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Studying the Influential Parameters of an Office Building's Energy Consumption in North America

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by

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Studying the Influential Parameters of an Office Building's Energy Consumption in North America

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I hereby declare that this major research paper incorporates material that is the result of joint research, as follows:

Thesis Chapter	***Details***
Chapter 2	*This major research paper incorporates the outcome of a joint research undertaken under the supervision of Dr. Jacqueline A. Stagner and Dr. David S-K. Ting. In all cases, the key ideas, primary contributions, data analysis and interpretation, were performed by the author, and the contribution of the co-author was primarily through the feedback corrections, improvement of ideas and editing the manuscript.*

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ABSTRACT

The study of building energy consumption has gained immense significance in recent times due to the burgeoning global population and the rapid depletion of energy resources. The present research focuses on analyzing individual parameters that impact building energy usage and devising methods and strategies to reduce energy consumption. An existing office building in Philadelphia was chosen as a reference for simulation in TRNSYS. The factors that affect the building, such as ambient temperature, solar radiation, building envelope, wind speed, and internal gains, were studied and defined according to the existing building standards. Predictive modeling is performed with these inputs for a range of infiltration rates – 0.25 ACH to 0.85 ACH, considering the variability of the parameter. The validated model was subjected to a sensitivity analysis by changing one potential parameter at a time to examine the influence of variation of these parameters on energy usage. The analysis found that the highest energy reduction is executed by replacing double-glazing windows with triple-glazing, with an energy saving of 8.43%. To evaluate the effect of location, a similar sensitivity study is conducted for the same office building in Edmonton and Mexico City. It is found that by replacing the same triple-glazing window with double-glazing, a 12.3% and 5.44% energy saving is achieved for the building in Edmonton and Mexico City, respectively. Henceforth, depending on electricity prices for the respective cities, building in Philadelphia, Edmonton and Mexico City is found to have a monthly savings of $3,133, $7582, and $1,552, respectively (all $ in USD). When considering identical parametric inputs, distinct energy savings are observed across varying locations. These statistics serve as valuable tools for making well-informed and rational decisions regarding investments in energy-efficient technologies and the pursuit of Net Zero energy buildings.

DEDICATION

To my parents, Bhoopal Sreenivasan, Shobana Bhoopal

and my brother Sharath Bhoopal

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CHAPTER I

Introduction

1.1 Background and Motivation

Building energy use has a considerable impact on greenhouse gas (GHG) emissions and global warming. Energy usage in buildings is currently shifting in favor of higher sustainability and energy efficiency. Buildings consume approximately 40% of global energy [1]. This proportion is expected to increase globally with population growth in the next 20 years [2]. A greater understanding of the need to cut back on energy use and GHG emissions in order to mitigate the effects of climate change is driving the current trend. Building regulations and standards are being modified to reflect the increasing usage of energy-efficient building design, HVAC (Heating Ventilation and Air Conditioning) systems, lighting, and building automation systems. The International Energy Agency (IEA) estimates that the building sector was responsible for 10.9 Gt CO_2 emissions in 2020, which is equal to the European Union's entire yearly CO_2 emissions [3]. Most of these emissions are caused by heating, cooling, and lighting, all of which are connected to how much energy is used in buildings. Furthermore, it is anticipated that the need for energy in buildings will continue to climb, with a 50% increase in energy consumption in the construction industry predicted for the year 2050 [4]. Given that new building development will continue to rise, especially in emerging economies, this tendency is especially alarming. Buildings use a lot of energy because of a number of things, including inefficient building design, old technology, and poor maintenance. However, via renovations and the adoption of energy-efficient technologies, it is possible to lower energy use and GHG emissions in buildings. Studies have shown that energy use and greenhouse gas emissions can be greatly reduced by upgrading existing buildings. According to a study conducted by Nadel and Ungar [5] in the American Council for an Energy-Efficient Economy (ACEEE), upgrading commercial buildings in the US could cut energy use by 50% by 2050.

In 2018, the US Energy Information Administration (EIA) estimates that the energy consumption in commercial buildings, including office buildings, was about 7% of the primary energy consumption [6,7]. The commercial building sector in the United States accounts for 1995 GWh (per square meter) of total energy in 2018 [8]. Among the commercial buildings illustrated in Figure 1.1, office buildings have the highest energy consumption, consuming approximately 300 GWh (in total) with 75% electricity and 25% natural gas [9]. Thus, the importance of discussing the nuances of office building's energy consumption should not be underestimated.

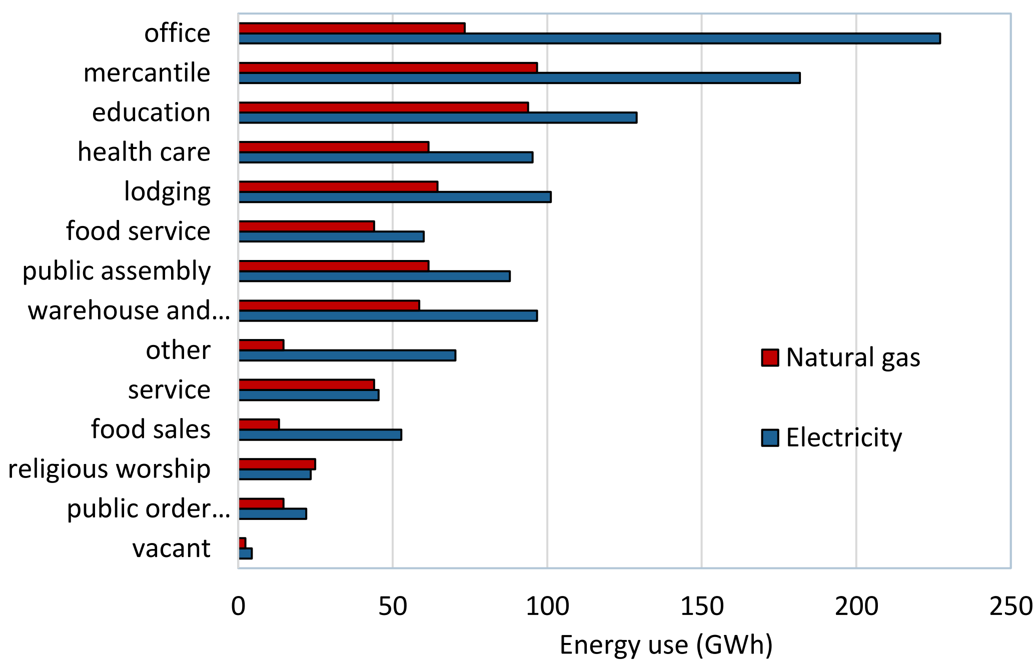

Figure 1.1. Types of commercial buildings and their energy usage in US for the year of 2018, based on [9].

The energy consumption from office buildings is mostly caused by the requirement for ventilation, lighting, heating, and cooling systems to keep occupants comfortable inside. Retrofits and energy-efficient technology can dramatically lower energy use and greenhouse gas emissions in office buildings. For instance, the US Department of Energy estimated that energy-efficient lighting solutions can reduce lighting energy usage in buildings by up to 75% [10]. Additionally, the Leadership in Energy and Environmental Design (LEED) certification program for commercial buildings, run by the US Green Building Council, has been effective in promoting sustainable and energy-efficient practices in office buildings [11]. The United States Green Building Council (USGBC) declared that it had recertified more than one billion square feet of commercial green building space under LEED [12].

The office building industry, in particular, is responsible for a sizeable amount of energy consumption and GHG emissions. But these buildings' energy consumption and GHG emissions can be significantly reduced with retrofitting and energy-efficient equipment. To lessen the negative effects of climate change, it is essential to keep developing and putting into practice sustainable building techniques given the expected rise in world population and energy consumption.

This major paper model’s an office building located in the United States using TRNSYS software with the aim of determining the influential parameters and varying the parameters to check for energy reduction. Modern software tools have significantly improved the ability to model an existing building with decent accuracy, regardless of when the building was constructed. Modern architects and engineers can generate building models that include specific details about the physical qualities of the structure, such as its geometry, materials, and thermal properties, thanks to the development of cutting-edge software like TRNSYS, Energy Plus, and others. These technologies estimate the building's energy performance using complex algorithms and modeling approaches, taking into consideration a number of variables including weather patterns, internal gains, and building envelope. This lets users analyze the effects of various design choices, materials, and equipment on the building's energy performance and simulate various scenarios, allowing for the optimization of energy efficiency while minimizing the building's overall environmental impact. For example, Colmenar-Santos et al. [13] achieved 30% energy savings in an office building by using optimization techniques with energy modelling software. TRNSYS can be applied to both new and old buildings, which is very advantageous for retrofitting projects. Designers and engineers may replicate the energy performance of an existing building using modelling software, find places where energy can be saved, and choose the best retrofit options. This strategy enables building managers and owners to decide which retrofit options to select, optimizing energy efficiency and lowering the overall carbon footprint of the structure. TRNSYS is utilized in this major paper to calibrate energy data, since it assures that the simulation model is based on actual data, in order to predict the energy consumption of a building with minor errors. Some of the advantages of TRNSYS over other energy simulation tools are: (1) TRNSYS consists of a wide range of components that can be added as a retrofit to the existing building like water heating facility, PV panels, HVAC systems, etc. (2) It has built-in weather information for various locations that is averaged over the past twenty years called Typical Meteorological Year (TMY) data. (3) TRNSYS is integrated with multiple software tools for physical modeling, which can be imported using idf file format. TRNSYS is currently extensively used as energy simulation software, given its user-friendly interface [14-18]. However, the reliability and validity of the software is checked in this paper based on real data.

1.2 Objectives and Scope

This work develops a comprehensive modeling approach for analyzing the energy usage of buildings and assesses the various factors that influence it. Furthermore, it introduces the location parameter in calculating the energy consumption, and the effect it has on the sensitivity study. The primary objectives of this major paper are as follows: (a) predictive modeling of an office building situated in Philadelphia using TRNSYS energy simulation, (b) perform sensitivity analysis for energy consumption by systematically varying one parameter at a time, (c) analyzing the effect of different climate locations on the energy consumption. A brief outline of this paper is given below based on chapters.

Chapter I: Introduction

This chapter delves into the fundamental context and driving forces behind this significant paper, emphasizing the criticality of energy conservation in commercial buildings. It also provides an extensive literature review, exploring the key parameters utilized in this study. Furthermore, the chapter elucidates the core aspects of the paper, including its objectives, scope, and research questions. Ultimately, the chapter concludes by identifying the research gap and highlighting the unique contributions made by this paper.

Chapter II: Identifying Key Parameters Affecting Building Energy Consumption to Achieve Modeling Prediction.

This chapter goes into extensive detail about the factors that could have an impact on how much energy a building of offices uses. The building's energy efficiency can be increased, and energy use can be decreased by comprehending and analyzing these aspects. Some of the key factors covered are ambient temperature, solar radiation, infiltration, ventilation, ground temperature, windows, building walls, lighting, equipment, and occupancy. The thermal mass delay in the building envelope is demonstrated using TRNSYS. Predictive Modeling is covered in detail by assigning parameters that are similar to actual data from the existing building.

Chapter III: Conducting Sensitivity Study by Incorporating Location: Analyzing Parameter Variations and Their Impact.

This chapter presents a sensitivity analysis of building energy consumption, wherein each potential parameter is varied individually while maintaining upper and lower limits based on factors such as location, statistics, and building standards and codes. To study the influence of climatic location on building energy consumption, two distinct locations are selected, which are north (Edmonton) and south (Mexico City) of the actual building.

Chapter IV: Conclusions and Recommendations

This chapter synthesizes the findings of the major paper and provides recommendations for future work.

This paper aims to answer the following research questions: (a) Can the simulation model in TRNSYS be deemed reliable for conducting sensitivity study? (b) Which potential parameters have the most significant impact on the energy consumption of an office building? (c) How does the impact of these parameters change by moving the location of the building?

To answer the study's research questions, a building model with an energy simulation was created using TRNSYS software. The main goal of this study is to conduct a sensitivity analysis of the parameters to find the most influential factor affecting energy consumption. These values are then compared with energy values after changing the building location to Edmonton and Mexico City. It should be highlighted that the scope of this study is limited to office buildings in North America. This limitation was implemented to assure the validity and reliability of the research results by concentrating on a specific building type in a particular geographic area. Future study can be carried out to offer a more thorough review of the effects of building retrofits on various building types. The simulation, for instance, can be expanded to include additional sites, with the parameters changed appropriately. The study can also be expanded to encompass a greater variety of building types, such as residential homes, industries, etc. It is important to recall that the suggested research objectives and limitations are meant to guarantee the validity and rigor of the study. The research findings can be more reliable and representative by concentrating on a specific building type in a particular region. Furthermore, additional locations and building types can be investigated in future studies to broaden the scope of the research.

1.3 Literature Review

1.3.1 Ambient Temperature

The building's HVAC systems, which oversee preserving indoor comfort, have a significant impact on the relationship between ambient temperature and energy usage. During hot weather conditions, the increased ambient temperature has a direct impact on the cooling load leading to higher energy consumption. Similarly for cold conditions, the heating system will be functioning to compensate for the drop in ambient temperature. The amount of cooling and heating load depends on many factors like location of the building, structure of the building, wind speed, building envelope, etc. Radhi [19] performed an analysis in which Radhi found that by increasing the average ambient temperature in Al-Ain city by 5.9°C, there is an increase in the cooling load by 23.5%. Radhi [19] also discussed the implementation of energy saving strategies demonstrating that by improving the insulation and window design of the building the energy savings are observed to be 13%-15% and 6.8%-8.1%, respectively. Hoyt et al [20] modified the indoor temperature and found considerable energy savings by adjusting the cooling and heating setpoints. They observed that it is possible to achieve up to 73% energy savings depending on the outdoor temperature conditions.

Ambient temperature, in general, is sinusoidal in nature, fluctuating between day and night with a time period of one day. The maximum temperature occurs after local noon, called diurnal maximum, and the minimum temperature occurs before sunrise, called diurnal minimum. However, the peak timings will tend to differ with the location, seasons, and other climatic parameters [21,22]. Figure 1.2 shows the ambient temperature behavior patterns of Philadelphia and Mexico City taken from NSRDB data [23] for 3 days (72 hours). The difference in the diurnal timings for each cycle can be observed along with differences in the ambient temperatures between the two locations, giving us a small picture of how different locations affect the building. This sinusoidal pattern influences the building's power consumption when variations are recorded with a time step of one hour or less [24].

It is clear that the ambient temperature varies continuously, unlike the indoor setpoint temperatures, which are maintained constant. This difference in temperatures between outside and inside will lead to convective and conductive heat transfer involving the outside air, building walls, and inside air. The transient heat transfer mechanism in this paper is demonstrated by the transfer function relations by Mitalas and Areseneault [25], which is explained in detail in the Methodology section of Chapter 3.

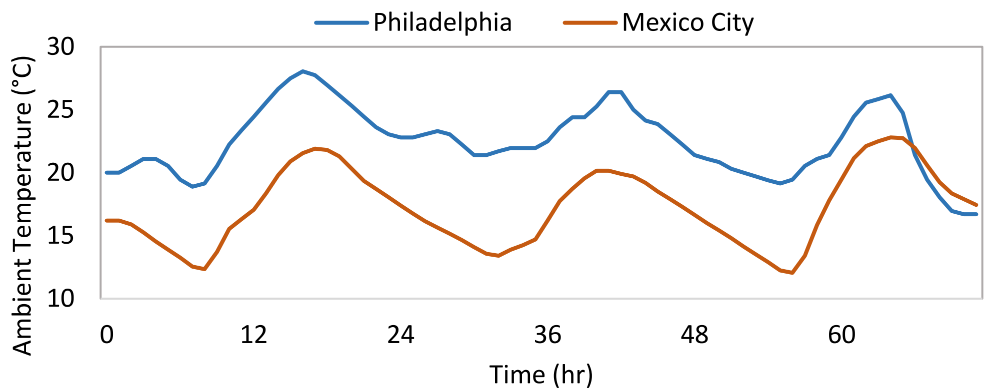

Figure 1.2. Weather data for Philadelphia and Mexico City.

From this literature review, it is clear that ambient temperature varies sinusoidally and greatly depends on the location of the building. Therefore, this literature places a strong emphasis on location being a key factor in building energy efficiency.

1.3.2 Solar Radiation

It is essential to comprehend how solar radiation affects a building's performance in order to develop sustainable and energy-efficient workplace spaces. In order to maintain a suitable indoor environment, air conditioning systems must be used to reduce the amount of solar heat gain that enters the structure through windows, walls, and roofs. Several solar radiation models are frequently employed to determine the amount of solar radiation that enters a structure. Based on variables including geographic location, season, weather, and building orientation, these models calculate the amount of solar radiation. Kim et al. [26] used three radiation models to calculate solar radiation in an office building and compared with the measured results for reliability. Depending on the accuracy, two models are used for low SHGC and WWR, while the final model is used for a high SGHC (Solar Heat Gain Coefficient) and WWR (Window-Wall Ratio) on a building. These solar radiation models estimate the amount of solar radiation incident on a building at a given location and time. There is much literature on the topic of estimating solar radiation, where a suitable model is preferred according to the building conditions [27-31].

Building energy use is significantly influenced by solar radiation, which affects both cooling and lighting requirements. Solar radiation, particularly in areas with hot temperatures, contributes to the cooling load of the structure. The surfaces of the building, including the roof, the walls, and the windows, are heated by sunlight as it enters the structure, raising the inside temperature. Because of the increase in temperature, mechanical cooling equipment like air conditioners must be used, which increases energy demand [32-34]. Vlachokostas and Madamopoulos [35] studied an indirect relation between the cooling energy demand and the direct normal irradiance and diffuse horizontal irradiance (DNI and DHI, respectively) entering the building.

Solar radiation incident on the wall is in the form of three components: beam incident radiation, diffuse incident radiation, and ground reflecting radiation. The total incident radiation is the summation of these three incident radiation components, as shown in the following equation [36]:

$$G_t = R_B\, G_B + G_D \left[\frac{1+\cos\beta}{2}\right] + (G_B + G_D)\rho_G \left[\frac{1-\cos\beta}{2}\right] \tag{1}$$

where R_B is the radiation tilt factor, G_B is the beam radiation for a horizontal surface, G_D is the diffuse radiation for a horizontal surface, β is the tilt angle, and ρ_G is the ground albedo. This total incident solar radiation is accessible in the weather data files from the available weather stations.

The planning and execution of a building's exterior is essential for reducing energy usage. The effects of solar radiation can be controlled by including insulation, energy-efficient windows, and efficient shading elements like overhangs or blinds. Significant literature has been covered on introducing new retrofits on the building envelope and recording its heating and cooling energy savings [37-41]. Well-insulated walls, windows, and roofs restrict solar heat input and heat transmission, which lowers the cooling demand.

To summarize, solar radiation has a major impact on buildings, especially in hot and humid climates. The solar gain entering buildings via the windows, walls, and roof affects the indoor cooling load. This research emphasizes the need to consider building location when studying energy consumption trends, particularly in connection to solar heat gain. Vlachokostas and Madamopoulos [35] achieved considerable energy savings of up to 37% for a certain building orientation by altering the DNI and DHI values. This literature emphasizes the significant influence of changing the location of a building on overall energy consumption, emphasizing the need of location-specific considerations for energy-efficient design.

