Modeling and Energy Simulation of and Educational Building,

A case study in Pakistan

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Copyright Statement

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Abstract

Climate change is increasing the average temperature of world due to emission of greenhouse gases (GHGs) in large amount. This has increased the annual energy consumption of buildings. These energy demands are fulfilled by non-renewable energy resources mostly. The infrastructural development in the fields of educational buildings, hospitals, industries, etc. is necessary requirement for growing country like Pakistan. The building sector of Pakistan consumes approximately 50 % of country's total energy. To reduce the energy consumption of the buildings, different passive climate adaptation measures (PCAMs) can be implemented. In this study, several low-cost and medium-cost passive measures and their combinations were applied on the building model. This study analyzes their effects on annual energy consumption of the educational buildings in Pakistan. Energy simulations were performed by implementing these passive measures using DesignBuilder. The result shows that 2 °C variation in temperature setpoints and green wall are the most effective passive measures for reducing the annual energy consumption of the building. The implementation of these passive measures can reduce the cooling and heating energy consumption by 27.18 % and 62 % respectively. The energy use intensity (EUI) of the SMME building was 154.71 kWh/m^2/year which is higher than EUI requirement for buildings. Furthermore, the payback period of each passive measure and their combinations was also calculated. Variation in temperature setpoints can reduce the significant energy consumption with a zero-payback period. Finally, the cost benefit analysis was performed to suggest some low-cost and medium-cost passive measures.

Key Words: Building energy consumption, Energy simulation, Educational building, Passive climate adaptation measures, Energy use intensity, Pakistan.

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CHAPTER 1: INTRODUCTION

The research work in this chapter gives a brief overview about the energy consumption of the buildings in the world as well as Pakistan. In this thesis, different passive climate adaptation measures are applied on an educational building in climatic conditions of Pakistan to reduce the energy consumption of the building. These passive measures are implemented on the building by using simulation software known as DesignBuilder. The aim of this chapter is to give a brief introduction about this study. This chapter includes the background, motivation, scope, and objectives of the study.

1.1 Background

The human activities are the major reason of global warming and climate change. The continuously use of fossil fuels to meet energy demands has caused the rise in greenhouse gases (GHGs) in the atmosphere. Studies have found that there will be an increase in global temperature from 1 to 3.7 °C during the span of 21st century depending upon on GHG emissions [1]. This has caused the significant impact on energy consumption of all sectors. Disasters like floods, heatwaves, volcanic eruptions, storms, and forest fires are happening more frequently than ever. Studies have discovered that the heatwaves in the 21st century are going to be life threatening as well as will be long lasting [2]. Due to rapid growth of human population, energy demands are increasing every day. Infrastructure development in the fields of educational buildings, hospitals, industries, technology parks, etc. is a necessary requirement for a growing country. The increase in energy consumption was observed due to growth of infrastructure sector at a rate of 12.5% [3]. Building sector constitutes the 40% energy consumption of the world and in Pakistan building sector consumes 55% of its total energy consumption. Educational building is third most energy consuming non-residential building. Different strategies are being applied by the organizations to reduce the energy consumption in the buildings. In a study, it was suggested that government should focus on renewable energy sources to meet energy demands. It was also suggested that Pakistan should follow the path of European countries like Denmark, Norway, Germany etc. who have increased the use of renewable energy sources as to reduce the emissions of CO_2 that are directly related to energy consumption [4].

Another related study was carried out by [5] in the hot climate of Abu Dhabi, UAE to observe the human activities impact on office, dormitory, and classroom buildings. It was observed that classroom is the most sensitive building among all. It was suggested that the researchers should focus on classroom building which can result in considerable energy savings. It was also suggested that multiple passive strategies should be applied in the building to reduce the energy consumption without compromising the thermal comfort as well as well-being of the residents.

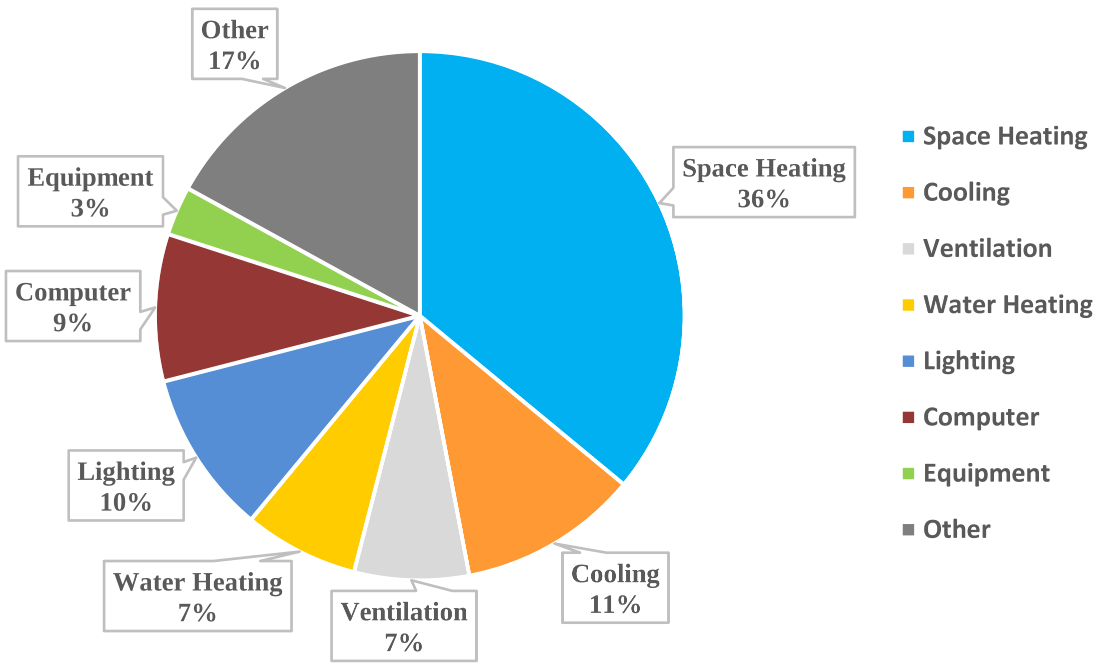


Figure 1.1: Energy consumption breakdown of an educational building based on CBECS data

The Commercial Building Energy Consumption Survey (CBECS) data for the year 2012 revealed the energy breakdown of an educational building shown in Figure 1.1. It was observed that space heating consumes 36% of total energy consumption followed by cooling 11%, lighting 11%, computer 9%, etc. [6]. In another study [7], a university building was selected in Wuhan city of China to optimize the energy demands. In this study, different simulations were carried out using 10 passive climate adaptation measures for the optimization purpose. It was observed that by selecting the combination of 4 optimum parameters resulted in energy savings of 4% without compromising the thermal comfort.

1.2 Motivation

The increasing temperature is significantly affecting the thermal comfort of the occupants in the building. Thus, the people are forced to use the active cooling systems even more. This results in increased cooling energy consumption of the building. To tackle temperature change, most of the residential buildings and commercial buildings including educational buildings have installed active cooling systems. Even the residential buildings in rural areas are now installing air conditioning systems. This is contributing to greenhouse gas emissions in the atmosphere.

Most parts of the country face extreme temperatures in summer that eventually leads to use of air-conditioning systems and other cooling sources. Most of the buildings in the Pakistan are not constructed according to standards that also lead to increase in energy consumption. So, there is need to perform energy simulations on building prior to construction works. This will also help us to improve the energy security of the country.

To overcome these problems, there is a dire need of implementing passive climate adaptation measures on the buildings to reduce the energy consumption as well as energy demands in the buildings. PCAMs have significant effect on reducing energy usage in the buildings. Some of the studies are explained below.

[8] carried out a study in the residential building of Netherlands to evaluate the influence of PCAMs on cooling and heating energy utilization. Simulation was performed using different combinations as well as different orientations. It was observed that by implementing external shading or natural ventilation, cooling energy demand can be reduced by 59-74% approximately and heating energy savings were almost negligible. Another study was performed by [9] in the lightweight as well as semi-portable residential building in Netherlands to evaluate the impact of PCAMs on energy requirement for heating and cooling. This study was performed using simulations for the current and 2050 climatic conditions. The results showed that annual heating and cooling requirement can be lowered by 11% for current and 15% for future scenarios. It was also observed that annual energy savings of 4% for current conditions and 3% for future climate conditions can be achieved by the optimization of building orientation. A recent study [10] was carried out in an educational building located in Karachi, Pakistan. It focuses on reduction in indoor environment temperature as well as cooling energy demand by implementing passive energy efficiency measures. It was observed that by replacing single glazing windows with double low emissivity electro reflective glass windows resulted in reduction of cooling energy demand by 8.6%. The minimum indoor temperature that was observed was 29.4 °C from 34.3 °C by applying optimum combination of strategies. [11] carried out a study in the residential building of Quetta, Pakistan to identify the most impactful passive measures on thermal comfort by performing sensitivity analysis.

It was observed that passive measures like thermal control passive solar heating as well as passive cooling can improve the comfort of the building without using any type of mechanical systems.

1.3 Scope of the Study

As already mentioned, educational buildings are ranked third for consuming more energy in the category of non-residential building. Educational buildings use active measures such as HVAC systems that are major cause of GHG emissions, leading to global warming. So, it is necessary to implement PCAMs on the educational buildings to reduce the dependency of the buildings on active measures. These passive climate adaptation measures will help to reduce energy utilization of the buildings without affecting the thermal comfort of the residents.

This study evaluates the performance of School of Mechanical and Manufacturing Engineering (SMME) building located in National University of Sciences & Technology (NUST), Islamabad by focusing on the energy consumption analysis. Islamabad, the capital city of Pakistan is selected to carry out the energy simulations. Islamabad is classified as humid and subtropical (Cfa) climate according to Köppen-Geiger climate classification system.

