

Investigation into Energy Efficiency and Energy Management Systems of Buildings: A Case Study



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Abstract

This study investigates the energy efficiency of residential, academic, and office buildings at the University of Cape Town (UCT) and suggests energy management strategies to improve this through the implementation of Building Energy Management Systems (BEMS). Using OpenStudio and EnergyPlus simulation tools, the research explores historical energy consumption patterns ,power demand and energy usage costs, uncovering distinct energy usage profiles for each building type. BEMS Logic is developed to achieve energy management and improve the buildings' energy efficiency in response to the energy usage profiles. The results indicate substantial reductions in energy consumption and peak power demand following BEMS implementation. As a subsequent result, the total cost savings were estimated at approximately R 1.68 million, illustrating the significant economic benefits of energy management. This study not only demonstrates the potential for cost savings but also emphasizes the importance of integrating innovative energy management practices in building operations. The findings serve as a valuable reference for UCT and other institutions facing similar energy challenges as it promotes the broader adoption of BEMS as a strategic approach to enhance energy efficiency and sustainability.

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Chapter 1

Introduction

1.1 Introduction

1.1.1 Background and Context

Energy efficiency has become a critical focus area in building management due to increasing energy costs, growing concerns about environmental sustainability, and the need to reduce carbon emissions. Globally, buildings account for nearly 40% of total energy consumption, highlighting the substantial opportunity for energy savings through innovative technologies and efficient practices [1]. Energy Management Systems (EMS) are designed to monitor, control, and optimise energy usage in buildings to lower operational costs.

In South Africa, energy challenges are exacerbated by an aging electrical grid, frequent load shedding, and high energy prices, particularly for commercial and educational institutions [2] [3]. The University of Cape Town (UCT), like many other institutions, faces rising energy costs and environmental pressures to reduce its carbon footprint. As a result, exploring effective Building Energy Management Systems (BEMS) within this context offers an opportunity to not only reduce energy consumption but also contribute to UCT's sustainability goals.

1.1.2 Problem Statement

Despite advances in energy management technologies, many buildings still rely on outdated or inefficient systems, leading to unnecessary energy wastage and inflated operational costs. In UCT's case, buildings have unique energy consumption patterns given their diverse range of uses, which include servicing residential, academic and administrative demands. The absence of comprehensive energy management practices in many of these buildings results in inefficient energy use, contributing to high electricity costs and increased demand on the institution's financial reserves. This study investigates the existing energy management practices within selected UCT buildings, identifying inefficiencies and proposing recommendations for improvement through BEMS. The goal is to explore how energy management systems can reduce energy consumption and operating costs.

1.1.3 Scope of the Case Study

This case study focuses on a select group of buildings at UCT to assess their energy trends and efficiency levels. The investigation includes evaluating energy usage patterns, identifying inefficiencies, and proposing potential energy-saving measures through the implementation of a Building Energy Management System (BEMS). The study explores how BEMS can contribute to reducing energy costs

while maintaining the operational integrity of the buildings. Additionally, it will consider factors such as the buildings' operational profiles, current energy loads, and opportunities for automation and the better management of energy.

1.1.4 Research Objectives

The primary objectives of this study are:

- To analyse the energy consumption patterns of selected UCT buildings.
- To assess the load composition in buildings and identify trends in energy usage.
- To explore energy-efficient technologies and management strategies suitable for the UCT context.
- To estimate the potential savings in energy that can be achieved through BEMS, including reductions in peak demand and overall consumption.
- To determine the cost benefits through the implementation of a Building Energy Management System (BEMS).

1.1.5 Research Questions

The following research questions guide this study:

- How can the existing energy management practices at UCT be improved to reduce energy consumption and costs?
- What are the major inefficiencies in energy use within the selected buildings?
- What innovative BEMS technologies can be implemented to optimize energy usage?
- What are the financial implications of implementing energy-efficient systems in these buildings?

1.1.6 Significance of the Study

This study is significant for several reasons. Firstly, it addresses the urgent need for energy efficiency in buildings, particularly in the South African context, where energy costs are rising and sustainability is becoming increasingly important. By providing an analysis of energy usage in UCT buildings and offering practical, cost-effective measures and systems for its improvement, the study can contribute to reducing the institution's operating costs and carbon footprint. Furthermore, the findings from this case study could serve as a blueprint for other educational institutions facing similar energy and cost challenges. The successful implementation of a building energy management system at UCT may also inspire broader adoption of such systems in other universities, helping to create more energy-efficient and sustainable institutions across the country.

1.1.7 Structure of the Report

This report is structured as follows:

- **Chapter 1: Introduction** – This chapter provides the background, problem statement, research objectives, scope, and significance of the study.
- **Chapter 2: Literature Review** – This chapter explores existing research on energy efficiency, Building Energy Management Systems (BEMS), and their implementation in similar contexts. It provides an overview of relevant technologies, frameworks, and case studies.
- **Chapter 3: Theory Development** – This chapter introduces the theoretical frameworks that underpin BEMS modeling, establishing the basis for further analysis and implementation.
- **Chapter 4: Methodology** – This chapter outlines the methods used to collect and analyse data on energy usage within the selected UCT buildings and simulate models of the buildings before and after energy management has been implemented. It includes the data collection processes, tools used for modeling simulation and development of the energy management system.
- **Chapter 5: Simulation Results** – This chapter presents the findings from the data analysis and modelling, highlighting trends, inefficiencies, and key insights derived from the energy usage data.
- **Chapters 6-8: Analysis of Results** – These chapters break down the results further, focusing on specific aspects of the energy data. Chapter 6 focuses on the residential building, Chapter 7 focuses on the academic building, and Chapter 8 focuses on the office building.
- **Chapter 9: Feasibility Study** – This chapter evaluates the realistic implications of implementing a BEMS in the context of the selected buildings, considering the technical, economic, and operational feasibility of such a task.
- **Chapter 10: Conclusion** – This chapter summarises the key findings of the study and offers insights into future research opportunities.
- **Chapter 11: Recommendations** – This chapter discusses potential improvements to the current study and suggests further work that could be done to better the value of this investigation.

Chapter 2

Literature Review

2.1 Introduction

This literature review aims to provide a review of prior knowledge in the study of energy efficiency in building and the implementation of Building Energy Management Systems (BEMS). The relevance of this study aligns with the ever growing need for energy as more active devices become embedded in everyday living and the drive to reduce carbon emissions and mitigate their negative effect on the earth's climate. These two ideas lead to the need for efficient designs of energy consuming entities (such as buildings) and the effective management of any available energy. In the subsections to follow, accurate definitions of efficiency within the context of building energy management, will be explored. Standards that certify buildings as efficient, will be reviewed and theory on the structure, operation, simulation and feasibility of BEMS in buildings, will be analysed.

2.2 Energy Demand and Carbon Savings

2.2.1 Energy baseline modelling

To initiate the discussion of energy efficiency and its management in buildings, it is essential to evaluate the energy requirements and the energy usage patterns of the building being studied. Creating an energy baseline model by using a buildings historical consumption data to model its energy consumption patterns is a strategy suggested in a study by Grillone et al.[\[4\]](#). The strategy suggested by Grillone et al. [\[4\]](#) is echoed and subsequently enhanced, in a separate study by Tian et al. [\[5\]](#), where they suggest the usage of machine learning models on historical data to predict even the future energy consumption patterns of a building. The application of machine learning in energy benchmarking and energy baseline model development has seen fruitful implementation in parts of the USA and Canada through the Energy Star System[\[6\]](#). However, it is worth noting that its widespread adoption has been stunted by the considerable uncertainty of $\approx 35\%$ that is a result of the presence of a multitude of stochastic factors that influence a building's energy baseline, with the most notable stochastic factors being weather patterns and energy usage patterns by occupants. In a more optimistic light, Pandarasamy et al. [\[6\]](#) have experimented with two techniques (Multiple Linear Regression with interaction terms and Gradient Boosting with implicit interactions) that have achieved significantly reduced uncertainty in their performance. Although these techniques have been successful, they have been tested with a small dataset relative to the number of regions on earth and therefore cannot be generalized.[\[6\]](#).

2.2.2 Carbon Savings

Due to the positive proportionality of energy generation and greenhouse gas emission, the energy efficiency and energy management in a building directly affects the amount of greenhouse gas produced to generate power for that building. For the purposes of this study and according to a review by Lu and Lai [7] that mentioned the common terminology, the emission of greenhouse gases to generate energy will be viewed from a carbon perspective and thus will be termed the carbon footprint and/or the carbon emission of a building. Carbon savings will refer to the reduction in the carbon footprint and carbon emission of a building. Carbon savings are a result of successful carbon footprint management which aims to reduce carbon emissions from human activity [8]. The need for the quantification of carbon footprints is the starting point for the effective evaluation for carbon savings and has been mentioned, in a study by Labaran et al. [8], to be of paramount importance even at the United Nations level of governance. In an effort to quantify carbon footprints, a Well-to-Wheel method suggested by Scarlat et al. [9], considers emissions at different stages of energy productions to derive the total emissions that are emitted during the generation of energy. Such information is attainable from the power utility providing electricity to the building.

2.3 Energy Efficiency in Buildings

Energy efficiency aims to describe the performance of the usage of energy within a given system to achieve a certain task. In the context of buildings, previous energy efficiency analyses have focused on a set of functional metrics in order to reach a building's measure of energy efficiency. A study by Lidelöw et al. [10], based on heritage buildings, revealed common metrics found in a variety of articles that aimed to measure the energy efficiency of a building. These metrics include the insulation of the building, energy used for heating, ventilation and air-conditioning and the energy usage due to the daily activities of users/occupants of the building. An additional metric of the energy used for lighting is considered in the study by Tian et al. [5]. With regards to the topic of occupant energy usage patterns, conclusions from the study by Schakib-Ekbatan et al. [11] suggest that this may be the most evasive metric of them all as occupants respond to a multitude of factors that influence their overall energy usage patterns. An example from the study [11] outlined the possibility of occupants responding to ambient noise pollution and consistently keeping their windows closed and thus requiring active ventilation which consumes energy. These studies suggest that in determining the metrics for evaluating efficiency, it is prudent to consider both functional metrics as well as behaviour driven metrics.

2.4 Energy Efficiency Standards and Certifications

Given the growing demand of energy in the world and its generation becoming an environmental burden, the formulation of energy usage standards in buildings and methods to ensure the environmentally fair usage of energy in buildings became ever important [12].

2.4.1 BREEAM

The British Building Research Establishment Environmental Assessment Method (BREEAM) is the earliest certification system used to determine a rating for a building's energy efficiency [12]. Since its inception in 1990 [13], this method has claimed international presence, having different versions developed to suit various regions, which include Hong Kong, Canada, Denmark and Australia etc. This system was renamed to Building Research Establishment Global (BRE Global) [14], in accordance with the worldwide adoption of BREEAM. It was indicated that instead of the traditional comprehensive licensing approach, BRE Global services are to be provided on a needs basis of a particular country/region to optimize its cost of usage vs benefit delivered [15].

2.4.2 LEED

A latter designed American parallel to BREEAM is the Leadership in the Energy and Environmental Design (LEED) system which also has similar international adoption and today, has become the most common energy efficiency certification system [12]. As mentioned in an article by Ottelin and Sorvari [12] that a useful consequence of the popularity of the LEED certification system is its ability to assess many building structures at various stages i.e., from construction of new structures to the modification of existing structures. However, a study by Jeong et al. [16], revealed their skepticism regarding the efficacy of the LEED certification system, as a detailed analysis revealed that buildings certified under LEED only achieved a maximum energy reduction of about 15% compared to non-certified buildings. Furthermore, when categorized into specific groups, particularly the multi-family housing complex group that was studied, the LEED-certified buildings showed no statistically significant differences in energy performance compared to non-certified ones. Ultimately, the usage of LEED is heavily driven by the economic factors where due to its international status, developing countries use LEED to attract international investors to their building projects as it is an internationally acclaimed system [15].

2.4.3 ISO 50001

The International Organization for Standardization 50001 (ISO 50001) is a relatively new international certification framework that saw its initial publication in 2011, followed by a subsequent revision in 2018. The framework is aimed at providing a systematic approach to energy management that aims to develop standards that are both region and organisation agnostic thus achieving universal application [17]. By having this property, ISO 50001 lends itself to being a relevant guiding document in the design of Energy Management Systems in various regions and organisations. A case study analysis by Fuchs et al. [17], revealed that behind sustainability goals and integration into management practices, a cost saving (with respect to greenhouse gas emissions) was a notable driver in the motivation for the usage of ISO 50001. In a survey of ISO 50001 certified organisations, by Afnor energies [18], it was revealed that organisations were 89% satisfied and had a 95% potential to recommend the standard to other organisations. The majority of surveyed organizations identified the framework as a valuable tool for energy consumption zone analysis, with strong potential to support long-term organizational growth.[18].

2.4.4 SANS

The South African National Standards (SANS) are a collection of standards that are used collectively to promote energy conscious design approaches and efficient usage of energy in buildings. They each address different aspects of energy efficiency and energy management that amalgamate to an energy efficient building design guide that yields a structure with measurable energy efficiency and effective energy management systems. The SANS 10400-XA standard outlines energy efficiency requirements of buildings and aids to promote energy efficiency in the design and construction and/or major renovation of buildings [19]. SANS 204 is a standard that provides the technical energy requirements and specifications of components and systems within a building and lay a foundation for understanding key components that will require management [20], [21]. Harris and Kreuger [22] mention software packages for generating star ratings to assess the efficiency of buildings in accordance with the SANS 283 standard. These packages include Building Toolbox and NewQuick. It is worth mentioning that a SANS/ISO 50001 standard exists but was formulated to adhere and correlate with the aforementioned ISO 50001 framework thus providing similar ideas and certifications [23].

As discussed by Rehm and Ade [24], it is worth noting that ensuring that a building conforms to efficient energy usage standards comes with additional costs related to consulting the various tools and regulating bodies. However the consequent energy and carbon savings result in the overall reduction in the operational costs associated with the building. There is also a pertinent concern to design assessment and certification systems that also consider the climate and culture of the region being assessed [15].

2.5 Building Energy Management Systems (BEMS)

2.5.1 History

Building Energy Management Systems (BEMS) are technological systems that saw their introduction in the 1970s as a remedy for the prevalent energy crises at the time. These systems were built to monitor and offer a manual control interface to allow for the efficient management of energy usage in a building. After subsequent revisions in latter years, new technology including sensors arrays and networking functionality was added to expand and refine the scope of control for the BEMS [25].

2.5.2 Structure of BEMS

A modern Building Energy Management System consists of a bidirectional interface with energy consuming devices in the building i.e. lighting, HVAC etc. The BEMS then uses the data obtained from the states of the energy consuming devices to analyse the overall energy usage profile of the building and then present the output to an interface accessible to human users. If the functionality allows it, the data obtained by the BEMS may be used to forecast future energy usage patterns of the building.

The Building Energy Management System (BEMS) diagram in Figure 2.1 illustrates how a BEMS integrates various subsystems such as Heating, Ventilation, and Air Conditioning (HVAC), lighting, electrical loads, photovoltaic (PV) systems, and battery banks [26]. These subsystems generate data

that flows through an interface to the BEMS, where it is processed and analyzed to make informed energy management decisions. The system also incorporates external data inputs such as weather forecasts, and real-time building state information, as well as user-specific data like occupancy schedules and behavioral patterns.

Central to the BEMS is the Human-Machine Interface (HMI), which allows users to interact with the system by setting preferences and monitoring energy usage in real-time. The HMI displays analysis results, enabling users to make informed decisions about energy consumption. The analysis module within the BEMS processes user inputs and system data to identify trends and anomalies in energy usage. Based on these insights, the system utilizes forecasting techniques to predict future energy demands, drawing on historical and current data to create accurate consumption models.

Energy management is a key function of the BEMS, where the energy usage data is used to determine the most efficient strategies for energy use, aiming to reduce energy costs and minimise waste. By continuously updating and refining its control settings, the system can adapt to changing building conditions and occupancy patterns in real-time. The integration of analysis, forecasting, and energy management within the BEMS allows for a holistic approach to energy management, making it a crucial tool for achieving energy efficiency in buildings. This interconnected system exemplifies how advanced technology and predictive analytics can be leveraged to enhance sustainability in modern infrastructure.

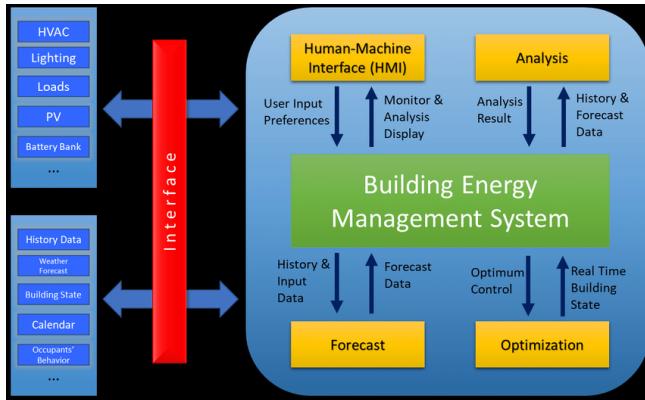


Figure 2.1: BEMS Module diagram.

2.5.3 Benefits and Challenges

Although the benefits of BEMS are abundant and are continually unfolding as their usage in various regions increases, the main benefits of BEMS have been noted by a study by Digitemie and Ekemezie [25]. BEMS offer energy savings as they allow for the adjustment of the energy usage of key energy consuming device based on the protocols set to optimize energy usage. Another benefit is the insight provided by the energy usage data generated by the BEMS and presented on the user interface. Finally, the interface between the BEMS and energy consuming devices in the building allows the BEMS to notify operators of ill performing devices and ensure swift maintenance action [25].

However, there are also challenges associated with the implementation of BEMS, especially in existing

buildings. The installation phase may be often complex and riddled with different stakeholders. This requires careful planning and often results in a costly and time expensive planning phase [25]. Another issue arises when BEMS consisting of newer technology needs to be integrated with legacy systems in older buildings. This results in limited usage of the features of the BEMS [25]. In the collection and analysis and transmission of energy usage data, data safety concerns may arise with the privacy, integrity and safety of internal data and systems within the building being analysed [25].

2.5.4 Future Trends and Research Directions

In keeping with the constant evolution of technology attributed to the 21st century, there has been constant progression in the innovation of current BEMS. A foundational concept in further research and development in energy management is the ‘Internet of Energy (IoE)’ [27]. An article by Bui et al. [27] explains how the pursuit for more sustainable energy management models has been influenced by the development of smart devices to ultimately produce the IoE concept. It is worth noting that this concept has seen initial implementation in an Italian University of Padova [27]. The main takeaways were that there are potential gains for stakeholders in the energy sector, there is need for a system with sufficiently robust communication especially in low power conditions. There is also a need for robust communication when using transmission media that is prone to losses. However, the solution should be a lightweight system to minimize complexity already present in the smart energy devices that already form part of this ‘internet of energy’ (a network of smart energy devices that can share energy data with each other) [27]. In a review by Hannan et al. [28], a smart ‘Internet of Energy’ based BEMS is discussed. This type of BEMS would potentially maximise energy saving by not only exchanging information with other smart constituents (e.g. smart grids) in the energy generation and usage cycle but also generating energy usage statistics that can be used to compare different buildings and influence building conventions to maximise the construction of energy efficient buildings. Another driver in the research trends behind the innovation of modern BEMS is the push to develop BEMS with smart onboard controllers that are integrated with artificial intelligence and machine learning [25].

2.6 Techniques for modelling Energy usage in Buildings

One of most critical tasks to execute before the assembly and installation of a BEMS is the generation of simulations of the BEMS. These simulations require sufficiently accurate models of the building. The building model is the bedrock on which a BEMS is simulated and the building’s response determines the efficiency of the BEMS. The initial challenge is determining the best and most efficient way to generate a model of the building.

2.6.1 Deterministic Techniques

As mentioned in the above sections, initial BEMS were designed to report building energy usage data to human controllers who would implement the required adjustments to ensure efficient energy usage. In recent times, the main strategy is the usage of Model Predictive Control (MPC) based energy management mechanisms. Although this method is effective and relatively intuitive, the major challenge is that it requires a significantly accurate model of the building which is feasible in simple projects but quickly approached impossibility in more complex building projects [29]. One such method

is using a RC (Resistor - Capacitor) Network to model the energy usage dynamic in a building. This network scales rapidly and becomes unmanageable in complex buildings [30].

2.6.2 Data Driven Techniques

In larger and more complex buildings where using deterministic techniques is not feasible, data driven solutions have been used to make generating the building model more efficient. In a report by Prívara et al. [30], it was noted that this approach required historic energy usage data of the building which is not always available. Additionally, this approach required persistent excitation to be satisfied which was often a mere assumption for most buildings that did not have enough data to meet this condition. This assumption resulted in models that deviated from real building behaviour [30].

2.6.3 Stochastic Techniques

To combat the inaccuracies presented in the data driven approach to generating building models and result in more realistic simulations, stochastic identification methodologies are incorporated to the data driven models [31]. The incorporation of stochastic methods in the generation of building models is also motivated by Virk et al. [32] in a report as it addresses the effects of human occupancy, interaction of internal building structures and systems which nowadays are subject to relatively frequent modifications.