1.3.3 Infiltration and Exfiltration

Infiltration and exfiltration in buildings is the uncontrolled entry and exit of air, respectively, from a structure through openings, cracks, and gaps in the building envelope. Infiltration occurs due to pressure fluctuations between the interior and exterior of the building, caused by variables like wind, temperature variations, and HVAC systems [42]. Henceforth, in locations where the wind and temperature fluctuations are high, elevated infiltration rates can be observed for the same building design. Dai and Chen [43] experimentally proved that there is a positive impact of infiltration rate with the wind speed, however, no direct relation can be observed between both. Infiltration rate (α; h^{-1}) can be obtained by [44]:

$$\alpha = \frac{Q}{3600V_i} \tag{2}$$

where Q is the airflow rate (m^3/s) and V_i is the volume of the indoor space unit (m^3). To obtain the airflow rate, the following equation can be used:

$$Q = \frac{A_{ELA}C_D}{10000}\sqrt{\frac{2\Delta P}{\rho}} \tag{3}$$

where C_D is the discharge coefficient (unitless), A_{ELA} is the air leakage area (m^2), ΔP is the pressure difference due to wind speed (Pa), and ρ is the density of air (kg/m^3).

Building design plays a major role in altering the infiltration rates. Wind patterns surrounding and inside a structure are influenced by its general building design. Areas of high and low pressure can be produced by tall structures or structures with complicated designs, which can increase or reduce infiltration rates. Controlling infiltration requires considerable attention to the materials and design of a building envelope. Envelopes that are properly insulated and sealed decrease the likelihood of air leakage, which lowers infiltration [45-47].

The contribution of infiltration gain is noticeably high, ranging from 10%-35% of the total heat gain [48]. Infiltration rates can be minimized by managing the airtightness of a building, which contributes to energy savings. Almarzouq and Sakhrieh [49] observed that by reducing the infiltration rate by 50% in a residential building, 19.4% energy saving is recorded. Hu et al [50] showed a decrease in cooling load and heating load by 13.54 kWh/m^2 and 7.81 kWh/m^2, respectively, by reducing the infiltration rate by 0.016 h^{-1} for an office building in China.

Controlling infiltration rates is necessary to maintain indoor occupancy comfort and ensure energy efficiency. This can be achieved by using appropriate building design, construction, and maintenance techniques. Furthermore, wind speed varies based on location, with colder regions experiencing higher wind speeds, and warmer regions experiencing lower wind speeds, due to temperature gradients. Thus, the geographical location of the building is crucial in analyzing the variation of infiltration rate.

1.3.4 Building Envelope

Building envelope describes the building’s exterior, which includes walls, roof, windows, and doors. The building's construction and design directly affect how heat is transmitted between indoors and outdoors. Building envelopes is a wide topic of research with several articles and findings in its name. Different types of envelopes, such as thermal insulation, PCM, PV panels, etc., are utilized for vertical walls (and roofs) with the intention of conserving energy [51-53].

1.3.4.1 Opaque walls

Numerous studies have investigated the integration of retrofits into the existing building envelope to assess potential energy-saving benefits. This literature review highlights key research articles that contribute significantly to the subject matter. Atmaca et al [54] worked on achieving an optimized building envelope for a Mosque building and found an energy saving of 33% by implementing thermal insulation on roofs and vertical walls. Al-Shamrani et al [55] worked on concrete, masonry, steel, and wooden building envelopes and found an energy saving up to 32% in total energy consumption. Similarly, Al-Nuaimi and AlMadani [56] established that plywood is the best inner layer for domestic buildings in Bahrain, which shows a reduction in energy consumption by 8%. However, thermal insulation is the most common type of retrofit integrated with building envelopes for reducing energy consumption. Fang et al [57] investigated the effects of building envelope insulation on an experimental chamber and compared it with a basic envelope used in residential buildings. They found that the insulation envelope was less affected by the outdoor conditions and consumes less energy, with a savings of 23.5% for the same indoor thermal comfort. Hassan and Al-Ashwal [58] found that by providing exterior wall insulation, a reduction in peak cooling load is achieved by 29%. Cheung et al [59] discussed six different scenarios for a building envelope on a high-rise apartment and achieved an energy savings of 31.4% in yearly cooling load and 36.8% in the peak cooling load.

1.3.4.2 Windows

Glass window is a common and important type of building envelope that is used in all types of buildings mainly for daylight illuminance and aesthetic view factor. Window-Wall Ratio (WWR) is a common term used, that can be changed in building models intending to obtain a considerable energy saving. Since this value depends on the location of the building, orientation, building type etc., many articles tried this method and proposed various strategies to improve energy efficiency [60-63]. Hassan and Al-Ashwal [58] replaced a single clear glass with a double-glazing low-emissivity glass to attain annual energy savings up to 19%. Bojic et al [64] conducted a thorough analysis of three distinct window scenarios within an apartment setting. In the first case, they replaced a single clear glass window with a more energy-efficient option featuring a lower shading coefficient. The second case involved comparing the glass windows of two separate units with different window orientations. Lastly, they replaced a single clear glass window facing west with a tinted, reflective glazing window oriented towards the south. By implementing these scenarios, a considerable decrease in annual cooling load is observed for the first, second and third case by 10%, 7%, and 13%, respectively.

When these building envelopes are discussed, it is equally important to examine the life-cycle cost analysis for the retrofits to check for feasibility in the current market [65-68]. From this literature review, it can be inferred that it is primarily important to consider building envelopes as an influential factor in a building. In addition, we can also observe that the selection of these envelope designs depends on the building type, location, and orientation of the building. In this paper, we use windows and vertical walls as potential parameters to conduct the sensitivity analysis for energy consumption. This can be used to evaluate the building envelope options available in the commercial market and the amount of energy savings.

1.3.5 Internal Heat Gains: Lighting, Equipment and Occupancy

Lighting is a type of building retrofit that involves replacing or modifying existing lighting systems in order to improve energy efficiency and create a more pleasant and visually engaging indoor environment. Older fluorescent lights and incandescent bulbs, which consume more energy and are less effective than contemporary lighting solutions, are still used in many older buildings. Building owners and managers may lower their energy expenses and support environmental sustainability by implementing a lighting upgrade. According to Energy Information Administration (EIA), in the United States, lighting accounts for 4% of the total electricity used in commercial buildings [69]. Many different lighting options are utilized to save energy like daylight sensing technology, tracking movements of individuals, and hearing sensors [70]. Ciobanu and Pentiuc [71] replaced the old lighting system with LED luminaire which is 81.5% more efficient to find that there is an increase in energy efficiency by 44.21%. However, it is highly recommended for the occupants to override the automatic lighting schedule whenever possible to save energy. This combination of computerized lighting and manual switch on and off technique is found to work effectively, to achieve considerable energy savings [72].

Computers, printers, copiers, monitors, servers, and other office machinery are just a few examples of electrical and electronic devices that are used regularly in modern office environments. The heat released from the electrical consumption of the equipment in office spaces should not be overlooked. According to Chartered Institution of Building Services Engineers (CIBSE) [73], the sensible heat gains of office equipment in use like PCs, printers, and kettles is given by 113 W, 88 W, and 12 W, respectively. Thus, for office buildings with multiple stories, with several PCs and printers, the amount of heat gained from the systems can be substantial. However, there are numerous methodologies and research articles published on controlling the heat gain from the computer equipment in office spaces. For example, Wei et al [74] achieved up to 19% energy savings by proposing an optimized setting to the existing one with the help of deep learning method. Wang et al [75] introduced cost-effective measures in an office building, and by adjusting the improper equipment settings and installation, achieved an energy saving of 10% of the baseline energy consumed.

Finally, occupancy heat gain is a potential parameter to be considered in the sensitivity analysis, as it contributes considerable heat inside office spaces. Heat produced by inhabitants causes the interior temperature to rise, particularly in highly inhabited locations or during peak occupancy hours. In order to maintain a pleasant temperature, the cooling system must work harder, which increases the amount of energy used for air conditioning. According to chapter 18 of ASHRAE fundamentals, the total heat gain from one human in an office space environment is 140 W [76]. Thus, the total heat gain in the office depends on the total number of people present inside the room.

Several other parameters influence the energy consumption of buildings. Some of the key factors include ground temperature, ventilation, and heat transfer coefficient. Despite their importance, these variables were not considered in the current sensitivity study because of the following reasons:

1. The ground temperature model is defined in the methodology section, and it is found to vary with ambient temperature. Therefore, it is not used as another potential parameter for the analysis.
2. The model used for infiltration and ventilation are similar in TRNSYS; hence the ventilation parameter is kept constant for the study.
3. Regarding the heat transfer coefficient, it was determined to have a linear correlation with wind speed, as described in Equation 6 in Chapter 2. To simplify the analysis, the values for the heat transfer coefficient were calculated for each month and kept constant throughout that respective month.

Summarizing the literature review on internal heat gains, it is clear that the amount of energy consumed, and the amount of energy saved is abundant compared to the total energy usage. Thus, it is crucial to include these parameters in this study.

1.3.6 Literature Gap

The literature review strongly emphasizes that the geographical location of a building is a crucial factor that requires significant attention. This is because the building's major energy contributors – ambient temperature and solar radiation, depend solely on the location of the building [19,20,35]. Extensive research was done to find an optimal location for a specific type of commercial building with the aim of reducing energy consumption [77-79]. Renuka et al [80] modified the location and orientation of a residential building in India to find the optimal location at which the energy consumption is minimum. It is found that there is a major decrease in energy consumption in Delhi and Chennai when the building is facing north in both cases. Chidiac et al [81] improved the thermal resistance of a building roof to find reductions in energy consumption of 18%, 19%, and 24% for Vancouver, Edmonton, and Ottawa, respectively.

The literature review presented in this study emphasizes the significance of considering the location when evaluating building energy consumption. However, it also reveals a noticeable research gap in conducting sensitivity analysis for office buildings by varying the building location across North America. Conducting sensitivity analysis is vital as it enables the identification of the most influential parameters that significantly impact building energy usage. This knowledge empowers engineers to enhance building efficiency, improve occupant comfort, and minimize energy wastage [82]. To address this literature gap, the current paper conducts a comprehensive sensitivity analysis of potential parameters for three distinct locations: Philadelphia, Edmonton, and Mexico City.

1.3.7 Contribution

The primary contribution of this paper lies in discerning variations in energy consumption associated with different parameters across different geographical locations. By undertaking this analysis, the study provides valuable insights into the energy performance of office buildings in different climatic conditions and geographical settings. The findings contribute to this body of knowledge by showing the magnitude of the effect that each parameter has on the energy requirements of the building for the different geographic locations.

Philadelphia is the original location of the building and is considered in the analysis for predictive modeling. In addition, the values obtained from the sensitivity analysis for this location can be used as a reference to compare with other locations. Edmonton and Mexico City are north and south of Philadelphia, respectively. Hence, the results can be observed and inferred by changing the location of the building to colder (Edmonton) and warmer region (Mexico City), with respect to Philadelphia to determine the variation in sensitivity analysis. By obtaining results for various locations, the goal is to analyze the variations in parameter values. This exploration allows us to consider the possibility of a shift in the most influential parameter based on each location's unique characteristics. This paper is restricted to the North America region to keep the climatic and seasonal variation limited.

In addition, there are some critical assumptions made to this model: (1) infiltration rates and ventilation rates are constant (2) the heat transfer coefficient is constant for a month (3) solar radiation data used is a typical meteorological year model which is an average of the past 20 years. Apart from these assumptions, there is one limitation that can be observed in this TRNSYS model equation; the infiltration equation only depends on the difference in the outdoor and indoor temperatures However, in real life cases, as depicted in the literature review, the infiltration rate depends on the outdoor wind speed, as well (but has no fixed relation) [43].

This study encompasses eight crucial parameters, namely ambient temperature, solar radiation, infiltration, lighting, equipment, occupancy, window glazing, and wall U-value. In the literature review section, each of these parameters is extensively discussed to highlight its significance. To execute the sensitivity analysis, every parameter is systematically varied by specific values, derived from weather data, and building codes relevant to each parameter. Detailed explanations are provided to ensure clarity and transparency in the process. Subsequently, the energy consumption value is meticulously recorded for each case, contributing valuable insights into the influence of these parameters on the office building's energy performance.

Table 1 provides a comprehensive analysis of the literature review, focusing on five major concepts: sensitivity analysis, predictive modeling, energy savings, influential parameters, and location change. Each concept is carefully examined to identify relevant articles in the field. Table 1 specifically highlights the literature gap by counting the number of relevant articles that fail to encompass at least one of the five specified concepts. It demonstrates how this paper stands out by incorporating all five concepts in its analysis. This comprehensive approach ensures the research addresses critical aspects of sensitivity analysis in relation to predictive modeling, energy savings, influential parameters, and location change, setting it apart from previous research in the field.

This paper presents an in-depth investigation of influential parameters using a detailed building model. Each parameter is thoroughly examined based on the existing building and adherence to building codes and standards. Through robust evidence and supporting data, a final model is developed for TRNSYS simulation. This model enables the analysis and modification of various parameters to record their impact on the energy consumption. Consequently, the research is deemed suitable for an MASc major research paper.

For future work, it is recommended to explore diverse retrofit options for the office building. Factors such as total cost, availability, and demand should be taken into consideration when evaluating these options. Introducing various feasible retrofit strategies can enhance the practicality and relevance of the study, further contributing to sustainable energy efficiency in office buildings.

Table 1.1. Gaps in literature and how my research fits in with the relevant literature.

Reference / Citation	Major topic addressed	Sensitivity Analysis	Predictive Modeling	Energy savings	Influential parameters	Location change
[13]	Building Energy Consumption		X	X		
[19]	Ambient Temperature, Building Envelope		X	X	X	
[20]	Indoor Air Temperature		X	X		X
[35]	Solar Radiation		X		X	
[48]	Infiltration	X	X		X	X
[49]	Infiltration		X	X	X	

[50]	Infiltration		X	X	X	
[54]	Building Envelope		X	X	X	
[55]	Building Envelope		X	X	X	
[56]	Building Envelope		X	X	X	
[57]	Building Envelope		X	X	X	
[58]	Building Envelope		X	X	X	
[59]	Building Envelope		X	X	X	
[64]	Building Envelope		X	X	X	
[69]	Lighting				X	
[71]	Lighting			X	X	
[74]	Equipment heat load		X	X	X	
[75]	Equipment heat load		X	X	X	
[80]	Location	X			X	X
[81]	Location	X			X	X
	Current paper	X	X	X	X	X

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CHAPTER II

Identifying Key Parameters Affecting Building Energy Consumption to Achieve Modeling Prediction

2.1 Introduction

Energy has become an essential component of today's standard of living. As of 2020, non-renewable sources such as coal, oil, and natural gas account for 85% of total global energy consumption, while renewable sources account for 15% [1]. Energy usage in buildings is currently shifting in favor of higher sustainability and energy efficiency. As mentioned in the first chapter, around 40% of the world's energy is used by buildings [2]. With population expansion, this percentage is anticipated to rise internationally during the next 20 years [3]. A greater understanding of the need to cut back on energy use and greenhouse gas emissions in order to lessen the effects of climate change is driving the current trend. Building regulations and standards are being modified to reflect the increasing usage of energy-efficient building design, HVAC systems, lighting, and building automation systems.

2.1.1 Factors Influencing Building Energy Consumption

The energy consumption of a building is shaped by various parameters, but certain ones hold particular significance and necessitate dedicated scrutiny. These can be categorized into environmental parameters and building parameters. The former involves ambient temperature, solar radiation, ground temperature, and heat transfer coefficient, while the latter encompasses lighting, equipment, HVAC units, occupancy, windows, and walls (as illustrated in Figure 2.1). The power load of a building is significantly affected by environmental factors, which cannot be controlled. Among these factors, ambient temperature has a particularly noteworthy impact on building energy consumption, and this impact has been exacerbated by climate change [4,5]. Papakostas et al. [5] explored changes to heating and cooling loads in Athens resulting from rising ambient temperatures over the past decade, which they attributed to climate change. According to their model, the heating load is projected to decrease by 14%, while the cooling load is estimated to increase by 44%. Following ambient temperature, the contribution of solar radiation is highly notable [6,7]. The solar radiation is incident on the building in the form of three components: beam radiation, diffuse radiation, and ground reflected radiation. Huang and Liu [8] found that solar radiation contributes to 26.12% of energy consumption during the winter season for a building in Western Sichuan. The incident radiation on the windows of the building is transmitted, absorbed, and reflected, while on opaque walls, it is only absorbed and reflected.

Another critical parameter that significantly impacts a building's energy consumption is the building envelope. The amount of solar heat gained entering the building is determined by the thermal properties of the windows and opaque walls, which include transmissivity, solar absorptance, and window-to-wall ratio (WWR). For example, according to ASHRAE standard 90.1, commercial buildings should have a maximum of 40% WWR in the United States to minimize energy use.

Furthermore, infiltration and exfiltration are the air entering and exiting (respectively) the building through the leaks and cracks of the building envelope. Infiltration accounts for approximately 15% to 30% of total energy consumption (heating and cooling loads) in office buildings in the United States [9,10].

The ventilation rate is expressed as the amount of air entering or leaving a building, is measured in air changes per hour (ACH), the same unit used for infiltration rate. Ventilation in office buildings can be divided into two main categories: natural ventilation and mechanical ventilation [11]. According to ANSI/ASHRAE standard 62.1-2022, Ventilation and Acceptable Indoor Air Quality [12], the ventilation air flow rate for office spaces is given as 0.06 cfm/sf, which can be converted to 1.098 m^3/hr./m^2 in SI units. This can be converted to ACH (h^{-1}) by multiplying the floor surface area and dividing it by the volume of the room.

Internal heat gains are a significant contributor to a building's energy consumption, which largely originate from sources such as lighting, equipment, and occupancy. Lighting has been found to be the most significant contributor to overall energy consumption, accounting for 20% to 40% of energy usage [13-15]. Recent studies suggest the preferred lighting density for an office workspace is from 13.4 W/m^2 to 16.7 W/m^2 [16]. Likewise, the equipment load density for office buildings typically falls within a range of 10 W/m^2 to 18 W/m^2 [17]. In the case of occupancy, it changes with building space, as the allowance is given in terms of number of people per foot exit from egress building code.

Finally, the ground is a parameter which acts as a heat sink during summer and a heat source during winter. The earth is solid ground that is of infinite thickness when compared to the size of the building. Therefore, the heat transfer between the ground and the building is different from other common heat transfer modes (conduction, etc.). Several equation models have been developed to calculate the ground temperature according to various parameters like depth, ambient temperature, etc., in aiming to obtain accurate results when compared to measured values [18-20]. In this research paper, the TRNSYS software is employed, utilizing a specific ground model to compute ground temperatures (discussed in Section 2.2.2.1). TRNSYS is commonly used to calibrate energy data in transient analyses with a defined time step, and its applicability to building energy simulations for structures of varying complexity has been demonstrated [21]. The software proves to be user-friendly for energy simulations and has significant advantages over other simulation software. This paper confirms the reliability of TRNSYS for subsequent simulations of the same building model, by exploring the thermal mass of the building envelope.

This chapter develops a predictive model for an office building's energy consumption. Although there has been much research on energy consumption prediction, it is still challenging to predict energy usage with any degree of accuracy without providing thorough justification and details [22-24]. This chapter addresses this limitation by simulating a range of building energy consumption values to consider the real-life challenges that affect the accuracy of the prediction.