According to best of my knowledge, only few studies were conducted concerning the implementation of passive measures on buildings in the climatic conditions of Pakistan. However, no elaborated study was carried out in which passive measures are implemented individually as well as their combinations for reducing the energy consumption of an educational building in Pakistan.

The implementation of passive climate adaptation measures does not need any type of energy, so there is no chance of GHG emissions. These measures not only help us in reducing energy consumption of the building but also helps in mitigating the effects of global warming. The passive measures used in this study are natural ventilation, short-wave reflectivity, green roof and green walls, window shading, window glass thickness, window glazing, and temperature set points.

1.4 Research Objectives

Following are the objectives of this research:

1. To model and simulate SMME building energy consumption.
2. To calculate energy use intensity (EUI) of the SMME building.
3. To suggest low and medium cost passive measures for reduction in energy consumption.

1.5 Thesis Structure

This section contains the thesis structure that have been followed. This thesis contains 5 chapters which are as follow:

Chapter 1: This chapter contains the introduction of the thesis. It outlines the thesis background, scope, motivation as well as research objectives.

Chapter 2: This chapter focuses on the literature review of past studies that have been conducted related to energy consumption of the buildings such as educational, residential, etc. It also explains several PCAMs than can be used to reduce energy consumption of the building.

Chapter 3: This chapter involves the methodology that have been carried out to perform the energy simulations. It also contains the building modeling and construction details.

Chapter 4: This chapter focuses on the results obtained by implementing passive climate adaptation measures on the building. It also contains the base case results, model validation as well as cost and payback period of PCAMs.

Chapter 5: This chapter provides the conclusion of this research. It also focuses on the future recommendations that can be carried out.

CHAPTER 2: LITERATURE REVIEW

In the past, various research has been carried out to reduce the energy usage in the building domain. These studies were carried out using actual data as well as computer simulations. Many studies have been carried out using different passive climate adaptation measures in the commercial sector for different climates across the world. Some studies were carried out on residential, industrial as well as educational sectors in different cities of Pakistan. Some of these studies are discussed in this literature review section.

2.1 Climate Change around the World

The increase in temperature due to human activities is eventually leading to global climate change. Climate change can cause severe consequences on the society. Many countries across the world are giving social awareness to their people related to this issue on media [12]. The climate change and increasing population are the major reasons behind the increase in energy consumption of the buildings. The global climate change can lead to increase in cooling energy demands up to 72% over the next few years [13]. Climate change have serious impact on our daily life. The increase in temperature on regular basis can increase the chances of heatwaves as well as the forest fires. Thousands of the people lost their lives due to heatwaves during 2015-16 in India. It was reported that rise in heatwaves was due to increase in global warming [14].

The increase in temperature is usually more in Pakistan as compared to global temperature average due to its warm climate. This puts Pakistan at a risk of climate change [15]. Several research has been carried out to understand the influence of climate change on the human health. One such study [16] was carried out in the city of Karachi. Karachi is the most populated city in Pakistan. The annual average temperature and highest temperature recorded was 25.9 °C and 44.8 °C respectively. It has also suffered from the severe heatwaves over the years. In 2015, a lethal heatwave led to killing of more than 1200 people in 10 days only. These heatwaves were due to increase in mean temperature of 2.25 °C over the last 59 years. As a result of these heat spells, it was noted that many patients were admitted to hospitals.

2.2 Global Warming

The impact on climate is huge due to different human activities such as large-scale use of fossil fuels and deforestation. These activities result in carbon emissions and GHG emissions. A rapid increase has been observed in the anthropogenic gases over the years. These gases are real threat to human life in this world. The main source of CO_2 emissions is the burning of fossil fuels [17]. Global warming is directly leading to increase in annual temperatures around the world. It was observed that in the 21st century, the temperature will get about 20% more warmer than the world in the Mediterranean region [18].

Different countries are trying their best to reduce their dependency on the fossil fuels. This act will ultimately help us to mitigate the Greenhouse gases as wells as the CO_2 emissions. The best way to reduce the burning of fossil fuels is to move towards renewable energy resources. The humans have already contributed so much to the global warming that even if we stop emitting GHGs today, it will take decades to mitigate the effect of these gases as they are trapped in the air for many years [19].

2.3 Building Energy Consumption

Energy Consumption is increasing day by day due to rapid growth in human population. This has accelerated the energy demands across the globe [20]. Figure 2.1 shows that the building sector consumes almost 40% energy of the world [21]. Building sector includes commercial as well as residential buildings. About half of energy consumption in the buildings is used for space heating and cooling. Therefore, to reduce energy global energy demand, building energy consumption must be reduced.

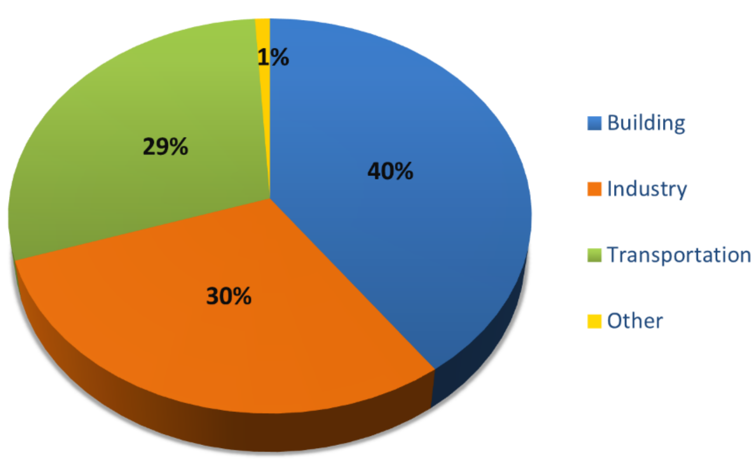


Figure 2.1: Energy consumption in different sectors

Climate change significantly affects the building energy usage. In the building sector, residential buildings are contributing to one third of GHG emissions worldwide. This has grown the risk of climate change and global warming [22]. Educational buildings are the third largest non-residential building category in terms of energy consumption [23]. As public buildings are larger in size than residential buildings, so there is greater potential of reducing building energy consumption [24]. Different retrofit measures can reduce energy demand in building sector leading to improved energy performance of already existing buildings [25].

Pakistan is a developing country, trying to meet the energy demand. Pakistan is blessed with greater potential of renewable energy resources but still heavily relying on use of fossil fuels that are finite and going to end sooner or later [26]. Figure 2.2 represents the energy mix of Pakistan for the year 2020 [27]. It can be clearly seen that oil, hydro and gas are the major energy sources to meet the country's energy. Pakistan's energy mix is mainly based on fossil fuels 61% and hydro power is expected to grow from 29% to 40% by 2040.

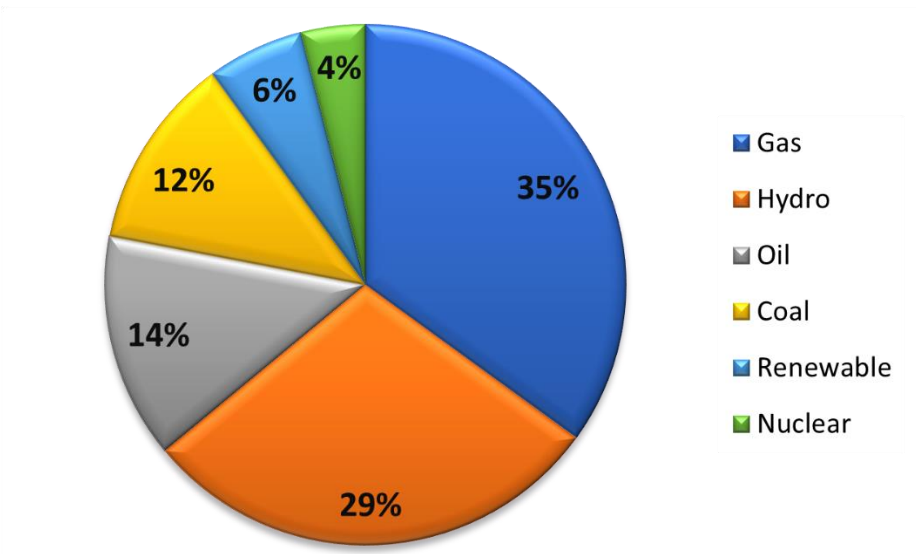


Figure 2.2: Energy mix of Pakistan for year 2020

Building sector consumes 40% of world's energy but buildings in Pakistan are consuming 55% of the country's total energy. Non-implementation of building codes in Pakistan is the possible reason behind high energy consumption by buildings. The major portion of building's energy consumption is being used to meet heating and cooling demands [28]. Several studies have been conducted on reduction in building energy consumption. Some of these prominent studies are explained in section 2.4.