2.7 Load identification and monitoring

In order to effectively monitor and improve the energy efficiency of a building, it is important to have an understanding on the loads present in the building being studied. This will allow the precise detection of components that use energy intensively. In addition, to also analyse any improvements after energy management has been implemented, loads need to be clearly defined to allow them compared accurately.

2.7.1 Intrusive load monitoring

This form of load monitoring involves attaching monitoring devices on each appliance in the building, in an effort to measure the energy consumption of each appliance in a building [33]. This approach is simpler and comprehensive but involves higher cost due to the need for multiple sensors and sensors and wiring [34].

2.7.2 Non intrusive load monitoring

This techniques of load monitoring involves estimating the loading effects of appliances in a building by taking readings from a limited number of locations [35]. To aid in identifying appliances machine learning and pattern matching techniques demonstrate the good performance as noted by Schirmer and Mporas [34].

In 2015, Aladesanmi and Folly [33] concluded, in a comparative review of intrusive and non intrusive load monitoring techniques, that achieving a non intrusive and more cost effective load monitoring technique comes at a sacrifice. The ability that is present in more costly intrusive technique, to uniquely

identify electrically identical appliances and/or to monitor appliances with continuously changing states, is compromised in the non intrusive technique.

2.8 Building Energy Simulation Tools

In order to quantify the expected performance of a BEMS, there needs to be a clearly defined model of the building in which the BEMS will be installed. Energy usage models for buildings need to take into account a wide range of contributing phenomena in order to generate sufficiently accurate simulation given the complexity of today's world [36].

2.8.1 OpenStudio

OpenStudio is a building energy modelling tool equipped with a graphical user interface which allows for 2 dimensional and 3 dimensional modelling of buildings and their internal components [37], [38]. The oldest OpenStudio version available on the creators' website is dated 2008 indicating the year in which this tool was created by the United States Department of Energy [39]. While this modelling tool achieves excellent building models, to actually model and analyse energy in buildings, it is often used in conjunction with EnergyPlus [40], an open-source software plugin designed to model energy behaviour and usage in buildings. The approach of using the two software packages together has seen success in previous models by Yadav et al. [41], Brackney et al. [42] and Erdem et al. [43]. In addition to modelling energy in buildings, OpenStudio also has the capability to also model water usage in buildings [44].

2.8.2 EnergyPlus

EnergyPlus is a building energy simulation software package invented in the 1990s as a means to continue the journey started by the Department of Energy-2 (DOE-2) [45] and Building Loads Analysis and System Thermodynamics (BLAST) [46] simulation software packages, its predecessors which had become expensive to maintain due to the aging programming language by which they had been constructed [36], [47]. This simulation software is an open-source project funded by the United States' Department of Energy [40]. EnergyPlus is primarily a simulation engine that does not consist of a graphical user interface (GUI) but rather consists of ASCII valued text outputs. However there have been successful efforts by external developers to create an interface for EnergyPlus [47]. Figure 2.2 illustrates how the EnergyPlus software package interacts with other third-party software packages such as OpenStudio to form a complete tool with a GUI.

The main benefit gained from the creation of EnergyPlus is its modular approach to sub-modules that handle different aspects of the entire building energy simulation e.g. heating and cooling, building systems and simulation management [47]. Another key improvement is an increased number of building dynamics analyses that are included in the package [40]. Interfaces to communicate with other analysis software packages are also included. The more elaborate structure of EnergyPlus requires more input parameters to generate a realistic simulation. This may prove more fruitful in more complex buildings with well defined and quantified attributes rather than in more simpler buildings or buildings with a few attributes defined. Figure 2.3 shows the available modules in the EnergyPlus software package. The calibration of each module contributes to creating realistic building energy dynamics.

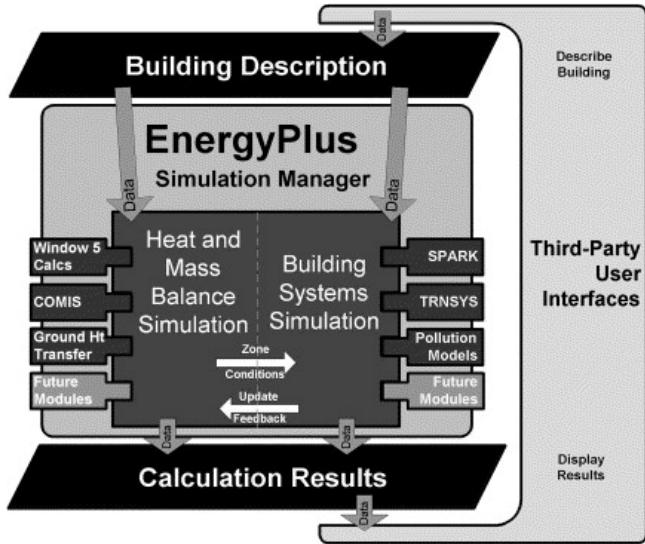


Figure 2.2: EnergyPlus Design

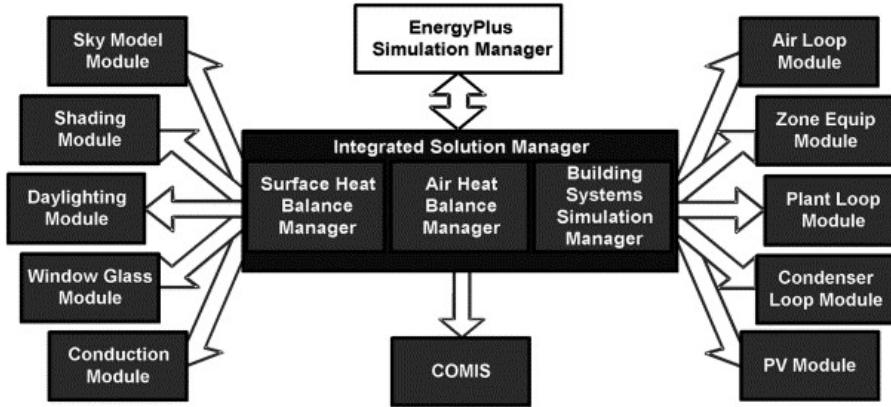


Figure 2.3: EnergyPlus module breakdown

2.8.3 IESVE

The Integrated Environmental Solutions Virtual Environment (IESVE) is another software platform for building energy simulations. This tool has been shown to have more testing and validation studies conducted. One of these studies has been conducted in Malaysia which has a tropical climate, similar to the sub-tropical climate in South Africa [48], [49]. As a result, more quantitative data on the performance of IESVE has become available. A study conducted by Reeves et al. [50], of two academic buildings in Florida, revealed IESVE to have a percentage difference of 14.55% with physically measured energy usage values in the building [50]. In another study by Oleiwi et al. [48] in a Malay climate which is similar to the South African climate, IESVE was found to have only a 1.1% percentage difference between the model and the physical building dynamics. In both studies the percentage difference between the physically measured values and simulated values was calculated and used to determine the accuracy of this modelling software. These results verify the accuracy and reliability of IESVE. A challenge that comes with using IESVE is that the program is not open-source and requires a subscription fee. Figure 2.4 illustrates the user interface of the creation of a typical building model using the IESVE tool.

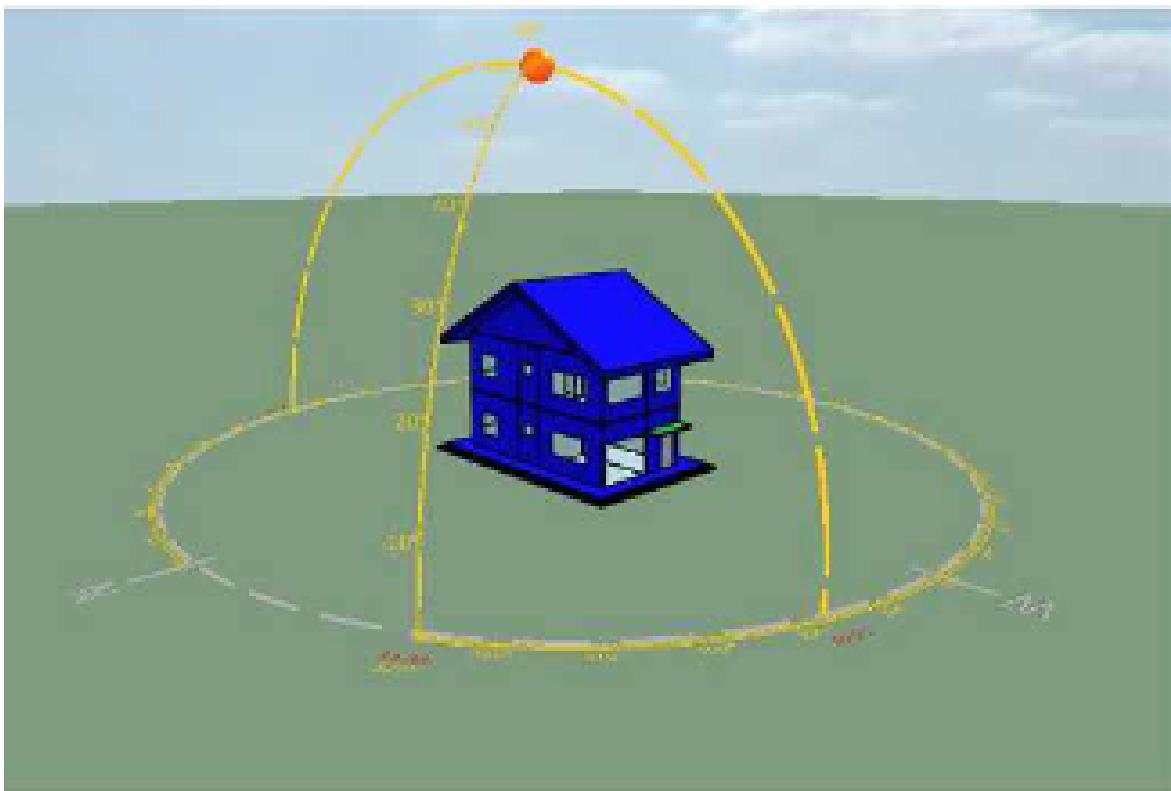


Figure 2.4: Building model in IESVE

2.8.4 MATLAB and Simulink

MATLAB is technical and high performance computing language, developed by MAthWorks, that is often used for modelling and data analytics. The full MATLAB system consists of an interactive IDE, package library and API [51]. For the application of simulating building energy usage patterns, MATLAB comes equipped with a building energy forecasting library which has machine learning capabilities [52], [53]. Simulink is a program (also developed by MathWorks) that is complementary to MATLAB and adds functionality to model dynamic systems[51]. Simulink offers a BEMS modelling library [52]. MATLAB and Simulink make it is possible to model and forecast a building's energy usage, create a BEMS and observe their interaction. This option presents the most complete package of tools on one platform which significantly reduces any potential data mismatch errors due to using different platforms for the building energy model and the BEMS. It is worth noting that the license to this software system is considerably high. However, a large number of academic institutions have obtained this license for researchers and students.

2.9 Previous work in energy efficiency investigations in buildings : Case Studies

To complete our understanding in energy efficiency and energy management in buildings, reviewing previous case studies is a prudent decision to ensure that prior successes are adopted and prior failures are avoided.

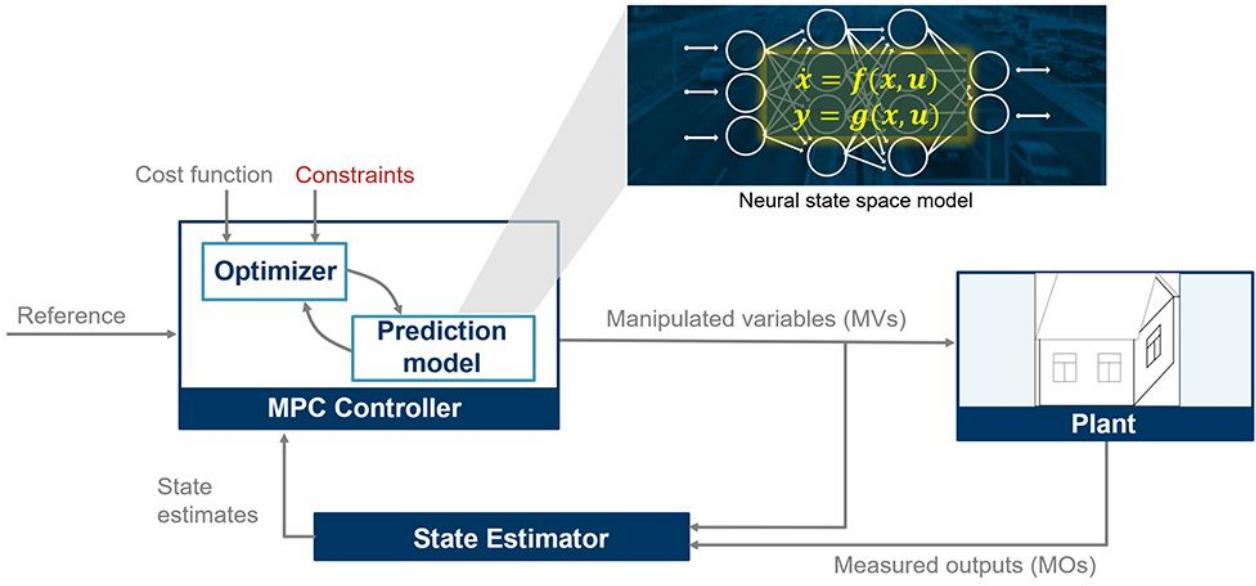


Figure 2.5: Generic MATLAB BEMS Model

In an effort to improve the energy efficiency of an aging retail building in Lisbon, Poço et al. [54], aimed to reduce the building's energy consumption while maintaining acceptable service to retain customers. The motivation was due to a 4% increase in electricity consumption within the services sector which included retail stores. To model the building and energy usage trends, historical data in conjunction with machine learning through the usage of Artificial Neural Network (ANN) models. These models consistently generated energy consumption predictions with low error. The ANN produced 3.39% error when modelling energy consumption and 1.45% when modelling the average indoor temperature. They achieved a reduction energy consumption by adding insulation to the building and implementing regular maintenance on HVAC equipment to repair any damage and maximise efficiency. These measures resulted in a 9.59% reduction energy in consumption.

Shirazi et al. [55] motivated for the focus of energy consumption management to be on HVAC systems as they typically consume the majority of the energy. This was followed by an approach to implement and optimise solar powered heating and cooling. Building data on which their solution was simulated was obtained from the United States Department of Energy, the same institution that produce the EnergyPlus software package. The results presented a method to optimise the operation of solar heating and cooling to strengthen the case of it being a viable alternative to the conventional energy intensive and costly HVAC systems. However, it was noted the solar powered alternative included high capital costs that would required public funding to ensure a return on investment in a period less than 6 years which would be regarded as satisfactory.

A method regarded as very successful by Poço et al. [54] to effectively manage energy towards achieving energy efficient buildings was applied by Pisello et al. [56]. This approach involved the analysis of the population of a certain area and proportionally increasing and decreasing energy supply to the loads in that area. This approach, motivated by the energy wastage resulting from only considering the

thermal needs of the building and not the times when occupants actual occupy the building, resulted in an energy reduction of more than 70 kWh/m² through the adoption of occupancy schedules into energy management strategies and logic.

In more futuristic work, Ryzhov et al. [57] attempted to achieve reductions in energy usage by predicting the occupancy patterns of apartment buildings based on previous occupancy statistics. This approach applied Model Predictive Control techniques to maintain acceptable climate conditions while lowering energy consumption. In the two cases of an older and newer building design, it was noted that opposing result were obtained as reductions were only recorded in the newer building. This meant that this approach was not universal and required a suitability assessment before implementation as the previous occupancy trend data different significantly from building to building. As a means to counter this difficulty, a real time control approach was proposed by Erickson et al. [58] which saw the installation of camera nodes to detect occupancy in real time. This approach saw a 5% reduction in energy consumption from the then current HVAC ventilation solutions.

2.10 Feasibility Analyses

Feasibility analyses are conducted prior to the implementation of any project in order to determine the viability of that project while also minimising any future problems and the need to implement costly changes [59], [60]. The study should consist of a need analysis, environmental impact study, possible alternative designs, economic analysis of the project to be undertaken and any accompanying recommendations[61], [62]. To realise the the viability of a proposed design, conducting a sound feasibility study is imperative in order to make a time and financial investment in a realisable system.

2.11 Conclusion

In this literature review, the topics of energy efficiency and carbon savings were reviewed to gain a clear idea on how to recognise a buildings efficiency and possibly quantify it carbon savings. From different regions and governing states, various building efficiency certifications were observed to drive towards the same idea of reducing the carbon emissions associated with generating energy for buildings. Building Energy Management Systems were reviewed and their recent developments were noted. Trends indicated a strong motivation for the inclusion of real building data, stochastic modelling and machine learning to create more realistic models of buildings and their proposed BEMS. Possible simulation tools were investigated in both the open source and proprietary domains. At current time it has appeared that it is prudent to utilise tools that implement all functionality on a single platform to minimise any data transfer and formatting errors. There was a gap in literature with regards to the feasibility analysis of BEMS. However, since similar studies have been conducted, the core ideas were transferable to the topic of this study. Although the study is quite mature, the age of big data and machine learning has caused a shift in the modelling and design approach of BEMS which opens the field to new and innovative research topics.

Chapter 3

Theory Development

3.1 Theory Development

3.1.1 Introduction

This section outlines the theories and mathematical relationships used in the OpenStudio/EnergyPlus software to model various aspects of building energy performance. The equations described here are essential for simulating heat transfer, airflow, psychometrics, HVAC systems and solar radiation building environments. These principles are integral to generating sufficiently realistic models that become the testbed for analysing and improving the energy efficiency of the building under study in this investigation.

3.1.2 Heat Transfer Equations

Heat transfer is a critical factor in building energy modeling as it determines how heat flows in and out of the building envelope. This process involves conduction, convection, and radiation.

- **Conduction through walls, roofs, and floors** is modelled using *Fourier's Law* [63]:

$$q = -k \cdot A \cdot \frac{dT}{dx} \quad (3.1)$$

where:

- q is the rate of heat transfer (W).
- k is the thermal conductivity of the material (W/m · K).
- A is the surface area through which heat is being transferred (m^2).
- $\frac{dT}{dx}$ is the temperature gradient across the material (K/m).

Understanding conduction is essential for evaluating the thermal insulation properties of building materials and designing energy-efficient walls and roofs.

- **Convection on surfaces** follows *Newton's Law of Cooling* [64]:

$$q = h \cdot A \cdot (T_s - T_f) \quad (3.2)$$

where:

- q is the surface flow density of the heat flux (W/m^2).
- h is the convective heat transfer coefficient ($\text{W}/\text{m}^2 \cdot \text{K}$).
- A is the surface area on which heat is being transferred (m^2).
- T_s is the surface temperature (K).
- T_f is the fluid temperature (K).

Improved understanding of convection helps optimize thermal comfort and reduce energy consumption.

- **Radiative heat exchange** between surfaces is calculated using the *Stefan-Boltzmann Law* [65]:

$$q = \epsilon \cdot \sigma \cdot A \cdot (T_s^4 - T_e^4) \quad (3.3)$$

where:

- ϵ is the emissivity of the surface (dimensionless).
- σ is the Stefan-Boltzmann constant ($5.67 \times 10^{-8} \text{ W}/\text{m}^2 \cdot \text{K}^4$).
- T_s is the surface temperature (K).
- T_e is the environmental temperature (K).

Analyzing radiative heat transfer supports efforts to minimize energy loss and improve the building's energy efficiency by modelling the energy radiated by heated elements.

3.1.3 Airflow and Ventilation Equations

Airflow plays a crucial role in determining indoor air quality and energy performance, influencing the amount of heating or cooling required to maintain comfortable indoor conditions.

- **Infiltration and natural ventilation** are described using the airflow equation [66], [67]:

$$Q = C \cdot A \cdot \sqrt{2 \cdot \Delta P / \rho} \quad (3.4)$$

where:

- Q is the airflow rate (m^3/s).
- C is the flow coefficient (dimensionless).
- ΔP is the pressure difference across the opening (Pa).
- ρ is the air density (kg/m^3).

Accurate modeling of airflow is essential for evaluating ventilation strategies and their impact on energy efficiency.

- **Mechanical ventilation** is represented by the mass flow rate equation [68]:

$$\dot{m} = \rho \cdot V \cdot \Delta T \quad (3.5)$$

where:

- \dot{m} is the mass flow rate (kg/s).
- V is the volume flow rate (m^3/s).
- ρ is the air density (kg/m^3).
- ΔT is the temperature difference (K).

Optimizing mechanical ventilation contributes to more effective energy management within the building.

3.1.4 Psychrometrics (Moisture and Air Properties)

Psychrometrics, which deals with the properties of moist air, is a key factor in maintaining indoor comfort and efficient HVAC system performance.

- **Relative humidity (RH)** is determined using:

$$RH = \frac{p_v}{p_{vs}} \times 100 \quad (3.6)$$

where:

- p_v is the partial vapor pressure of water in the air (Pa).
- p_{vs} is the saturation vapor pressure of water at the air temperature (Pa).

Maintaining appropriate RH levels is vital for indoor comfort and preventing issues such as mould growth or excessive dryness.

3.1.5 HVAC System and Equipment Performance

HVAC systems are a major component of energy consumption in buildings, with their efficiency directly affecting operational costs and overall energy use.

