	157.63	102.00
Total Onsite Electric sources	157.63	102.00
Power is drawn from the utility provider	0.00	0.00
Residual energy diverting to the grid	3.05	2.00
Net energy from grid	0.00	0.00
Total energy sources	154.58	100.00
Total energy usages	154.58	100.00

Table 9.3 represents the outcome of net positive energy building by taking into account the outcome of optimisation results for future weather condition, the retrofitting scenario considering future weather. The concluding issue of the optimised model comprises the optimised solutions of the building systems that are not only suitable considering the historical weather condition but also are capable of dealing with the potential future uncertain climatic situation. This finding is particularly important because, only the cooling and total electricity consumptions, LCA, CO_2 emission of the energy system and discomfort hours have been modelled. The outcome of resultant energy balance using future extreme weather condition are more significant than the present building energy balance by around 7% to 18% as a consequence of both the need and production aspect of the energy. All the optimisation

scenarios display moderately consistent outcomes and meet the zero net source energy usages criteria and move towards further defining positive energy building.

9.9 CONCLUSIONS

This chapter is not an endeavour to deliver particular regulation for the operation of future buildings. Instead, the finding highlights the mathematical approach to offer a specialized knowledge of individual variables to measure the potential lack of expertise to evaluate the understanding of interior conditions to potential climate transformation in future and its potential impact on the overall efficacy of envelope and mechanical systems in buildings. The results reported in this chapter is not intended to replace human reasoning by ever-smarter computer algorithms or tools instead the study wants to illustrate just how far consequence of not understanding the imminent climate transformation on indoor comfort, energy use etc.

Chapter 10: Conclusions and Future Work

10.1 CONCLUDING REMARKS

The research undertaken in this thesis offers progression in the knowledge of precise energy consumption analysis, thermal comfort evaluation and optimization of building systems using high-performance phase adjusted organic material-based building envelope and low emission cooling method that can satisfy the objectives of maximising the energy savings and thermal comfort in an environmentally friendly way in the subtropical climate. As far as literature reviewed, there is little, or no information identified which considered an integrated application of bioPCM building envelope and cooled beam-based cooling method in building to reduce rising energy demand. In this study, a combined application of bioPCM, as well as cooled beam, are evaluated to check the applicability of such combination in buildings in the subtropical climate. The analysis showed that incorporating PCMs right into building envelopes along with cooled beam has a higher potential for energy conservation and offer better indoor environment depending on present and future weather conditions.

An in-depth audit of the current mechanical systems is undertaken on the selected office building. A comprehensive performance evaluation model is developed using Designbuilder and EnergyPlus algorithm by considering all the potential variables that may stimulate the overall efficacy of the building system. The mathematical model and the simulation outcome were verified through the measured data collected. The tested version of the EnergyPlus and Designbuilder model is applied to assess the efficacy of several different high-performance exterior building envelopes and low emission cooling techniques to accomplish much better thermal performance and reduce power cost in both summer and winter season in the subtropical climate. An elaborated multicriteria based optimisation study is then conducted where alternative envelope systems and cooling methods are examined based on the objectives to support the choices for retrofitting of the existing systems that will endure the requisite of the present and the future depending on the potential climate change scenario. The succinct outcomes of the analysis and suggestions for potential research work in future are elaborated below.

10.2 SYNOPSIS OF RESULTS

In cities of a subtropical climate, air-conditioning subsists to essentially deal with air contamination by offering a unique interior environment. Subsequently, it might be impractical to reject conditioned air to employees in the workplace. A variety of settings to comfort parameters should be supplied that agree with the psychological needs of the respective area. Cooled beams might play a more significant function in tropical workplaces. Well-controlled cooled beams should not have any condensation problems.

The main conclusion of the thesis is that BioPCM and Cooled Beam can be successfully incorporated into buildings in subtropical climate to improve energy efficiency by 30% and human comfort. The study found that both cooled beam and ground source heat pump as low energy high-performance cooling alternatives. The combined optimised approach produces significantly less emission (21%) per year at the same time ensures the comfortability of the occupants, says the study. It also found that the study offered a net positive energy operating method to ensure that carbon footprint is minimised considering the present and future weather conditions.