2.4 Previous Studies

Monna et al. [29] conducted a study in a residential building of Palestine. In this study, passive measures of three cost levels were applied for reduction in energy consumption. Level 1 was low expense measures in which variation in heating and cooling set points were done. It resulted in reduction in energy consumption up to 19-24%. In level 2 was medium-cost measures were implemented. Along with level 1 measures, insulation of roof and walls, window shading and glazing, natural ventilation, changes in electric lighting were made. These changes resulted in 50-57% reduction in energy consumption. Level 3 was high-cost measures in which efficient heating and cooling systems, mixed ventilation, water heating systems using solar were applied in addition to first 2 measures and 71-80% reduction in energy consumption of the building was observed. Another study [30] in the residential building was conducted by Anwar et al. in Pakistan. In this study, different passive climate adaptation measures were applied on the building to get the suitable combination for reduction in building energy consumption. It was observed that by the implementation of PCAMs, cooling and heating demands were reduced 27.75% and 35%, respectively. Balbis-Morejón et al [31] conducted a study in the educational building of Colombia in which energy usage of the building was assessed using already installed AC system and then by replacing it with variable refrigerant flow (VRF) direct expansion system. It was observed that air conditioning system has the highest energy utilization of the building approximately 66%. It was also observed that by the installation of VRF systems, approximately 38% energy savings in electrictity consumption, 50% savings in initial investment, 30% in maintenance and 35% in life-cycle cost could be made. Another study [32] was conducted in 3 different cities of Pakistan by Hamza, 2020. in which residential as well as educational building was discussed. In this study, future weather files were generated using morphing method and future energy demand was predicted for 2020, 2050 and 2080. Building energy simualations were performed on buildings for different climates of Pakistan. A significant increase in cooling demands during summer and decrease in heating demands were observed. It was also monitored that a residential buiding in Lahore required 51.85% more energy as compared to now to meet the energy demands. 2.44% reduction in annual average relative humidity was observed in 2080 as compared to now in the city of Islamabad. Another study [21] was conducted in the office building of the university in Iran. In this study, the building was first modeled and simulated in DesignBuilder using 2 different scenarios. Simulations were performed with and without phase change materials (PCMs) as well as using different combinations of PCMs on the south wall of the building for potential reduction in building energy consumption. It was observed that using combinations of PCMs resulted in significant reduction in energy consumption as compared to single material. In the best scenario. 3.8% reduction in energy consumption was observed. Márquez-Martinón et al. [33] conducted a study in the residential buildings of Finland, Spain and Germany in which energy simulations were performed using different combinations of 4 factors i.e., insulation, internal partitions, region and building typology. Simulations were performed for the cooling and heating energy demands as well as the energy consumption of three different european cities. It was observed that the highest and lowest heating demands that can be improved were 72% in rectangular building of Madrid and 46% in inner courtyard building of Helsinki, respectively. It was also assessed that by using insulation in the building slightly decreased the cooling energy demand. Similarily, heating consumption also showed a decreasing trend with the use of insulation.

2.5 Energy Use Intensity (EUI)

The ratio of a building's energy consumption for a year to the building's total area is referred to as the energy use intensity of a building, and it is usually measured in kWh/m^2/year. The energy use intensity is usually calculated to compare the energy consumption of different buildings, and the energy use intensity is often compared with standards of that type of buildings set by the country. Sometimes, it is also represented as building energy index. The formula to calculate the EUI of the building is given below:

$$\text{Energy use intensity (EUI)} = \frac{\text{Total energy consumption (kWh / year)}}{\text{Total floor area } (\text{m}^2)}$$

A study [34] was carried out in the hospital building of Malaysia in which building energy index was calculated for a hospital building and to make comparison with other hospital buildings as well as Malaysian standards for hospital buildings. It was observed that approximately 63% of total energy consumption of the building was used by AC systems, 18-22% for the lighting purposes and approximately 17% for the other equipment. It was noted that BEI of the building was 384 kWh/m^2/year, and it was way above the country standards that recommends 200 kWh/m^2/year BEI for the hospital buildings. It was also higher than the previously investigated hospitals having a building energy index less than 300 kWh/m^2/year. In another study, it was observed that EUI for the residential buildings of Pakistan is 24 kWh/m^2/year.

2.6 Passive Climate Adaptation Measures

Passive climate adaptation measures (PCAMs) are the passive measures that are applied to the existing building for the reduction building energy consumption. PCAMs can be classified into low, medium, and high-cost measures according to their prices. These measures help us to reduce the energy consumption of the building. Many PCAMs have been analyzed in the past studies for different type of buildings under different climatic conditions. In this section, different passive climate adaptation measures are discussed that were used for reduction in energy consumption of the educational building. Simulations have been performed using these PCAMs and results have compared with the base scenario of the building. These passive climate adaptation measures are briefly explained below:

2.6.1 Short Wave Reflectivity

The reflection of short-wave radiations from the building's surface is known as albedo effect. In this passive measure, instead of cemented grey color, white paint is applied on the surfaces that are directly exposed to sun for the reduction of energy consumption. This passive climate adaptation measure can also improve the thermal comfort of the building in addition to reduction in cooling energy consumption. There are direct as well as indirect benefits by the implementation of short-wave radiation on the building surfaces. By performing simulations, energy savings up to 41% as well as improvement in thermal comfort by 23% were observed due to direct and indirect effects, respectively [35].

Cooling energy consumption in the buildings of Gulf countries are higher than the other regions due to hot climate. So, by the implementation of short-wave reflectivity materials can reduce the cooling energy loads. A study [36] was conducted to check the effects of short-wave solar reflectivity on the energy consumption of the household building located in Saudi Arabia. By replacing common roof with the short-wave reflectivity materials resulted in reduction of total energy loads by 25%. In another study [37], different PCAMs including short-wave reflectivity was implemented on three different types of residential buildings in Netherlands. It was observed that by increasing the short-wave reflectivity, average overheated hours and degree hours were reduced. This measure was most effected in detached house as compared to terraced house and apartment.

2.6.2 Green Roof and Green Wall

Green roof and wall are often referred as Vegetated roof and wall. In this technique, an extra layer of grass or plants is added to the roof and walls for the insulation purpose. It is very useful for the improvement of energy performance of buildings. It should be kept light weight to avoid overloading of the roof. This passive measure not only helps in energy savings but also provide environmental advantages [38]. Green roofs are usually divided into 2 types i.e., extensive green roof and intensive green roof. The extensive green roofs are lighter in weight such as grass and requires minimum maintenance. On the other hand, intensive green roofs are heavier in weight such as small trees and are planted at a deeper level. The only constraint is that intensive green roofs can cause roof overloading as compared to extensive one.

A study [39] was performed to analyze the performance of green roof on the existing buildings. It was performed at the Mediterranean city of Catania in Italy by Cascone et al. in which different types of green roofs were applied to find out the load limit for existing buildings and compared against previous studies. It was observed that the load limit of implementing green roof for existing building is 1.46 kN/m^2. This measure resulted in decrease of cooling and heating energy consumption 31 to 35% by and 2 to 10% respectively. Another study [40] was conducted on green walls performance on buildings by Freewan et al. in which vertical green wall was applied to the building as a passive climate adaptation measure. It was performed to analyze the energy performance of the buildings in a hot arid climatic region. The study was performed by actual experiments as well as simulations on the university building in Jordon. It was observed that by implementing vertical green wall resulted in decrease of outer wall surface temperatures by 6 to 11 °C as compared to the base case. Similarly, a decrease of 5 °C was observed in the southern façade of the building. In another study [41] impact of green roof on residential building was analyzed by Khotbehsara et al. The effect of green roof was observed and compared with usual roofs to reduce the heat transfer. This study was conducted in different climatic cities of Iran using simulation software DesignBuilder. It was observed that only in the city of Rasht, green roof was able to reduce the heat transfer during the months of April and July. In other cities, it helped in increasing heat transfer.

Ragab & Abdelrady [42] conducted a study in school buildings of different Egyptian cities to evaluate the impact of green roof on reduction in cooling energy consumption. Different types of green roofs were used to reduce the energy consumption using DesignBuilder. At the same time, cost analysis of each green roof was also carried out to identify the most suitable green roof. It was observed that different green roofs can be used to reduce the energy consumption up to 39.74% approximately. It was suggested to use the 0.1 m soil depth for better energy savings. The decrease in average temperature of about 4 °C was also observed in hot arid areas using green roof.

2.6.3 Window Shading

Window shading is an efficient way of reducing heat gains through windows and thus reducing energy consumption of the building. It can be done in multiple ways such as by installing overhangs, louvres, blinds as well as side fins. Figure 2.3 represents that windows blinds can be installed in different ways such as inside the zone, outside the zone and mid-pane [43].

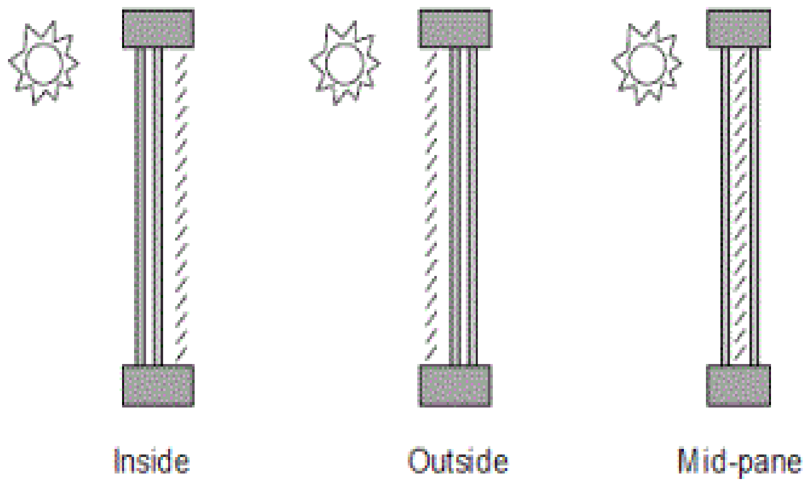


Figure 2.3: Positioning of window blinds

Window louvres, side fins and overhangs are installed outside the window and are usually referred as local shading. Figure 2.4 represents the local shading devices [44]. The length of overhangs may vary up to 1 meter.

A study [45] was conducted in residential building of Bangladesh to analyze the influence of window shading on energy consumption. Different simulations were performed for multiple cases using Energy Plus Software. Simulations were performed without using overhangs and side fins, overhangs only and then using both overhangs as well as side fins. Among all cases, it was found to be useful when overhangs and side fins were implemented in north and west facing windows. Similarly, for south facing windows, use of overhangs and side fins on transparent windows was the best solution. It was observed that using overhangs and side fins does not produce any remarkable impact on East facing windows.