- The **sensible heat equation** quantifies the heating or cooling load required to change the air temperature [69]:

$$q_s = \dot{m} \cdot c_p \cdot \Delta T \quad (3.7)$$

where:

- c_p is the specific heat capacity of air ($\text{J}/\text{kg} \cdot \text{K}$).

This equation is used to design HVAC systems that meet thermal comfort requirements while minimizing energy consumption.

- The **latent heat equation** accounts for the moisture control aspect of HVAC systems:

$$q_l = \dot{m} \cdot h_{fg} \cdot \Delta W \quad (3.8)$$

where:

- h_{fg} is the latent heat of vaporization (J/kg).
- ΔW is the change in humidity ratio (kg water/kg dry air).

Understanding latent heat loads is essential for optimizing HVAC systems to enhance overall energy efficiency.

3.1.6 Solar Radiation and Daylighting Calculations

Solar radiation is a significant factor affecting the thermal performance of buildings and their reliance on artificial lighting.

- **Solar heat gain through windows** is calculated using [69]:

$$Q_{\text{solar}} = A \cdot SHGC \cdot I_{\text{incident}} \quad (3.9)$$

where:

- $SHGC$ is the Solar Heat Gain Coefficient (dimensionless).
- I_{incident} is the incident solar radiation (W/m^2).

Effective management of solar heat gain is crucial for implementing passive solar strategies to enhance energy efficiency.

3.1.7 Energy Efficiency and Consumption Equations

Energy efficiency is a fundamental aspect of building performance modeling, aimed at reducing energy consumption and promoting sustainability. Before reduction energy consumption needs to be evaluated.

- **Energy consumption** over a period is calculated using:

$$E = P \cdot t \quad (3.10)$$

where:

- P is the power (W).
- t is the time period of operation (s).

3.1.8 Conclusion

In conclusion, this theoretical framework provides a comprehensive understanding of the key equations and principles governing building energy performance as modeled in OpenStudio/EnergyPlus. By examining the critical aspects of heat transfer, airflow, psychometrics, HVAC

3.1. Theory Development

system dynamics, solar radiation, and energy efficiency, a solid foundation for analyzing the energy behavior of buildings is established. Each equation serves as a vital tool for evaluating and optimizing building design and performance, ultimately leading to improved energy efficiency and sustainability. The integration of these principles into the building energy modeling process enables a detailed assessment of how various factors interact to influence overall energy consumption. Through this investigation, we aim to identify opportunities for enhancing the energy efficiency of the buildings being studied, providing insights that can inform future design strategies and energy management practices. As we move forward, the application of these theoretical concepts will guide the development of effective energy management solutions that not only reduce energy utilisation but also contribute to environmental sustainability.

Chapter 4

Methodology

This chapter outlines the methodology employed to systematically investigate the energy efficiency and management systems of buildings, with a specific focus on developing a Building Energy Management System (BEMS). The methodology involves several key phases: data collection, analysis, building modeling, simulation, energy management policy development, and post-implementation analysis. It leverages the equations described in the Theory Development chapter to ensure a thorough evaluation of energy consumption patterns and the optimization of energy efficiency.

4.1 Data Collection

Initially, energy usage data and energy cost data was collected from open-source historic records available on the [University of Cape Town website](#). Data on the buildings structure was physically observed through visiting the

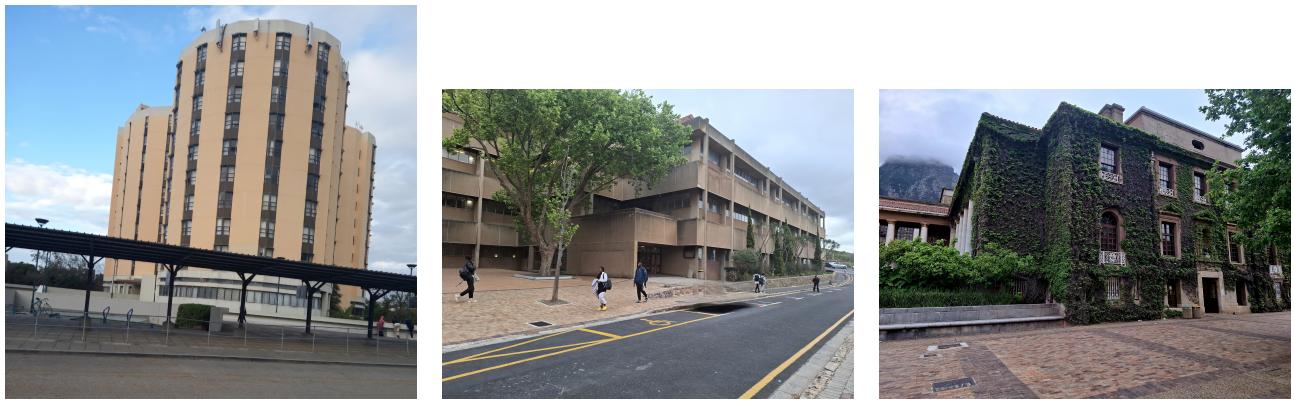
4.1.1 Building Structural Data

Data on the building's structure is essential for creating an accurate model. The collected information includes:

- **Building Geometry:** Detailed dimensions of the building, including wall thickness, window areas, and roof configurations, are required to calculate heat transfer through conduction using Fourier's Law (Equation 3.1).
- **Material Properties:** Thermal properties of the construction materials, such as thermal conductivity and specific heat capacity, are critical inputs for evaluating conduction, convection, and radiation heat transfer.

The figures below represent the specific buildings studied in this investigation, categorized as Residential, Academic, and Office buildings. These buildings include:

- **Leo Marquard Hall** (Residential building)
- **Molecular and Cell Biology Building** (Academic building)
- **Otto Beit Building** (Office building)



(a) Leo Marquard Hall (Residential Building)

(b) Molecular and Cell Biology Building (Academic Building)

(c) Otto Beit Building (Office Building)

Figure 4.1: Images of the buildings under study: Residential (Leo Marquard Hall), Academic (Molecular and Cell Biology Building), and Office (Otto Beit Building).

4.1.2 Load Composition Analysis of the Investigated Buildings

In the respective buildings, the primary electrical loads were assessed based on their respective functions and usage patterns. Each type of building i.e., residential, academic, and office has distinct energy consumption characteristics influenced by the types of equipment and their function. Below is a breakdown of the main load categories for each building type:

- **Leo Marquard Hall (Residential Building):** In the student residence, the primary loads consist of:
 - **HVAC systems:** Predominantly concentrated in common areas like the dining hall and common areas.
 - **Lighting:** For corridors, rooms, and common areas, contributing significantly to the overall load.
 - **Plug loads/equipment:** Including dining hall cooking equipment as well as personal electronics (laptops, phones) and equipment such as computers used by the students.
- **Molecular and Cell Biology Building (Academic Building):** The primary function of this building is to facilitate lecturing and tutoring, which defines its key energy consumers:
 - **Lighting:** To illuminate lecture rooms, hallways, and study areas.
 - **Educational equipment:** Projectors, computers, and other teaching aids are essential loads that vary based on usage throughout the day.
- **Otto Beit Building (Office Building):** The office environment has a more predictable energy load profile, dominated by:
 - **Computers and office equipment:** Such as printers, scanners, and personal workstations.
 - **HVAC systems:** Though typically smaller than in residential buildings, these systems are important for maintaining a comfortable working environment and are considerable given

the smaller size of the building.

- **Lighting:** Essential for office spaces, corridors, and meeting rooms, contributing to a portion of the load.

The buildings in this investigation were selected based on their distinct load compositions, representing a range of energy consumption patterns. A residential building, an academic building, and an office building were chosen to provide a comprehensive analysis of varying electrical demands, from HVAC systems and personal electronics in residential settings to lighting and educational equipment in academic spaces, and office equipment in work environments. This diverse selection ensures a more robust study of energy efficiency and management, capturing the impact of different load types on overall building performance.

4.1.3 Energy Usage Data

Energy usage data from historical records, such as electricity and HVAC consumption, are collected to establish a baseline for energy consumption. The energy consumption equation (Equation 3.10) will be used to correlate this data with other parameters such as equipment performance and occupancy patterns.

The following graphs illustrate the actual energy usage for the buildings under study before the implementation of any energy management strategies. Each graph represents the energy consumption data for 2018, highlighting the baseline performance of each building type: Residential (Leo Marquard Hall), Academic (Molecular and Cell Biology Building), and Office (Otto Beit Building).

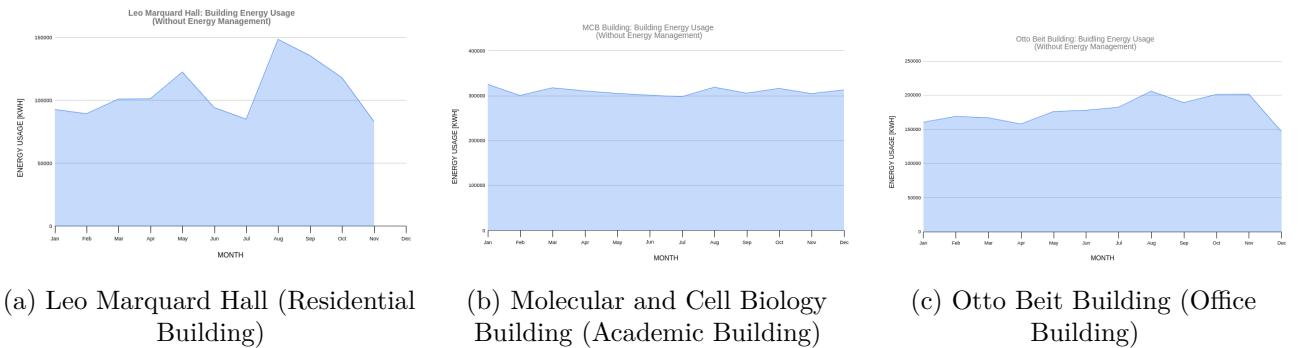


Figure 4.2: Energy usage graphs for the buildings under study in 2018 before energy management implementation: Residential (Leo Marquard Hall), Academic (Molecular and Cell Biology Building), and Office (Otto Beit Building).

4.1.4 Peak Power Demand Data

The peak power demand for the three different buildings at the University of Cape Town (UCT) in the year 2018 is illustrated below. This data aims to provide insights into the power consumption patterns and demands associated with these facilities, highlighting fluctuations throughout the year. By examining the peak power demand, we can better understand the operational characteristics of each building and identify potential areas for enhancing energy efficiency through strategic management techniques.

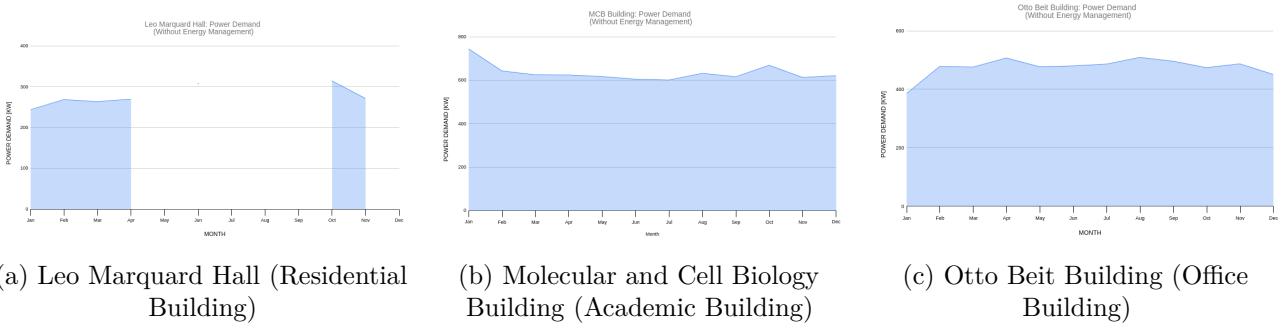


Figure 4.3: Peak power demand graphs for the buildings under study in 2018 before energy management implementation: Residential (Leo Marquard Hall), Academic (Molecular and Cell Biology Building), and Office (Otto Beit Building).

4.1.5 Energy Cost Data

The monthly energy costs for the three different buildings at UCT in year 2018 are illustrated below. The data aims to provide insight into the energy consumption patterns and costs associated with these facilities, highlighting fluctuations throughout the year.

Month	Energy Cost (ZAR)
January	95,630
February	89,835
March	95,773
April	96,101
May	115,492
June	143,637
July	154,696
August	256,680
September	142,883
October	133,014
November	98,249
December	Not Found

Table 4.1: Monthly Energy Costs (ZAR) for the Leo Marquard Hall (Residential Building) in 2018

4.1.6 Weather and Occupancy Data

Weather data, including solar radiation, temperature, and humidity levels, are gathered to assess their impact on building energy performance. These factors directly influence heat transfer processes and energy demand in buildings. Occupancy patterns are also analyzed to understand internal heat gains and their effect on energy demand using the sensible and latent heat equations (Equations 3.7 and 3.8).

- **Summer (December to February):** Cape Town experiences warm and dry summers, which generally lead to a lower demand for heating. However, cooling requirements might increase, impacting energy usage in buildings.
- **Autumn (March to May):** During this transition period, temperatures start to drop, leading to moderate energy demands for both heating and cooling as conditions are relatively stable.

Month	Energy Cost (ZAR)
January	292,527
February	273,279
March	278,708
April	272,556
May	266,878
June	401,813
July	463,786
August	499,850
September	303,615
October	324,340
November	307,490
December	310,027

Table 4.2: Monthly Energy Costs (ZAR) for the Molecular and Cell Biology Building (Academic Building) in 2018

Month	Energy Cost (ZAR)
January	157,285
February	168,451
March	165,301
April	163,370
May	174,020
June	276,448
July	325,827
August	367,636
September	209,699
October	218,543
November	219,273
December	168,162

Table 4.3: Monthly Energy Costs (ZAR) for the Otto Beit Building (Office Building) in 2018

- **Winter (June to August):** Winters in Cape Town are cold and wet, significantly increasing energy consumption due to the higher demand for heating in residential, academic, and office buildings. The combination of low temperatures and high humidity levels exacerbates the need for thermal comfort control.
- **Spring (September to November):** As temperatures rise again, the energy demand for heating decreases. Spring weather can be unpredictable, with occasional shifts that might slightly impact building energy requirements.

The seasonal trends in Cape Town have been sourced from detailed climate information available [here](#) [70].

Occupancy data was obtained from direct venue visits, interviewing residents and an analysis of available venue capacity data to accurately reflect the internal usage patterns and their contribution to internal heat gains in the studied buildings.

Building	Type	Occupancy
Leo Marquard Hall	Residential	400
Molecular and Cell Biology Building	Academic	320
Otto Beit Building	Office	120

Table 4.4: Occupancy Data for the buildings under study

4.2 Data Analysis

The data analysis involves identifying trends in the gathered energy usage, occupancy data, and weather patterns to establish relationships between these variables and energy consumption. This phase includes a thorough analysis of the collected data to provide insights into changes in usage patterns across different periods. The analysis aims to find alignment between occupancy patterns, general university academic terms, vacation periods, and weather conditions. This alignment helps determine whether the observed energy usage trends in the gathered data can be attributed to typical residential, academic, and office-related operations influenced by external weather conditions.

- **June to July Period (Mid-Year Break):**

- During this period, the university has a mid-year vacation, coinciding with the winter season in Cape Town. The occupancy levels in residential buildings decrease significantly as students leave for the break, leading to a reduction in energy usage in these facilities.
- Despite the reduced occupancy, heating systems are used more frequently due to colder temperatures, resulting in an overall increase in energy consumption in both residential and office spaces that remain occupied.

- **December to January Period (Main Vacation):**

- This period marks the main vacation for the university when most students and staff are away, causing a significant drop in occupancy across all building types. Consequently, energy consumption in residential, academic, and office buildings decreases sharply due to reduced activities.
- During these summer months in Cape Town, the demand for cooling is relatively low, leading to a further reduction in energy usage, as compared to winter.

- **Winter Months in Cape Town (May to August):**

- Energy consumption across all building types increases during the winter months due to higher heating requirements. Residential buildings experience a notable rise in energy usage as students actively use heaters, and academic and office spaces also require additional energy to maintain comfortable indoor temperatures.
- The increased heating demand during these months results in a higher baseline of energy consumption, even when occupancy levels are lower during the mid-year break.

- **University Term Periods (February to November):**

- During the active academic terms, occupancy levels in both academic and residential

buildings are high, leading to increased energy consumption due to routine university operations, including the use of lighting, HVAC systems, and various electrical equipment.

- Energy usage remains consistently high during these periods, reflecting normal university activities, with fluctuations corresponding to specific weather conditions and daily occupancy patterns.

The alignment of energy usage trends with the university's academic terms, vacation periods, and seasonal weather conditions indicates that the data accurately reflects typical operational patterns for the university's residential, academic, and office buildings. The observed increase in energy consumption during winter months and a decrease during vacation periods, along with corresponding changes in occupancy, validates that the energy consumption trends identified in the study are indeed representative of standard residential, academic, and office-related activities, influenced by both internal occupancy dynamics and external weather conditions.

4.3 Building Modeling and Simulation

Using the insights gained from data analysis, a detailed model of the building's energy usage is developed using OpenStudio/EnergyPlus software. This model incorporates the theoretical principles outlined in the Theory Development chapter to simulate energy dynamics accurately.

4.3.1 Modeling Process

The building model is developed with a focus on the following elements:

- **Building Geometry Model:** A new project was initiated within OpenStudio, where the geographic location of the building was defined using the software's climate zone settings, influencing energy performance simulations. The building footprint was sketched with the 2D drawing tools, defining its dimensions, shape, and layout while paying specific attention to architectural features that impact energy efficiency, such as overhangs, balconies, and external walls. Individual spaces within the building, including offices, meeting rooms, and common areas, were identified and their intended use specified to reflect energy consumption patterns. Additionally, the vertical geometry was constructed by specifying the number of floors and their respective heights, with spaces grouped into thermal zones based on heating and cooling requirements to enable accurate energy modeling.

The figures below represent the specific buildings studied in this investigation, categorized as Residential, Academic, and Office buildings. These buildings include:

- **Leo Marquard Hall** (Residential building)
- **Molecular and Cell Biology Building** (Academic building)
- **Otto Beit Building** (Office building)

Each figure illustrates the geometric models developed in OpenStudio, showcasing the unique characteristics and design features of these structures. By examining these models, insights can

be gained into their energy performance and potential efficiency improvements relevant to their respective categories.

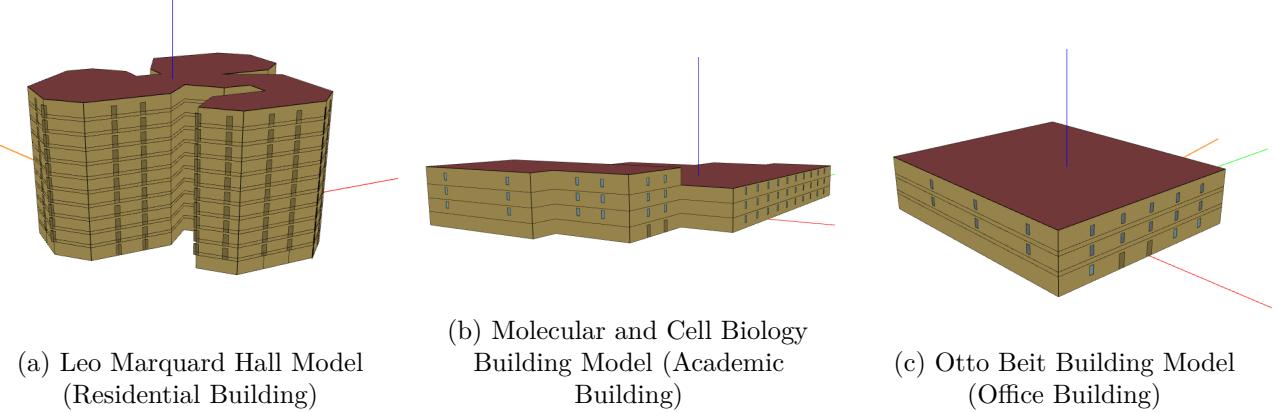


Figure 4.4: Models of the buildings under study: Residential (Leo Marquard Hall), Academic (Molecular and Cell Biology Building), and Office (Otto Beit Building).

- **Thermal and Energy Modeling:** The model simulates the thermal response and energy consumption of the building by incorporating key thermodynamic principles. It utilizes Fourier's Law for conduction (Equation 3.1), Newton's Law of Cooling for convection (Equation 3.2), and the Stefan-Boltzmann Law for radiation (Equation 3.3) to characterize heat transfer mechanisms. Furthermore, the model assesses the performance of the HVAC system by employing the sensible and latent heat equations (Equations 3.7 and 3.8) to analyze its influence on indoor air quality and thermal comfort. The impact of solar radiation on building energy performance is quantified using the solar heat gain equation (Equation 3.9). Additionally, the model accounts for internal electrical loads from equipment, including lighting, computers, appliances, and other devices, to ensure an accurate representation of the building's overall energy consumption.