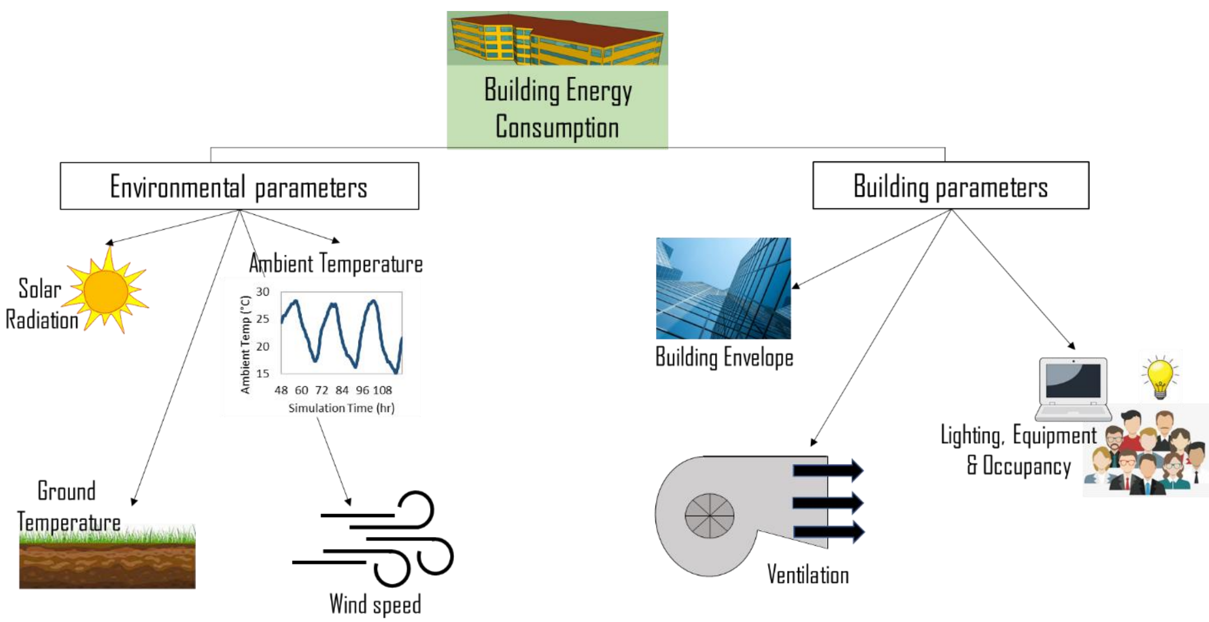


Figure 2.1. Influential parameters for a building's energy consumption

2.2 Methodology

SketchUp software is used to create a model of an existing building from the information provided in Reddy et al. [25-27]. To study the impact of environmental and building parameters, data for each month was analyzed separately. Hourly dry bulb temperature data is extracted from National Solar Radiation Database (NSRDB) for the year 2004 as the available temperature data model in TRNSYS is for a typical meteorological year (TMY). However, TMY data was utilized for solar radiation due to the complexity of the parameters involved. The model is imported as a multi-zone building in TRNSYS using the trnsys3d addon in SketchUp software. The following parameters or building inputs are defined in TRNBuild and are discussed below: building envelope material, workday schedule, infiltration, ventilation, heating input, cooling input, and internal gains like lighting, equipment, and occupancy.

2.2.1 Preprocessing

2.2.1.1 Building case study

The office building selected for this study is located at 400 Campus Drive, Collegeville, Philadelphia. It is a four-storey building with a floor area of 2500 m^2. The vertical wall is constructed with concrete masonry units (CMU) with concrete between hollow blocks, as shown in Figure 2.2 [28]. The roof is fabricated with concrete and a layer of insulation, while the floors are made of lightweight concrete (Figure 2.2). Table 2.1 contains information on the conductivity values, wall thickness, and heat capacity of the building envelope. The list of material property values is extracted from Reddy et al. [25-27], while the values marked with an asterisk are obtained from the TRNSYS library. The values in TRNSYS library are derived from trusted sources like ASHRAE fundamentals and German sources like SIA 2024, VDI 2078.

A front view and top view of the office building is shown in Figure 2.3. The building's exterior vertical walls are painted red with a solar absorptance of 0.6, while the roof is painted white with a solar absorptance of 0.4. The orientation of the building is 5° west of north as shown in Figure 2.3b. Double-glazed windows are installed in the building with a window-to-wall ratio (WWR) of 0.4 and with U-value, g-value, and transmissivity given as 2.78 W/m^{2}K, 0.59, and 0.61, respectively [25-27]. They are encased in a hardwood frame with a 0.15 window-frame fraction.

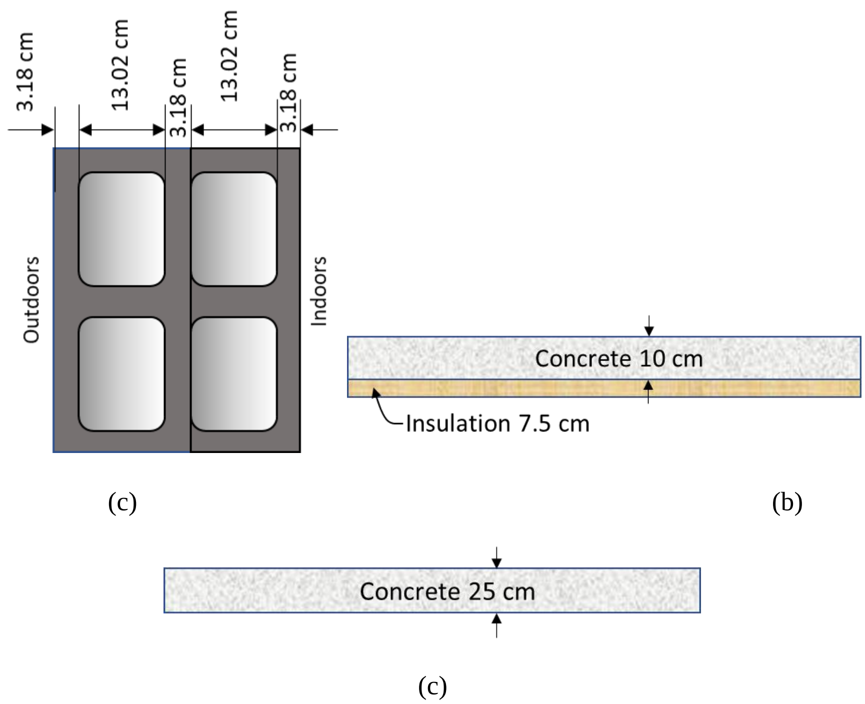


Figure 2.2. Building envelope details of (a) vertical walls, (b) Roof and (c) ground floor.

(a) (b)

Figure 2.3. (a) Front view and (b) top view of the office building in Philadelphia.

Table 2.1. Thermal properties of the building envelope

Properties	Vertical walls	Roof		Floor
	CMU	Concrete slab	Insulation	L.W. Concrete
Conductivity, k (W/m·K)	0.51	4.07	0.11*	1.76*
Heat Capacity, c (kJ/kg·K)	1.00	1.00	1.00	1.00
U-value (W/m^2·K)	0.38	0.37		0.77
Thickness (m)	0.35	0.10	0.075	0.25

*Values obtained from TRNSYS library

2.2.1.2 SketchUp modeling

Great care was taken in modeling the building to ensure that even minor variations in measurements are reflected in energy usage calculations. To this end, SketchUp was employed as a modeling and simulation tool, with the trnsys3d add-on used to save the model in a compatible format for import into TRNSYS Simulation Studio [29]. Figure 2.4 illustrates the isometric views of the model building, designed according to the actual office building dimensions.

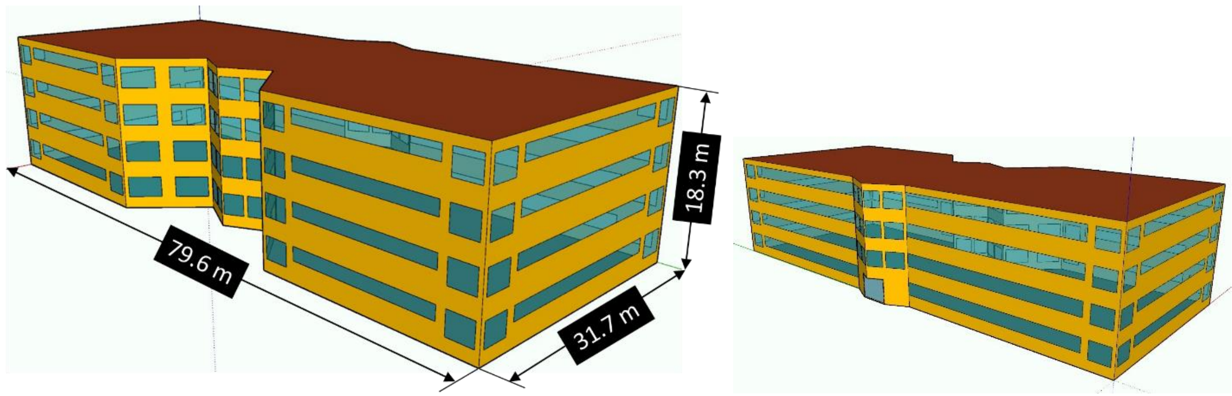


Figure 2.4. Isometric views of the SketchUp building model

2.2.2 TRNSYS simulation

The building model in SketchUp is imported in an idf file format to TRNSYS Simulation Studio. Figure 2.5 illustrates the Simulation Studio layout in TRNSYS with each icon representing a type-file. The main type-file among the three solar radiation components is the Type 15 file, also called a weather data file. The main parameters involved in the calculation of this file are solar zenith angle, solar azimuth angle, angle of incidence for all surfaces, and beam and diffuse radiation of all surfaces. Secondly, there is the ambient temperature file (Type 9), which accepts the NSRDB dry bulb temperature data in the form of a text file. The ground temperature model is Type 77. These files contain parameters that act as inputs to the Type 56 building model for running the simulation. Finally, the Type 65 file is used to generate the required plots and the results are printed using the Type 25 file. TRNBuild is used to define other modeling parameters of the building like workday schedule, internal gains, outputs needed, heating and cooling, infiltration and ventilation rates, and building envelope information including windows and heat transfer coefficient.

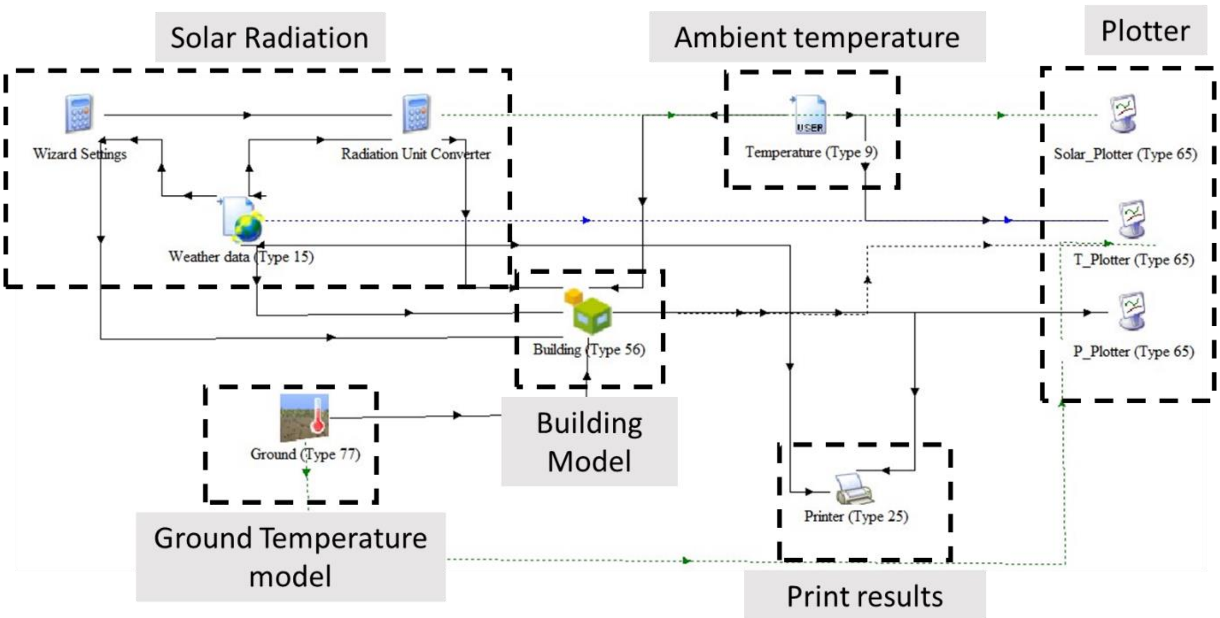


Figure 2.5. TRNSYS layout of type files in Simulation Studio.

2.2.2.1 Ground temperature

Unlike other surfaces, the ground floor is directly connected to the earth, which is considered to be solid ground with infinite thickness. TRNSYS uses the concept of Kasuda's Underground Temperature (UGT) model to define the heat transfer between the ground and the building [20],

$$T_G = T_{mean-} - T_{amp} e^{-D\left(\frac{\pi}{365\alpha}\right)^{0.5}} \cos\left(\frac{2\pi}{365}\left(t_{now} - t_{shift} - \frac{D}{2}\left(\frac{365}{\pi\alpha}\right)^{0.5}\right)\right) \tag{4}$$

where, T_G is the ground temperature (ºC), T_{mean} is the average ambient temperature (ºC), T_{amp} is the amplitude of the surface temperature (ºC), D is the depth below surface (m), α is the thermal diffusivity of the ground (m^2/day), t_{now} is the current day of the year (day), and t_{shift} is the day of the year corresponding to the minimum surface temperature (day). From Equation 4, it can be inferred that ground temperature varies with ambient temperature, depth, and thermal properties of the ground. The important thing to observe is the understanding of heat transfer between the ground and the building. Two main points can be noted here: (1) the building is attached directly to the earth/ground, and (2) ground temperature varies with depth. The outer surface of the ground floor has a temperature that varies according to Equation 2 with D=0. Now, this can be considered a standard heat transfer problem with conduction through the ground floor and convection to the indoors.

2.2.2.2 Heat transfer around the building

The incident solar radiation from the sun and the convective heat gain from the temperature difference between indoor and outdoor are the main contributors in the heat balance equation. This heat is transferred to the indoors by conduction through opaque walls, given by the following equation (all units are in W/m^2):

$$q_{cond} = q_{SW} + q_{conv} + q_{LW} \tag{5}$$

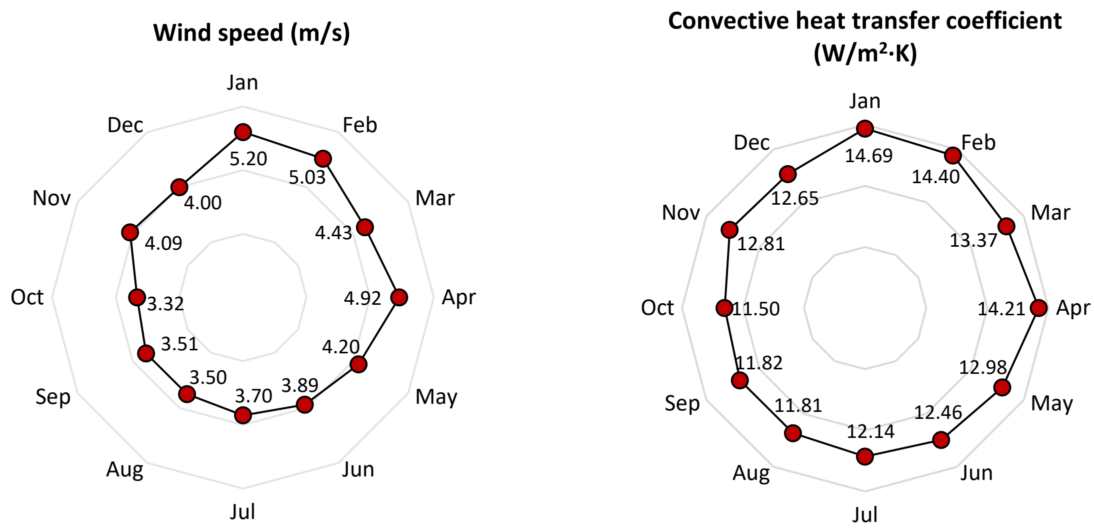
where q_{cond} is the heat flux through conduction, q_{SW} is the shortwave radiation, q_{LW} is the longwave radiation, and q_{conv} is the convective heat flux. The convective heat transfer coefficient exhibits variability with wind speed leading to discernable differences between indoors and outdoors of the building. The TRNSYS default value for the convective heat transfer coefficient inside a building is $h_i = 3\ W/m^2{\cdot}K$. In outdoor environments, wind speed can fluctuate significantly throughout the year. Strong winds that encourage heat exchange between the building and the surrounding air during winter often result in a greater convective heat transfer coefficient. In contrast, the convective heat transfer coefficient is significantly lower in the summer since there are fewer opportunities for heat transfer due to slower winds [30]. The relation between the wind speed and convective heat transfer coefficient is given by the following equation obtained from regression analysis for the central area of the building in outdoor conditions [31]:

$$h = 1.444v + 4.955 \quad (6)$$

where v is the wind speed and h is the convective heat transfer coefficient. However, since the wind speed impact is greater on the edges of the building compared to central area, Sparrow and Ramsey [32] found the average heat transfer coefficient is 1.18 times the central area heat transfer coefficient,

$$h_{av} = 1.18\,h = 1.7v + 5.85\,. \quad (7)$$

Heat transfer coefficient values for vertical and horizontal walls are assumed to vary by the same equation, as a negligible difference has been reported for outdoor conditions [31]. The convective heat transfer coefficient is evaluated for all the months for a year according to the wind speeds in Philadelphia given by Figure 2.6 [33].



(a) (b)

Figure 2.6. Monthly average (a) wind speed taken from [33] and corresponding (b) heat transfer coefficient values.

The building's exterior is exposed to incident radiation on 11 surfaces, excluding the ground level. The solar absorptance values of concrete, and red and white painted walls are 0.6, 0.6, and 0.4, respectively [34]. Consequently, the vertical walls have an overall solar absorptance of 0.36 (0.6 × 0.6), signifying that they absorb 36% of the radiation. Similarly, the roof has an overall solar absorptance of 0.24 (0.6 × 0.4). It is crucial to note that sunlight enters the building through the installed windows on these surfaces. The window-to-wall ratio (WWR) is 0.4, indicating that a maximum of 40% of the total incident radiation on the walls is converted into indoor solar heat gain.

2.2.2.3 Indoor regime types

The regime types are input information that represent infiltration gain, HVAC systems, and internal gains inside the building. HVAC systems are used to create a comfortable human environment by inducing ventilation and air circulation inside the building [35]. The list of HVAC inputs for the current case includes heating, cooling, ventilation, and the internal gains: lighting, infiltration, equipment density, and occupancy.

2.2.2.4 Infiltration

Air infiltration in buildings can affect energy consumption and indoor air quality. The infiltration in the buildings is caused by the leaks and cracks present in the building envelope. However, another major factor that influences the infiltration rate is the outdoor wind speed. The kinetic energy from the wind affects the pressure gradient on the surfaces, which in turn impacts the infiltration rate [36]. Furthermore, because wind speeds vary continuously, the building's infiltration rate is described as a range rather than a set amount. Due to the dynamic nature of wind conditions, assuming a fixed infiltration rate can result in modeling inaccuracies and deviations from actual results. The typical range of infiltration rates for buildings in North America is given from 500 $cm^3/s \cdot m^2$ to 3000 $cm^3/s \cdot m^2$, according to Chapter 16 of 2017 ASHRAE Fundamentals [37]. For the current office building being studied (surface area = 2588 m^2, volume = 12165 m^3, for each floor), the range of infiltration rates in air changes per hour (ACH) is given by:

$$Q_{inf-min}(\text{ACH}) = \frac{500cm^3}{12165m3} \times \frac{(60\times60s)}{s\cdot h} \times \frac{2588.3m^2}{m^2} = 0.38\text{h}^{-1} \tag{8}$$

and

$$Q_{inf-max}(\text{ACH}) = \frac{3000cm^3}{12165m3} \times \frac{(60\times60s)}{s\cdot h} \times \frac{2588.3m^2}{m^2} = 2.30\text{h}^{-1} \tag{9}$$

Although the values are called infiltration rates, they are the total ACH values of the building, i.e., including ventilation rates. Focusing on the infiltration gain calculation in TRNSYS, the infiltration heat gain ($\dot{q}_{infl}$, W) is given by:

$$\dot{q}_{infl} = \dot{m}C_p(T_a - T_i) \tag{10}$$

$$\dot{m} = V \times \rho \times \alpha \tag{11}$$

where C_p is the specific heat of air (J/kg·K); $\dot{m}$ is the mass flow rate (kg/s) of infiltration air given by multiplying the volume (V, m^3), density (ρ, kg/m^3), and infiltration rate (α, h^{-1}); and T_a (°C) and T_i (°C) are the ambient temperature and indoor temperature, respectively.