10.3 SUMMARY OF CONTRIBUTION

10.3.1 Energy Assessment of Building Systems

The findings of the assessment and recorded data for a considerable amount of time will be essential resources to evaluate the parameters influencing the performance of mechanical systems in buildings. Contrasted to the year 1, it was found that the yearly power cost is raised 7.9% with the complete increase in the use of the power of 1.9% in year 3. The research recommends that the additional power usage to overcome the harsh effect of extreme outdoor environment can be minimized by enhanced control and low energy cooling methods. With the electricity record analysis, it was located that electricity costs on year on year basis is boosted 2-3% with a total boost in intake of 8.5%. The findings of this research highly endorse that the enhanced usage of AC and ventilation units, to compete with temperature and humidity rise, can easily be reduced by improved seasonally adjusted control procedures and optimised usage of the equipment. The results reported from the energy analysis are easily adopted to analyse the variables influencing excessive electricity consumption and to identify methods to improve the energy effectiveness.

10.3.2 Building Energy Modelling and Simulation

A base case model was formed and evaluated alongside the measured data. Simulation outcome implied that the system consistently maintains 23 °C temperature thought the zone, which is a good testimony of the simulation algorithms' ability to simulate the actual comfort condition in the building. The simulation results suggested that electrical power usage rises throughout the summertime months once the outside atmospheric temperatures are elevated. The energy expenditure is reasonably lesser, and the variant of energy consumption corresponds to the same in wintertime. The most significant a/c energy demand remains in the summertime at the start of the day, which differs between 45 to 53 Wh/m^2. The power needed is substantially less during the wintertime week, which will certainly alter in between 22 to 44 Wh/m^2. The entire building energy consumption simulation results recommend that the everyday energy consumption trend differs from 65 Wh/m^2 to 76 Wh/m^2 in summer as well as additionally from 46 Wh/m^2 to 64 Wh/m^2 in winter. The finding of the analysis, as well as recorded data for a longer duration, is a handy resource to examine the criteria influencing the performance of mechanical systems.

The outcome of the simulations of the different scenario was matched with onsite determined data: the measured and simulated temperature values in the summertime. The variances amongst the measured and simulated temperature are around 5.5% for summer and winter days which is statistically very significant. The simulated and measured temperature values are in good agreement between 12 pm to 5 pm. The temperature profile in the simulation varied a little bit with the calculated value of 8 am to 1 pm in line with the elevated interior heat gain at the beginning of the day. The average humidity level varies in between 50-85% during the summertime and between 32-65% during the wintertime. The differences between simulated as well as measured values in working hours are the highest 9% during summertime and the highest 11% during the winter.

10.3.3 Evaluation of Alternative Cooling Techniques

Comparison of the alternative cooling methods shows that GSHP, VRF as well as Cooled beam has the higher ability for savings of up to 20% and also up to 9.5% decrease of operational CO_2 emission contrasted to the base circumstance. As an alternative air conditioning method, GSHP, VRF and even Cooled Beam have a higher capacity for energy savings of up to 20% and up to 9.5% reduction of operational CO_2

emission contrasted to the base case situation. Therefore, applications of, GSHP, VRF as well as Cooled Beam to subtropical areas like Rockhampton are quite suitable for overall energy savings. The analysis reveals that alternative cooling techniques can be effectively adopted integrated into buildings found in a tropical climate.

10.3.4 Analysis of Alternative Envelope Systems

PCMs represents practical storage products that could decrease peak energy demand and energy intake in A/C buildings. From the analysis of the annual complete energy-conserving rate, Australian subtropical environment shows to have a good energy-conserving possibility using the integrated option. The results highlight the capacity of bioPCM in the cooling and heating building to lower the power consumption throughout the summer and winter seasons.

Efficient HVAC systems and BioPCM based building envelope would considerably decrease the CO_2 releases and would produce 22148 kg/sqm/yr fewer CO_2 releases to the atmosphere on a yearly basis contrasted to the current arrangement in place in the building. By entirely making use of the potential of the cooled beam and by the improved influence of the envelope heat storage mechanism using bioPCM, a building can lower yearly cooling energy usages by 30% compared to the existing building HVAC and envelope system.

The ability of building envelope to support improved thermal comfort performs a meaningful function in evaluating the efficacy of low energy cooling systems. An envelope with inferior heat transfer characteristics helps to apply the cooled beam cooling method quite favourably. This integrated mechanism can absorb internal heat being at a low temperature compared to the heat sources, which is then either absorbed by the envelope and /or transmitted to the cooling water from the chiller. This integrated approach using BioPCM and cooled beam would direct to a short heat transfer that would lessen external heat gains to a level within the capacity of the cooled beam unit. Merging cooled beam with the thermal storage capacity of BioPCM is able to successfully decrease energy usages for cooling around 30% per annum.