The two-node state-space model depicted in Figure 4.5 illustrates how EnergyPlus simulation software models the thermal responses within a building [69]. EnergyPlus employs similar lumped-parameter models to represent the thermal behavior of building components, where nodes correspond to different temperatures within the system. In this example, the thermal network includes nodes T_1 and T_2 , with resistances and capacitances representing conductive and capacitive properties, respectively. The resistances between the nodes (R) and to the external temperatures ($\frac{1}{hA}$) account for heat transfer via conduction and convection, while the capacitances (C) represent the ability of building materials to store thermal energy. By discretizing the building's thermal properties into such state-space models, EnergyPlus can accurately simulate dynamic thermal interactions, capturing how heat flows between different zones and the environment over time. This method enables detailed analysis of the building's thermal performance, essential for evaluating energy efficiency and the impact of various design and operational strategies.

- **Occupancy Schedules:** Occupancy patterns are modeled using detailed schedules that reflect the actual usage of the building by its occupants. These schedules are based on data collected from venue visits, capacity information, and typical occupancy trends aligned with university

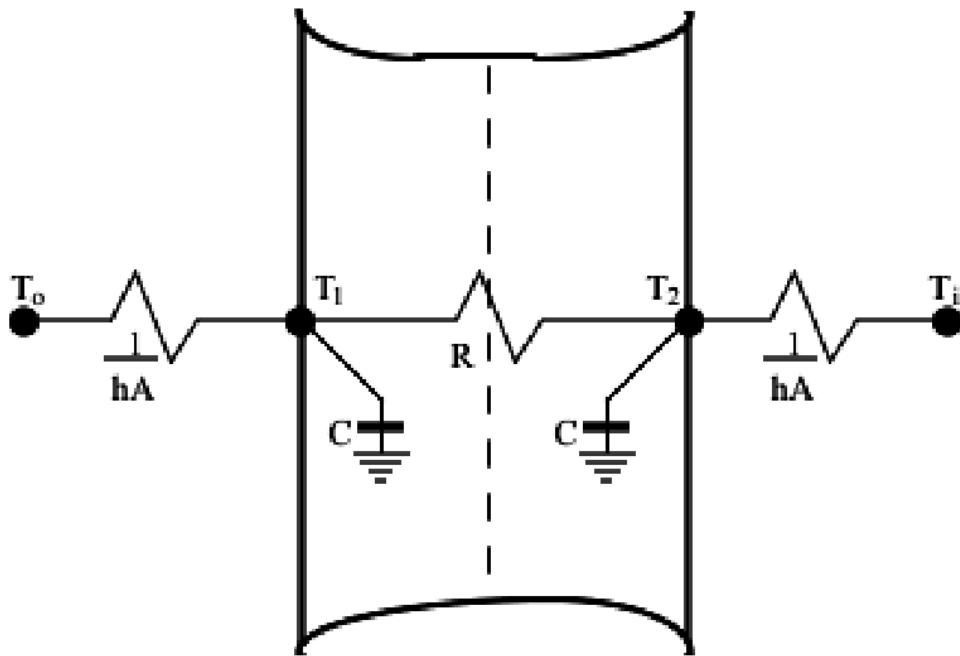


Figure 4.5: Two-node state-space model for thermal response.

academic terms and vacation periods. The integration of occupancy schedules helps simulate internal heat gains and their influence on energy demand more precisely.

The figures in Figure 4.6 below present the occupancy schedules for the buildings studied, categorized into Residential, Academic, and Office buildings. Each subfigure illustrates the specific occupancy patterns for each building type, highlighting variations in usage throughout the day and week. The data represented in these occupancy schedules is crucial for understanding how occupancy levels impact energy consumption, as they provide insights into peak usage times and typical occupancy trends. By analyzing these occupancy patterns, one can infer the underlying occupant activity, which is essential for accurately modeling energy demand. The x-axis of each graph represents the time of day, while the y-axis, indicates the percentage of active occupants within each building. This detailed analysis allows for a more precise simulation of internal heat gains and overall energy demand in each building, ultimately leading to improved energy management strategies.

The occupancy (occupant activity) schedules behave in the following manner:

- **Residential Occupant Activity (Leo Marquard Hall):**
 - * Exhibits peak activity in the morning, during lunch, and after supper.
 - * Activity decreases steadily as residents go to bed in a staggered fashion, reflecting varied schedules among individuals.
- **Academic Occupant Activity (Molecular and Cell Biology Building):**
 - * Peaks in the morning as students arrive for classes.

4.4. Development of Building Energy Management System (BEMS)

- * Experiences a drop during lunch, followed by a secondary peak after lunch as students return for afternoon lectures and tutorials.
- * Activity decreases after lectures and tutorials conclude, indicating a pattern aligned with academic schedules.

– **Office Occupant Activity (Otto Beit Building):**

- * Shows peak activity in the morning as staff begins work.
- * Experiences a slight drop during lunch, as many workers tend to leave their desks active, indicating a continued engagement with tasks.
- * Activity significantly decreases after regular working hours, reflecting typical office closure times.

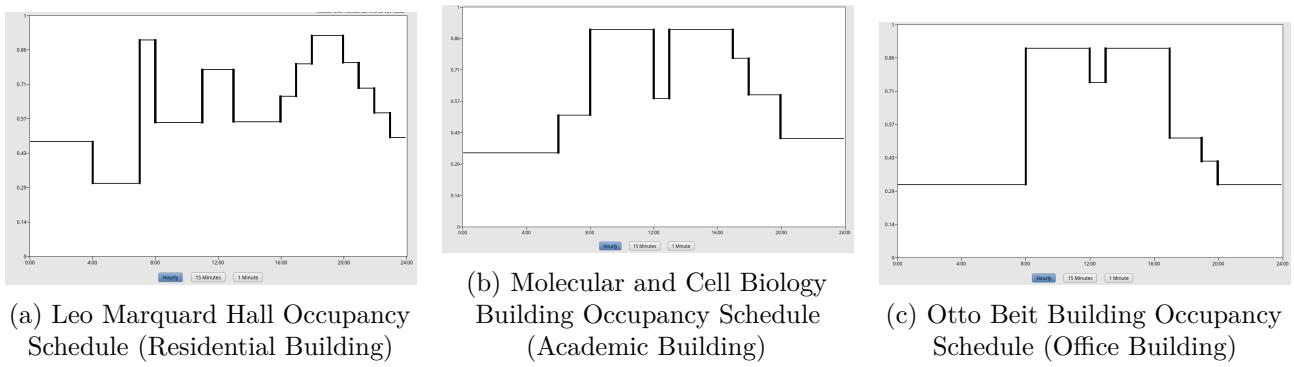


Figure 4.6: Occupancy schedules of the buildings under study: Residential (Leo Marquard Hall), Academic (Molecular and Cell Biology Building), and Office (Otto Beit Building).

4.3.2 Simulation

Simulations were conducted to evaluate energy usage in the different buildings as weather conditions and occupancy conditions varied. The simulation was performed in two iterations: the first iteration modelled the building's energy usage before the implementation of the energy management policy via the Building Energy Management System (BEMS) logic, and the second iteration modeled the building's energy usage after the policy was applied. The energy and power savings achieved through the implementation of the BEMS logic were recorded and analyzed to assess the effectiveness of the energy management strategy.

4.4 Development of Building Energy Management System (BEMS)

Based on the simulation results, a BEMS logic framework was developed to optimize the building's energy consumption. This framework focused on improving the efficiency of HVAC systems, lighting, and other energy-intensive equipment. It provides logic on how to control loads depending on weather and occupancy conditions that would be integrated into the model on OpenStudio/EnergyPlus to enhance the building's energy performance and generate new results.

4.4. Development of Building Energy Management System (BEMS)

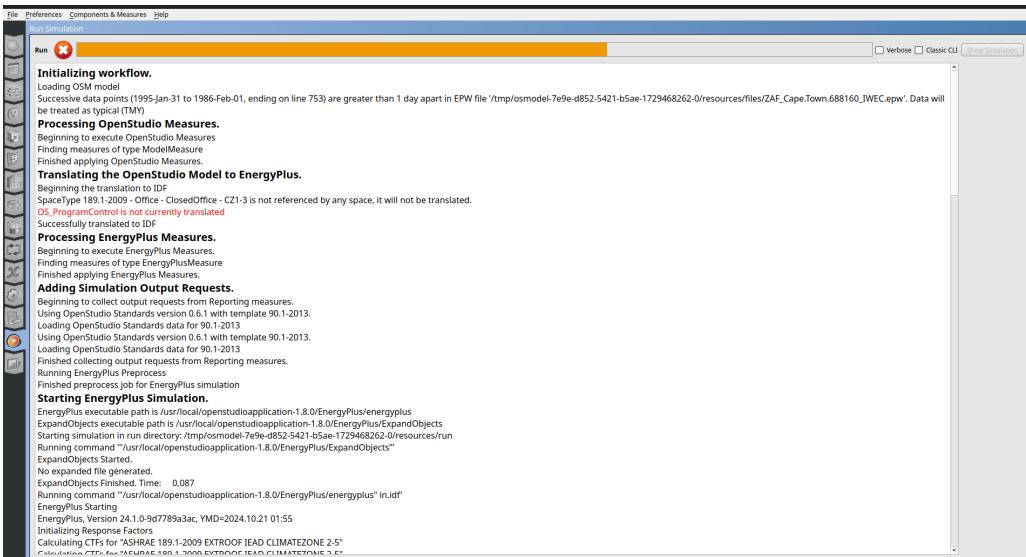


Figure 4.7: OpenStudio simulation window with EnergyPlus plugins.

The Building Energy Management System (BEMS) operates by receiving real-time data from multiple sensors and making energy-efficient decisions accordingly. The control flow is broken down in Figure 4.8 as follows:

1. **Sensor Input:** The BEMS receives input from occupancy, illumination, and temperature sensors located throughout the building.
2. **BEMS Control Unit Processing:** The BEMS Control Unit processes the input data and determines the current state of the building, assessing factors like room occupancy, illumination levels, and temperature.
3. **Active Time Check:** During active hours, the system checks if a room is occupied:
 - If occupied, equipment, lighting and HVAC are turned ON.
 - If unoccupied, these systems are turned OFF or switched to a lower energy mode.
4. **Critical Equipment Monitoring:** If there is critical equipment in operation, the system will switch it to low power mode rather than turning it off completely.
5. **Illumination and Temperature Checks:** The system evaluates whether there is sufficient natural light or optimal temperature:
 - If sufficient natural light is available, the lights are turned OFF.
 - Similarly, if the room temperature is within the desired range, the HVAC system is deactivated.
6. **Building State Update:** The current state of the building is displayed on the central display unit, providing real-time information on system operations, such as equipment status, lighting conditions, and HVAC activity.

4.5 Results Analysis

The final phase involves comparing energy usage data before and after implementing the BEMS to assess the impact of the energy management policy on the building's overall energy performance as a percentage saving of the energy and power. The effectiveness of the energy management policy is evaluated using the percentage reduction of the energy consumption and of peak power demand after the implementation of the BEMS. Also included in this phase, is the cost savings analysis and well as environmental considerations.

Cost Savings Analysis

The cost saving is considered to demonstrate the financial gain of the BEMS implementation. The monetary savings were calculated in proportion to the cost of energy per kilowatt hour as derived from observed from the initial building energy usage and energy cost data collected from the UCT website. The method is as follows (figures are calculated monthly then summed together to determine yearly results):

- **Total Energy Cost:** This value is provided in the results of the simulation.
- **Cost Per kWh Calculation:**

$$\text{Cost Per kWh} = \frac{\text{Total Energy Cost}}{\text{Energy Usage (kWh)}} \quad (4.1)$$

This equation is used to calculate the cost per kilowatt-hour based on the collected data.

- **Cost Savings Calculation:**

$$\text{Cost Savings} = \text{Total Energy Cost before BEMS} - \text{Total Energy Cost after BEMS} \quad (4.2)$$

This calculation provides the absolute monetary savings achieved due to the implementation of BEMS.

- **Percentage Cost Savings:**

$$\text{Percentage Cost Savings} = \left(\frac{\text{Cost Savings}}{\text{Total Energy Cost before BEMS}} \right) \times 100 \quad (4.3)$$

This calculation provides a percentage representation of the cost savings relative to the total energy cost prior to the implementation of BEMS.

4.5.1 Feasibility Analysis

To enhance the investigation, a Feasibility Analysis was performed to assesses the practicality of implementing proposed energy efficiency measures and energy management systems in the respective buildings. This included evaluating the technical feasibility of integrating new technologies with existing infrastructure and the availability of skilled personnel for installation, an economic analysis examining the cost-effectiveness of the measures, considering installation costs, energy savings, and return on investment. Operational implications for building management and occupant behavior are

also reviewed, along with legal and regulatory considerations.

4.6 Conclusion

This chapter detailed a comprehensive methodology for developing a Building Energy Management System (BEMS) that optimized energy consumption while maintaining occupant comfort. By integrating the theoretical principles outlined in the Theory Development chapter with practical data analysis and simulation techniques, the project aimed to provide a robust framework for enhancing energy efficiency in buildings. This methodology not only facilitated the identification of potential energy savings but also supported sustainable energy management practices in buildings located in subtropical regions like South Africa. It involved analyzing a building and improving its efficiency through the development of an energy management policy, which was then derived into BEMS logic to improve energy efficiency, enhance energy cost savings, and promote environmental sustainability.

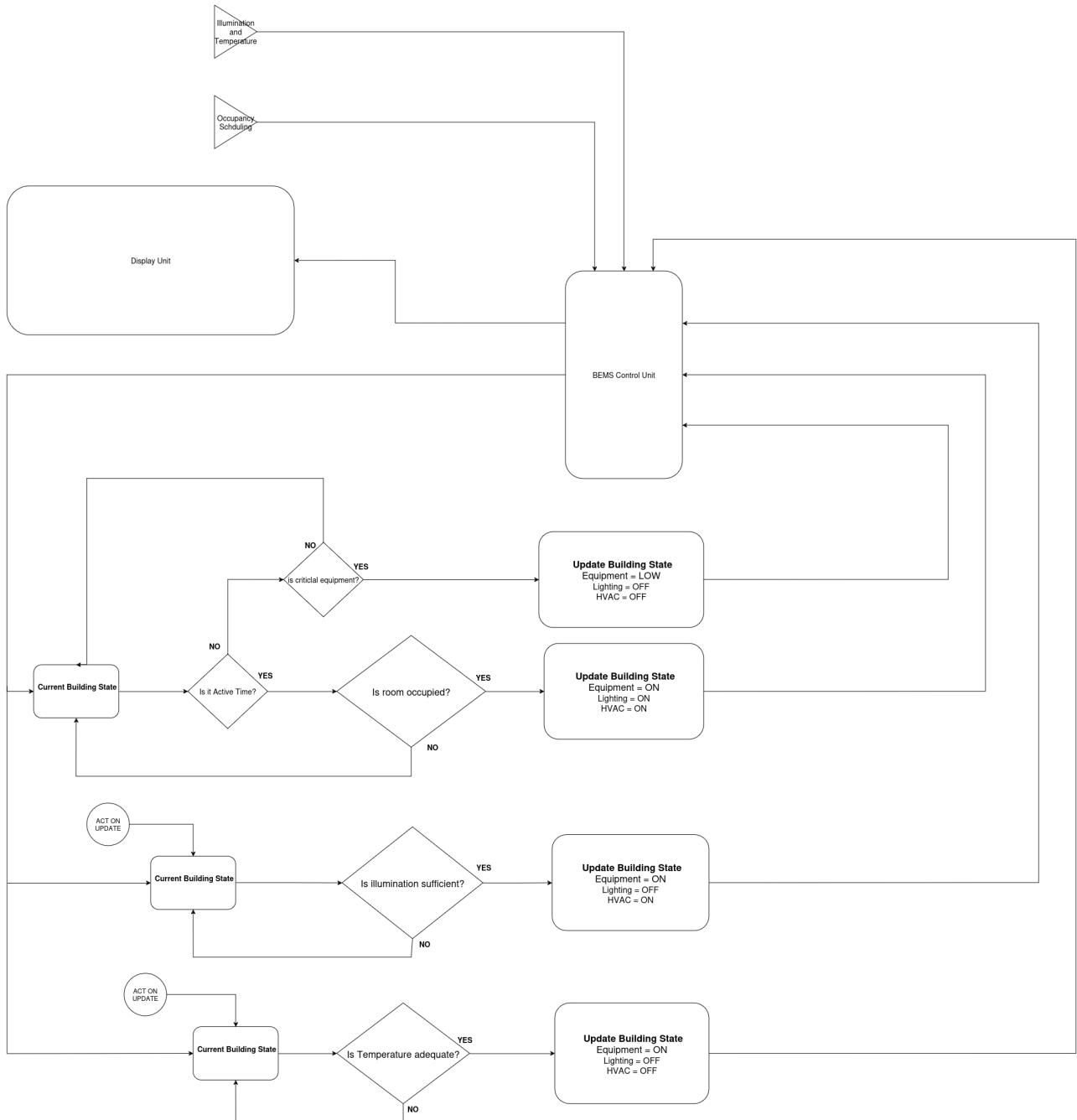


Figure 4.8: BEMS Logic control flow diagram

Chapter 5

Simulation Results and Analyses

5.1 Introduction

This chapter presents the modeled energy consumption and power demand of the buildings prior to the implementation of the Building Energy Management System (BEMS). It is structured into several key subsections: Building Model Results Before Energy Management, which details the energy performance metrics before the BEMS was introduced; Building Model Results After Energy Management, which details the energy performance metrics after the BEMS was introduced; Post Implementation Analysis, which evaluates the effects of the BEMS on energy usage; and Cost Savings Analysis, which examines the financial benefits resulting from the implementation of energy management strategies. The results were generated using OpenStudio/EnergyPlus modeling software, accurately simulating energy usage based on the buildings' characteristics and operational parameters, thereby establishing a comprehensive baseline for assessing future energy management efforts.

5.2 Building Model Results Before Energy Management

The figures below present the modeled energy consumption and power demand of the buildings before the implementation of the Building Energy Management System (BEMS).

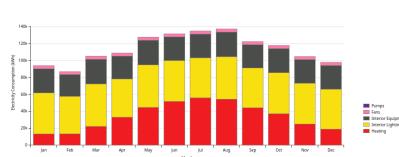
5.2.1 Energy consumption

The graphical data in the figures in Figure 5.1 reflects the energy consumption patterns for each building type:

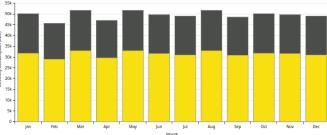
- **Residential Building (Leo Marquard Hall):** Figure 5.1a showed that energy consumption was significantly higher during the cooler months compared to the warmer months, particularly the building's HVAC system. The maximum energy usage was 137.3×10^3 kWh in the month of August and the minimum energy usage was 86.9×10^3 kWh in February.
- **Academic Building (Molecular and Cell Biology Building):** Figure 5.1b showed relatively consistent energy consumption patterns. The maximum energy usage was 51.7×10^3 kWh in the months of March, May and August and the minimum energy usage was 45.7×10^3 kWh in February.
- **Office Building (Otto Beit Building):** Figure 5.1c also showed elevated energy consumption during the cooler months compared to the warmer months where the HVAC system was a minor

5.2. Building Model Results Before Energy Management

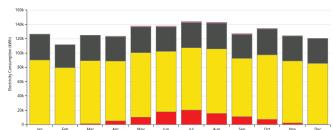
contributor. The maximum energy usage was 144.1×10^3 kWh in the month of July and the minimum energy usage was 111.8×10^3 kWh in February.



(a) Leo Marquard Hall Energy Consumption (Residential Building)



(b) Molecular and Cell Biology Building Energy Consumption (Academic Building)



(c) Otto Beit Building Energy Consumption (Office Building)

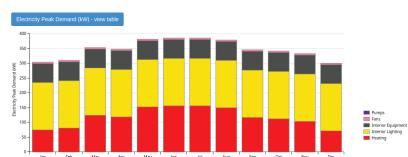
Figure 5.1: Modelled Energy Consumption patterns of the buildings under study before energy management.

These visual representations provide a baseline of the building's energy behavior before the introduction of energy management strategies.

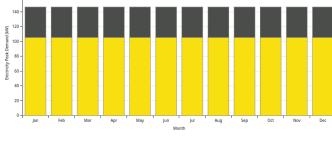
5.2.2 Peak Power Demand

The graphical data in the figures in Figure 5.2 reflects the Peak Power Demand patterns for each building type:

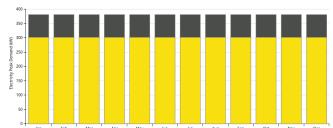
- **Residential Building (Leo Marquard Hall):** Figure 5.2b showed variations in power demand across the year, with the maximum power demand of 385.7 kW occurring in both June and July. The minimum power demand was 300.69 kW, recorded in December.
- **Academic Building (Molecular and Cell Biology Building):** Figure 5.2b showed relatively constant power demand throughout the year, with no fluctuations across the months. The model without energy management consistently recorded a power demand of 146.58 kW for each month
- **Office Building (Otto Beit Building):** Figure 5.2c showed relatively constant power demand throughout the year, with no fluctuations across the months. The model without energy management consistently recorded a power demand of 381.45 kW for each month.



(a) Leo Marquard Hall Peak Power Demand (Residential Building)



(b) Molecular and Cell Biology Building Peak Power Demand (Academic Building)



(c) Otto Beit Building Peak Power Demand (Office Building)

Figure 5.2: Modelled Peak Power Demand patterns of the buildings under study before energy management.