2.2.2.5 Ventilation

Like infiltration, the simulation input for office building ventilation in TRNSYS is given by air exchange rate (α_v, h^{-1}). In addition, the ventilation heat gain ($\dot{q}_{vent}$, W) is calculated using:

$$\dot{q}_{vent} = \dot{m}C_p(T_a - T_i) \tag{12}$$

where C_p is the specific heat of air (J/kg·K), $\dot{m}$ is the mass flow rate of ventilation air (kg/s), and T_a (°C) and T_i (°C) are the ambient temperature and indoor temperature, respectively. The ventilation rate of the selected office building with 256 people is given as 7.08 cfm/person [25-27], which, when converted to ACH (air changes per hour), yields:

$$Ventilation\,rate(\alpha_v) = 7.08\frac{cfm}{person} \times 256people = 3840\frac{ft^3}{min} = \frac{1}{1718412ft^3(Volume)} \times \frac{60min}{h} \approx 0.15h^{-1} \quad (13)$$

2.2.2.6 Lighting, equipment and occupancy

The lighting, equipment, and occupancy heat gain information in TRNSYS are given directly in terms of Watts or Watt/meter^2. As a result, simply adding individual heat gains yields the final heat load. The lighting density and equipment density is given by 16.1 W/m^2 and 12.38 W/m^2, respectively. From the Chartered Institution of Building Services Engineers (CIBSE) Guide A: Environmental design [38], the average heat emitted by a person is 75 W/person while sitting, standing, or walking in an office space. Therefore for 256 people in the office building, the occupancy gain for the complete building is given by:

$$75\frac{W}{person} \times 256people = 19200W \quad (14)$$

It is important to note that occupant density is given in terms of absolute gain, while the lighting and equipment gains are related to the reference floor area.

The workday schedule of lighting, equipment, and occupancy is depicted in Figure 2.7. The vertical axis in the plot depicts the proportion of the given density value for lighting, equipment, and occupancy. In other words, during the workday hours of 8:00 am to 6:00 pm, the lighting, equipment, and occupancy are at 90% full capacity. While in the off-hours (6:00pm-8:00am), lighting is at 10% full capacity, equipment is at 40% full capacity, and occupancy is at 5% of full capacity.

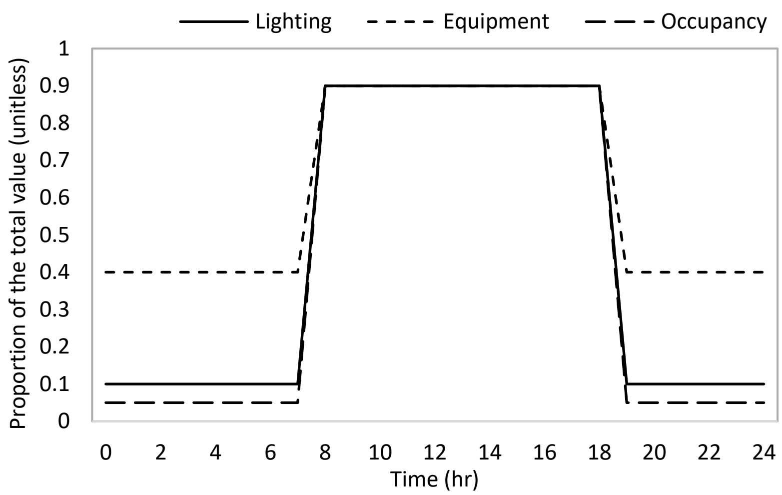


Figure 2.7. Workday schedule for lighting, equipment, and occupancy

2.2.2.7 Heating and cooling

The temperature settings for heating and cooling are different, to save energy during non-working hours. For instance, the temperature setting for heating during working hours is 23°C, and during non-working hours is 19°C. The temperature setting for cooling during working hours is also 23°C, but during non-working hours is 27°C (Figure 2.8). In addition, during the weekends, i.e., Saturday and Sunday, the temperature is set to 19°C for heating and 27°C for cooling. The relative humidity of the building is maintained constant at 50%, according to ASHRAE Standard 55 for occupancy comfort. The total heat balance equation in TRNSYS is given in terms of total power demand (Q_i, W) and is given by:

$$Q_i = Q_{infl} + Q_{vent} + Q_{int} + Q_{sol} + Q_{abs} \quad (15)$$

Here, Q_{infl} is the infiltration gain (Equation 10), Q_{vent} is the ventilation gain (Equation 12), Q_{int} is the internal gains like lighting, equipment, and occupancy, Q_{sol} is the fraction of solar radiation through external windows converted to indoor convective gain, and Q_{abs} is the absorbed heat gain on the walls of the building converted to indoor convective gain (all units in W).

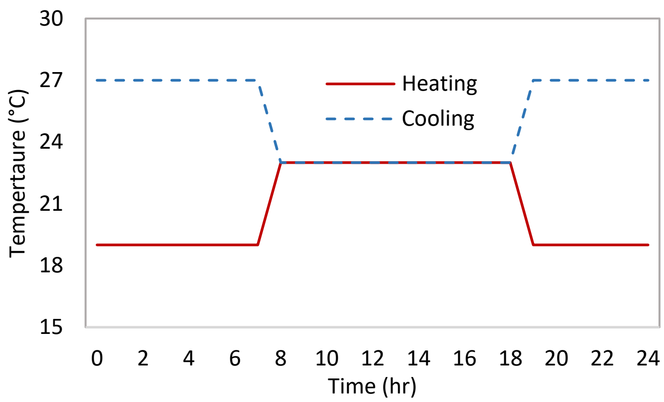


Figure 2.8. Indoor temperature setting

2.3 Results and Discussion

As per the usual practice, conducting a computational study requires verification of the software used for modeling. To accomplish this, an analysis is carried out on the indoor temperature and indoor power demand (in kJ/hr) of the building. The purpose of this study is to demonstrate the impact of the thermal mass and thermal resistance of the building envelope on the performance of the model [39]. Through this analysis, the TRNSYS model can be validated for future work. Finally, to model the building, the parameters discussed in the methodology are employed to obtain monthly energy consumption figures, which are compared to the data obtained from Reddy et al. [25-27] to establish the accuracy of the model.

2.3.1 Verification model

In this case, the behavior of indoor temperature and indoor power consumption are investigated with ambient temperature as the only input i.e., no effect of solar radiation, infiltration, ventilation, and internal gains on the building. The default time step in TRNSYS is one hour; however, to accommodate for more accuracy, the simulation is carried out with a time step of 15 minutes. Ground temperature is kept at 13°C, which is one degree lower than the mean ambient temperature. A user-defined sinusoidal weather data input is used to study the variation of indoor temperature. The outdoor temperature range values are taken for Philadelphia and are based on the weather reports collected during 1985-2015, to replicate the meteorological data of the real office building [40]. The heating and cooling inputs of the building are turned off to analyze the fluctuation of indoor temperature based on the ambient temperature.

Figure 2.9 shows the behavior of indoor temperature (red dashed curve) according to the sinusoidal weather data (blue curve). A delay and attenuation in the indoor temperature is observed in the simulation plot (Figure 2.9), because of the finite thermal resistance and finite thermal mass of the building envelope. In other words, not all the heat from the surroundings enters the building due to the building envelope. From the indoor temperature plot (Figure 2.9), the following observations are made: (1) due to the ground temperature of 13°C, there is a minor shift in mean indoor temperature by 0.62°C below the mean ambient temperature of 14°C; (2) the indoor temperature has a thermal delay of 15.70 hours when compared to the ambient temperature; and (3) an attenuation value of 9.68°C can be observed in the indoor temperature from the ambient temperature.

Similarly, to check the variation of indoor power demand of the building, the indoor temperature is set constant at 21°C for both heating and cooling (Figure 2.10). The ambient temperature is shown on the primary axis and the power demand on the secondary axis. The negative value in the secondary axis denotes a heating load, as TRNSYS uses a negative value for heating and positive value for cooling. There is a considerable delay of 17 hours in the power demand (red) when compared to the ambient temperature (blue) cycle, as shown in Figure 2.10. An attenuation check is not possible in this case, due to the difference in the units.

In addition to the delay and attenuation, it is noted that the indoor temperature and power demand plot takes around 24 to 48 hours to stabilize. In other words, the mean value of the property takes about 24-48 hours to attain a constant value, i.e., due to the transient nature of the simulation, considerable time is required to stabilize the outputs. Henceforth, to illustrate the stabilization of indoor properties to a constant sinusoidal curve, the simulation is carried out for a period of 180 hours.

The property of thermal mass and thermal resistance influences the building envelope walls to mitigate the incident heat by absorbing and emitting energy. Thus, by observing the delay and attenuation in this sensitivity study on indoor parameters, the effect of building envelope is conspicuous. On exhibiting this thermal behavior of the building envelope, the simulation model in TRNSYS is verified as reliable for further calculations.

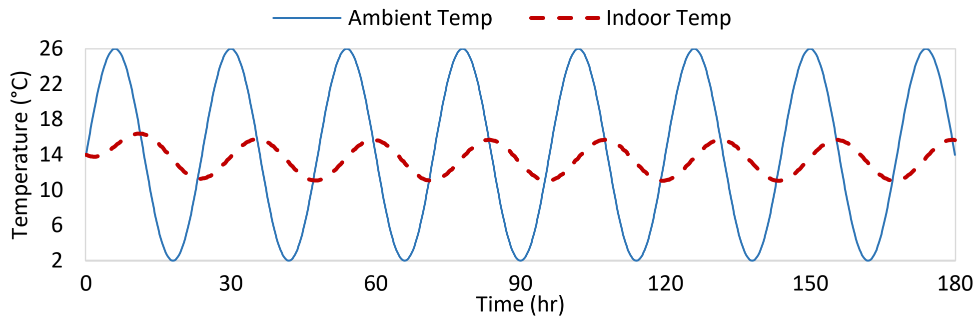


Figure 2.9. Variation of indoor temperature with time.

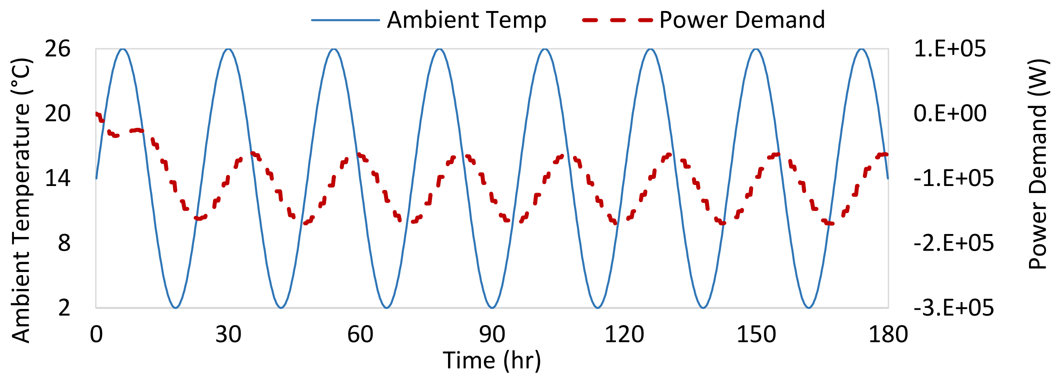


Figure 2.10. Variation of indoor power demand with time.

2.3.2 Predictive modeling

By examining the details of the reference building from Reddy et al. 2006 [27], the current work concentrates on the daily energy consumption (in kWh/day) averaged for a month. The objective is to model the energy consumption for each month of the year 2004 by inputting the required data into TRNSYS. The simulation's time step is one hour, which matches the frequency of the ambient weather data obtained from NSRDB. The direct output values from TRNSYS are given in power demand terms (kJ/hr), which are attained for every hour throughout the simulation. These values are averaged for one day and the values are converted to kW units (divide by 3600). The values for each day are summed for the complete month to give the total energy consumption (kW) for that particular period. Finally, the total energy consumption is multiplied by 24 hours and divided by the number of days in the month to give the average daily energy consumption for the month (in kWh/day):

$$Average\ daily\ energy\ consumption\ for\ the\ month\ = \frac{(P_1+P_2+P_3+\cdots+P_{Tmon})\times 24}{T_{mon}} \quad (16)$$

where P_n is the average power demand for a 24-hour cycle for the n^{th} day (kW) and T_{mon} is the number of days in that particular month.

The total daily energy consumption data for each month is derived by combining the heating and cooling power demand values. Two different infiltration rates, namely 0.25 ACH and 0.85 ACH, are considered, which accounts for the variability of wind speeds throughout the year. The minimum and maximum values of the total air changes per hour (ACH) for the building, which include the ventilation rate, are determined to be 0.4 ACH and 1.0 ACH, respectively. These values are well within the range of ACH values obtained using the 2017 ASHRAE Fundamentals [41], as detailed in section 2.2.2.4. The simulated values for both ACH rates are provided for all twelve months and are depicted in Figure 2.11. The power consumption curve for 1.0 ACH (red curve) is observed to be higher than the curve for 0.4 ACH for all the months, with an average difference of 5705 kWh/day. It is notable that the measured results fall within the range of power consumption values for the minimum and maximum ACH rates. Therefore, it can be inferred that the actual ACH rate of this office building lies between 0.4 ACH and 1.0 ACH for all the months. Furthermore, from Figure 2.11, it is observed that the measured consumption values during winter months are closer to the modeled values for 0.4 ACH than the values for 1.0 ACH, despite greater wind speeds. Also, Figure 2.11 shows that for a given ACH value, energy usage during winter is greater than during summer.

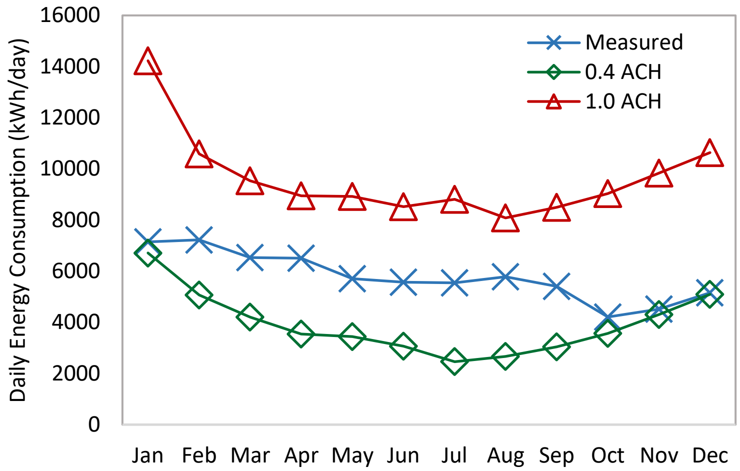


Figure 2.11. Building simulation plot for 0.4 ACH and 1.0 ACH.

2.3 Conclusion

Building managers, energy analysts, and policymakers may utilize predictive modeling of energy consumption in office buildings as a valuable tool to understand the trends of the building's energy usage, spot inefficiencies, and optimize energy usage. This work shows it is possible to develop predictive models that can forecast the energy consumption of a building with a high degree of accuracy by analyzing historical data and other pertinent parameters such as ambient temperature, solar radiation, infiltration, ventilation, building envelope, internal lighting, equipment, occupancy, and ground temperature. To verify the reliability of the building model studied, an analysis is performed on indoor temperature and indoor power demand using sinusoidal weather data. The analysis reveals a dampened effect on indoor temperature (and indoor power demand) with a delay, attributable to the thermal mass and thermal resistance of the building envelope.

Some of the key parameters in predictive modeling (ambient temperature, solar radiation, and ground temperature) are varied hourly for two different ACH values, reflecting the unpredictability of the infiltration and ventilation rates. The results indicate that the measured energy consumption of the actual building falls between the curves of the two ACH rates: 0.4 ACH and 1.0 ACH. This suggests that the infiltration rates of the building range from 0.25 ACH to 0.85 ACH, with a constant ventilation rate of 0.15 ACH. As well, the data presented illustrate that the energy consumption during winter is higher than during the summer, for the same ACH value. The analysis further reveals that a change of 0.6 ACH (= 1.0-0.4 ACH) corresponds to an annual average energy usage difference of 5705 kWh. The indoor ACH adjusted by altering the ventilation rate, regulating air flow from outside to inside of the building by opening and closing windows, and checking for cracks and leaks in the building's airtightness. These are important considerations when trying to reduce the energy usage of a building.

In addition to infiltration, other parameters also affect an office building’s energy consumption. To further improve the understanding of the factors affecting energy consumption in buildings, the upcoming chapters of this paper will involve conducting a comprehensive sensitivity analysis of the building parameters. This analysis will provide insights into the relative importance of each parameter and how they contribute to energy consumption. By identifying the most influential parameters, engineers can prioritize their efforts towards reducing energy consumption by focusing on the parameters that have the greatest impact. These might involve retrofits to the HVAC system or building envelope, adjustments to occupant routines or behavior, or energy-saving technology. Engineers may significantly reduce energy use and related expenses while advancing sustainability objectives and lessening environmental impact by using a focused strategy to reducing energy usage.

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CHAPTER III

Conducting Sensitivity Study by Incorporating Location: Analyzing Parameter Variations and Their Impact

3.1 Introduction

Understanding the factors influencing a building's energy use requires analyzing the energy balance equation. The relevance of applying the energy balance equation to pinpoint the sources of energy use and the related variables that may be changed to generate considerable energy savings has been emphasised in a number of studies. For instance, a study by Permana et al. [1] that looked at the energy modeling equation uncovered that the main energy consumers were ambient temperature and occupancy rate for a hotel building in central Taiwan. Furthermore, the research elucidates the significance of evaluating the potential variables affecting a particular building before executing tactics and methodologies aimed at conserving energy. In addition, examining the energy balance equation helps to identify the energy waste and inefficiency in the building. Consequently, by separating the variables in the equation, a sensitivity analysis can be carried out to comprehend the individual effects they have on the energy balance.

Furthermore, sensitivity analysis is a necessary step that should be undertaken prior to implementing any new building designs or retrofits to mitigate energy usage. Due to the uniqueness of each building type, certain parameters may have a more substantial impact on energy consumption in one building than in another. This variation depends on several factors such as building location, design, and internal comfort demands. Identifying and analyzing the critical parameters within the energy balance equation is a crucial component of conducting a sensitivity study on a building's energy consumption. By performing a sensitivity study, the most influential factors that impact a building's energy consumption can be determined. Engineers and designers can then use this information to implement available technologies and techniques that can effectively reduce energy consumption without compromising human comfort [2-4]. For example, Elhadad and Orban [5] conducted a sensitivity analysis on building envelope parameters of a residential building in Budapest (Hungary). Their findings indicate that the type of material used in the exterior flooring of a building has the most significant influence on the energy consumption. Panizza and Nik-Bakht [6] performed a sensitivity study on 17 ASHRAE baseline models and found that HVAC systems have the highest energy consumption in all the models.