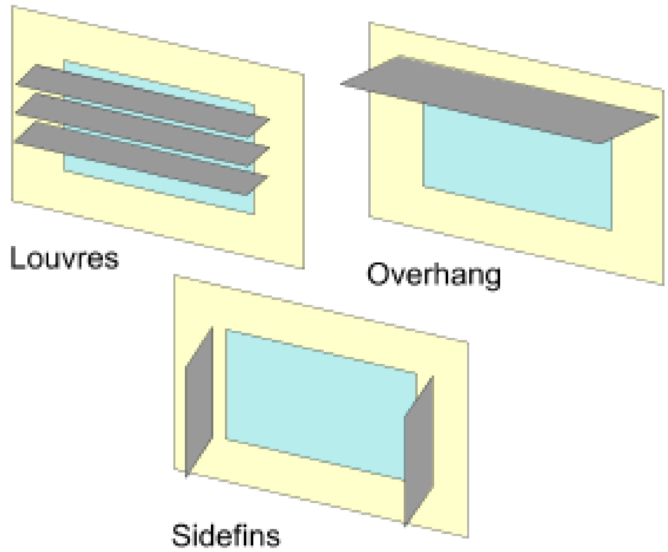


Figure 2.4: Representation of louvres, overhangs and side fins

Multiple studies have been performed to analyze the impact of window shading on energy consumption of the building. A recent study [30] was conducted by Anwar et al., in which effects of different passive climate adaptive measures were observed on the building using DesignBuilder. In this study, effects of window shading on building energy consumption were also analyzed in residential building of Islamabad. In this study, window overhangs as well as window louvres were used for shading purpose. It was observed that window overhangs and window louvres helped to reduce the energy consumption by 11.44% and 19%respectively.

2.6.4 Temperature Set Points

Variation in temperature set points without compensating the thermal comfort of the residents is a cheaper of reducing the cooling and heating energy consumption. It can be done either by increasing the cooling set point or decreasing the heating set point. Multiple studies [46, 47] have been conducted related to variation in temperature setpoints by 1 °C to 4 °C. When temperature setpoint is varied by 4 °C, it may affect thermal comfort and when setpoint is varied by 1 °C, energy consumption is reduced by a small amount. So, to reduce the maximum energy consumption and to maintain the thermal comfort of the occupants, 2 °C variation in temperature setpoints for heating and cooling was observed. Several studies have been performed to analyze the influence of changing the heating and cooling set points.

One study of a residential building in Hong Kong shows that by increasing the cooling setpoint from 23 °C to 27 °C at night resulted in an energy consumption reduction by a factor of 2. In another study [48], it was observed that there is a great potential of energy savings by changing the cooling set points slightly. It was also noted that there were some negative impacts on thermal comfort when temperature setpoints were raised above 28 °C. But below this temperature no problems were reported by the occupants.

2.6.5 Window Glass Thickness

In this technique, windows glass thickness will be varied to find out its impact on building energy consumption. In a study, it was observed that thickness of window glass has significant effect on heating energy consumption than cooling energy consumption. From the research, it was found that there is a lack of studies being carried out on the effect of windows glass thickness on energy consumption.

One such study [49] was found related to glass thickness impact on building energy consumption in the cities of Semnan, Tabriz, and Bandar Abbas. In this study, multiple simulations were performed to analyze the result of different window configurations on energy performance. Single pane as well as double-pane windows were used with the combination of thickness. It was observed that by increasing the window glass thickness for a single pane, heating energy load was reduced whereas cooling load was slightly increased. It was noted that glass thickness of double-pane windows has direct relation with heating and cooling energy loads. It was suggested that using double pane windows along with 4mm glass will be helpful in the selected cities of Iran.

2.6.6 Window Glazing

The use of glass in the modern buildings is increasing day by day, eventually leading to heat gains. This increases the energy demand for the building to maintain the comfort level. Glazing is the essential part of the windows. Window glazing can be classified into 1) single glazing, 2) double glazing, 3) triple glazing, 4) quadruple glazing. Window glass allows the most solar radiations pass through it. If right type of glazing is used for windows of the building, it will result is energy savings by reducing the cooling energy consumption of the building [50]. Figure 2.5 represents the multiple glazing [51].

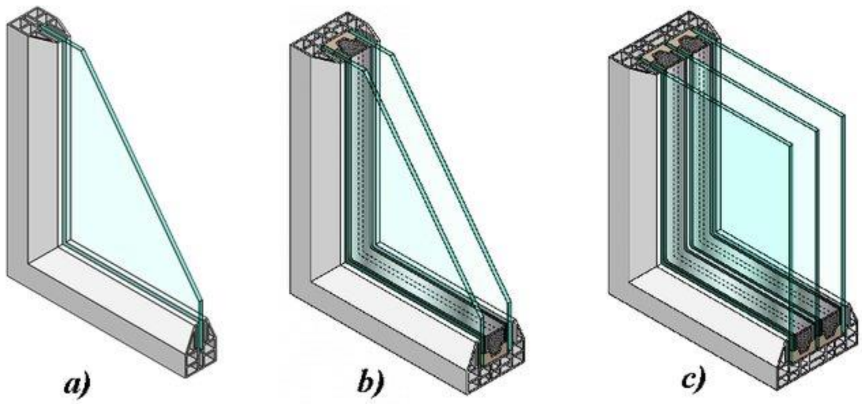


Figure 2.5: Representation of a) single glazing b) double glazing c) triple glazing

A study [52] was conducted in four cities of India having different climate. In this study, the impact of all glazing types was analyzed using clear glass, bronze glass, green glass, and bronze-reflective glass. In this study, 64 simulations were performed for all façades. The south facing windows were found to be more efficient in terms of cooling energy consumption. It was observed that the window having bronze reflective glass was more efficient in all types of glazing than any other glass materials.

CHAPTER 3: METHODOLOGY

This chapter describes the complete methodology that have been used in this study. Each detail starting from building and software selection to implementing passive climate adaptation measures is explained in this chapter. The sequence of the methodology is explained in the below flowchart.

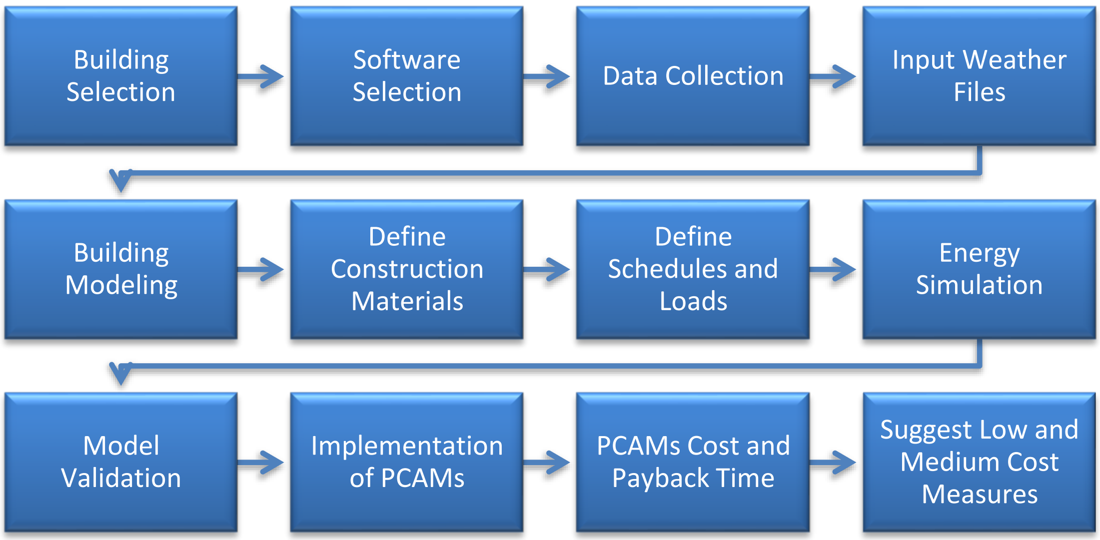


Figure 3.1: Methodology

3.1 Building Selection

Building selection is a critical decision. Every building has its own working schedule. The schedule of educational buildings, office buildings and residential buildings are different. Based on their schedule, there energy consumption also varies. As already explained in the literature review, no significant research has been carried out in the educational buildings of Pakistan. For this purpose, building of School of Mechanical and Manufacturing Engineering (SMME) building located in National University of Sciences & Technology (NUST), Islamabad was selected. The selection of a building was influenced by the schedules, as there is a fixed schedule that is followed as compared to residential building.

3.2 Software

There are multiple software available in the market for the modeling of the buildings. But in all these software, after the modeling of the building you must import to EnergyPlus software for the energy consumption analysis. Instead of this, DesignBuilder has a built-in EnergyPlus simulation engine for performing energy simulations. Due to its simple and user-friendly interface, it is preferred over other software. A brief overview of DesignBuilder is explained in next section.

3.2.1 DesignBuilder

DesignBuilder (DB) is a 3D modeling tool for the buildings. It's simple, flexible, and user-friendly interface helps the designers to build and modify the building model quickly. This software accompanied with EnergyPlus helps the users to evaluate the energy performance of the buildings [53]. It also allows users to make comparison using passive retrofit measures for the buildings. It allows the user to input the weather files of specific climate, construction materials, openings, lighting, equipment, and different HVAC systems. A schedule can be defined for occupancy, activity, lighting, equipment, HVAC, etc. There are hundreds of templates in the software library that can be assigned to any parameter. It also assists the users by estimating the costs of each module. It can generate the rendered pictures and movies of the buildings in the visualization tab. It can also perform the CFD simulations. This software also allows the user to import the building geometry. The software is widely used for performing energy simulations, calculating heating and cooling energy demand, rendering of building models, visualization of the buildings etc. [54].

3.3 Building Modeling and Description

This section provides the modeling details of the building as well as complete building description. It also provides the details of data collection, building description, weather files, building geometry, construction details, HVAC system, schedules set for occupancy, lighting, HVAC systems, equipment, etc.

3.3.1 Data Collection

NUST Project Management Office (PMO) is responsible for all the building construction projects, roads as well as oversees other utility services. So, for modeling of the building floor plans were collected from the PMO. Data related to construction details, installed HVAC, equipment, etc. were obtained from the PMO. Bills of quantities (BOQs), electricity utility bills, drawings of building were also provided by PMO for the research purpose.