These visual representations provide a baseline of the building's power demand before the introduction of energy management strategies.

5.3 Building Model Results After Energy Management

The figures below present the modeled energy consumption and power demand of the buildings after the implementation of the Building Energy Management System (BEMS).

5.3.1 Energy consumption

The graphical data in the figures in Figure 5.3 reflects the energy consumption patterns for each building type:

- **Residential Building:** Figure 5.3a showed that energy consumption remained higher during the cooler months compared to the warmer months. However, after the implementation of the BEMS, the maximum energy usage became 120.3×10^3 kWh in the month of August and the minimum energy usage became 72.4×10^3 kWh in February.
- **Academic Building:** Figure 5.3b showed that energy consumption patterns remained relatively consistent . However, after the implementation of the BEMS, the maximum energy usage became 43×10^3 kWh in the months of January, May, August and October and the minimum energy usage became 37.9×10^3 kWh in February.
- **Otto Beit Building:** Figure 5.3c showed that energy consumption patterns remained relatively consistent . However, after the implementation of the BEMS, the maximum energy usage became 118.3×10^3 kWh in the month of July and the minimum energy usage became 87×10^3 kWh in February.

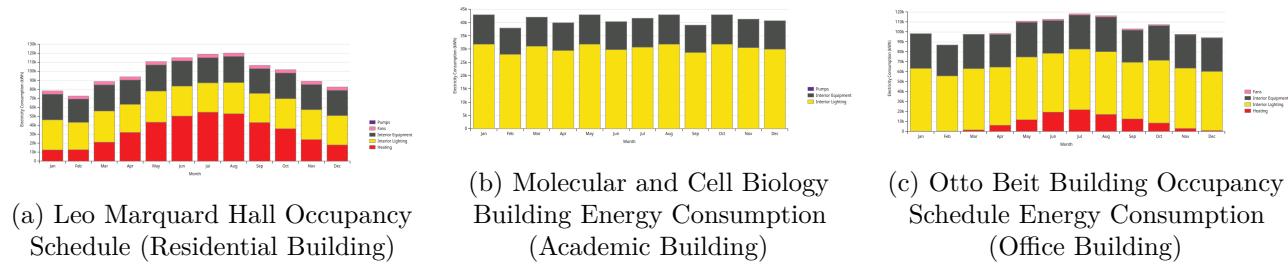


Figure 5.3: Modelled Energy Consumption patterns of the buildings under study: Residential (Leo Marquard Hall), Academic (Molecular and Cell Biology Building), and Office (Otto Beit Building).

These results indicate a overall reduction in energy consumption, with the figures providing visual evidence of the reduction achieved through the BEMS integration.

5.3.2 Peak Power Demand

The graphical data in the figures in Figure 5.4 reflects the Peak Power Demand patterns for each building type:

- **Residential Building (Leo Marquard Hall):** Figure 5.4a also showed variations in power demand across the year, with the maximum power demand of 332.35 kW occurring in both July. The minimum power demand was 234.4 kW, recorded in January.

- **Academic Building (Molecular and Cell Biology Building):** Figure 5.4b continued to show a constant power demand throughout the year, with no fluctuations across the months. However, after the BEMS implementation, a power demand of 134.27 kW for each month was recorded.
- **Office Building (Otto Beit Building):** Figure 5.4c continued to show a constant power demand throughout the year, with no fluctuations across the months. However, after the BEMS implementation, a power demand of 290.81 kW for each month was recorded.

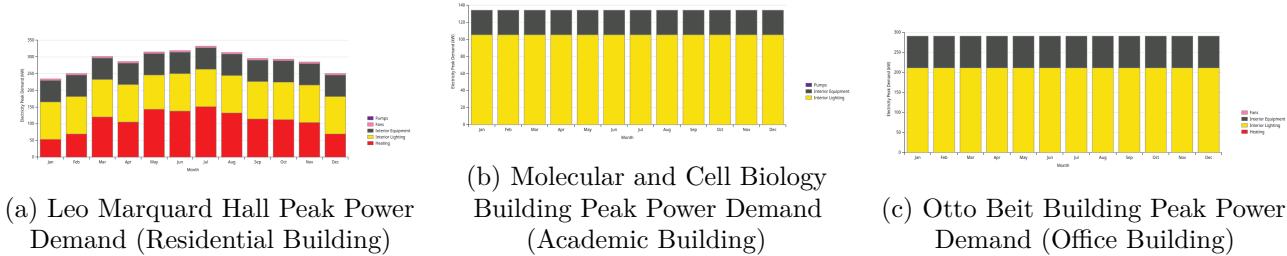


Figure 5.4: Modelled Peak Power Demand patterns of the buildings under study: Residential (Leo Marquard Hall), Academic (Molecular and Cell Biology Building), and Office (Otto Beit Building).

5.4 Conclusion

This chapter illustrated the modeled energy consumption and power demand of the buildings before and after the implementation of the Building Energy Management System (BEMS). The results highlighted changes in energy usage patterns across different building types, with noticeable reductions in overall consumption and peak demand post-implementation. These results establish a foundation for further analysis, which will assess the effectiveness of the BEMS and explore the potential for cost savings and improved energy efficiency.

Chapter 6

Analysis of Results: Leo Marquard Hall (Residential Building)

6.1 Introduction

The figures in this section illustrate a detailed analysis of the energy and power demand changes before and after BEMS implementation. The data visualized through the OpenStudio/EnergyPlus software allows for a comparative evaluation of the system's impact on energy efficiency.

6.1.1 Energy Savings Analysis : Model

The results from the simulation are analysed to determine the relationship between values prior and post implementation of the BEMS.

Month	Energy usage without BEMS (kWh)	Energy usage with BEMS (kWh)	Percentage Reduction (%)
January	93,994.06	78,222.25	20.16%
February	86,874.42	72,462.03	19.89%
March	105,148.36	88,629.11	18.64%
April	108,843.92	93,840.58	15.99%
May	127,667.64	110,780.14	15.24%
June	131,565.36	115,104.81	14.30%
July	134,952.36	118,892.92	13.51%
August	137,308.75	120,251.53	14.18%
September	122,372.61	106,567.06	14.83%
October	117,867.36	101,775.69	15.81%
November	104,784.86	88,887.39	17.88%
December	97,917.83	82,521.81	18.66%

Table 6.1: Monthly Energy Consumption Comparison between Model without BEMS and Model with BEMS: Leo Marquard Hall (Residential Building)

6.1.2 Energy Savings Analysis : Actual Building

The percentage reduction in the various month as obtained in the building model was projected to the actual building data collected initially to determine the realisable energy usage figures in the actual building post implementation of a BEMS. Each month in the actual building data receives a reduction corresponding to the reduction in the model data. This process is applied to all building categories in this investigation.

The figures above demonstrate a comparison of energy consumption for a building with and without

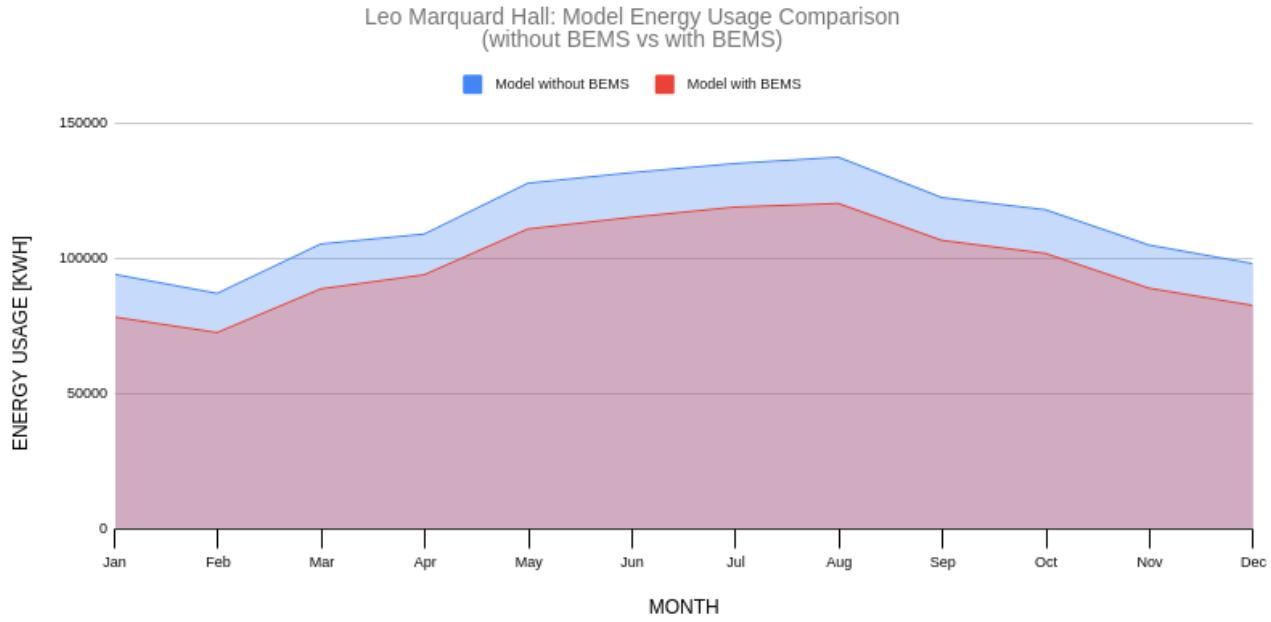


Figure 6.1: Graph of the Monthly Energy Consumption Comparison between Model without BEMS and Model with BEMS: Leo Marquard Hall (Residential Building).

Month	Energy Usage without BEMS (kWh)	Energy Usage with BEMS (kWh)
January	92,573	73,907.67
February	89,203	71,460.90
March	100,829	82,035.86
April	101,106	84,941.06
May	122,286	103,644.53
June	94,110	80,651.81
July	84,850	73,388.90
August	148,292	127,257.35
September	135,388	115,307.86
October	117,890	99,250.51
November	83,160	68,286.87
December	Not Found	Not Found

Table 6.2: Building Energy Data for 2018: Comparison between BEMS and Non-BEMS Systems

the Building Energy Management System (BEMS) over the course of the year. The results reveal a consistent reduction in energy usage across nearly all months following the implementation of BEMS. This decrease signifies the effectiveness of the system in optimizing energy consumption, leading to enhanced operational efficiency within the building. By managing energy more effectively, the BEMS minimizes energy wastage, ensuring that resources are used more effectively during both peak and off-peak periods.

The implications of these reductions are also significant from both financial and environmental perspectives. With lower energy consumption, the building can achieve substantial cost savings on energy costs, ultimately enhancing financial sustainability. Furthermore, reduced energy usage translates into a smaller carbon footprint, supporting the broader environmental goals and promotes compliance with sustainability initiatives.

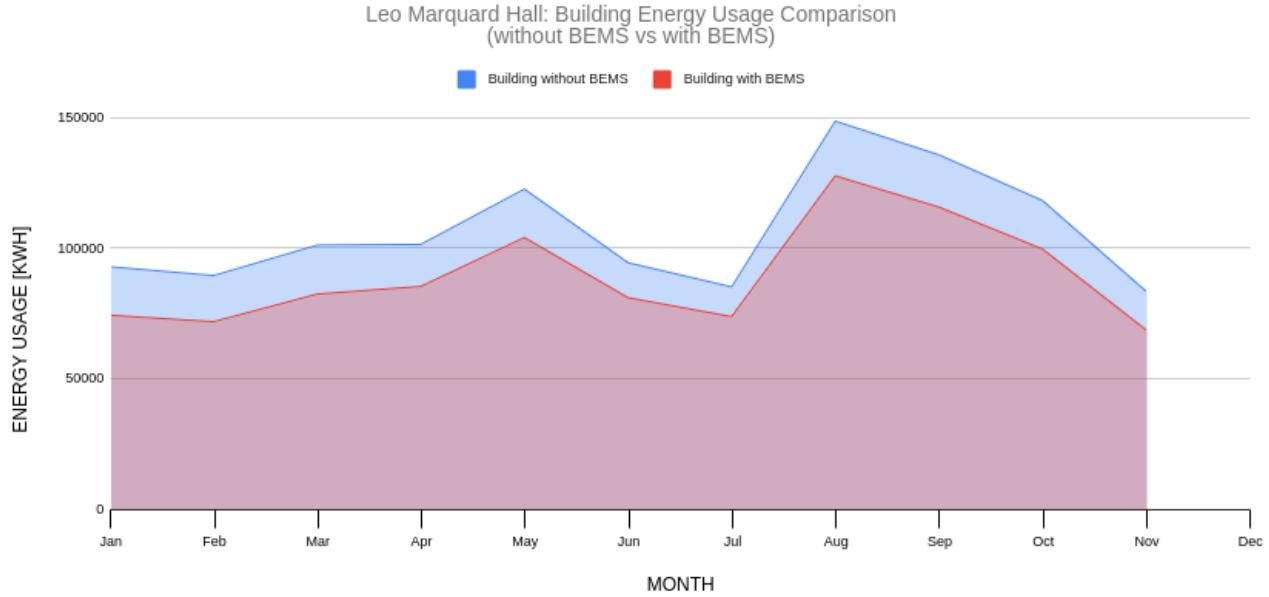


Figure 6.2: Graph of the Monthly Energy Consumption Comparison between Building without BEMS and Building with BEMS: Leo Marquard Hall (Residential Building).

6.1.3 Peak Power Savings Analysis : Model

Month	Model without BEMS (kW)	Model with BEMS (kW)	% Reduction
January	304.15	234.40	29.76%
February	310.40	250.50	23.91%
March	353.51	301.56	17.23%
April	348.11	286.36	21.56%
May	381.90	315.04	21.22%
June	385.70	319.07	20.88%
July	385.70	332.35	16.05%
August	379.13	313.48	20.94%
September	346.05	295.49	17.11%
October	341.61	293.50	16.39%
November	333.10	284.98	16.89%
December	300.69	250.61	19.98%

Table 6.3: Peak Power Demand with and without BEMS: Leo Marquard Hall (Residential Building)

6.1.4 Peak Power Savings Analysis : Actual Building

Similar to the energy usage case, the peak power savings of the real building data are derived from the percentage reductions obtained in the model and simulation.

The implementation of the Building Energy Management System (BEMS) has resulted in a noticeable reduction in peak power demand throughout the year. This trend underscores the effectiveness of BEMS in optimizing energy consumption during high-demand periods, which is crucial for enhancing the operational efficiency of the building. By lowering peak power usage, the system helps to mitigate strain on the electrical grid, contributing to a more stable energy supply and improving the overall reliability of power delivery to the facility.

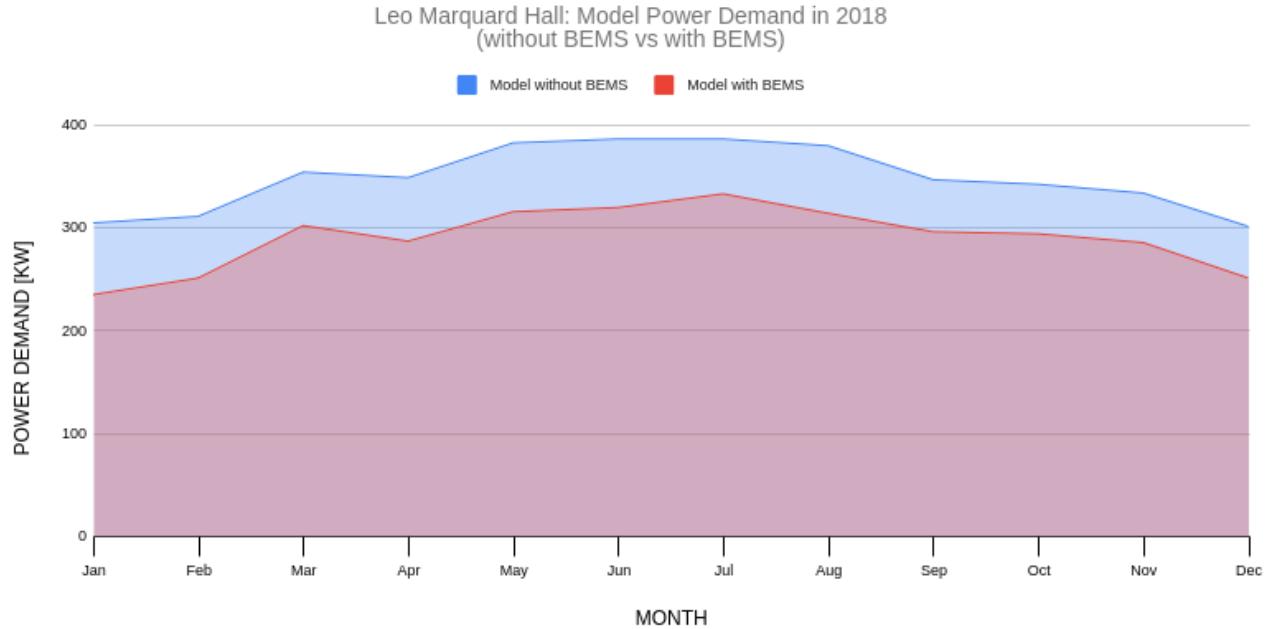


Figure 6.3: Graph of the Monthly Peak Power Demand Comparison between Model without BEMS and Model with BEMS: Leo Marquard Hall (Residential Building).

Month	Building without BEMS (kW)	Building with BEMS (kW)
Jan	243	170.69
Feb	268	203.92
Mar	263	217.69
Apr	269	210.99
May	Not Found	Not Found
Jun	308	243.68
Jul	Not Found	Not Found
Aug	Not Found	Not Found
Sep	Not Found	Not Found
Oct	314	262.53
Nov	271	225.24
Dec	Not Found	Not Found

Table 6.4: Peak Power Demand for Buildings with and without BEMS

The significance of these reductions extends to financial implications as well. With decreased peak power demand, the building can benefit from lower demand charges possibly imposed by utility providers, leading to substantial cost savings over time. Additionally, the reduced energy consumption contributes to sustainability efforts, lowering the building's carbon footprint and aligning with environmental goals. Overall, the BEMS plays a vital role in promoting efficient energy management, providing operational, economic and ecological advantages.

6.2 Cost Savings Analysis

Figure 6.5 presents a comparison of energy usage, energy costs, and cost savings before and after the implementation of a Building Energy Management System (BEMS) in the Leo Marquard Hall

6.2. Cost Savings Analysis

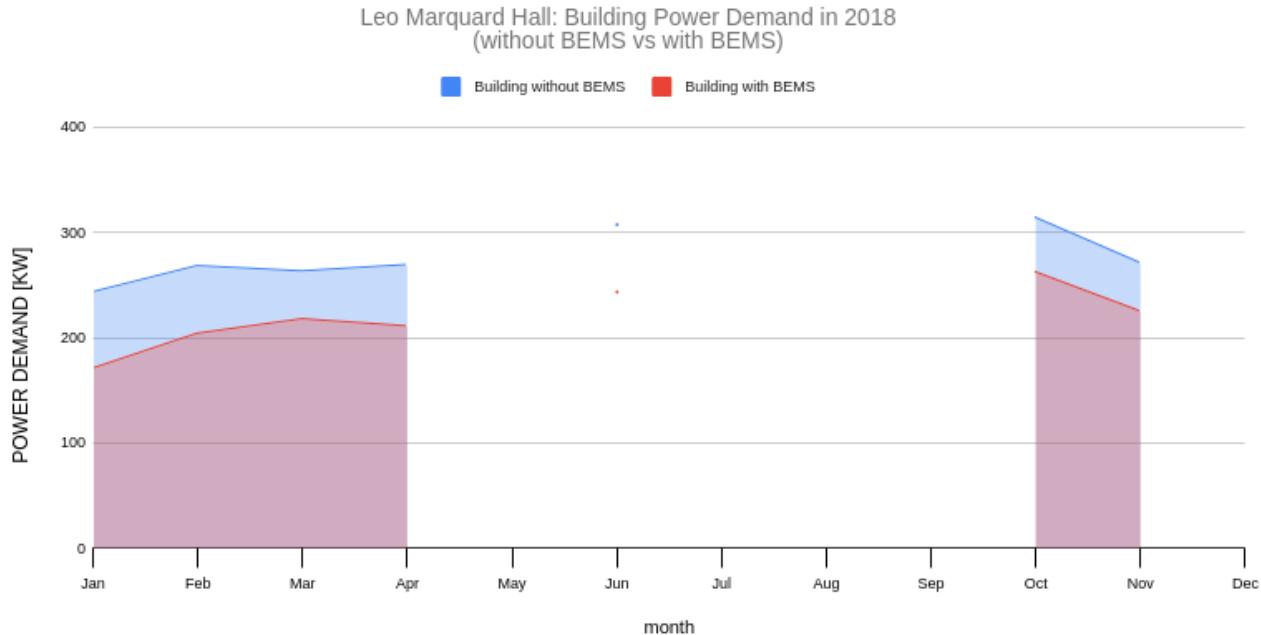


Figure 6.4: Graph of the Monthly Peak Power Demand Comparison between Model without BEMS and Model with BEMS: Leo Marquard Hall (Residential Building).

(Residential Building). It covers monthly data for the the year and illustrates the cost savings per month post implementation of the BEMS.