A sensitivity analysis is crucial to optimising a building's energy performance, and its significance cannot be overemphasized. It can lead to strategies to cut down on energy waste, slash energy costs, and encourage sustainability by identifying and examining the crucial factors that have an influence on energy use. Within this chapter, the parameters that hold significant importance for this building via the use of the energy balance equation are identified. Furthermore, a sensitivity analysis is conducted.

3.2 Methodology

3.2.1 Energy Balance Equation

It is critical to analyze the energy balance equation to list out the parameters individually involved in the calculation. The overall energy balance equation for a building encompasses some crucial factors including heat convection to and from the building due to the ambient temperature and solar radiation falling on the opaque building walls. These two parameters significantly influence the surface temperature of the walls and consequently facilitate the conduction heat transfer process through the wall thickness. The factor that is used in the energy balance equation is the convection heat gain from the inside wall surface to the indoors ($\dot{Q}_{\mathrm{conv}}, \mathrm{W/m^2}$). The overall energy balance is given by the following equation:

$$\dot{Q}_{Heating/Cooling} = \dot{Q}_{\mathrm{conv}} + \dot{Q}_{\mathrm{sol-trn}} + \dot{Q}_{vent} + \dot{Q}_{inf} + \dot{Q}_{intgains} \quad (17)$$

where, $\dot{Q}_{\mathrm{sol-trn}}$ (W) is the transmitted solar radiation given by:

$$\dot{Q}_{\mathrm{sol-trn}} = f_{sol} \cdot (I_{dif} + I_{dir}) \quad (18)$$

where, f_{sol} (unitless) is the solar to air fraction, I_{dif} (W) is the diffuse solar irradiance, and I_{dir} (W) is the diffuse solar irradiance. $\dot{Q}_{inf}$ (W) and $\dot{Q}_{vent}$ (W) are the infiltration and ventilation gains, given by Equation 10 and Equation 12, respectively. $\dot{Q}_{intgains}$ (W) is the internal gain from lighting, equipment, and occupants. The convective heat gain ($\dot{Q}_{\mathrm{conv}}, \mathrm{W}$) inside the building is obtained by the transfer function method used in TRNSYS (Figure 3.1). As shown in Figure 3.1, the heat convection due to ambient temperature and the solar gain to the wall is converted into the indoor convective gain as given by the following equations:

$$\dot{q}_{s,o} = \dot{q}_{sol,o} + \dot{q}_{c,s,o} + \dot{q}_{r,s,o} \quad (19)$$

and

$$\dot{q}_{s,i} = \dot{q}_{sol,i} + \dot{q}_{c,s,i} + \dot{q}_{r,s,i} \quad (20)$$

where, $\dot{q}_{s,o}$ (W/m^2) is the conduction heat flux to the wall from outside surface, $\dot{q}_{s,i}$ (W/m^2) is the conduction heat flux to the inside surface, $\dot{q}_{sol,i}$ ($\mathrm{W/m^2}$) is adiation heat flux absorbed at the inside surface due to solar radiation and internal radiative gains from lighting, equipment, and occupancy. Similarly, $\dot{q}_{sol,o}$ (W/m^2) is the radiation heat flux absorbed at the outside surface from the solar gains, $\dot{q}_{r,s,i}$ (W/m^2) is the net radiative heat transfer with all other surfaces within the zone, $\dot{q}_{r,s,o}$ (W/m^2) is the net radiative heat transfer with all surfaces in view of the outside surface, $\dot{q}_{c,s,i}$ is convection heat flux from the inside surface to the air, $\dot{q}_{c,s,o}$ (W/m^2) is the convection heat flux to the outside surface from the ambient temperature. The conduction heat flux inside the wall is obtained using the time series equations using transfer function relationships by Mitalas and Arseneault [7]:

$$\dot{q}_{s,o} = \sum_{k=0}^{n_{a_s}} a_s^k T_{s,o}^k - \sum_{k=0}^{n_{b_s}} b_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,o}^k \quad (21)$$

and

$$\dot{q}_{s,i} = \sum_{k=0}^{n_{b_s}} b_s^k T_{s,o}^k - \sum_{k=0}^{n_{c_s}} c_s^k T_{s,i}^k - \sum_{k=1}^{n_{d_s}} d_s^k \dot{q}_{s,i}^k \quad (22)$$

where, a, b, c, d, n, k are the coefficients of the time series found within TRNSYS using the transfer function equations. These equations demonstrate the mechanism to obtain the potential parameter – indoor convective heat gain ($\dot{Q}_{\text{conv}} \equiv \dot{q}_{c,s,i}$), which is used in the final energy balance equation. These parameters on the right-hand side of the energy balance equation (Equation 17) are the contributors for the heating and cooling load of the building.

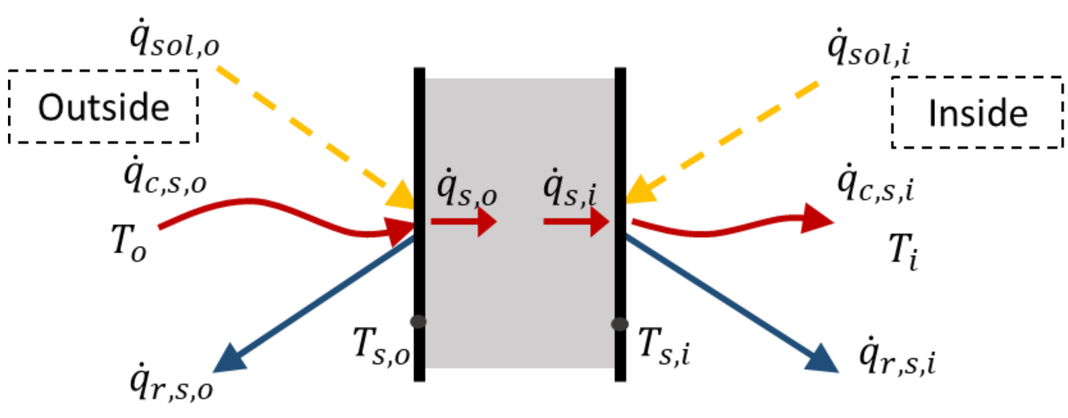


Figure 3.1. Heat transfer mechanism around the wall of a building.

Therefore, the parameters required for the computation of each term in Equation 17 can be deduced. To illustrate, $\dot{Q}_{\text{con}v}$ refers to the indoor convective heat gain which encompasses the parameters of ambient temperature and wall U-value. The term $\dot{Q}_{\text{sol-trn}}$ is reliant on solar radiation and window glazing, while $\dot{Q}_{inf}$ and $\dot{Q}_{vent}$ entail varying parameters of infiltration rate and ventilation rate, respectively. Lastly, the term $\dot{Q}_{intgains}$ comprises parameters of lighting, equipment, and occupancy.

3.2.2 Base Case Model

It is important to define the base case for the model before altering the crucial parameters to understand the sensitivity analysis. The base case is the average parametric setting used to represent the simulation case that closely resembles the measured data (Figure. 2.11). The infiltration rate is assumed to be 0.45 ACH, which gives the closest resemblance to the measured data, with an average difference of 8% in energy consumption (Figure 3.2). This value is obtained by taking the percentage difference in the values of the base case data and measured data and calculating its average value. The parameters involved in the sensitivity analysis are given in Table 3.1, along with the base case values. The sensitivity analysis is conducted for each parameter separately by monitoring the change in power consumption for each month.

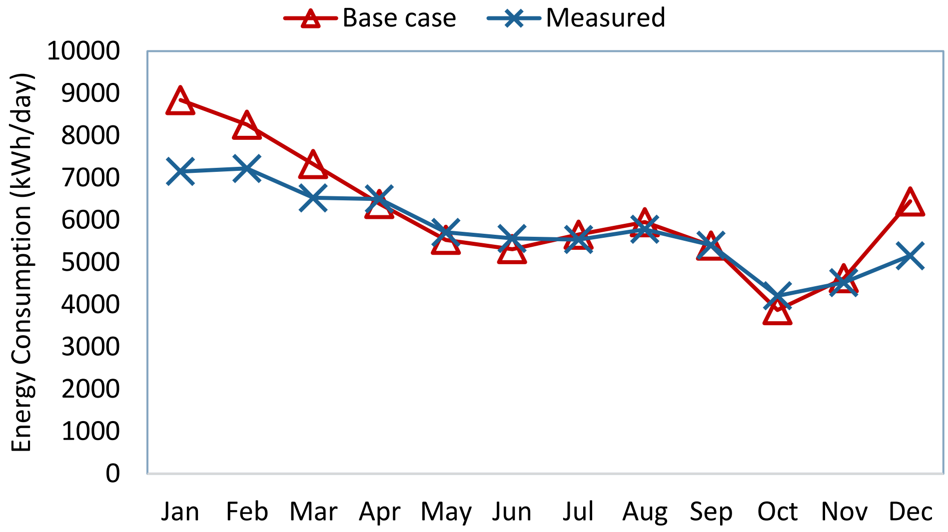


Figure 3.2. Base case results with 0.45 ACH infiltration

Table 3.1. Base case parameters.

Parameters	Indoor Temp	Ambient Temp	Solar Rad	Infiltration (ACH)	Lighting density (W/m^2)	Equip density (W/m^2)	Occupant density (W)	Window glazing	Wall U-value (W/m^{2}K)
Base case values	23°	NSRDB	TMY	0.45	16.1	12.38	19200	Double Glazing	0.4

3.3 Results

Each parameter from the base case model is individually modified based on established standards or values derived from prior years' data. As the units for each parameter is dissimilar, it would be unwise to compare the energy saving values for each case. Thus, the goal of this analysis is to assess the impact of varying each parameter, rather than the effect of the parameter itself. By performing this assessment, the alteration in energy consumption resulting from the variation of each parameter can be quantified, and effective strategies and techniques to curtail energy usage can be recommended.

3.3.1 Ambient Temperature

The impact of ambient temperature is calculated by altering the temperature values by adding and subtracting by a critical value and recording the change in energy usage values. This critical value is found by calculating the standard deviation of the past yearly average dry bulb temperature data. For this case, the average ambient temperature data for the past 40 years (1982-2022) in Philadelphia is noted from National Oceanic Atmospheric Administration (NOAA) [8], as shown in Figure 3.3. The standard deviation of the 40 temperature values is found to be 0.80°C, which can be assumed to be approximately 1.0°C. Henceforth, the analysis is conducted by adding and subtracting 1°C to the hourly temperature values from TMY data (Table 3.2).

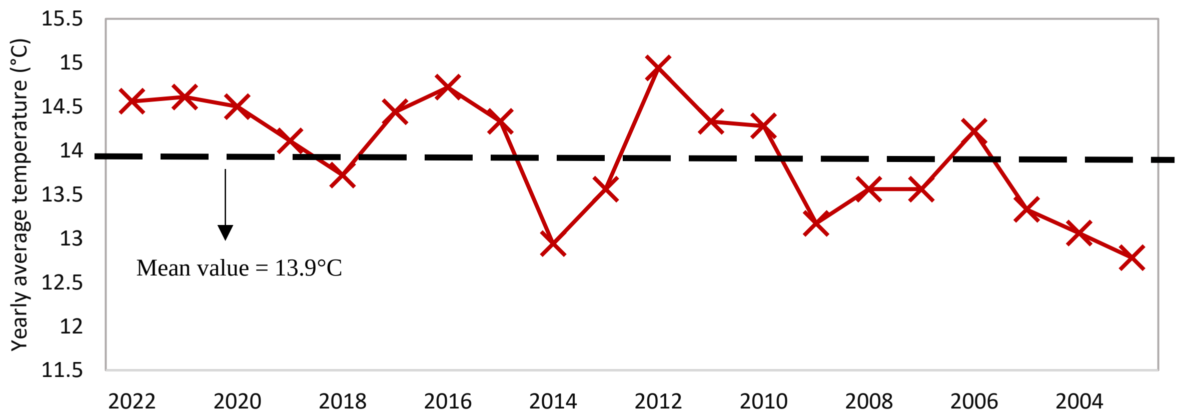


Figure 3.3. Yearly average temperature data for the past 20 years in Philadelphia [8].

Based on the provided plot (Figure 3.4), it is evident that energy consumption exhibits distinct seasonal patterns depending on the ambient temperature. Specifically, the data indicate that energy consumption is considerably higher during months characterized by a reduced ambient temperature, namely January, February, March, April, November, and December. In contrast, during months with increased ambient temperatures, notably during the summer and fall seasons, energy consumption is observed to be lower. Therefore, from the plot, it can be noted that, adding and subtracting 1°C from ambient temperature results in 4% energy savings and 4% excess energy used, respectively. When comparing the results to the study conducted by Radhi [19], as mentioned in the first chapter, it is noteworthy that Radhi observed a 23.5% increase in energy consumption when the average ambient temperature in Al-Ain city increased by 5.9°C. Indeed, given that the temperature increase in the Al-Ain city study is nearly 6 times greater than the current case, it is logical to observe a closely proportional relationship in terms of energy usage or savings (1°C:5.9°C::4%:23.5%). It's worth noting that this estimated value closely aligns with Radhi's findings, albeit with a key distinction: Radhi's study saw an increase in energy consumption, while the current case achieved energy savings. This divergence can be attributed to the disparity in weather conditions, with Al-Ain city experiencing hotter weather compared to Philadelphia.

Table 3.2. Altering ambient temperature by one-degree Celsius from the base case.

Parameters	Indoor Temp	Ambient Temp	Solar Rad	Infiltration (ACH)	Lighting density (W/m^2)	Equip density (W/m^2)	Occupant density (W)	Window glazing	Wall U-value (W/m^2K)
Base case values	23°	-1°C	TMY	0.45	16.1	12.38	19200	Double Glazing	0.40
		NSRDB							
		+1°C							

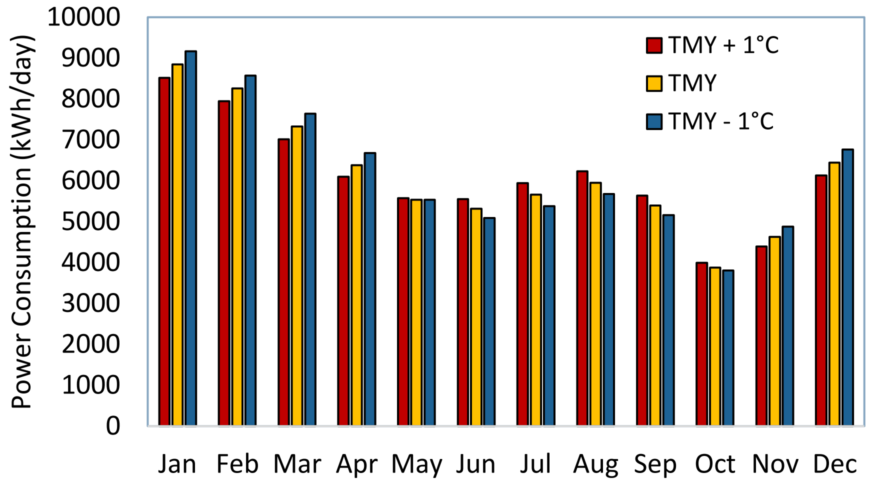


Figure 3.4. Variation of energy consumption by changing ambient temperature.

3.3.2 Solar Radiation

The impact of solar radiation on a building is influenced by a multitude of factors, including Global Horizontal Irradiance (GHI), Direct Normal Irradiance (DNI), Diffuse Horizontal Irradiance (DHI), zenith angle (θ), altitude angle, and slope angle, among others [9]. For the sensitivity analysis, the GHI is identified as the key parameter for varying total energy consumption, as it represents the total amount of solar radiation on a horizontal surface at a specific location for each hour (time step). In order to determine the upper and lower limits of GHI values, the yearly average values were extracted from the National Solar Radiation Database (NSRDB) [10] for the past 20 years (figure 3.5). The standard deviation of these GHI values was found to be 7.5 W/m^2, which was rounded up to approximately 10 W/m^2. However, as GHI can be zero before sunrise and after sunset, simply subtracting 10 W/m^2 would result in negative values during these times. Therefore, a ratio factor was introduced to account for this variation. To calculate this factor, 10 W/m^2 was added and subtracted from each of the GHI values listed in figure 3.5 and the ratio was calculated by dividing the new value by the original value. This process was repeated for all 20 GHI values, and the average ratio was calculated to be 1.1 for the upper limit and 0.9 for the lower limit, as shown in Table 3.3. The simulation is carried out for the upper and lower limits and the final values are plotted along with the normal GHI results (Figure 3.6). Note that the preserved GHI value (yellow bar) in this example differs from the base case since it is based on NSRDB records, whereas the solar radiation in base case is extracted from TMY data.

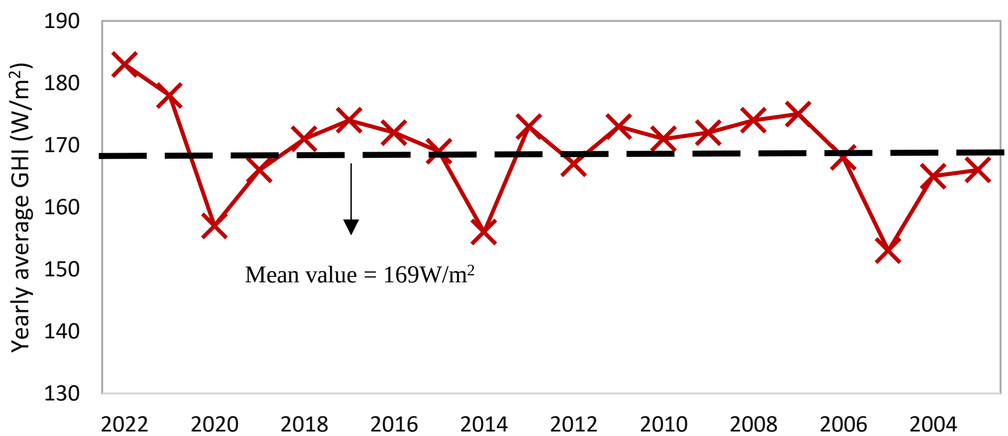


Figure 3.5. Yearly average GHI data for the past 20 years at Philadelphia [9].

From the plot in Figure 3.6, it is observed that by increasing GHI, which brings more solar gain inside the building, the cooling load increases during summer (Jun, Jul, Aug, Sep) and the heating load decreases during winter. In contrast, the reduced GHI value, which signifies reduced solar gain, increases the heating load in winter and decreases the cooling load during summer. Furthermore, changing the GHI values of solar radiation by 1.1 and 0.9 resulted in 0.67% energy savings and 0.67% extra energy usage, respectively. Relating the results with the literature review, Vlachokostas and Madamopoulos [35] observed 37% by decreasing direct solar radiation by 90%. When considering the substantial difference in solar irradiance change between the current paper (10%) and the referred literature (90%), it is reasonable to expect a significant disparity in energy saving values. As a result, the observed variance in energy-saving values can be seen to be rational and is caused by the notable divergence in solar irradiance values between the two cases.

Table 3.3. Altering the GHI value by a factor of 1.1 and 0.9.