3.3.2 Building Description

The university building is in National University of Sciences & Technology located in Islamabad, the capital city of Pakistan. The total covered area of the building is 10378 m^2. The building orientation is 10° from north. The department building consists of 4 floors. The building consists of three wings known as central wing, east wing, and west wing. East and west wing are identical to each other, mirrored to a 90° angle and are connected to each other using central wing between them. The façade of SMME building is shown in Figure 3.2.

Figure 3.2: Façade of SMME building

The building comprises of classrooms, labs, offices, conference rooms, library, seminar hall, etc. The central wing consists of administrative offices, faculty cabins, library, server room and a conference room. The east wing comprises of classrooms, demonstrator offices, laboratories for mechanical engineering students, electric room, and a seminar hall. The west wing belongs to School of Natural Sciences (SNS) department and consists of classrooms, demonstrator offices, laboratories, faculty cabins, etc. All rooms are equipped with HVAC systems. The equipment load is also added to the laboratories and server room. The building is constructed using locally available construction materials. Some of the floor plans are shown in Figure 3.3, Figure 3.4, and Figure 3.5. Full size pictures of these floor plans are shown in Appendix A.

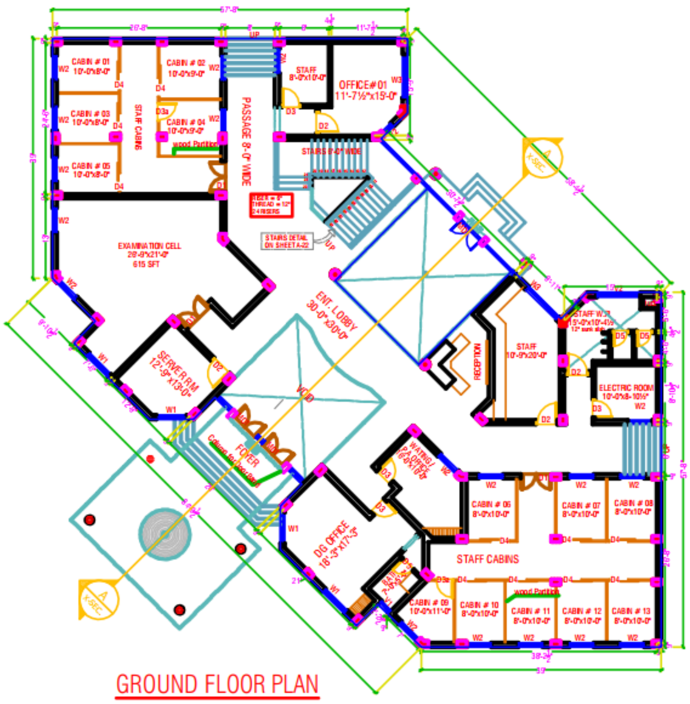
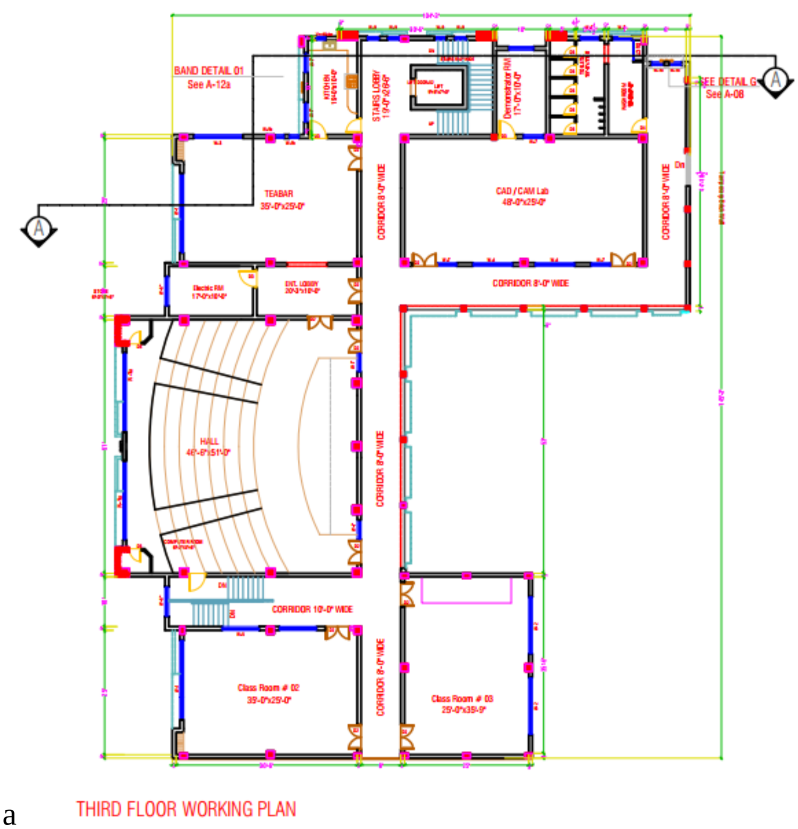


Figure 3.3: Central wing ground floor plan



a

Figure 3.4: East wing third floor plan

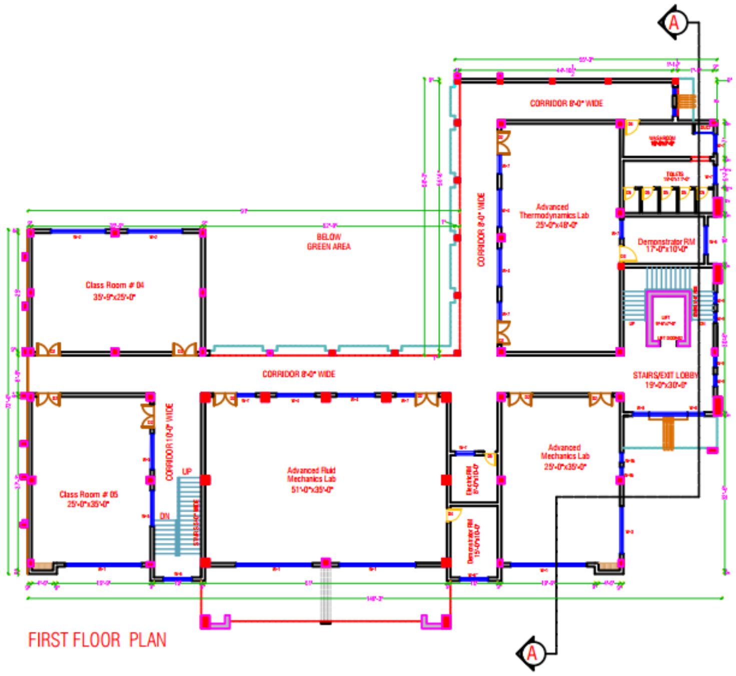


Figure 3.5: West wing first floor plan

3.3.3 Weather Data

As already explained, energy simulations are carried out using EnergyPlus simulation engine. EnergyPlus weather (EPW) file is imported in the DesignBuilder to carry out simulations. EPW files are based on typical meteorological year (TMY). A TMY is a compilation of weather data sets that represent the weather for a year. It is usually derived from the weather data sets for more than 10 years. It usually contains the hourly values of outdoor air temperature, wind speed, wind direction, air pressure, relative humidity, solar radiations, etc. that are usually averaged into monthly values. These weather files for the climate of Islamabad, Pakistan were extracted from climate.onebuilding.org, an authentic database which is widely used to access the weather data for a typical climate. The weather data from year 2004-2018 is used for the simulations in the DesignBuilder (DB). DesignBuilder usually accepts the (.epw), (.stat) and (.ddy) format files to correctly read the weather data. Islamabad is a clean and green city surrounded by Margalla hills which is the reason that it is classified under humid and subtropical climate (Cfa) according to Köppen-Geiger climate system. The Köppen-Geiger climate classification map of Pakistan for year 1980-2016 is shown in Figure 3.6 [55].

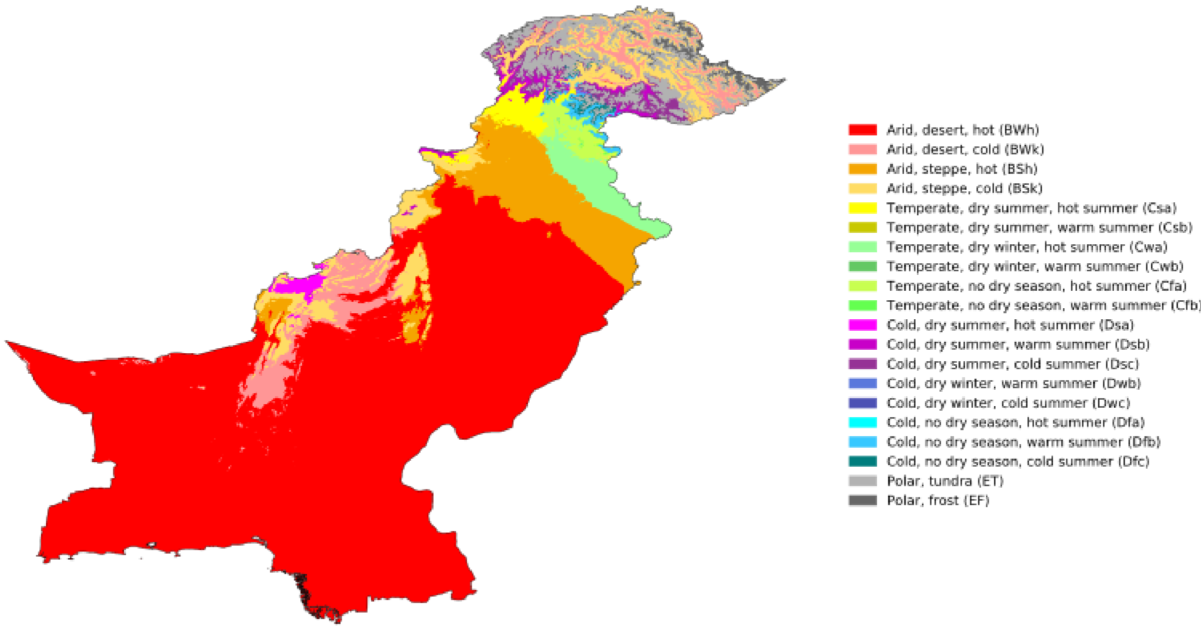


Figure 3.6: Köppen-Geiger climate classification map of Pakistan for year 1980-2016

3.3.4 Modeling

The modeling of the building is carried out using DB. The modeling was done according to the floorplans received from the PMO. The orientation of the educational building model was set according to existing building. The DesignBuilder model comprises of different zones such as classrooms, laboratories, offices, faculty cabins, corridors, toilets, seminar hall, library, etc. Some of the views of the SMME building model is shown in below figures.