Month	Energy Usage before BEMS (kWh)	Total Energy Cost before BEMS (R)	Cost Per kWh (R/kWh)	Energy Usage after BEMS (kWh)	Total Energy Cost after BEMS (R)	Cost Saving (R)
Jan	92573	95630	1.0330	73907.67	76348.30	19281.70
Feb	89203	89835	1.0071	71460.90	71967.20	17867.80
Mar	100829	95773	0.9499	82035.86	77922.23	17850.77
Apr	101106	96101	0.9505	84941.06	80736.26	15364.74
May	122286	115492	0.9444	103644.53	97886.22	17605.78
Jun	94110	143637	1.5263	80651.81	123096.21	20540.79
Jul	84850	154696	1.8232	73388.90	133800.47	20895.53
Aug	148292	256680	1.7309	127257.35	220270.92	36409.08
Sep	135388	142883	1.0554	115307.86	121691.23	21191.77
Oct	117890	133014	1.1283	99250.51	111983.27	21030.73
Nov	83160	98249	1.1814	68286.87	80677.21	17571.79
Dec	Not Found	Not Found	Undefined	Undefined	Undefined	Undefined
Total	1169687	1421990	13.3303	980133.32	1196379.52	225610.48

Table 6.5: Energy Usage, Cost, and Savings before and after BEMS (Residential Building)

To calculate the percentage cost savings after the implementation of the Building Energy Management System (BEMS), the following approach was used as mentioned in Chapter 4:

- **Total Energy Cost Before BEMS:** This represents the total energy cost before BEMS implementation.

$$\text{Total Energy Cost Before BEMS} = \text{R } 1,421,990$$

- **Cost Per kWh:** This represents the cost per kilowatt-hour per month as shown in equation 4.1. Using January as an example, the value is calculated as follows.

$$\text{Cost Per kWh} = \frac{95630}{92,573} = 1.033$$

- **Total Energy Cost After BEMS:** This represents the total energy cost after BEMS implementation. For each month, the cost per kWh id multiplied with the new energy usage value

post BEMS implementation.

$$\text{Total Energy Cost After BEMS} = \text{R } 1,196,379.52$$

- **Cost Saving:** The total cost saving is calculated by subtracting the total energy cost after BEMS from the total energy cost before BEMS as shown in equation 4.2.

$$\text{Cost Saving} = 1,421,990 - 1,196,379.52 = \text{R } 225,610.48$$

- **Percentage Cost Savings:** The percentage cost saving is then calculated as follows as shown in equation 4.3:

$$\text{Percentage Cost Saving} = \left(\frac{\text{Cost Saving}}{\text{Total Cost Before BEMS}} \right) \times 100$$

Substituting the values:

$$\text{Percentage Cost Saving} = \left(\frac{225,610.48}{1,421,990} \right) \times 100 \approx 15.87\%$$

From the simulation results and the calculations above, it can be observed that the implementation of the BEMS would result in a **15.87%** reduction in total energy costs. This reduction would be a direct result of improved energy efficiency and management practices achieved through the BEMS. A similar procedure was followed in the remainder of the building types i.e., Academic building and Office building to determine energy cost savings.

6.3 Conclusion

In conclusion, the analysis of energy usage, peak power demand, and cost savings results highlights the significant benefits of implementing a Building Energy Management System (BEMS) within the studied building. The data indicates a marked reduction in energy consumption and peak power demand following the installation of BEMS, demonstrating its effectiveness in optimizing energy usage and enhancing operational efficiency. This optimization not only leads to considerable financial savings through lower energy costs and demand charges but also contributes to environmental sustainability by decreasing the building's carbon footprint.

Chapter 7

Analysis of Results: Molecular and Cell Biology Building (Academic building)

7.1 Introduction

The figures in this section illustrate a detailed analysis of the energy and power demand changes before and after BEMS implementation. The data visualized through the OpenStudio/EnergyPlus software allows for a comparative evaluation of the system's impact on energy efficiency.

7.1.1 Energy Savings Analysis : Model

The results from the simulation are analysed to determine the relationship between values prior and post implementation of the BEMS.

Month	Model without BEMS (kWh)	Model with BEMS (kWh)	% Reduction
Jan	50168.36	42970.16	16.75%
Feb	45680.19	37940.78	20.40%
Mar	51708.19	42040.91	22.99%
Apr	47053.29	39973.07	17.71%
May	51708.19	42970.16	20.34%
Jun	49698.96	40364.46	23.13%
Jul	49062.80	41649.55	17.80%
Aug	51708.19	42970.16	20.34%
Sep	48593.13	39043.57	24.46%
Oct	50168.36	42970.16	16.75%
Nov	49698.96	41293.71	20.35%
Dec	49062.80	40720.02	20.49%

Table 7.1: Monthly Energy Consumption Comparison between Model without BEMS and Model with BEMS: Molecular and Cell Biology Building (Academic building)

7.1.2 Energy Savings Analysis : Actual Building

The percentage reduction in the various month as obtained in the building model was projected to the actual building data collected initially to determine the realisable energy usage figures in the actual building post implementation of a BEMS. Each month in the actual building data receives a reduction

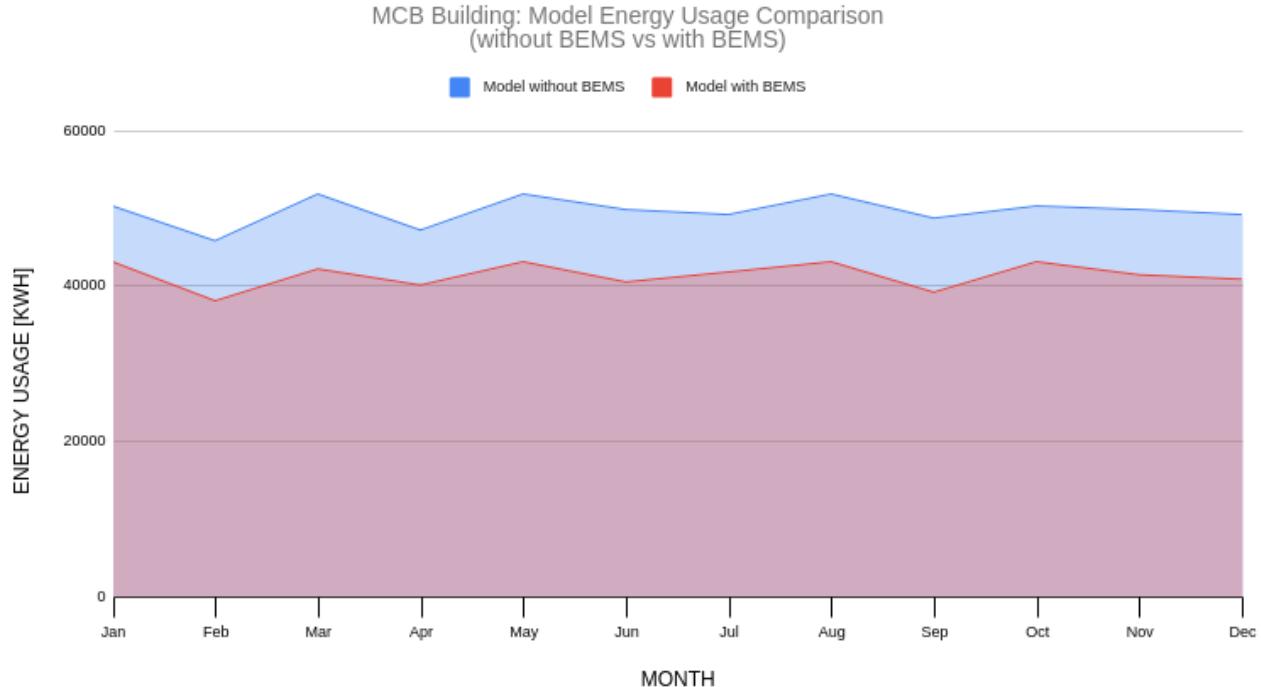


Figure 7.1: Graph of the Monthly Energy Consumption Comparison between Model without BEMS and Model with BEMS: Molecular and Cell Biology Building (Academic building).

corresponding to the reduction in the model data. This process is applied to all building categories in this investigation.

Month	Building without BEMS (kWh)	Building with BEMS (kWh)
Jan	324970	270532.24
Feb	299991	238796.86
Mar	317117	244196.15
Apr	310175	255235.33
May	304627	242680.76
Jun	300494	231003.13
Jul	297216	244314.19
Aug	318460	253700.80
Sep	305080	230461.32
Oct	315812	262908.36
Nov	304187	242270.36
Dec	312396	248391.83

Table 7.2: Building Energy Data for 2018: Comparison between BEMS and Non-BEMS Systems

The data presented in the figures above illustrates a clear trend of reduced energy consumption in the building equipped with the Building Energy Management System (BEMS) compared to the building without it throughout the year. This consistent decrease indicates that the implementation of BEMS effectively optimizes energy usage, resulting in lower overall consumption each month. Notably, the energy savings are particularly pronounced during peak demand periods, which suggests that the BEMS plays a critical role in managing energy loads more efficiently.

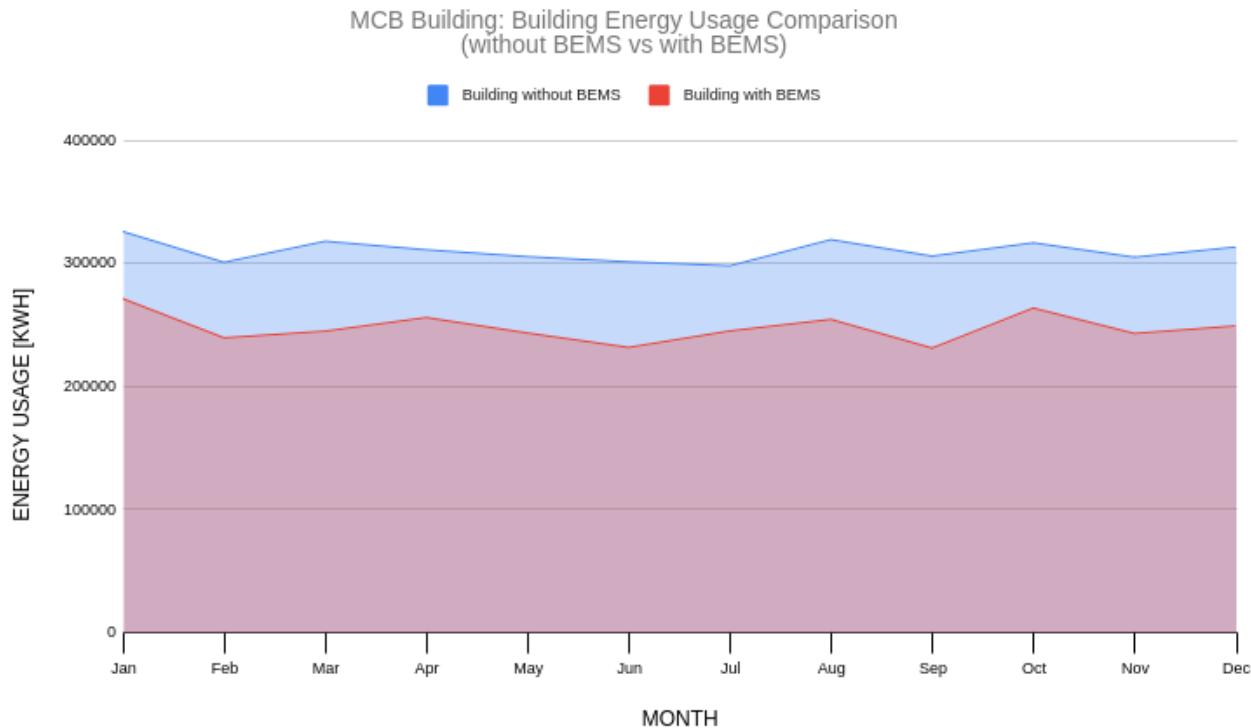


Figure 7.2: Graph of the Monthly Energy Consumption Comparison between Building without BEMS and Building with BEMS: Molecular and Cell Biology Building (Academic building).

The implications of this trend are significant for both operational efficiency and cost management. By minimizing energy usage, the building with BEMS not only achieves substantial cost savings on energy costs but also enhances its sustainability profile. This reduction in energy consumption contributes to lower greenhouse gas emissions, aligning with broader environmental goals. Thus, the results reinforce the value of BEMS in promoting energy efficiency and environmental responsibility within building operations.

7.1.3 Peak Power Savings Analysis : Model

7.1.4 Peak Power Savings Analysis : Actual Building

A noticeable trend emerges from the figures, indicates that the building equipped with BEMS consistently exhibits lower peak power demand compared to its non-BEMS counterpart. This reduction in peak power demand demonstrates the effectiveness of BEMS in managing energy loads, ensuring that energy consumption remains optimized even during high-demand periods.

The implications of these reductions are significant for both operational efficiency and energy cost management. By effectively reducing peak power demand, the building with BEMS can potentially lower its energy costs, as electricity supplier often charge higher rates during peak times. Furthermore, the enhanced ability to manage power loads not only contributes to cost savings but also supports the overall stability of the electrical grid by reducing strain during high usage periods. Thus, the data emphasizes the critical role of BEMS in improving energy efficiency and reducing operational costs.

Month	Model without BEMS (kW)	Model with BEMS (kW)	% Reduction
Jan	146.58	134.27	9.17%
Feb	146.58	134.27	9.17%
Mar	146.58	134.27	9.17%
Apr	146.58	134.27	9.17%
May	146.58	134.27	9.17%
Jun	146.58	134.27	9.17%
Jul	146.58	134.27	9.17%
Aug	146.58	134.27	9.17%
Sep	146.58	134.27	9.17%
Oct	146.58	134.27	9.17%
Nov	146.58	134.27	9.17%
Dec	146.58	134.27	9.17%

Table 7.3: Peak Power Demand with and without BEMS: Molecular and Cell Biology Building (Academic building)

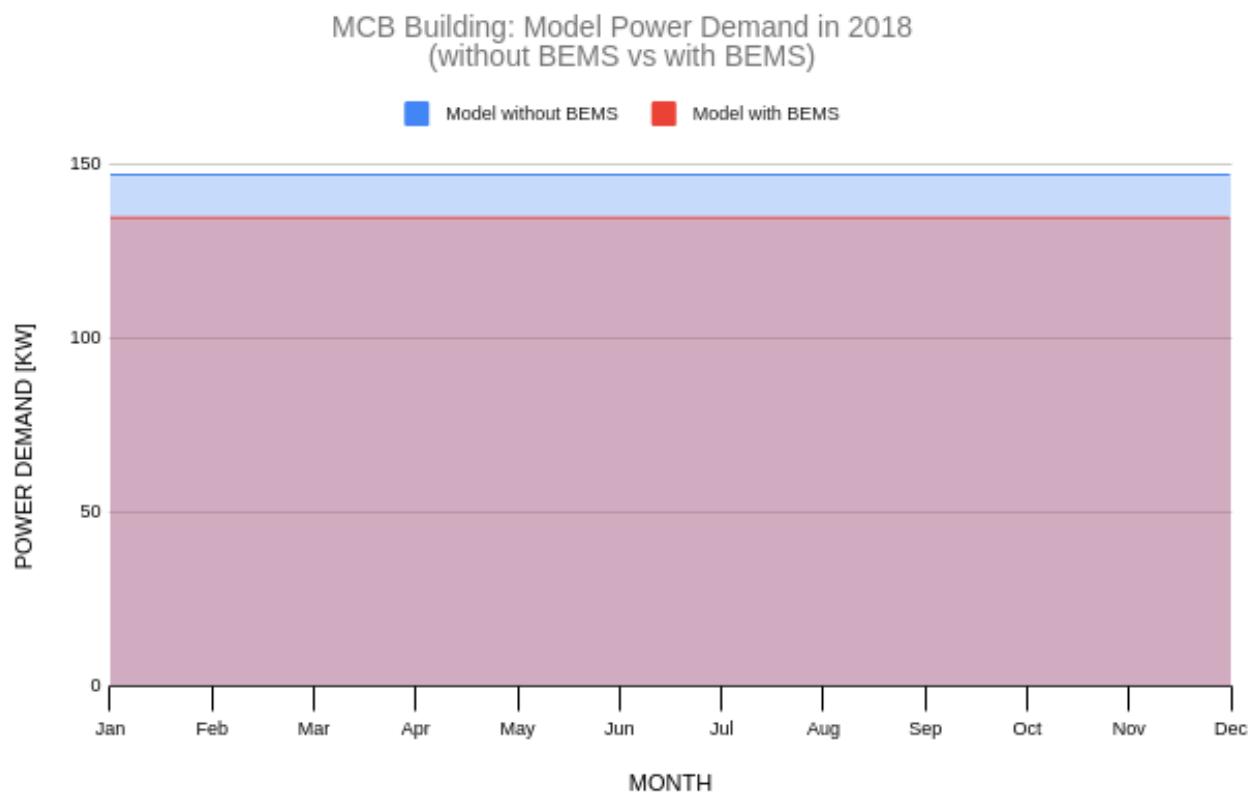


Figure 7.3: Graph of the Monthly Peak Power Demand Comparison between Model without BEMS and Model with BEMS: Molecular and Cell Biology Building (Academic building).

7.2 Cost Savings Analysis

Figure 7.5 presents a comparison of energy usage, energy costs, and cost savings before and after the implementation of a Building Energy Management System (BEMS) in the Molecular and Cell Biology Building (Academic Building). It covers monthly data for the year and illustrates the cost savings per month post implementation of the BEMS.

Month	Building without BEMS (kW)	Building with BEMS (kW)
Jan	744	675.79
Feb	642	583.14
Mar	624	566.79
Apr	623	565.88
May	616	559.52
Jun	604	548.62
Jul	600	544.99
Aug	631	573.15
Sep	615	558.62
Oct	668	606.76
Nov	612	555.89
Dec	620	563.16

Table 7.4: Peak Power Demand for Buildings with and without BEMS

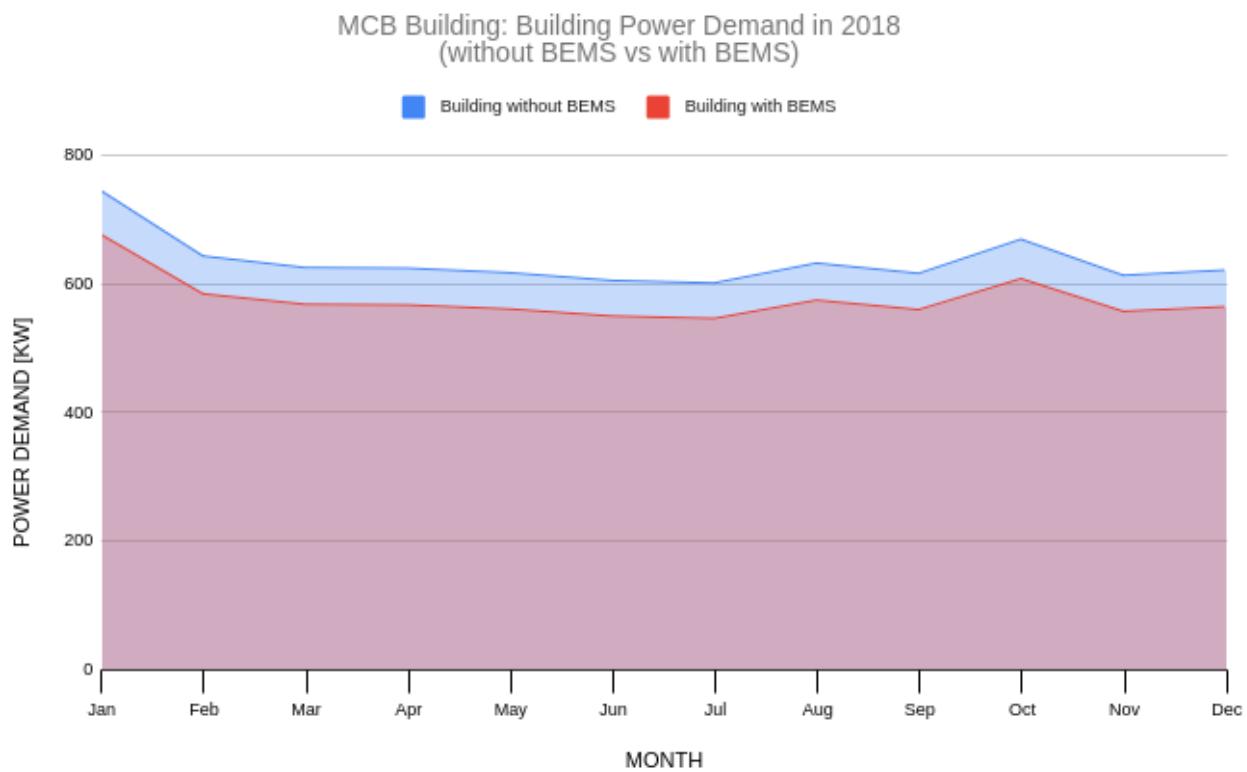


Figure 7.4: Graph of the Monthly Peak Power Demand Comparison between Building without BEMS and Building with BEMS: Molecular and Cell Biology Building (Academic building).

From the simulation results, the cost saving is calculated in the same manner as in Chapter 6. It can be observed that the implementation of the Building Energy Management System (BEMS) would result in a significant reduction in total energy costs, with a possibility of achieving a yearly saving of R 803,199.98. This corresponds to a percentage cost saving of approximately **20.10%** when comparing the total energy costs before and after BEMS.