The integrated, optimised approach reduced the sensible cooling load from 5% to 8% in summer season and 16% to 22% in the winter season. On average, the sensible cooling load drops average 10% yearly, which is quite impressive. The integrated approach also reduces the operational CO_2 emission around 19% to 24% in summer months and 13% to 25 % in winter month that can be specified average 21% per year. The integrated method could pay back the cost within three to four years; however, a firm payback period would vary based on the energy price fluctuation.

10.3.5 Optimisation of Building Performance

The retrofitted optimisation analysis shows that the influence of specifications, for instance, internal load, temperature setpoint, has an important impact on the building system efficacy vis-à-vis energy consumption and overall effectiveness. Furthermore, the efficacy of building envelopes is highly depended on the climate, e.g. the building envelope specifications have more effect on power usage and thermal performance in a tropical climate, for instance, in Rockhampton. The case study on the optimisation of the performance parameter of the academic building demonstrates the targeted objectives are achieved by the developed optimisation framework considering the variables of interest and the constraints in place to confirm the comfortability of the occupants. The case study on the optimisation of the performance parameter of the academic building demonstrates the targeted objectives are achieved by the developed optimisation framework considering the variables of interest and the constraints in place to confirm the comfortability of the occupants. It also demonstrates that the optimal building performance could be achieved by following the developed optimisation framework that helps to eliminate some of the challenges reported by researchers in the past and represent the novelty of the study.

The optimisation results against discomfort hrs and cooling energy consumption suggest Cooled Beam and BioPCM as one of the optimised solutions with 76203 kWh/annum cooling energy consumption and 1483 hrs discomfort per year due to potential average future weather condition. Cooled Beam HVAC and BioPCM external envelop combination was the standalone optimum combination considering yearly total cooling energy consumption and total discomfort hours due to the potential increase in external temperature from 0.5 ºC to 2.0 ºC respectively. The recommended optimum solution is Cooled Beam HVAC and BioPCM external envelop in all scenarios because of the overall performance considering the minimum cooling energy consumption, discomfort hours, operational CO_2 releases although a couple of other optimised solutions identified with higher consumption and/or discomfort hours and CO_2 releases.

10.3.6 Impact Assessment of Future Weather

Considering the emerging climate transformation issues and its potential effect on the energy usage in office building, the findings of the study have crucial ramification considering that they could be utilized to determine the likely modifications needed in reducing the power usages in the whole office complex in subtropical climate. The selection of appropriate cooling and heating method is actually of great importance to steer clear from the cooling and heating technique that is like to consume intensive energy to ensure people comfort in a tropical climate. The research demonstrated that it is actually feasible to embrace resolutions that compete positively alongside the alternative choices that are cost-effective as well as is able to adjust to the changeable indoor comfort due to the emerging climate transformation phenomena. The outcome of the study will offer the practising engineers and other relevant professionals and researchers an excellent knowledge base to better understand the compelling interactions of the climate-dependent variables on the energy preservation and thermal efficacy of the building systems in subtropical climates in Australia.

Overall, a practical thermal simulation orientated optimization framework is developed and executed that unites the objective of minimizing energy consumption of building systems as well as maintaining superior comfort of the people based on the present and future weather conditions This research serves as proof-of-concept that it can be used to provide air conditioning year-round without significantly affecting thermal comfort and operational CO_2 emission.

10.4 FURTHER WORKS

The Supplementary works could be undertaken in future:

10.4.1 Evaluating the efficacy of the alternative HVAC system for different building classes

The technique of entire energy performance simulation of the building to determine different cooling methods within this thesis may be related to various other building classes at the premises. The end results could be judged to establish overall effective energy retrofitting methods around other properties at the premises as well as in other high-rise buildings with similar climate conditions (Papachristos, 2020; Kim and Clayton, 2020).

All prospective energy-conserving computations provided in this research depends on a generic usage profile for an office building. Given that cooled beams possess much-improved capacity when they are utilized with a devoted outside air supply system, a rigorous amount of outside air requirements can reveal better savings.

10.4.2 Evaluating emerging PCM based PV system

Considerable accomplishments have actually been accomplished in this research; there are yet some chances exist for more progression consisting of (1) establishing new viable slurry-based PCM photovoltaic system following the experimental findings of Firoozzadeh et al. (2020); Chen et al. (2020); Eisapour et al. (2020) (2) adjusting the geometrical criteria of the present photovoltaic arrangements; (3) experimenting long-term efficiency of the photovoltaic units in future under emerging climate transformation scenario; and also (4) innovative economical as well as environmental appraisal taking into account the potential future weather conditions and the impact on the human body by means of long-lasting real-time measurement.

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