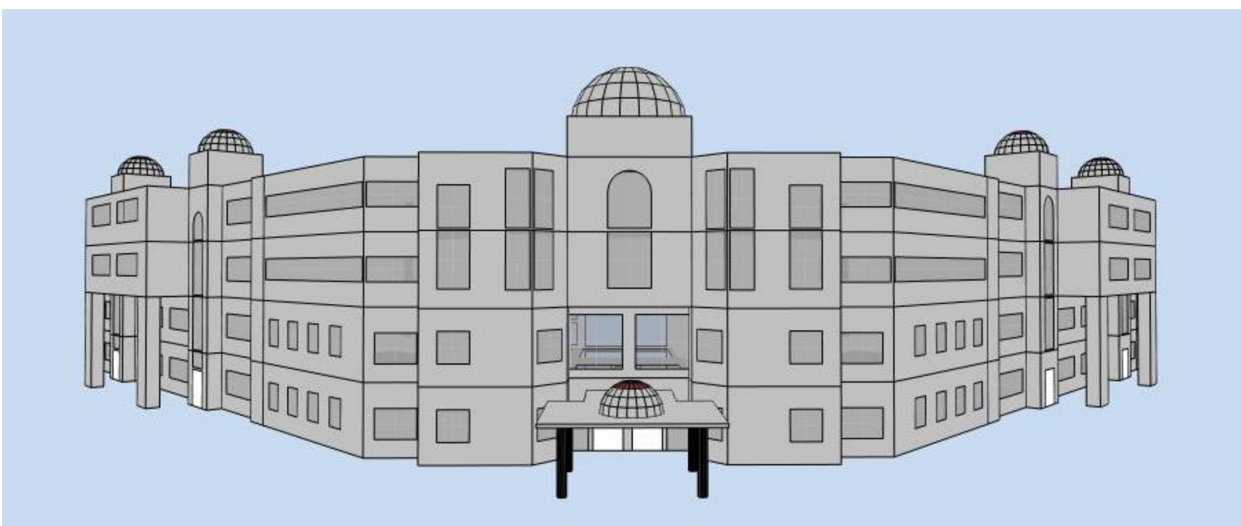


Figure 3.7: Front view of university building model on DesignBuilder

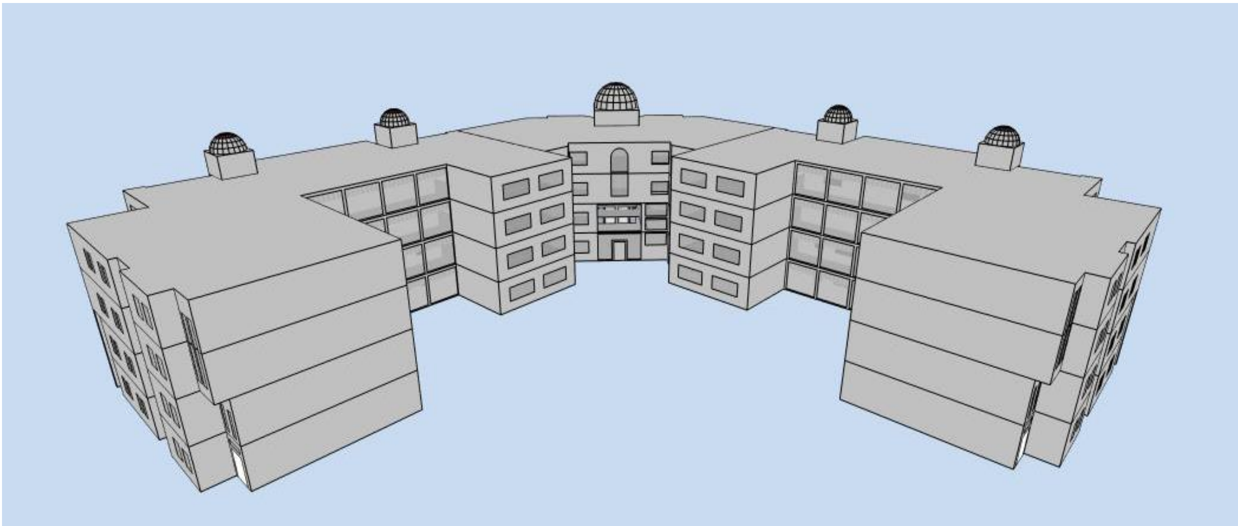


Figure 3.8: Rear view of university building model on DesignBuilder

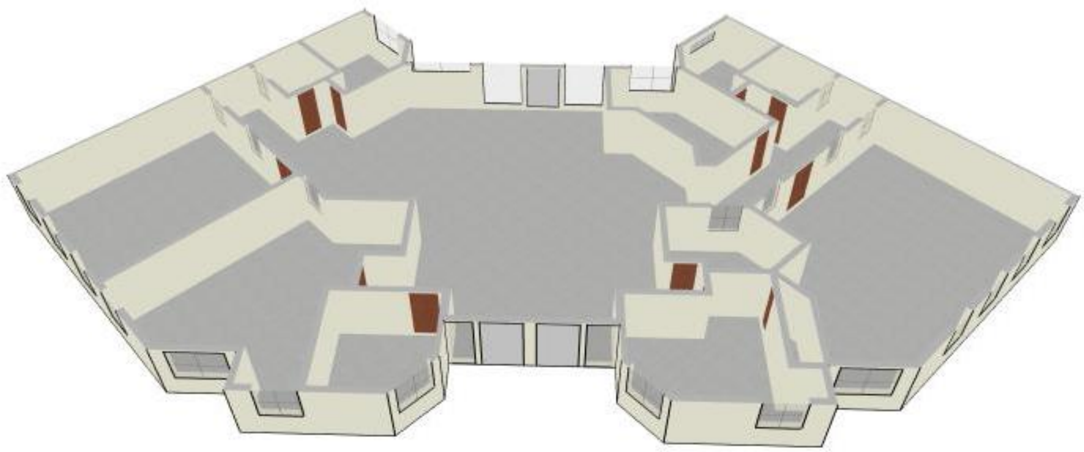


Figure 3.9: Top view of ground floor of central wing

3.3.5 Construction Detail

In the DesignBuilder, construction detail of the model is defined in construction tab. In the construction, one can define the construction detail of the external walls, roofs, internal partitions, floors, etc. There exists a lot of construction templates of each parameter in the DB library. Either these construction templates can be selected or can be defined new construction templates according to requirements. The construction detail was assigned to the model according to the actual building construction details received from the PMO. The construction detail of the SMME building is shown in Table 3-1.

Table 3-1: Construction details of SMME building

Construction Element	Construction Layers	Thickness (m)
Walls	Cement Plaster	0.013
	Brick	0.2286
	Cement Plaster	0.013
Roof	Cement Plaster	0.013
	Concrete Slab	0.1524
	Hot Bitumen	2 coats
	Polythene Sheet	2 layers
	RCC	0.0762
Ground Floor	Sand	0.0762
	P.C.C (1:4:8)	0.0762
	P.C.C (1:2:4)	0.0508
	Tiles	0.0127
Internal Floor	Concrete Slab	0.1524
	P.C.C (1:2:4)	0.0508
	Tiles	0.0127

3.3.6 Materials Detail

Each country uses different materials for the construction of the buildings. Burnt clay bricks of 9"x4.5" size are widely used in Pakistan for wall construction. Nowadays, concrete blocks are also used at some places. In SMME building, burnt clay bricks were used and material properties of other materials are given in Table 3-2.

Table 3-2: Material details of SMME building

Element	Construction Layers	U-Value (W/m^2-K)
Walls	Cement Plaster, Brick, Cement Plaster	1.910
Roof	Cement Plaster, Concrete Slab, Hot Bitumen, Polyurethane Sheet, RCC	2.688
Ground Floor	Sand, P.C.C (1:4:8), P.C.C (1:2:4), Tiles	1.334
Internal Floor	Concrete Slab, P.C.C (1:2:4), Tiles	2.617

3.3.7 Air Conditioning

Air conditioning is a significant requirement of the educational building to ensure the thermal comfort of the occupants. HVAC systems are installed based on region, project size, requirement, etc. Different HVAC systems have different efficiency. In SMME building, central HVAC system is used for air conditioning and heating purpose. Variable Refrigerant Flow (VRF) system is installed in the university building. HVAC is installed in all zones of the building except corridors, storerooms, toilets, etc.

3.3.8 Building Schedule

DesignBuilder requires the schedule of each parameter such as occupancy, lighting, HVAC, equipment, etc. to run the building energy simulation. These schedules are the operating hours of each parameter. These schedules are defined in the values from 0 to 1. If an equipment is fully operational, it is given the value of 1. Similarly, if it is off, it is assigned the value of 0. If it is operating partially, it is given the value between 0 to 1. The university timings are 9am to 5pm for undergraduate classes and 5pm to 8pm for postgraduate classes from Monday to Friday. The timetable was collected for the classes from the department. Schedules of some parameters that are implemented in the building are given below.