7.3. Conclusion

Month	Energy Usage before BEMS (kWh)	Total Energy Cost before BEMS (R)	Cost Per kWh (R/kWh)	Energy Usage after BEMS (kWh)	Total Energy Cost after BEMS (R)	Cost Saving (R)
Jan	324970	292527	0.9002	270532.24	243523.97	49003.03
Feb	299991	273279	0.9110	238796.86	217533.75	55745.25
Mar	317117	278708	0.8789	244196.15	214619.28	64088.72
Apr	310175	272556	0.8787	255235.33	224279.59	48276.41
May	304627	266878	0.8761	242680.76	212608.06	54269.94
Jun	300494	401813	1.3372	231003.13	308891.57	92921.43
Jul	297216	463786	1.5604	244314.19	381236.21	82549.79
Aug	318460	499850	1.5096	253700.80	398204.94	101645.06
Sep	305080	303615	0.9952	230461.32	229354.64	74260.36
Oct	315812	324340	1.0270	262908.36	270007.78	54332.22
Nov	304187	307490	1.0109	242270.36	244901.04	62588.96
Dec	312396	310027	0.9924	248391.83	246508.19	63518.81
Total	3710525	3994869	12.9375	2964491.34	3191669.02	803199.98

Table 7.5: Energy Usage, Cost, and Savings before and after BEMS (Academic Building)

7.3 Conclusion

In this building, the analysis of energy usage, peak power demand, and cost savings associated with the implementation of the Building Energy Management System (BEMS) reveals substantial benefits for building operations. The data consistently demonstrated a reduction in energy consumption across the monitored months, indicating that BEMS effectively optimizes energy usage and minimizes energy wastage. This efficiency not only leads to lower operational costs but also enhances the building's sustainability.

Chapter 8

Analysis of Results: Otto Beit Building (Office building)

8.1 Introduction

The figures in this section illustrate a detailed analysis of the energy and power demand changes before and after BEMS implementation. The data visualized through the OpenStudio/EnergyPlus software allows for a comparative evaluation of the system's impact on energy efficiency.

8.1.1 Energy Savings Analysis : Model

The results from the simulation are analysed to determine the relationship between values prior and post implementation of the BEMS.

Month	Model without BEMS (kWh)	Model with BEMS (kWh)	% Reduction
Jan	126495	98427.62	28.52%
Feb	111806.25	87019.41	28.48%
Mar	125073.41	97838.36	27.84%
Apr	123675.66	98539.91	25.51%
May	137761.56	110906.92	24.21%
Jun	137821.73	112828.28	22.15%
Jul	144087.38	118320.61	21.78%
Aug	143120.68	116389.47	22.97%
Sep	127303.43	103170.59	23.39%
Oct	134553.13	107398.19	25.28%
Nov	124284.71	97779.53	27.11%
Dec	120662.99	94389.91	27.83%

Table 8.1: Monthly Energy Consumption Comparison between Model without BEMS and Model with BEMS: Molecular and Cell Biology Building (Academic building)

8.1.2 Energy Savings Analysis : Actual Building

The figures above, comparing the building's energy consumption with and without the Building Energy Management System (BEMS) reveal a clear trend of reduced energy usage following the system's implementation. In nearly all months, the building with BEMS consistently consumes less energy than

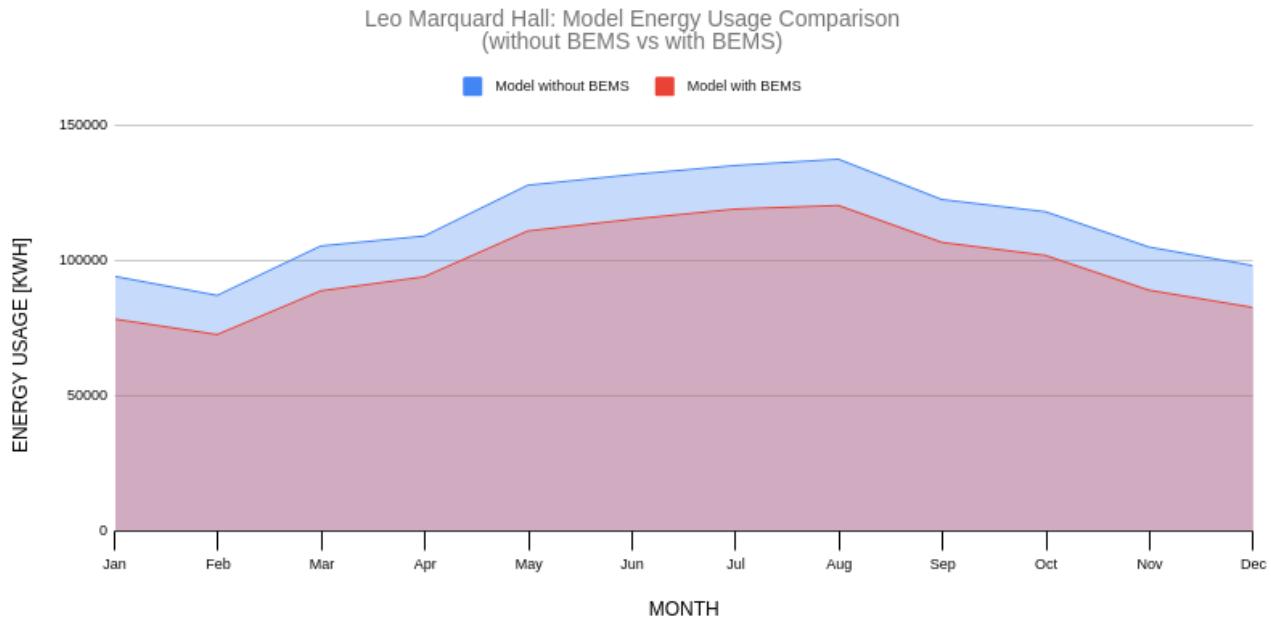


Figure 8.1: Graph of the Monthly Energy Consumption Comparison between Model without BEMS and Model with BEMS: Otto Beit Building (Office Building).

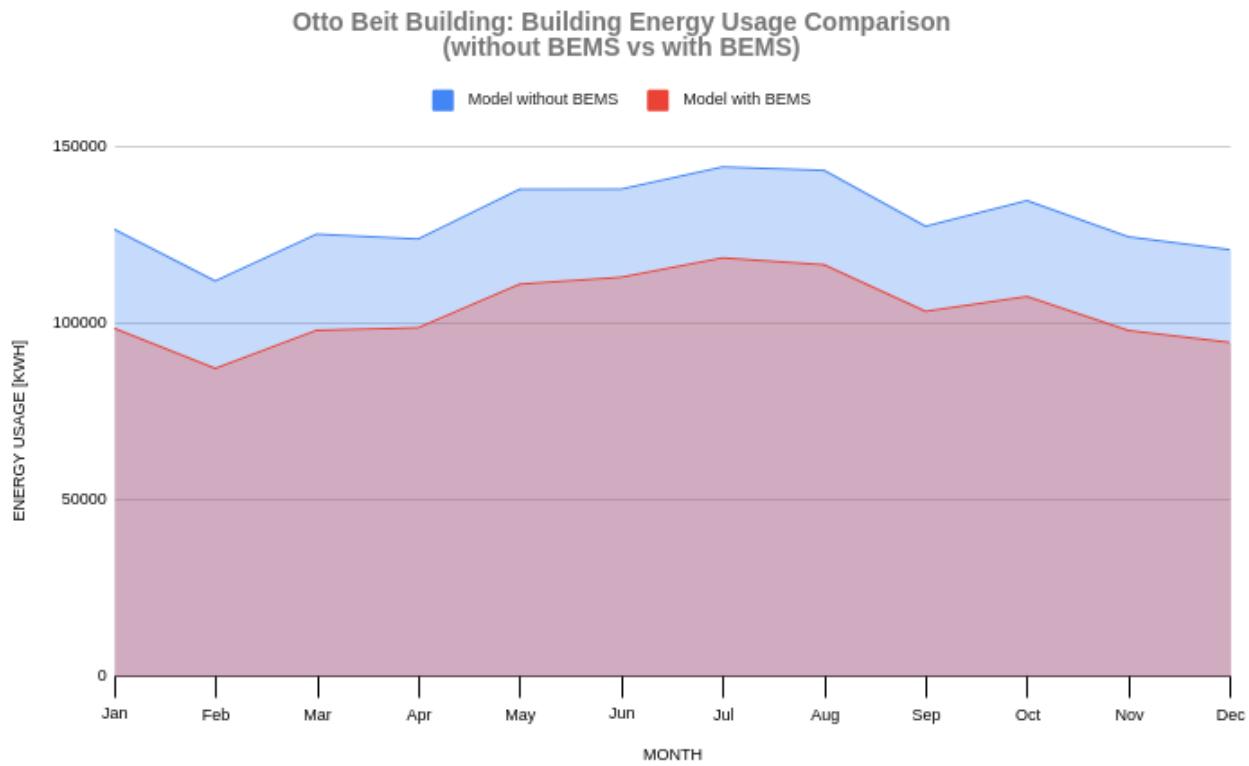


Figure 8.2: Graph of the Monthly Energy Consumption Comparison between Building without BEMS and Building with BEMS: Otto Beit Building (Office Building).

without it. This reduction signifies that the BEMS has successfully optimized the building's energy usage, leading to more efficient operations and reduced wastage.

The implications of this energy savings are significant for both financial and environmental considera-

Month	Building without BEMS (kWh)	Building with BEMS (kWh)
Jan	160231	114539.92
Feb	168800	120718.56
Mar	166892	120434.64
Apr	157657	117441.55
May	175852	133271.77
Jun	177815	138425.85
Jul	182272	142578.49
Aug	205830	158556.95
Sep	189051	144829.70
Oct	200909	150110.45
Nov	201550	146915.67
Dec	146704	105869.49

Table 8.2: Building Energy Data for 2018: Comparison between BEMS and Non-BEMS Systems

tions. Lower energy consumption directly translates into cost savings, contributing to the financial sustainability of the building's operations. Additionally, the reduction in energy usage helps to minimize the building's environmental impact, reducing its carbon footprint and aligning with environmental sustainability goals. This demonstrates the effectiveness of BEMS in enhancing energy efficiency while supporting eco-friendly practices.

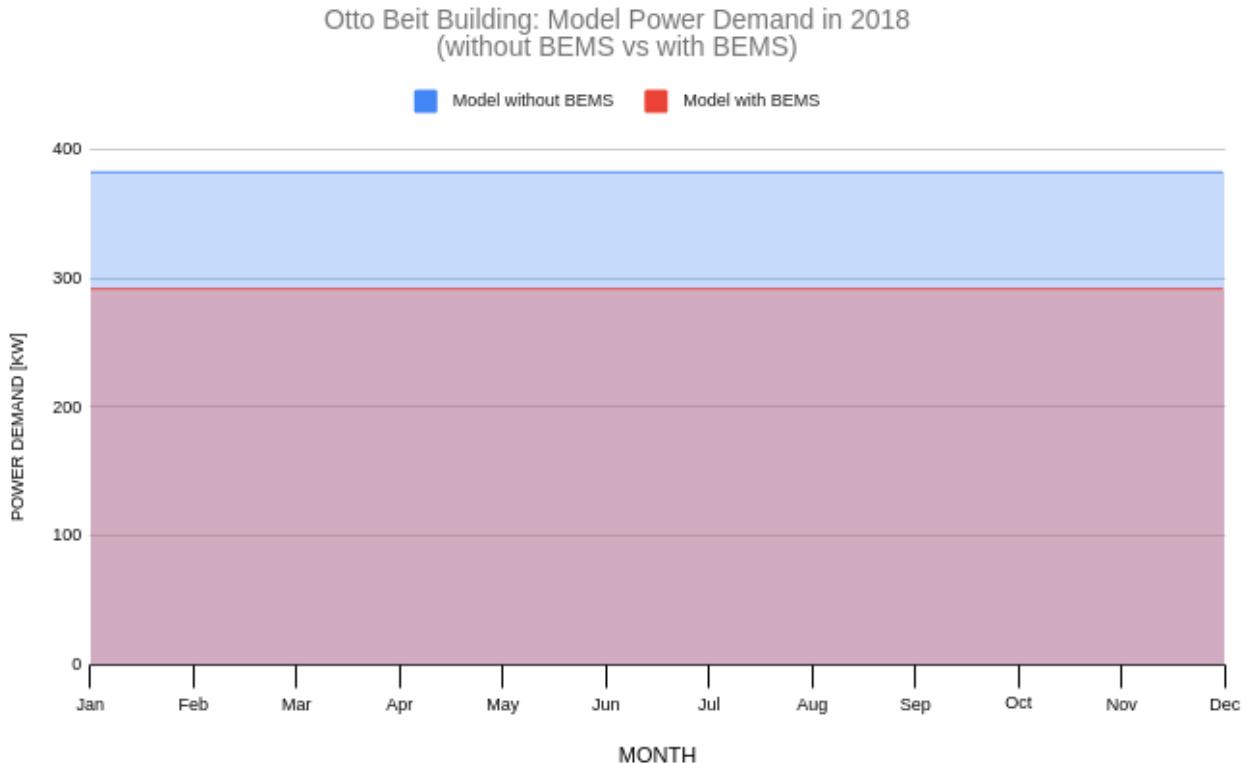
8.1.3 Peak Power Savings Analysis : Model

Month	Model without BEMS (kW)	Model with BEMS (kW)	% Reduction
Jan	381.45	290.81	31.17%
Feb	381.45	290.81	31.17%
Mar	381.45	290.81	31.17%
Apr	381.45	290.81	31.17%
May	381.45	290.81	31.17%
Jun	381.45	290.81	31.17%
Jul	381.45	290.81	31.17%
Aug	381.45	290.81	31.17%
Sep	381.45	290.81	31.17%
Oct	381.45	290.81	31.17%
Nov	381.45	290.81	31.17%
Dec	381.45	290.81	31.17%

Table 8.3: Peak Power Demand with and without BEMS: Molecular and Cell Biology Building (Academic building)

8.1.4 Peak Power Savings Analysis : Actual Building

The figures above, highlight a consistent reduction in peak power demand for the building after the implementation of the Building Energy Management System (BEMS). Across all months, the peak power demand with BEMS is notably lower than without the system. This trend suggests that BEMS effectively reduces the maximum power requirements during peak periods, ensuring more efficient use of electricity throughout the building's operations.



Peak Power Demand Comparison (Model): pre BEMS vs post BEMS] Graph of the Monthly Peak Power Demand Comparison between Model without BEMS and Model with BEMS: Otto Beit Building (Office Building).

From an operational perspective, lower peak power demand results in several key benefits. It reduces strain on the building's electrical infrastructure, potentially extending the life of equipment and reducing the likelihood of system overloads or unexpected outages. Financially, managing peak power demand also helps in minimizing costs, as energy tariffs are often higher during peak periods. This can lead to significant savings in operational expenses, further justifying the investment in BEMS.

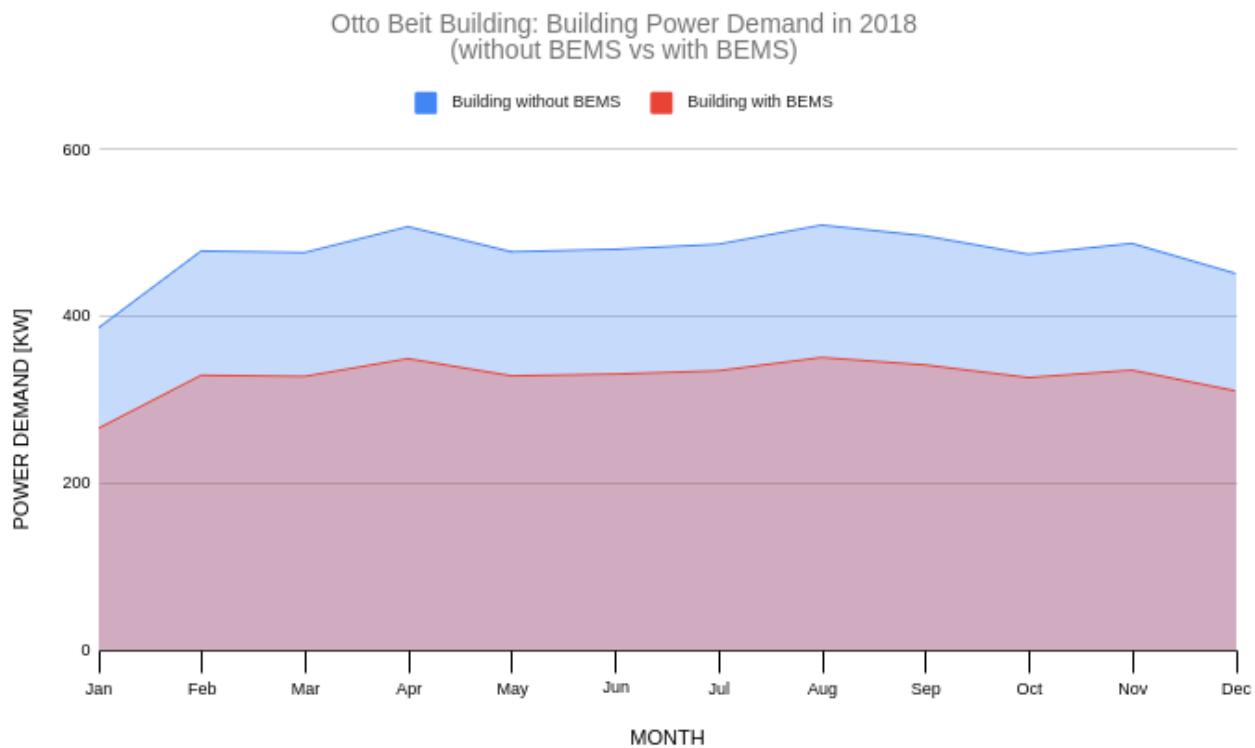
8.2 Cost Savings Analysis

Figure 8.5 presents a comparison of energy usage, energy costs, and cost savings before and after the implementation of a Building Energy Management System (BEMS) in the Otto Beit Building (Office Building). It covers monthly data for the year and illustrates the cost savings per month post implementation of the BEMS.

From the simulation results, the cost saving is calculated in the same manner as in Chapter 6. It can be observed that the implementation of the Building Energy Management System (BEMS) would lead to a substantial reduction in total energy costs, resulting in total savings of R 649,839.77. This represents a percentage cost saving of approximately **24.86%** when comparing the total energy costs before and after BEMS. This significant decrease underscores the financial advantages of utilizing BEMS, demonstrating its efficacy in improving energy efficiency and reducing operational expenses of the building.

Month	Building without BEMS (kW)	Building with BEMS (kW)
Jan	384	264.31
Feb	477	328.33
Mar	475	326.95
Apr	506	348.29
May	476	327.64
Jun	479	329.70
Jul	485	333.83
Aug	508	349.67
Sep	495	340.72
Oct	473	325.57
Nov	486	334.52
Dec	450	309.74

Table 8.4: Peak Power Demand for Buildings with and without BEMS



Peak Power Demand Comparison (Building): pre BEMS vs post BEMS] Graph of the Monthly Peak Power Demand Comparison between Building without BEMS and Building with BEMS: Otto Beit Building (Office Building).

8.3 Conclusion

The results obtained from the simulation and analysis, relating to energy, peak power, and cost savings demonstrate the overall effectiveness of the Building Energy Management System (BEMS). The energy usage results reveal a substantial reduction in energy consumption after BEMS implementation, indicating that the system optimizes the building's energy usage, minimising energy wastage and improving operational efficiency. Similarly, the peak power analysis shows a consistent decrease in peak demand, further contributing to energy optimization and preventing overloading during high-demand

8.3. Conclusion

Month	Energy Usage before BEMS (kWh)	Total Energy Cost before BEMS (R)	Cost Per kWh (R/kWh)	Energy Usage after BEMS (kWh)	Total Energy Cost after BEMS (R)	Cost Saving (R)
Jan	160231	157285	0.9816	114539.92	112433.99	44851.01
Feb	168800	168451	0.9979	120718.56	120468.97	47982.03
Mar	166892	165301	0.9905	120434.64	119286.52	46014.48
Apr	157657	163370	1.0362	117441.55	121697.27	41672.73
May	175852	174020	0.9896	133271.77	131883.36	42136.64
Jun	177815	276448	1.5547	138425.85	215209.90	61238.10
Jul	182272	325827	1.7876	142578.49	254871.40	70955.60
Aug	205830	367636	1.7861	158556.95	283200.91	84435.09
Sep	189051	209699	1.1092	144829.70	160647.89	49051.11
Oct	200909	218543	1.0878	150110.45	163285.81	55257.19
Nov	201550	219273	1.0879	146915.67	150834.48	59438.52
Dec	146704	168162	1.1463	105869.49	121354.73	46807.27
Total	2,133,563	2,614,015	14.5554	1,593,693.04	1,964,175.23	649,839.77

Table 8.5: Energy Usage, Cost, and Savings before and after BEMS

periods.

From a financial perspective, these reductions translate into significant cost savings. Lower energy consumption and reduced peak power demand reduce the building's energy expenses, enhancing its economic sustainability. Additionally, the environmental benefits of decreased energy usage and demand contribute to a smaller carbon footprint, aligning the building's operations with current sustainability goals.