Parameters	Indoor Temp	Amb Temp	Solar Rad	Infiltration (ACH)	Lighting density (W/m^2)	Equip density (W/m^2)	Occupant density (W)	Window glazing	Wall U-value (W/m^{2}K)
Base case values	23°	NSRDB	0.9GHI GHI 1.1GHI	0.45	16.1	12.38	19200	Double Glazing	0.4

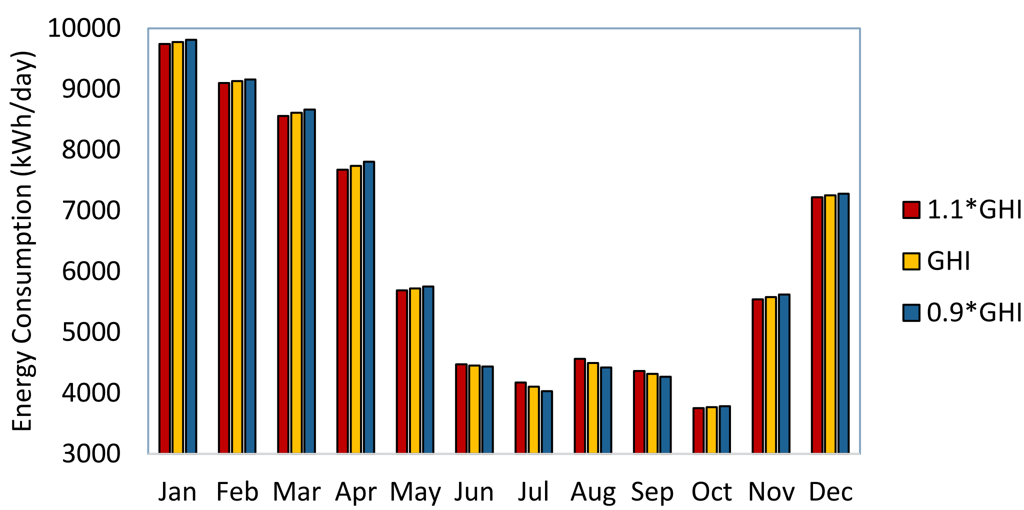


Figure 3.6. Variation of energy consumption by changing GHI.

3.3.3 *Infiltration*

The variation of infiltration rate for this building is studied in the previous chapter, where the simulation is carried out for two infiltration rates (Figure 2.11). The infiltration rate is changed between two values, 0.25 ACH and 0.85 ACH, obtained for this building from Chapter 16 of

ASHRAE Fundamentals 2017 [11] (Table 3.4). The streamline graph is converted into a bar graph for consistency with the other parameters and is plotted in Figure 3.7a.

Table 3.4. Altering the infiltration rate to 0.25 ACH and 0.85 ACH.

Parameters	Indoor Temp	Amb Temp	Solar Rad	Infiltration (ACH)	Lighting density (W/m^2)	Equip density (W/m^2)	Occupant density (W)	Window glazing	Wall U-value (W/m^2K)
Base case values	23°	NSRDB	TMY	0.25 0.45 0.85	16.1	12.38	19200	Double Glazing	0.4

A large difference is observed in energy values with a change in infiltration rate from 0.25 ACH to 0.45 ACH to 0.85 ACH. Adjusting the infiltration rates to 0.25 ACH and 0.85 ACH results in a 31% energy reduction and 69% extra energy used, respectively. The obtained energy values should be considered in the context of the complete range of commercial buildings in the United States, and as such, cannot be compared to the energy values of other parameters. While there is no direct relationship between wind speed and infiltration rate, they can be loosely correlated, as explained by Hadavi and Pasdarshahri [12]. Based on this literature and the wind speed data for the specific case (Figure 2.6a), with a standard deviation of 0.63 m/s, a reasonable assumption can be made that the infiltration rate may vary by up to 0.10 ACH over the course of a year in Philadelphia for this office building. This means that the upper and lower limits can be estimated to be 0.50 ACH and 0.40 ACH, respectively. The infiltration rates for some of the existing office buildings are taken from supporting literature: 0.09 ACH to 0.32 ACH for a 1000 m^2 floor area [13], 0.311 ACH for a 25.7 m^2 office space [14]. The simulation is carried out for infiltration rates of 0.50 ACH, 0.45 ACH, and 0.40 ACH and is plotted in Figure 3.7b. By reducing the infiltration rate to 0.40

ACH, an energy saving of 2.78% is observed, similarly, by increasing the infiltration rate to 0.50 ACH, 2.78% of excess energy was used.

In the first chapter, Almarzouq and Sakhrieh [49] were able to achieve energy savings of 19.4% by reducing the infiltration rate by 50%. In the current case, the infiltration rate was determined to be 0.225 air changes per hour (ACH) when reduced by 50% of the base case value. Additionally, it was observed that a 10% reduction in the infiltration rate (0.05 ACH) led to 2.78% energy savings, and a 45% reduction (0.20 ACH) resulted in a substantial 31% energy savings. These findings provide valuable supporting evidence for comparing the results obtained in this paper with the work of Almarzouq and Sakhrieh. While there may be minor differences due to factors such as location, building area, orientation, and other contextual variables, the overall trend of energy savings through the reduction of infiltration rates appears consistent and aligned between the two studies.

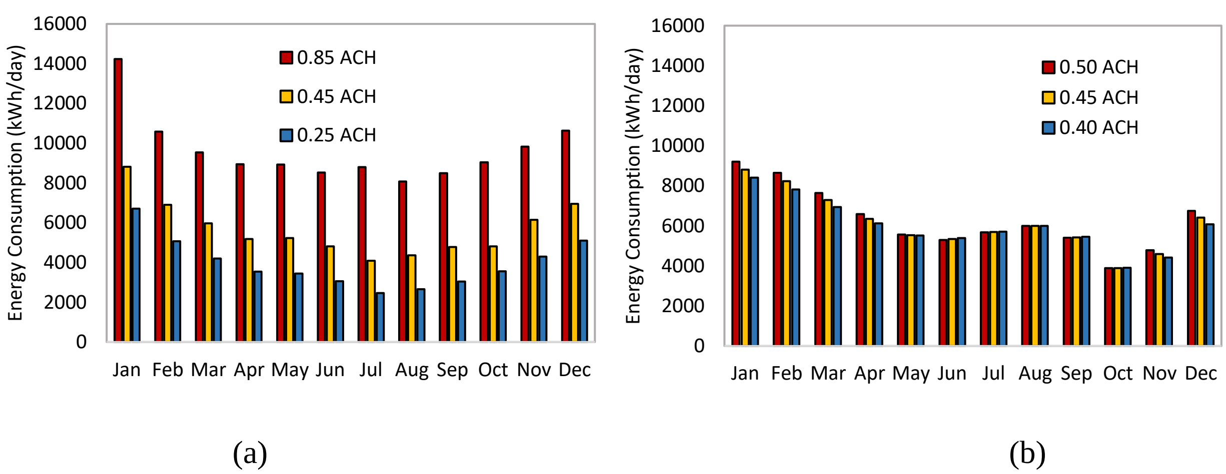


Figure 3.7. Variation of energy consumption by changing infiltration rate from (a) 0.25 ACH to 0.85 ACH and (b) 0.40 ACH to 0.50 ACH

3.3.4 Lighting

Lighting in buildings consumes a considerable amount of energy depending on the type of lighting used and hours of operation (Figure 2.7). According to ANSI/IES RP-1 [15], the most preferred lighting density for office workspace in United States is given in the range from 13.4 W/m^2 to 16.7 W/m^2. The model is simulated for the above-mentioned lighting density values along with the other base case parameters (Table 3.5).

Table 3.5. Altering the Lighting density to upper and lower limits.

Parameters	Indoor Temp	Amb Temp	Solar Rad	Infiltration (ACH)	Lighting density (W/m^2)	Equip density (W/m^2)	Occupant density (W)	Window glazing	Wall thickness
Base case values	23°	NSRDB	TMY	0.45	13.4	12.38	19200	Double Glazing	0.36
					16.1				
					16.7				

From the plot (Figure 3.8), it is observed that by increasing the lighting density, the radiative and convective indoor heat gain coming from the light increases, thereby increasing the cooling load during summer, and decreasing the heating load during winter. However, in contrast, by decreasing the lighting density, the indoor heat gains decrease, thereby decreasing the cooling load during summer and increasing the heating load during winter. In this case, for increasing and decreasing the lighting density to 16.7 W/m^2 and 13.4 W/m^2, 0.15% energy reduction is observed, and 0.89% extra energy is used, respectively. Henceforth, when increasing lighting by 3.7%, a marginal energy saving of 0.15% was observed. Conversely, when reducing lighting by 16.8%, there was an increase in energy usage by 0.89%. These results can be meaningfully compared to the findings in the literature study conducted by Ciobanu and Pentiuc [71]. In their study, they achieved a significant improvement in energy efficiency by employing 81.5% more effective lighting, resulting in a 44.21% energy efficiency improvement. The percentages in the current study may appear lower in comparison, but it's important to remember that different methods and scales of changes in lighting levels might have varied impacts on energy usage and efficiency. These variations might be explained by elements including architectural features, lighting control systems, and lighting technology.

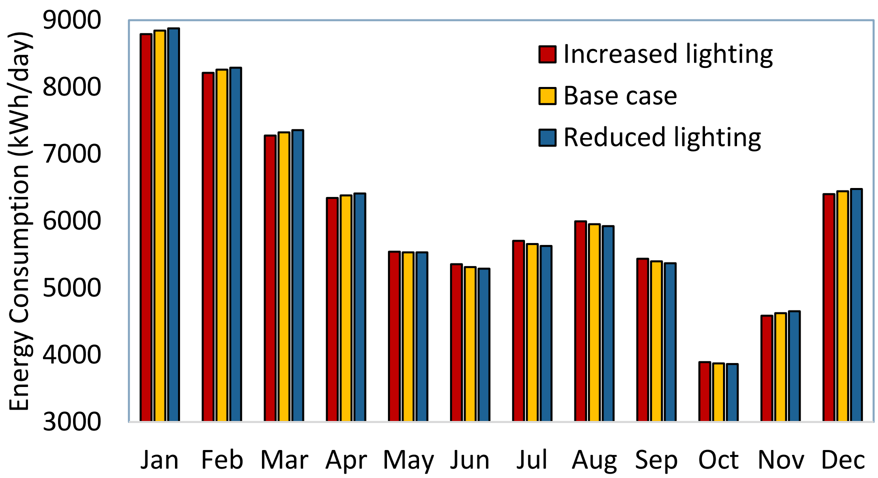


Figure 3.8. Variation of energy consumption by changing lighting density

3.3.5 Equipment density

Equipment density is the heat radiated from the machines and systems present in an office or any building. However, it is important to study equipment density in office buildings because of the number of operating machines present in an office space. According to the Energy Consumption Guide 19, the provided benchmark for the equipment load density is from 10 W/m^2 to 18 W/m^2 [16]. Therefore, the model is simulated for these two equipment density values and compared with the base case (Table 3.6).

Table 3.6. Changing the equipment density of the building.

Parameters	Indoor Temp	Amb Temp	Solar Rad	Infiltration (ACH)	Lighting density (W/m^2)	Equip density (W/m^2)	Occupant density (W)	Window glazing	Wall thickness
Base case values	23°	NSRDB	TMY	0.45	16.1	10	19200	Double Glazing	0.36
						12.38			
						18			

From the plot (Figure 3.9), it is observed that by increasing the equipment density, the indoor heat gains increase, thereby increasing the cooling load during summer and decreasing the heating load during winter. In contrast, by decreasing the equipment density, the indoor heat gains decrease, thereby decreasing the cooling load during summer and increasing the heating load during winter. Therefore, increasing and decreasing the equipment density to 18 W/m^2 and 10 W/m^2, results in 3.06% energy savings and 0.51% extra used energy, respectively.

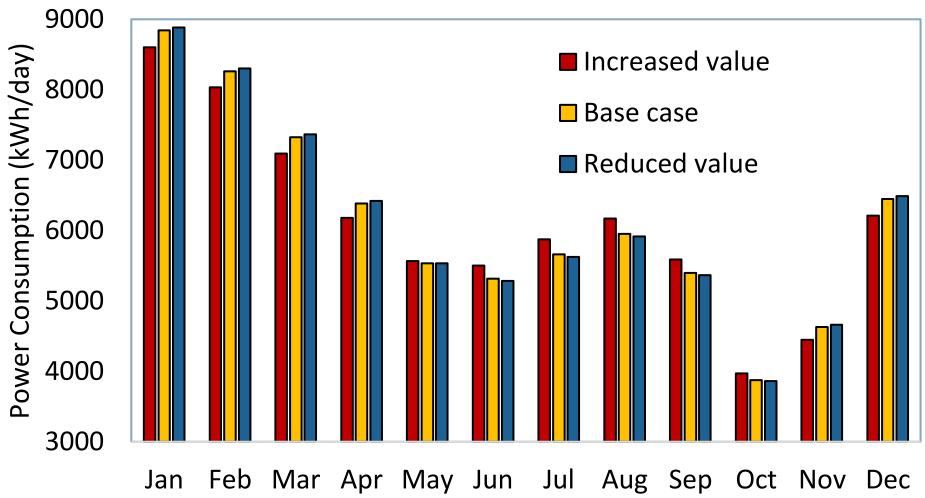


Figure 3.9. Variation of energy consumption by changing equipment density

3.3.6 Occupancy

Occupancy density is based on the number of people inside the building and the activities they perform. From Chartered Institution of Building Services Engineers (CIBSE) Guide, the heat emitted by a person is constant and given as 75 W/person [17]. Henceforth, the variable factor is presumed as the number of people which can vary by the absentees (as lower limit) and visitors (as upper limit) inside the building. According to the US Bureau of Labor Statistics [18], the absent percentage of employees in the US is found to be around 3% of the total office population. Therefore, with a total population of 256 people inside the building, 3% is 8 people. Rounding the number to 10, we a have lower limit of 10, i.e., 10 absentees and an upper limit of 10 i.e., 10 visitors to the building. Hence, the amount of reduced heat for absentees and additional heat for visitors is given as:

$$75 \text{ W/person} \times 10 \text{ people} = 750 \text{ W} \quad (25)$$

As shown in Table 3.7 the model is simulated for two new occupant densities, 18450 W and 19950 W. From the plot (Figure 3.10), it is observed that the change in energy consumption is negligible. Therefore, by considering the visitors and absentees in the occupants count, 0.08% energy savings is observed in the former case and 0.08% extra energy is used for the latter case.

Table 3.7. Varying the occupancy density of the building.

Parameters	Indoor Temp	Amb Temp	Solar Rad	Infiltration (ACH)	Lighting density (W/m^2)	Equip density (W/m^2)	Occupant density (W)	Window glazing	Wall U-value (W/m^2K)
Base case values	23°	NSRDB	TMY	0.45	16.1	12.38	18450	Double Glazing	0.4
							19200		
							19950		

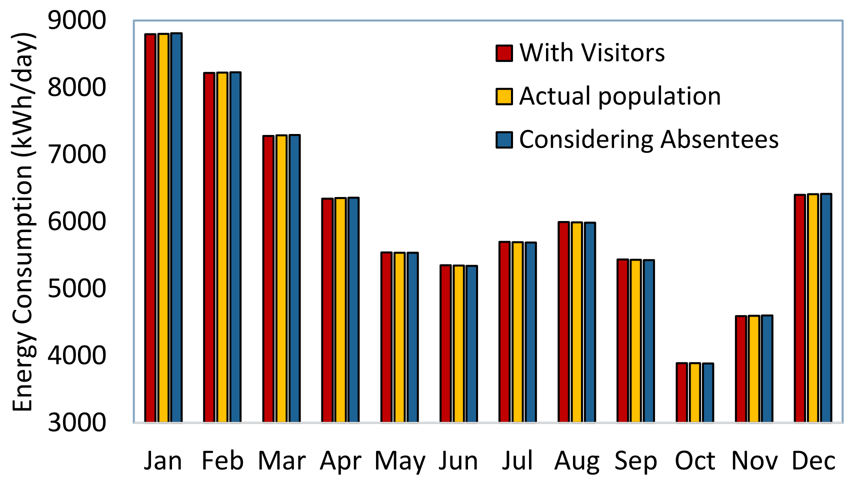


Figure 3.10. Variation of energy consumption by changing occupants inside the building

3.3.7 Window Glazing

Windows play a major role in allowing the solar gain to enter the building. Among the major window characteristics like WWR, U-value, g-value and transmissivity, window glazing is a key parameter that is used as the varying parameter in this case. In this context, the analysis is conducted for three different glazing scenarios, single glazing, double glazing (base case) and triple glazing, and the resulting energy consumption is plotted. The windows are selected according to the National Fenestration Rating Council (NFRC) standards, which is widely used in United States [19]. The single-glazed window selected has a U-value of 5.66 W/m^2K and g-value of 0.848. The double-glazed window that is also used for the base case has a U-value of 2.78 W/m^2K and g-value of 0.59. The triple-glazed window has a U-value of 0.73 W/m^2K and g-value of 0.3 (Table 3.8). These values are obtained from TRNSYS which uses the International Glazing Database (IGDB) for window properties [20]. Thus, the model is simulated and plotted for the three above-mentioned windows (Figure 3.11). From the plot, it is observed that the single-glazed windows consume the largest amount of energy, followed by the double-glazed windows, followed by the triple-glazed windows, irrespective of the time of the year. Henceforth, by replacing the window with triple-glazed windows, an 8.43% of energy savings is observed, whereas by replacing with single-glazed windows, 14.57% extra energy is used. Therefore, using triple glazing windows as a retrofit is a highly recommended method to achieve significant energy savings. However, the current cost of triple-glazed windows in the US market poses a challenge, which is significantly high compared to single- and double-glazed windows [21]. The results obtained in the current study can be closely compared to the findings in the study conducted by Hassan and Al-Ashwal [58]. In their research, they replaced a single-glazing window with a double-glazing window, resulting in a commendable energy savings of 19%. However, it's important to note that the observed difference in energy savings between the two studies may be attributed to various factors, including location of the building, building design, WWR, U-value and g-value of the windows, etc. As a result, even though the energy savings realized in both studies are comparable, the unique conditions and characteristics of each case have a significant impact on determining the extent of energy savings.

Table 3.8. Altering window glazing in the building

Parameters	Indoor Temp	Amb Temp	Solar Rad	Infiltration (ACH)	Light density (W/m^2)	Equip density (W/m^2)	Occupant density (W)	Window glazing	Wall U-value (W/m^2K)
Base case values	23°	NSRDB	TMY	0.45	16.1	12.38	19200	Single-glazed Double-glazed Triple-glazed	0.4

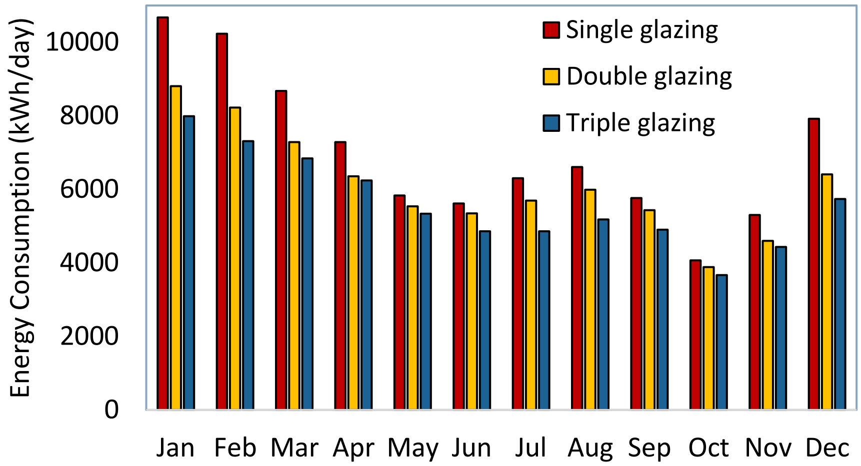


Figure 3.11. Variation of energy consumption by changing the window glazing

3.3.8 Wall U-value

Since, the building envelope acts as the only physical separator between the exterior environment and interior environment of a building, it plays a crucial role in the energy balance. Here, the U-values of the vertical walls of the building is altered to check the variation in energy use. U-value is given by the conductivity of the material divided by the thickness of the material. Thus, in order to change the U-value of the building envelope, either the conductivity can be altered by substituting a different material with the same thickness, or the same material can be added or removed to increase or decrease the thickness. In this case, the thickness of the CMU block used is altered by adding and reducing one CMU block from the base case scenario. The default base case consists of two combined CMU blocks, as shown in Figure 2.2a. In this case, for the lower limit, the wall is reduced to a one-layer block and, for upper limit, one additional block is added to the existing two-layer block (Figure 3.12). The dimensions of the blocks are taken from the standards developed by the American Society for Testing and Materials (ASTM) International [22].