3.3.8.1 Occupancy Schedule

Occupancy schedule is defined according to the occupants in that specific zone. For the university building, it is observed that the average no of students in a class are 35. So, during the class it was assigned the value of 1 showing that all students were present. In between the classes schedule, a small ratio of 0.1 was assigned according to the zone that represents that some students were present in the class.

3.3.8.2 Lighting Schedule

It is difficult to assume the lighting load as all rooms do not require lighting all day. Lighting is also an important parameter in building energy consumption. Lighting requirements may vary between classes, labs, offices, faculty cabins, library etc. It was observed that 8 W/m^2 is the average lighting power density for a university building. During daytime, the fractional value of 0.5 is assumed to represent the lighting requirement. Similarly, 0.9 value is used from 5pm to 9pm. For weekends, 0 value was used for lighting.

3.3.8.3 HVAC Schedule

VRF system is implemented in the SMME building for HVAC. During the working days, air conditioning system remain on during the university timings. It is observed that HVAC system does not remain fully operational during the whole day. It was controlled by the electrician according to the heating and cooling requirement. It was observed that in between the classes the fractional value of 0.25 was given for HVAC. So different fractional values were assigned according to zones. During the weekend, HVAC system remained turned off, so a fractional value of 0 was assigned to it.

3.3.8.4 Equipment Schedule

As the building consists of multiple number of laboratories, so equipment schedule is important to be defined. Equipment schedule was assigned according to timetable. During the lab schedule, it was assigned the load of 0.5 as only some equipment was running. Similarly, when the lab is not scheduled, it was given the value of 0. During the weekends, it remained turned off. Only equipment that was running continuously was server room. It was given the schedule of 24/7 and given the fractional value of 1. Similarly, equipment load was also assigned to classes as there are multimedia and computer running all day.

3.4 Settings of PCAMs

This section contains the detail of passive measures that are implemented in this study. These PCAMs were selected to reduce the energy consumption with low and medium cost. All material details that were added in the DesignBuilder were according to materials that are usually used in Pakistan for the construction of the buildings. The implemented PCAMs are given below.

3.4.1 Short Wave Reflectivity

Short-wave reflectivity is a useful passive climate adaptation measure that can reduce the energy consumption in a low cost. In this study, to evaluate the effect of short-wave reflectivity, white paint is applied to the building. So, in DesignBuilder, solar absorptance value for the walls and roof was changed. For base case, its value was 0.6 and it was changed to 0.3 as a passive measure. Similarly, 0.9 is used as thermal absorptance value. The surface properties of short-wave reflectivity that were incorporated in the software are shown in Figure 3.10.

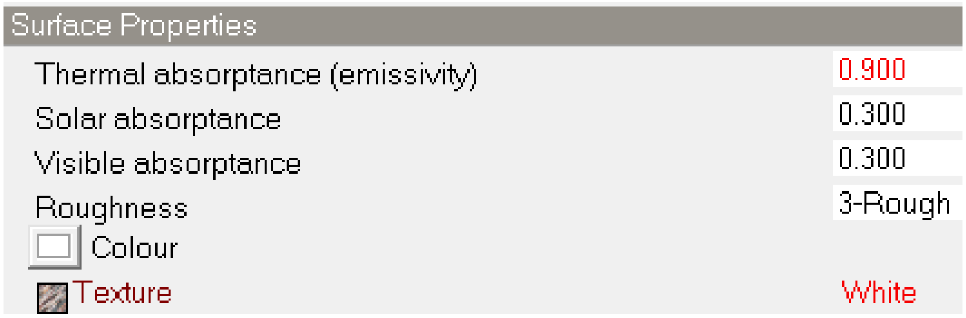


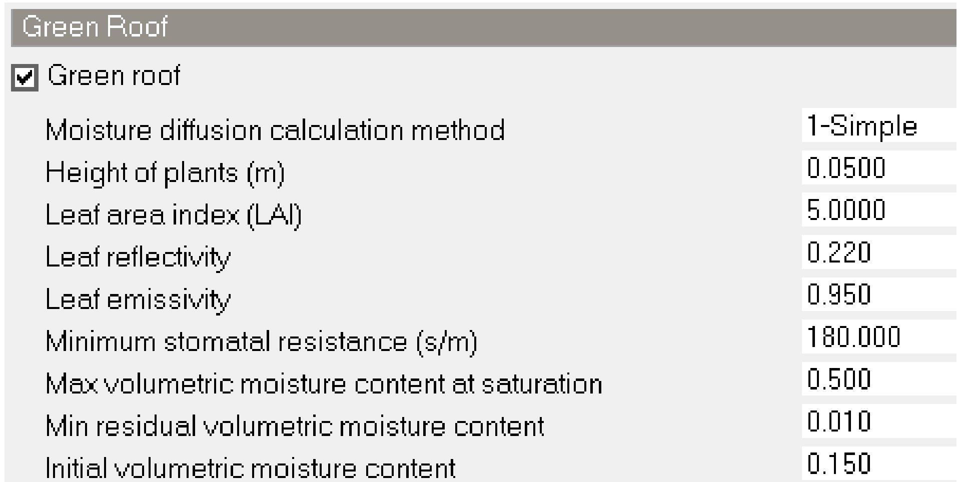
Figure 3.10: Surface properties for short-wave reflectivity

3.4.2 Green Roof and Green Wall

In this case, simulations were conducted for green roof and green wall in the SMME building using DesignBuilder. A vegetated layer was added in the top floor of the building for green roof as well as in walls of the south façade of the building that are directly exposed to solar radiations. This acts as a green wall. The Leaf area index (LAI) is set to 5. As the aim was to apply the extensive green roof and green wall so the plants height is set to 50mm in this case. Natural rubber is used as a waterproof layer in the green roof and green wall. Its thickness can vary depending on the type of green roof used. These green roof layers are added in addition to the existing layers of roof and wall of the university building. The layers of the green roof and green wall are shown in Figure 3.11. Similarly, the green roof properties that were defined in the DesignBuilder are shown in Figure 3.12.

(a) (b)

Figure 3.11: (a) Layers of green roof (b) Layers of green wall

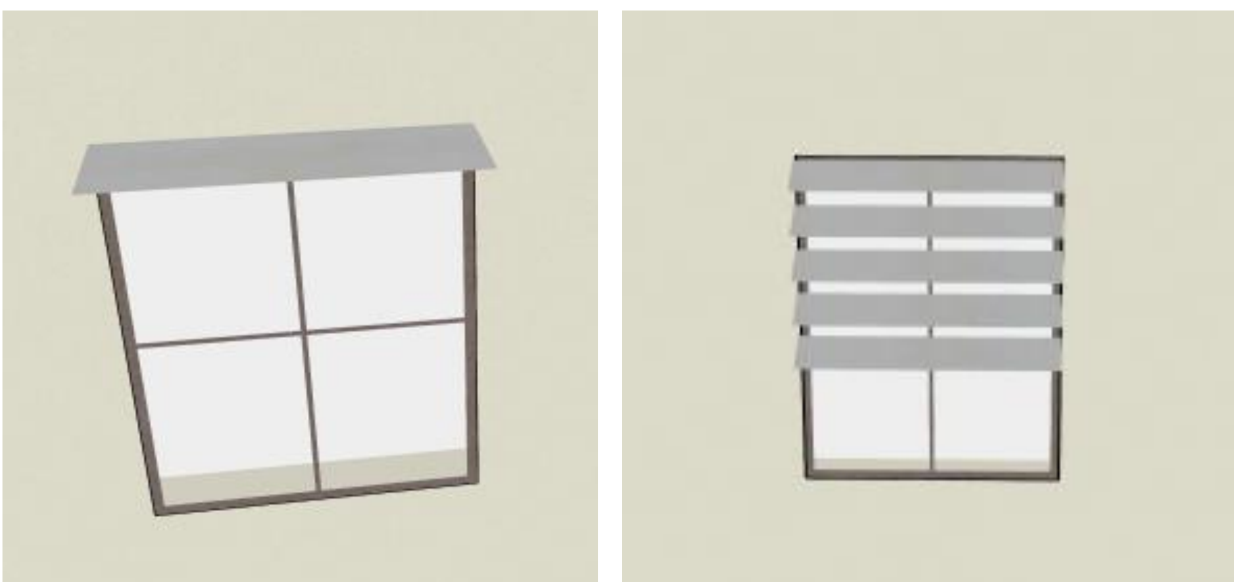


Green Roof	
☑ Green roof	
Moisture diffusion calculation method	1-Simple
Height of plants (m)	0.0500
Leaf area index (LAI)	5.0000
Leaf reflectivity	0.220
Leaf emissivity	0.950
Minimum stomatal resistance (s/m)	180.000
Max volumetric moisture content at saturation	0.500
Min residual volumetric moisture content	0.010
Initial volumetric moisture content	0.150

Figure 3.12: Green roof properties

3.4.3 Window Shading

In this measure, different shading devices were applied to the SMME building. It includes window overhangs, side fins and louvres. The simulations were performed for each shading device of 0.5 m and 1 m. For base case, there was no external shading, but window blinds were applied on the inner side of the windows. The rendered view of window overhangs and window louvres is shown in Figure 3.13.



(a) (b)

Figure 3.13: Rendered view of (a) window overhangs (b) window louvres

3.4.4 Window Glazing

In Pakistan, usually clear or single glazed windows are used. In the base case, clear windows of 5 mm thickness are used in the SMME building. In the case of passive climate adaptation measures, double glazed, triple glazed, and quadruple glazed windows are analyzed for the possible reduction in energy consumption of the building. The gap between the two panes is filled with air in window glazing. The layers of double-glazed windows that are used in DesignBuilder are shown in Figure 3.14.