Chapter 9

Feasibility Analysis

9.1 Introduction

This section discusses the feasibility of the implementation of a Building Energy Management System (BEMS) in the respective types of buildings that were studied. The analysis evaluates the technical, economic, and operational feasibility to determine the viability of the BEMS deployment.

9.2 Technical Feasibility

The implementation of a BEMS will necessitate the installation of daylight and temperature sensors, as well as a power control interface for HVAC systems, lighting and equipment. These components will allow for automated toggling based on BEMS logic. The BEMS logic will interpret data from the sensors and adjust equipment settings accordingly to optimize energy consumption. These components can be purchased off the shelf.

9.3 Economic Feasibility

The installation of a basic BEMS can range around €20 per square meter [71], which translates to $\approx R382/m^2$ which a significant total cost based on the building sizes. However, the combined savings from reduced energy consumption can be used to minimise these initial costs with only minimal financial assistance from the institution if the need arises. Assuming consistent savings in the subsequent years, a favorable return on investment (ROI) can be achieved.

9.4 Operational Feasibility

Since the BEMS operates automatically, it requires no human operators, thereby eliminating the need for extensive training. However, the interfacing with various systems may pose challenges. Any malfunctions could significantly disrupt operations, necessitating a reliable and swift maintenance and fault management plan.

Chapter 10

Conclusion

This study began by establishing the need for improved energy efficiency within UCT buildings through the collection of historical energy consumption and energy cost data. Chapter 1 provided the background, research objectives, and significance of the investigation. The problem statement and the proposed approach to address the problem were also discussed.

In Chapter 2 , a literature review revealed existing strategies and technologies for energy management, including the potential of Building Energy Management Systems (BEMS) to optimize energy usage and reduce costs. The relevant software packages to be used for simulating the implementation of a BEMS were also reviewed and compared. Regulatory bodies were also reviewed as well as developmental trend in the study of BEMS. Chapter 3 introduced the theoretical frameworks guiding the BEMS modeling process. These theories, laws and equations enabled a structured approach to understanding energy patterns and led to the formulation of accurate building dynamics which in turn yielded realistic load profiles for the buildings that were modelled. Chapter 4 outlined the methodology, detailing the data collection and simulation processes. Energy data from selected UCT buildings was analysed and used to develop models for predicting energy savings pre- and post-BEMS implementation. The logic flow of the BEMS was also discussed in this chapter.

Simulation results from the OpenStudio/EnergyPlus simulation tool were presented in Chapter 5, where energy usage and power demand trends were identified in the simulate building model before and after the implementation of the BEMS. After the implementation of the BEMS, lower energy usage and a decreased power demand were observed in all buildings when compared to before its implementation. Detailed analyses were conducted for each building in Chapters 6 to Chapter 8. From the the lower energy usage results obtained from the model simulation, similar reductions were mirrored on the real historical data. After determining the unit cost of energy using the historical data, the percentage cost savings were calculated in the residential, academic and office building, and found to be 15.87%, 20.10% , 24.86% respectively which amounted to a collective cost saving of approximately R 1.68 million.

In Chapter 9, a feasibility study evaluated the practical implications of implementing a BEMS across the selected buildings. Technical, economic, and operational factors were considered, demonstrating that BEMS is a viable solution for UCT's energy efficiency challenges. Finally, Chapters 10 and 11 concluded with the key findings and provided recommendations for future improvements. Implementing BEMS in UCT buildings can significantly reduce energy consumption thus improving the energy efficiency of the buildings and also reduce the buildings' operational energy costs thus making UCT a more sustainable institution.

Chapter 11

Recommendations

To further improve the accuracy and impact of this study, the following recommendations are proposed for future consideration.

Incorporating real-time data into future studies would provide more accurate and dynamic insights into energy consumption and peak power demand. Real-time data reflects the building's current operational status, allowing for the identification of inefficiencies and opportunities for energy savings in a timely manner. This approach could enhance the responsiveness of the Building Energy Management System (BEMS), ensuring more effective energy management.

A quantitative environmental impact study is highly recommended to assess the actual environmental benefits of the BEMS implementation. This study would involve collecting concrete data on the reduction of greenhouse gas emissions and other pollutants directly linked to decreased energy usage. Providing measurable environmental data would strengthen the case for BEMS as a tool for sustainability and help fulfill regulatory and environmental obligations.

Allocating additional time and obtaining relevant clearances to access a building's architectural data and electricity tariff information, which is not easily available, would improve the accuracy of the model. Access to such data would allow for better calibration of the simulation models and alignment with real-world energy consumption patterns. Moreover, using more complex statistical models to improve the randomness of occupancy levels and patterns would help simulate more realistic scenarios. This, however, would require both additional time and resources to fully integrate into the model.

Using multiple modeling and simulation software tools is another approach that could enhance the robustness of the study. Comparing results across different platforms ensures consistency and reliability. However, most of these advanced tools require paid licenses or subscriptions, so it is important to evaluate the cost-benefit of acquiring them for future research.

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Appendix A : AI Usage

Latex Table Energy Analysis

October 23, 2024

ⓘ This conversation may reflect the link creator's personalized data, which isn't shared and can meaningfully change how the model responds.

Month	Energy Usage before BEMS (kWh)	Total Energy Cost before BEMS	Cost Per kWh	Energy Usage after BEMS (kWh)	Total Energy Cost after BEMS	Cost Saving (%)
Jan	34970	292527	0.9001661692	270532.2447	243523.97	49001.03
Feb	299991	273279	0.9109573287	238790.8015	217533.75	55743.25
Mar	317117	278708	0.8788806655	244190.1514	214619.28	64088.72
Apr	310175	272256	0.8787160534	255233.3309	224279.59	48276.41
May	304627	266678	0.8760812403	242680.7395	213300.00	34209.54
Jun	300994	401613	1.337174786	231003.1349	308091.37	9321.43
Jul	297216	463786	1.500434102	244314.1916	381236.21	82548.79
Aug	318460	499630	1.569584077	253700.8035	398204.94	101645.06
Sep	303680	303615	0.9951979809	236461.3172	229354.64	74261.36
Oct	315812	324340	1.027003407	262908.3383	270007.78	54332.22
Nov	304187	307490	1.010058452	242270.3599	244901.04	62588.96
Dec	312396	310027	0.9924160763	248391.8295	240308.19	61516.81
Total	3710525	3994869	12.9374726	2964491.343	3191609.02	803199.98

create latex table

ⓘ Here's a LaTeX table formatted with your provided data:

```
\begin{table}[h]
\begin{array}{l}
\begin{array}{l}
\text{\textbackslash documentclass\{article\}} \\
\text{\textbackslash usepackage\{booktabs\}} \\
\\
\text{\textbackslash begin\{document\}} \\
\\
\text{\textbackslash begin\{table\}\{l\}}
\end{array}
\end{array}
```

Instructions

- Copy the code above into a `.tex` file.
- Compile the LaTeX document using a suitable editor (like Overleaf, TeXShop, or TeXworks) to view the table.

Let me know if you need any modifications!

make it smaller

ⓘ To make the LaTeX table smaller, you can use the `\newcolumsize` command to fit the table within a specified width. Here's the updated code:

Continue this conversation

Figure 11.1: AI Prompts and Responses.

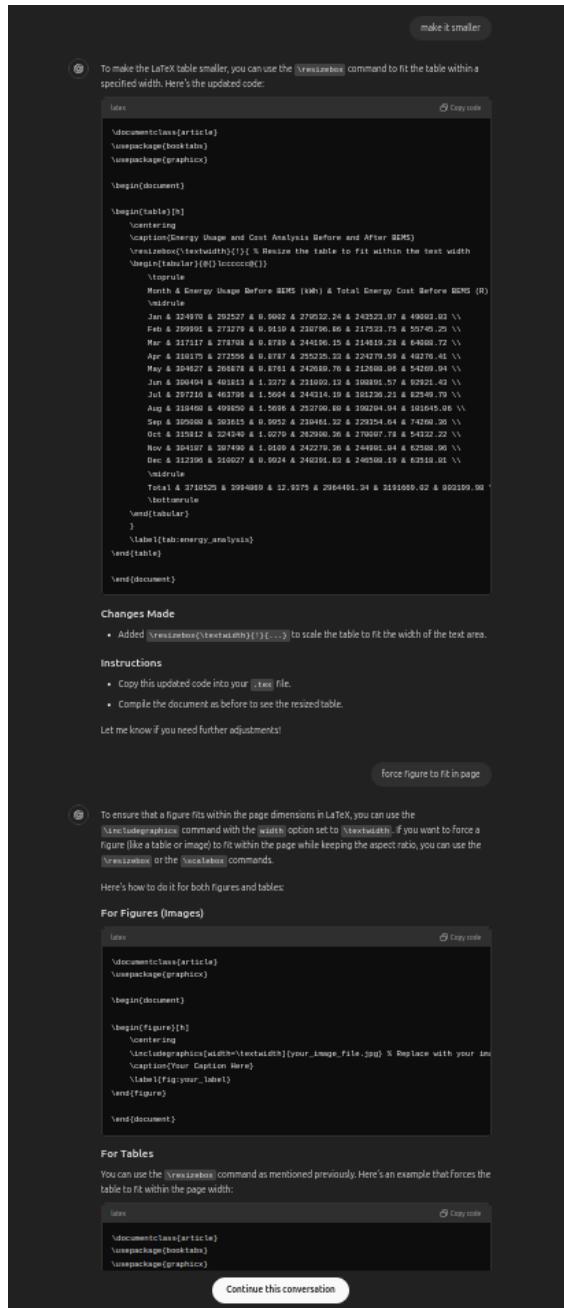


Figure 11.2: AI Prompts and Responses.

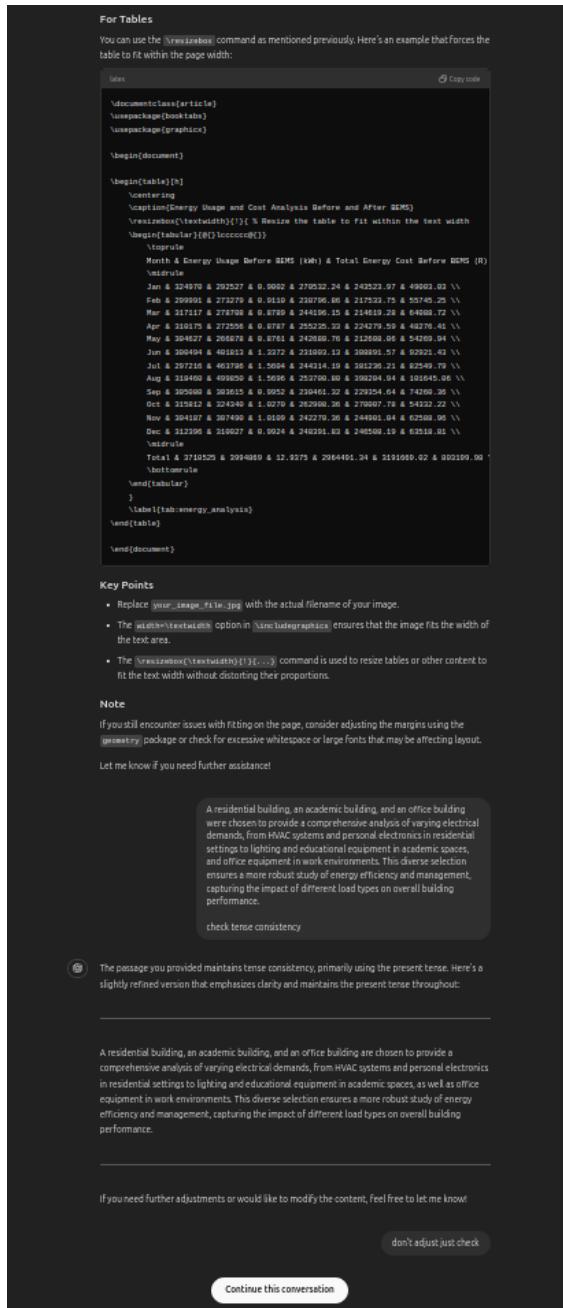


Figure 11.3: AI Prompts and Responses.

The passage you provided maintains tense consistency, primarily using the present tense. Here's a slightly refined version that emphasizes clarity and maintains the present tense throughout:

A residential building, an academic building, and an office building are chosen to provide a comprehensive analysis of varying electrical demands, from HVAC systems and personal electronics in residential settings to lighting and educational equipment in academic spaces, as well as office equipment in work environments. This diverse selection ensures a more robust study of energy efficiency and management, capturing the impact of different load types on overall building performance.

If you need further adjustments or would like to modify the content, feel free to let me know!

don't adjust just check

The original passage maintains consistent tense throughout, primarily in the present tense. Each verb used aligns with this tense, ensuring clarity in the analysis being described. There are no inconsistencies in the tenses used.

If you have any other specific concerns or additional text to check, let me know!

Message ChatGPT

ChatGPT can make mistakes. Check important info.

Figure 11.4: AI Prompts and Responses.

Appendix B : Modelling in OpenStudio

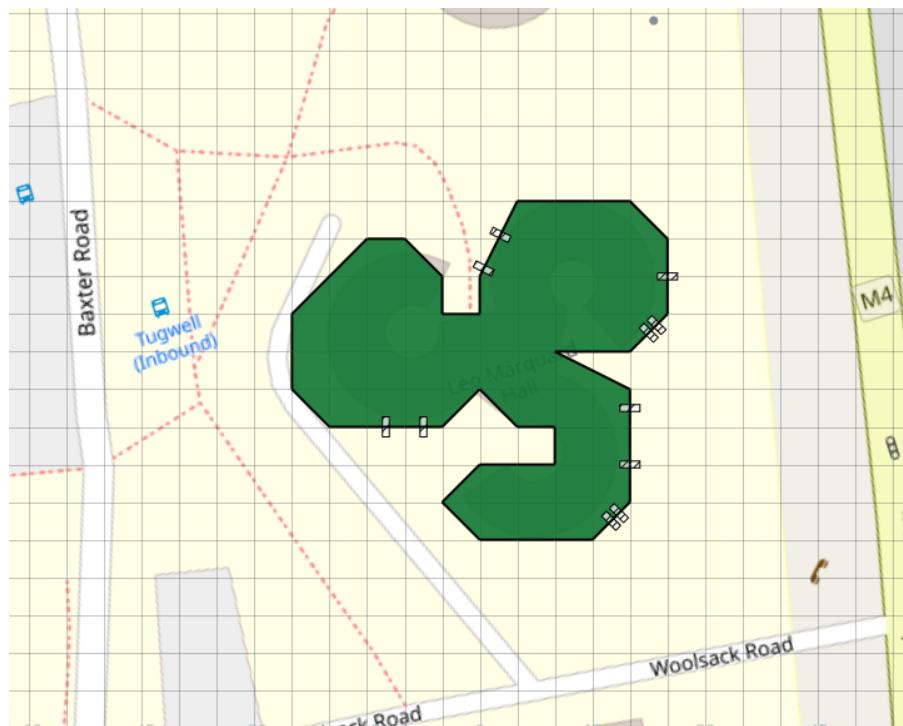


Figure 11.5: Location based Modelling in OpenStudio : Leo Marquad Hall.

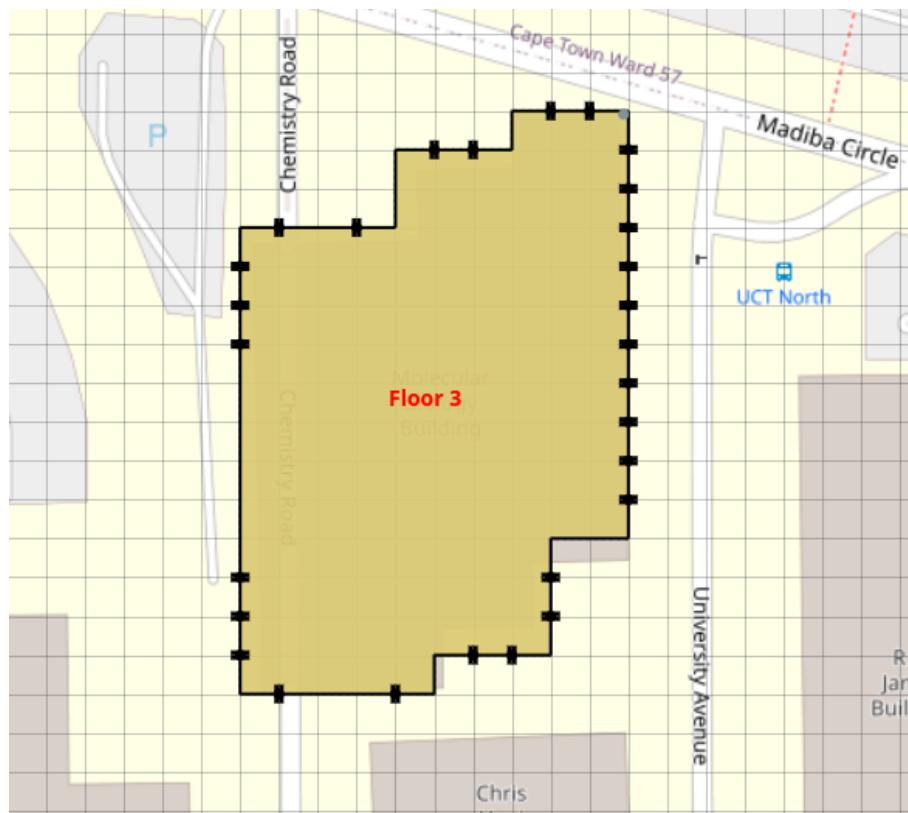


Figure 11.6: Location based Modelling in OpenStudio : MCB Building.

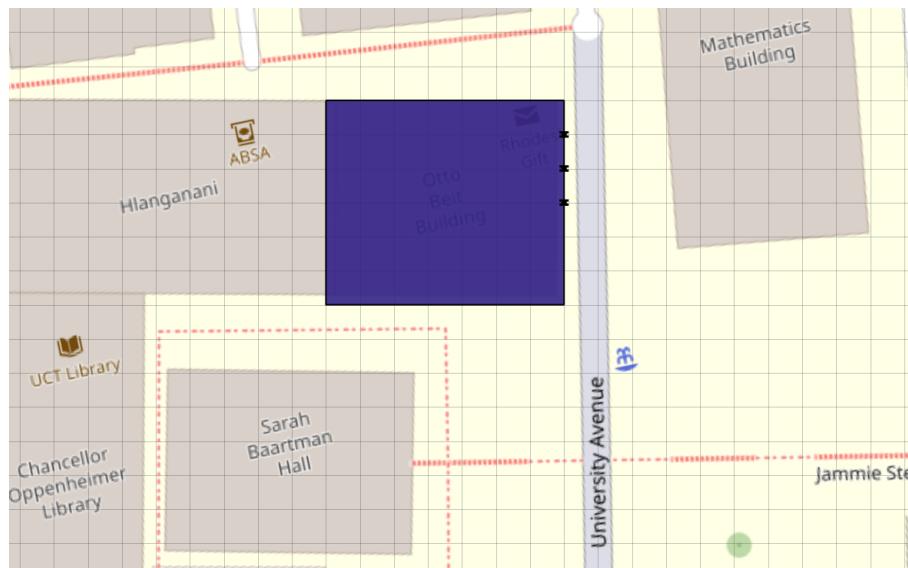


Figure 11.7: Location based Modelling in OpenStudio : Otto Beit Building.

Appendix C : GA Tracking

GA	Student Response (Key Ideas)
GA 1: Problem Solving	Defined the problem of investigating energy efficiency and BEMS at UCT to better manage energy consumption and improve energy efficiency. Researched literature on energy management, load analysis, efficiency certifications and simulation tools. Developed BEMS logic that achieved Energy and cost saving in UCT's context.
GA 4: Investigations, Experiments, and Data Analysis	Conducted a thorough literature review on Energy efficiency in buildings and BEMS implementation. Used UCT's open-source energy data for analysis and independently learned OpenStudio and EnergyPlus to model and experiments on building dynamics. Developed a methodology for evaluating the savings gained from energy management strategies. Used Microsoft Excel to assess pre- and post-BEMS implementation energy usage and drew insights.
GA 5: Use of Engineering Tools	Utilized OpenStudio and EnergyPlus to model building energy performance and to integrated and evaluate the effect of BEMS. Implemented mathematical analyses using these tools to simulate and manage energy usage in the buildings. Leveraged Draw.io and Overleaf for professional reporting and for constructing Flowcharts.
GA 6: Professional and Technical Communication	Created structured reports and presentations using formal, inclusive language to cater to technical and non-technical audiences. Used Overleaf for formatting and professional documentation, ensuring clarity in communication.
GA 8: Individual Working	Managed research independently while ensuring deadlines were met and standards maintained. Regularly communicated with the supervisor for guidance. Demonstrated responsibility in ethical research practices and continuous self-improvement.
GA 9: Independent Learning	Actively researched BEMS and learned OpenStudio and EnergyPlus independently to model energy data. Demonstrated resilience, adaptability, and initiative in complex situations. Modelled a building and integrated a BEMS, addressed uncertainties, and sought supervisor advice when needed. Focused on critical evaluation of BEMS design within time constraints.

Table 11.1: Summary of Graduate Attributes