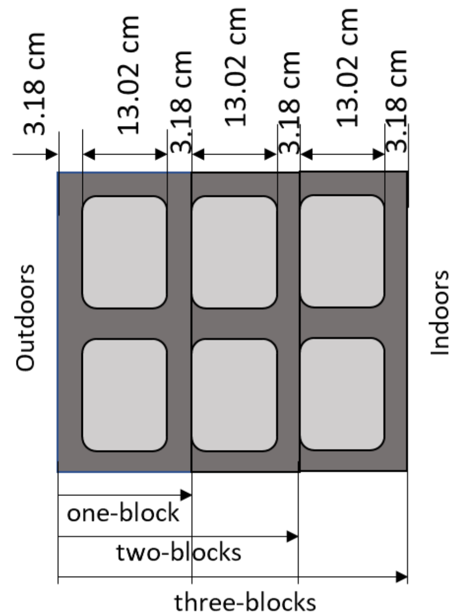


Figure 3.12. Multi-layered CMU blocks for the vertical walls.

For each of the wall thicknesses, the U-value is calculated, and the model is simulated (Table 3.9). According to the plot (Figure 3.13), the single-block envelope uses the most energy, followed by the two-block and three-block envelopes, regardless of the season. This is analogous to the previous case of the number of glazing of the glass in the windows. Thus, by using a three-block envelope 0.89% energy savings is recorded, whereas, for a single-block envelope, 2.66% extra energy is used. Therefore, using a building envelope with lower U-value is recommended to reduce energy usage; however, it usually comes with higher material costs and other structural disadvantages. The results obtained in the current study can be effectively compared to the literature studies referenced in the first chapter, such as those by Atmaca et al. [54], Al-Shamrani et al. [55], Al-Nuaimi and AlMadani [56], and others. Upon comparison, it becomes evident that the energy savings achieved in the current study are notably lower. This discrepancy can primarily be attributed to differences in the U-values of the building envelopes. In the referenced studies, energy savings were realized through reductions in U-values, often achieved by incorporating thermal insulation and implementing various retrofit measures. In contrast, the current case took a different approach by increasing the U-value of the building envelope by increasing the thickness of the building envelope, with no change in conductivity values.

Table 3.9. Changing wall U-value of the building envelope.

Parameters	Indoor Temp	Amb Temp	Solar Rad	Infiltration (ACH)	Light density (W/m^2)	Equip density (W/m^2)	Occupant density (W)	Window glazing	Wall U-value (W/m^{2}K)
Base case values	23°	NSRDB	TMY	0.45	16.1	12.38	19200	Double glazing	0.27
									0.40
									0.75

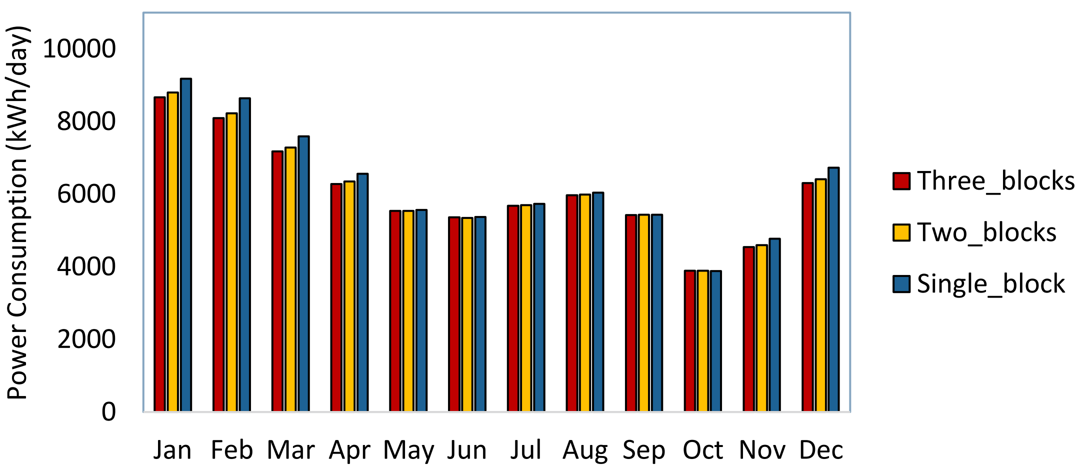
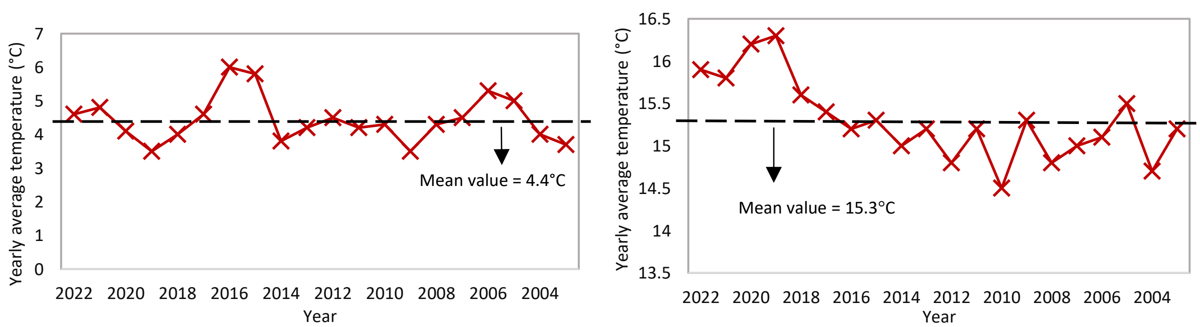


Figure 3.13. Variation of energy consumption by changing the wall U-value.

3.3.9 Impact of Climatic location

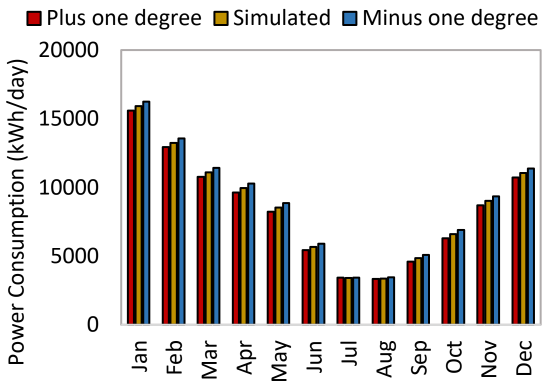
The fundamental idea is to conduct a parallel sensitivity analysis concentrating on the two specified locations: Edmonton and Mexico City. The primary goal of this endeavour is to investigate the changes in relevant parameters that result from the building's relocation. The section attempts to illuminate the correlation between geographical context and energy usage by inspecting these variances, providing useful insights into the potential alterations necessary for optimising energy savings.

The base case is defined with values similar to Table 3.1, by assigning the ambient temperature and solar radiation values for Edmonton and Mexico City, extracted from NSRDB [10]. Other parameters in the base case model are building parameters, which remain consistent, due to the utilization of the same building model throughout the study. The yearly average ambient temperature for the past 20 years in Edmonton is referred from the Environmental and Climate Change Canada [23] and illustrated in Figure 3.14a. The standard deviation of the values is calculated to be 0.7°C, which is approximately 1°C. Henceforth, the variation in energy usage values is calculated by adding and subtracting 1°C, with the other temperature values, to obtain the plot Figure 3.15a. Similarly, the yearly average temperature for Mexico City for the past 20 years is obtained from NSRDB [10] and the standard deviation is calculated to be 0.6°C (Figure 3.14b). Likewise, this can be approximated to 1°C and used for the sensitivity study for Mexico City (Figure 3.15b).

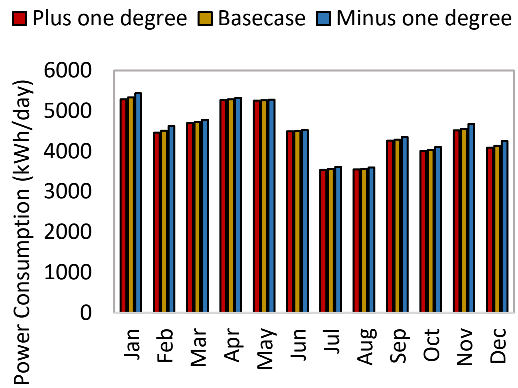


(a) (b)

Figure 3.14. Yearly average temperature data for the past 20 years in (a) Edmonton [48] and (b) Mexico [49].



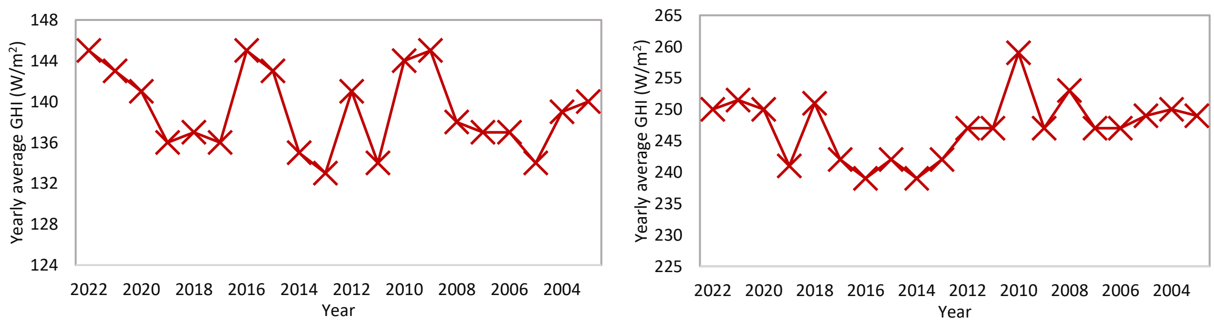
(a)



(b)

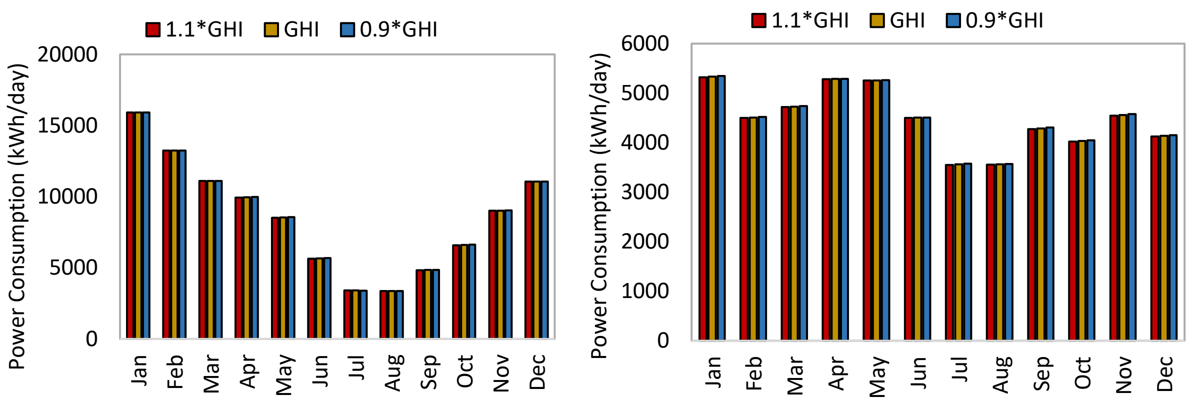
Figure 3.15. Variation of energy consumption by changing ambient temperature for (a) Edmonton and (b) Mexico City

In the same manner, the Global Horizontal Irradiance (GHI) data is sourced for both Edmonton and Mexico City from NSRDB [10], covering the past 20 years. This information is visualized in Figure 3.16. The standard deviations for GHI values in Edmonton and Mexico City have been calculated as 7 W/m² and 6 W/m² respectively. The ratio factor is calculated by adding and subtracting the above standard deviations from each of the GHI values from Figure 3.16 and dividing the new value by the original value. This process is repeated for all 20 GHI values, and the average ratio was found to be similar (for both cases) to that from the case of Philadelphia: 1.1 for the upper limit and 0.9 for the lower limit (Table 3.1). This adjustment is necessary as solar radiation is absent during nighttime hours, making simple addition and subtraction unsuitable in this context. Figure 3.17 is illustrated with a bar graph for the variations in energy consumption by changing the values of GHI according to Figure 3.16 for (a) Edmonton and (b) Mexico.



(a) (b)

Figure 3.16. Yearly average GHI data for the past 20 years in (a) Edmonton and (b) Mexico [49].



(a) (b)

Figure 3.17. Variation of energy consumption by changing Solar radiation (GHI) for (a) Edmonton and (b) Mexico City

Other parameters involved in the calculation, also called building parameters, are designed according to the selected office building. Since the same building model is used for the rest of the calculation, variation of these parameter's values remains consistent to what was used for Philadelphia location. For instance, (1) the infiltration rates are varied from 0.4 ACH to 0.5 ACH for both the designated locations to provide the plots given by Figure 3.18. (2) Adjustments are made in lighting (13.4 W/m^2 to 16.7 W/m^2), equipment (10 W/m^2 to 18 W/m^2), and occupants (8 people) based on ANSI/IES RP-1 [15], Energy Consumption Guide 19 [16], and US Bureau of Labor Statistics [18] guidelines, respectively. The energy consumption changes resulting from these variations are depicted in Figure 3.18, Figure 3.19 and Figure 3.20, respectively. (3) The type of windows is altered, switching between triple-glazing and single-glazing configurations with specifications detailed in Section 3.3.7. Finally, modification in the wall U-value is introduced through adjustments in the thickness of CMU blocks. The outcomes of these changes are illustrated through plots in Figure 3.21 and Figure 3.22, respectively.

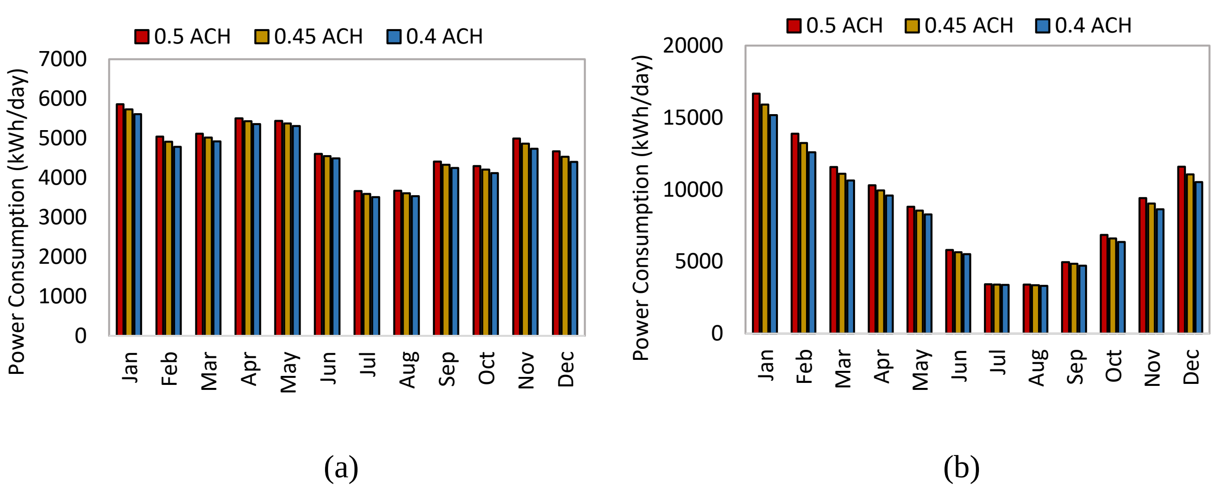
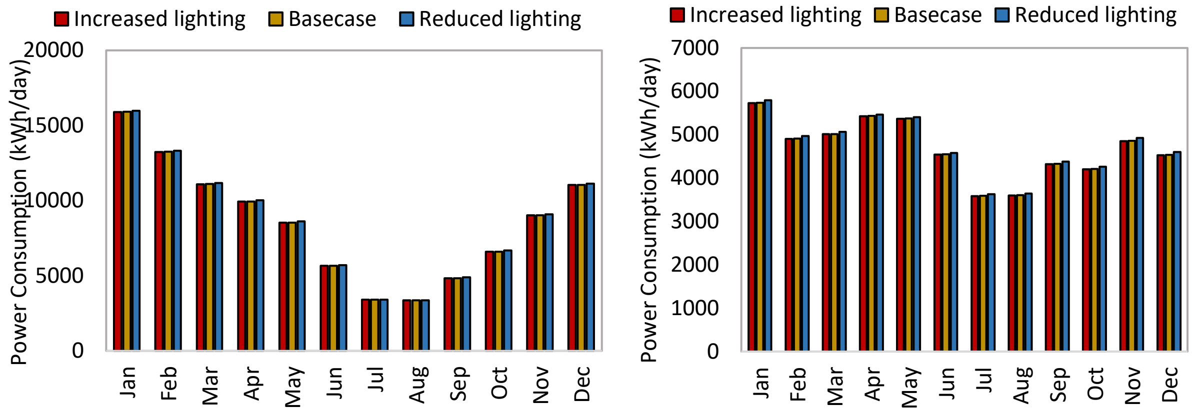
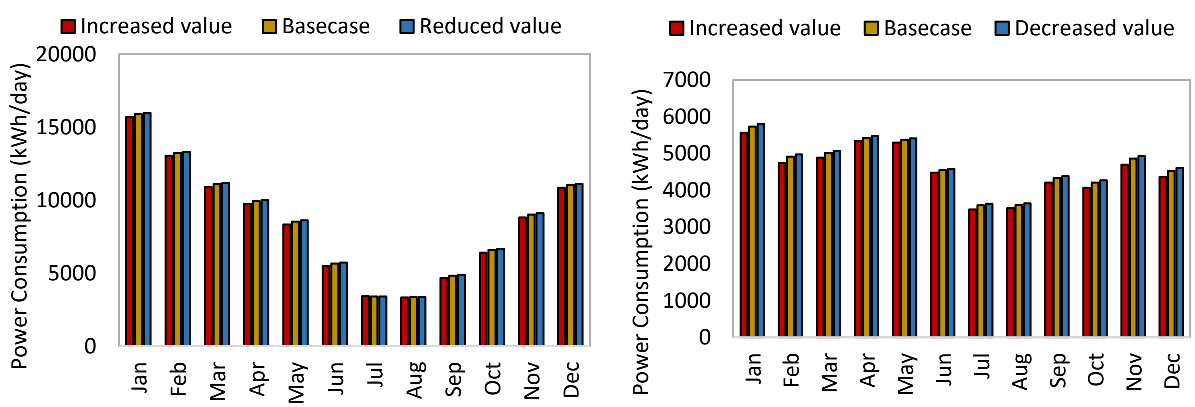


Figure 3.18. Variation of energy consumption by changing the infiltration rate for (a) Edmonton and (b) Mexico City.



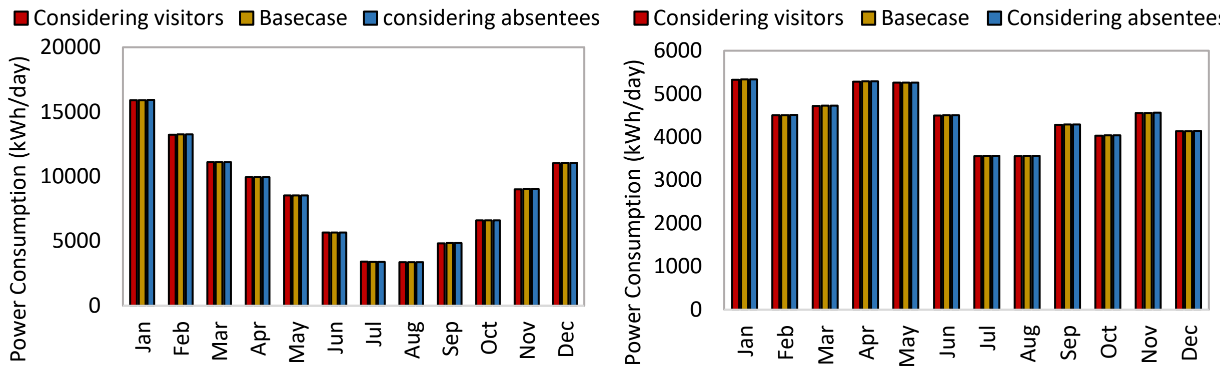
(a) (b)

Figure 3.19. Energy consumption variation by changing the lighting for (a) Edmonton and (b) Mexico City.



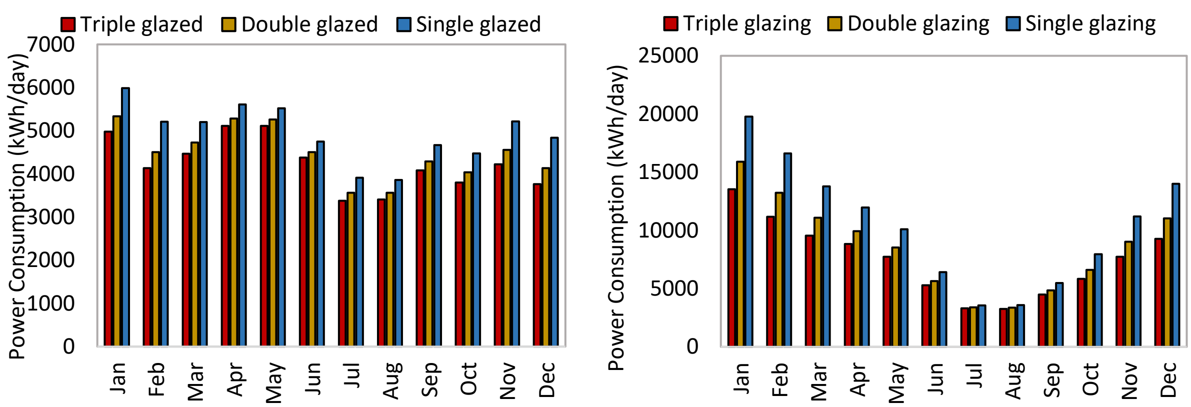
(a) (b)

Figure 3.20. Energy consumption variation by changing equipment heat for (a) Edmonton and (b) Mexico City.



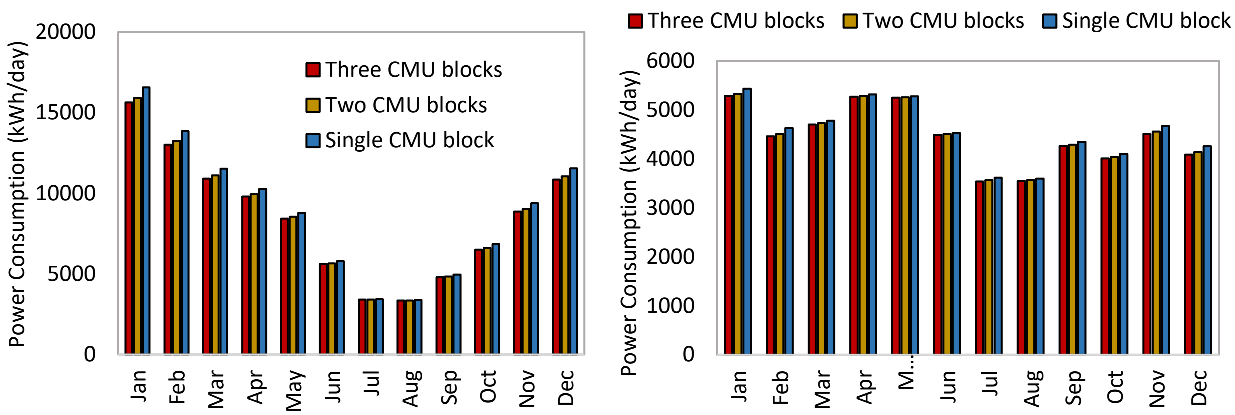
(a) (b)

Figure 3.21. Energy consumption variation by changing occupants for (a) Edmonton and (b) Mexico City.



(a) (b)

Figure 3.22. Energy consumption variation by changing window glazing for (a) Edmonton and (b) Mexico City.



(a) (b)

Figure 3.23. Energy consumption variation by changing wall U-value for (a) Edmonton and (b) Mexico City.

3.4 Discussion

From the sensitivity study conducted for the location of Philadelphia, the highest energy savings can be observed by changing the double-glazing window to triple glazing window, with low-e coefficient and low U-value. The change in energy consumption for each parametric variation in Philadelphia is illustrated in Figure 3.24. It is evident that the introduction of an additional glazing to windows with a WWR of 0.4, accompanied by a final U-value of 0.73 W/m²K and an emissivity of 0.54, results in a notable energy saving of 8.43%. Furthermore, adjustments in other parameters yield the following energy savings: (1) Raising the ambient temperature by 1°C results in a 4% reduction in energy consumption, (2) applying a multiplication factor of 1.1 to the GHI values leads to a 0.67% decrease in energy usage, (3) decreasing the infiltration rate to 0.40 ACH yields an energy reduction of 2.78%, (4) increasing the lighting to 16.7 W/m^2 will increase the indoor heat gains, leading to a 0.89% energy saving, (5) increasing the equipment density to 18 W/m^2

results in 0.51% savings, (6) increasing the occupant count to 266 people gives a 0.08% reduction in energy, and (7) finally, adding an additional layer of CMU block to the vertical walls gives us an energy saving of 2.66%. The positive value of the bar graph depicts the excess energy used by changing the parameter in the contrasting way compared to values mentioned above.

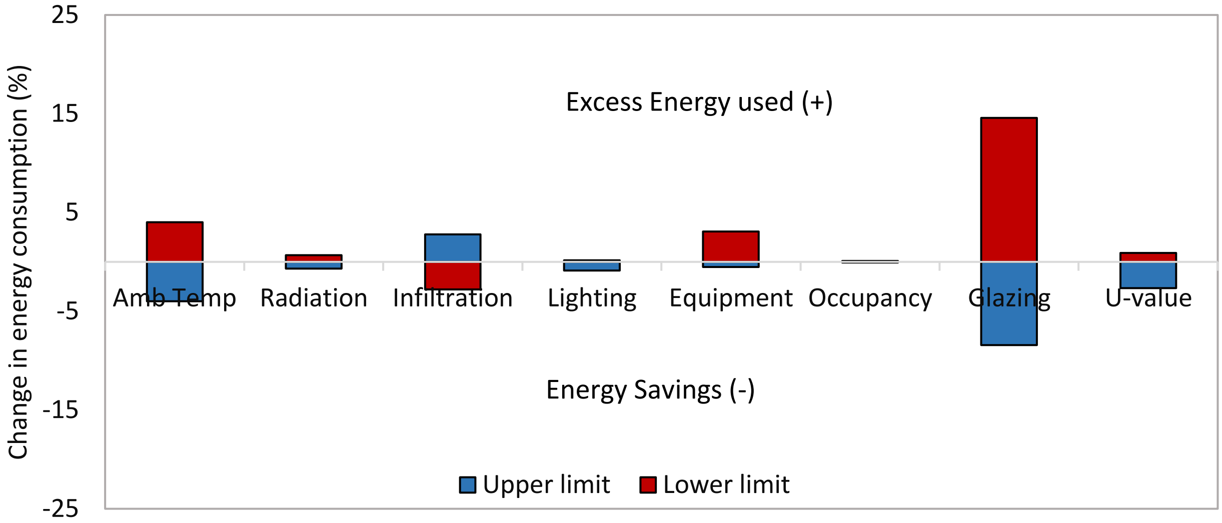


Figure 3.24. Sensitivity study results for the Philadelphia location

The same methodology is now employed and implemented for Edmonton and Mexico locations, and the energy savings figures collected are examined. The sensitivity study is conducted by varying one parameter at a time, and the energy values are plotted for Edmonton and Mexico as shown in Figure 3.25 and Figure 3.26. It can be observed that the window glazing still stands with the highest energy savings for both locations, with building in Edmonton gives 12.3% energy savings and building in Mexico City gives 5.44% energy savings, compared to overall energy consumption. It should be noted that by proposing the same triple glazing window with identical window specifications, to the office building at all the locations, more energy savings is shown in Edmonton followed by Philadelphia and Mexico City. It is important to note that, when considering the deployment of the same triple-glazed window retrofit in the office building across various locations, it becomes evident that Edmonton yields the highest energy savings, followed by Philadelphia and Mexico City. In real units, offering a triple glazing window in Edmonton saves 16.08 MWh per month more than proposing the same triple glazing window in Philadelphia for the same building. The difference is more in case of Mexico City, where the difference in energy saving is 24.27 MWh per month, with Edmonton more than Mexico City. To determine the electricity cost savings, one can refer to the present electricity prices for the respective locations to find that for Philadelphia, it is ¢20.2/kWh (USD), Edmonton, it is ¢24/kWh (USD) and for Mexico City, it is ¢21.2/kWh (USD) [24-26]. Through the implementation of triple-glazed windows, the office building situated in Philadelphia, Edmonton and Mexico City achieves a monthly saving of $3133.02, $7581.60, and $1,551.84 (all $ in USD). These prices are not directly comparable due to variations in window material expenses, maintenance costs, and labor rates across different cities.

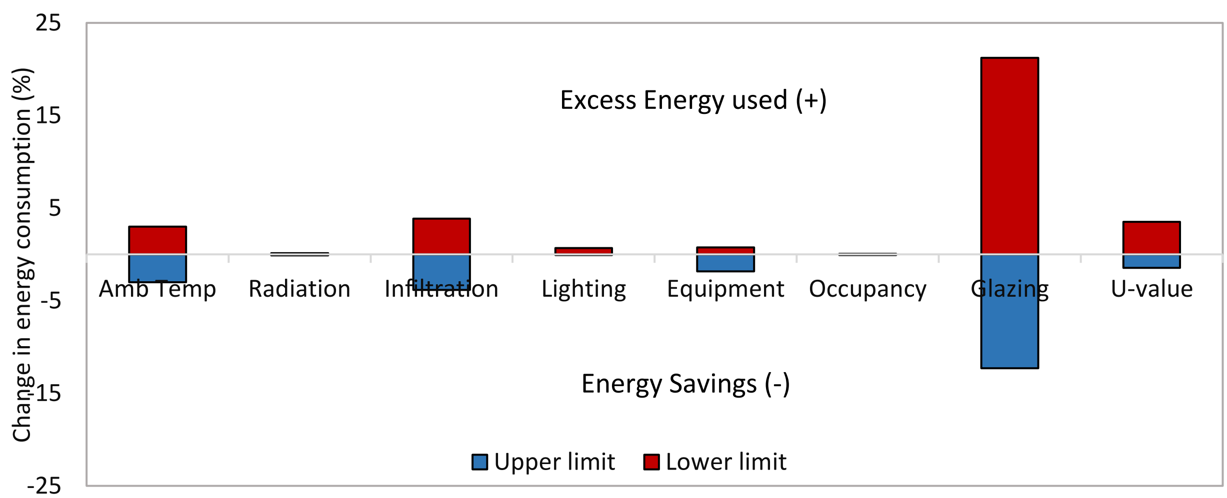


Figure 3.25. Sensitivity study results for the Edmonton location

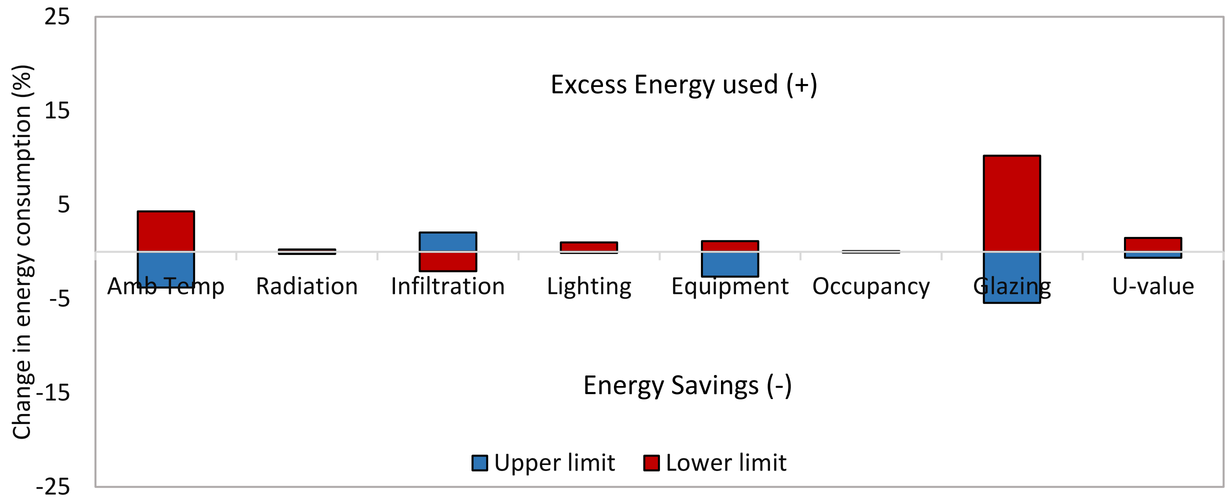


Figure 3.26. Sensitivity study results for the Mexico City location

3.5 Conclusion

Conducting a sensitivity study on a building's energy consumption necessitates a thorough examination of the key variables within the energy equation. When seeking to implement new architectural designs or retrofit strategies aimed at energy reduction, a sensitivity analysis becomes essential to evaluate the influential factors included in the calculations. This chapter analyzes the important parameters derived from the energy balance equation to conduct a sensitivity study for energy consumption by varying one parameter at a time. It is observed that, by conducting the sensitivity study for the existing building location – Philadelphia, changing the window parameter to a triple-glazed window is found to have the highest contribution towards energy saving of 8.43%.

Furthermore, to evaluate the location impact on the sensitivity study by involving the locations Edmonton and Mexico City, it is found that the order of impact on energy savings remains the same as the Philadelphia location. However, it is found that by changing to a triple glazed window, building in Edmonton is found to have 12.3% energy saving and building in Mexico City is found to have 5.44% energy saving. Henceforth, by replacing with the same triple-glazing window for the same office building, building in Edmonton is found to save more energy compared to building in Philadelphia and Mexico City by 16.08 MWh and 24.27 MWh per month, respectively. Evaluating the equivalent electricity prices for the respective cities, monthly cost savings are found to be $3133.02, $7581.60, and $1,551.84 in Philadelphia, Edmonton, and Mexico City, respectively (all $ in USD).

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CHAPTER IV

Conclusion and Recommendations

4.1 Conclusion

Given that buildings are responsible for 40% world's energy consumption and GHG emissions, it is essential to focus on the effect of energy conservation [1]. Energy consumption and its corresponding ecological effects can be mitigated by incorporating renewable energy sources, designing energy-efficient structures, and promoting sustainable actions. This study prioritizes energy usage in its computations. As a result, it seeks to detect and alter possible parameters to feasibly reduce total energy use.

TRNSYS is the software utilized in this paper to conduct the building simulations. The software allows engineers, scientists, and designers to simulate and assess how various energy systems and combinations work in various scenarios. The versatility of TRNSYS in complex modeling and its capacity to simulate transient models makes it well-known among building research community [2-6]. Furthermore, the reliability of the TRNSYS model is checked in this paper to verify whether the model is qualified for further calculations. This is carried out using a simple case by varying the indoor temperature with respect to a sinusoidal ambient temperature and neglecting other input parameters. The thermal mass of the building envelope is illustrated from Figure 2.9, where a considerable thermal delay of 15.7 hours is observed with a thermal attenuation of 9.68°C. Similarly, for the second case, a thermal delay of 17 hours is obtained by changing the power demand according to ambient temperature, keeping the indoor temperature constant (Figure 2.10). These findings lend credibility to the designed TRNSYS model as reliable for further analysis.

The key parameters involved in the calculation are identified, encompassing ambient temperature, solar radiation, infiltration and ventilation, heat transfer coefficient, ground temperature, internal gains – lighting, equipment, occupancy, and building envelope. Chapter 2 deals with defining these variables according to the allowable building codes and standards, along with the input from the reference paper of the actual building. Considering the variability of infiltration rates, predictive modeling is carried out for two different infiltration rates, extracted from 2017 ASHRAE fundamentals [7]. It is found that the measured results fall in between the simulated energy consumption values for assigned infiltration rates: 0.25 ACH to 0.85 ACH (Figure 2.7). Henceforth, the analysis results in a range of infiltration rate at which this specific office building operates at all conditions.

The assigned parameter from predictive modeling is varied to conduct a sensitivity analysis on the energy consumption to find the highest impact parameter. To understand the role of each parameter on the energy usage, energy balance equation is defined with detailed explanation of each term along with the heat transfer mechanism through the building envelope (Equation 17, Figure 3.1). In conducting the sensitivity study, a base case is defined, and one parameter is varied at a time from the base case, according to the previous weather data, building codes and standards, and commercially available building envelopes. The highest energy saving is observed by changing the windows to triple-glazing from double-glazing, which results in 8.43% energy savings.

The impact of geographical location on energy consumption is obtained by conducting a similar sensitivity study on the same building for the location Edmonton and Mexico City. The parameter with maximum energy saving remains the same for both the location. However, it is observed that by implementing the same triple-glazing retrofit, the energy saving in Edmonton is found to be 12.3%, and in Mexico City, it is found to be 5.44%. Furthermore, upon comparing the electricity expenditures in the three cities, the analysis reveals that through the adoption of a triple glazing retrofit, the office building in Philadelphia, Edmonton, and Mexico City realizes monthly savings of $3,133, $7,582, and $1552, respectively. However, these prices are not directly comparable owing to differences in window material costs, maintenance costs, and labour rates between cities.

It's critical to take into consideration the energy consumption behaviour imposed by the location while making investments in energy-efficient building designs, retrofit projects, or aiming for Net Zero energy goals. This entails carrying out in-depth energy modeling, analyzing the climate, and the potential variables. Thus, examining and addressing the geographical variation in energy usage increases the efficacy of energy-efficient projects, leading to more investment opportunities across the globe.

4.2 Recommendations

This study encompasses a comprehensive building energy analysis model that examines the influence of location-specific parameters on the calculations. Although an estimation of monthly energy cost savings has been computed for Philadelphia, Edmonton, and Mexico City, factoring in electricity prices, a more intricate life cycle cost assessment should be conducted. This would involve capturing the present triple glazing window costs, construction expenses, and maintenance costs to determine the payback period through energy savings.

Furthermore, while this sensitivity analysis varies one parameter at a time, exploring adjustments to two or more parameters concurrently could yield greater energy savings. Subsequently, conducting the corresponding life cycle cost analysis would provide insights into the viability and potential benefits of such modifications.

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