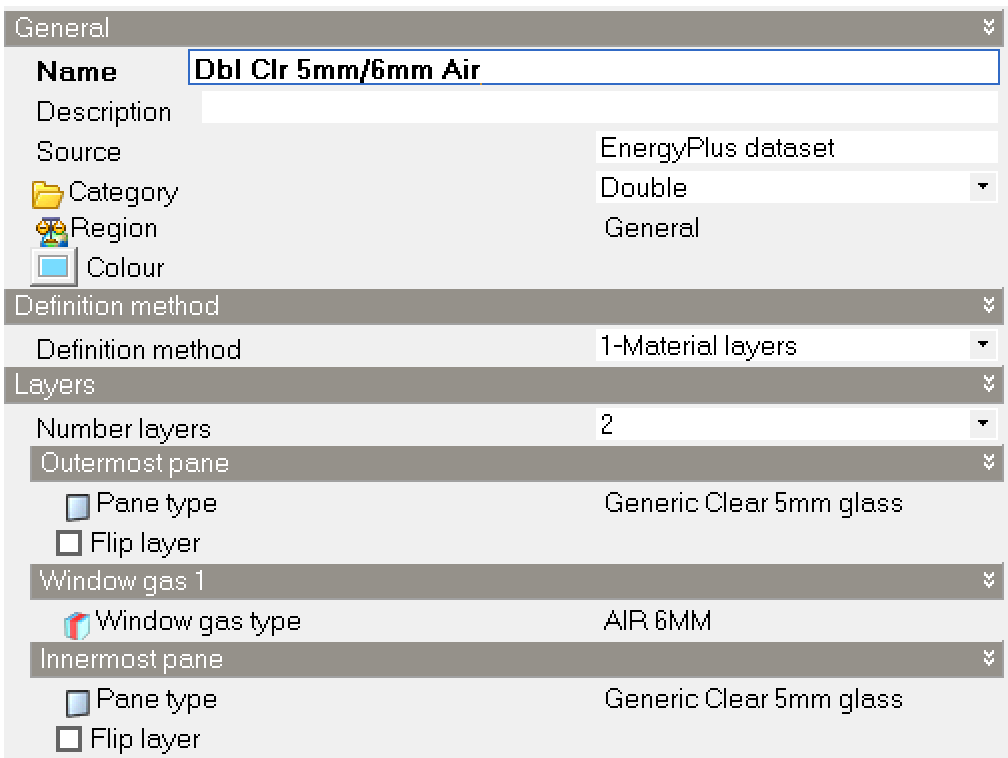


Figure 3.14: Layers of window double glazing

3.4.5 Window Glass Thickness

The 5 mm thick glass is usually used for the window construction in Pakistan. In SMME building, window glass of 5 mm thickness is used. So 5mm glass in used as a base case. As there exists a research gap on the use of different thicknesses window glass, so it is important to study its effect as a passive measure. Window glass of different thicknesses is analyzed in DesignBuilder. 3 mm, 8 mm, 12 mm window glasses are used in the simulations to identify their effect on building energy consumption.

3.4.6 Temperature Setpoints

Temperature setpoints are usually set by maintaining the thermal comfort of the occupants. In the base temperature setpoints are set to 24 °C and 22 °C for cooling and heating respectively. These setpoints along with the setback temperatures are mentioned in the Table 3-3. For the passive measures, 2 °C increase in cooling setpoints and 2 °C decrease in heating setpoints is observed. Their combine effect on energy consumption is also analyzed.

Table 3-3: Cooling and heating setpoint and setback temperatures in °C

Zone	Cooling		Heating	
	Setpoint	**Setback**	**Setpoint**	**Setback**
Classrooms	24	28	22	12
Labs	24	28	22	12
Offices	24	28	22	12

3.5 Combinations of PCAMs

After the implementation of different passive climate adaptation measures, effect of different combinations of PCAMs on building energy consumption is observed by performing energy simulations. The different combinations that are applied are shown in Table 3-4.

Table 3-4: Different combinations of passive measures

Combination	Symbol
Green Roof + Green Wall	$\mathbf{C_1}$
Green Roof + Window Overhangs	$\mathbf{C_2}$
Green Wall + Double Glazed Windows	$\mathbf{C_3}$
Green Wall + Window Overhangs	$\mathbf{C_4}$
Short Wave Reflectivity + Double Glazed Windows	$\mathbf{C_5}$
Short Wave Reflectivity + Window Louvres	$\mathbf{C_6}$
Window Overhangs + Window Louvres	$\mathbf{C_7}$
Window Overhangs + Window Side fins	$\mathbf{C_8}$
Window Overhangs + Window Louvres + Window Side fins	$\mathbf{C_9}$
2 °C Inc. and Dec. in C_{SP} and H_{SP} respectively	$\mathbf{C_{10}}$

CHAPTER 4: RESULTS AND DISCUSSION

This section contains the base case results that are required for validation of model created in DesignBuilder. It also contains the PCAMs results that are helpful in reducing building energy consumption. A comparison of these passive measures is carried out in this section to identify the suitable passive measures. After that cost benefit analysis is carried out to suggest the low and medium cost passive measures suitable for reduction in building energy consumption. Energy use intensity (EUI) of the SMME building was also calculated using formula and compared with the standards of the building.

4.1 Model Validation

Model validation is an important process to validate the results of simulations. For this purpose, the actual results are compared with the simulation results. If it lies within the acceptable limit, then model is accurate. In this study, actual energy consumption of the SMME building is compared with the energy consumption value from DesignBuilder simulations. The actual energy consumption of the building is 518,888 kWh whereas the energy consumption from DB simulations is 490,591 kWh.

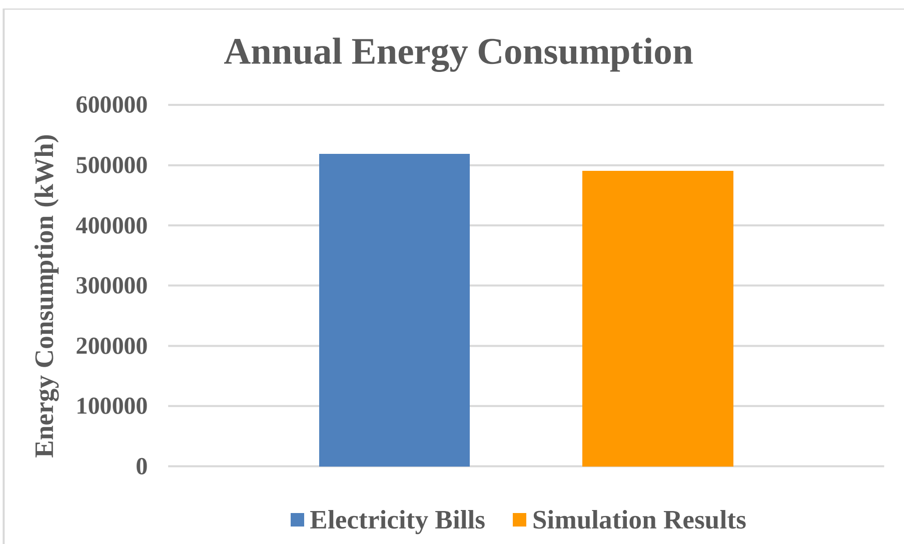


Figure 4.1: Comparison of actual and DesignBuilder annual energy consumption

The difference between actual and DB energy consumption is 5.45 % and it lies in acceptable limit. It is in acceptable limit if the difference is less than 10% annually. This difference between values exists due to different parameters discrepancies such as weather data, building model, construction details, etc. There exists a significant difference between actual and simulated energy consumption in the buildings according to a study [56]. The results of annual and monthly energy consumption are shown in a graph in Figure 4.1 and Figure 4.2 respectively.

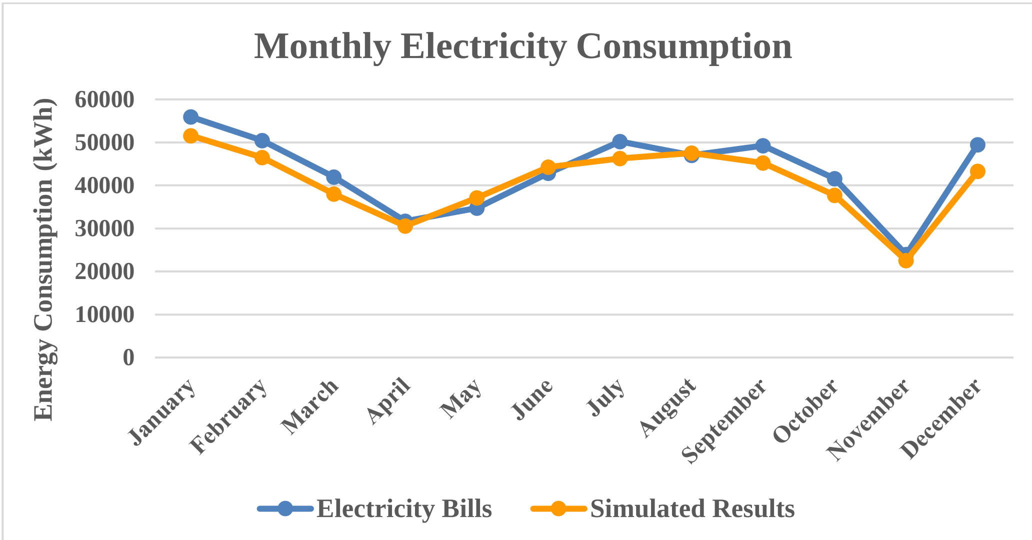


Figure 4.2: Monthly comparison of actual and DB energy consumption

4.1.1 Base Case Results

The total electricity consumption of the SMME building is 490,591 kWh per year. Results indicate that cooling energy is the highest electricity consuming parameter followed by lighting, heating, equipment, and other parameters. The equipment are lab and office equipment, computers, multimedia, etc. Figure 4.3 demonstrates the energy breakdown of SMME building.

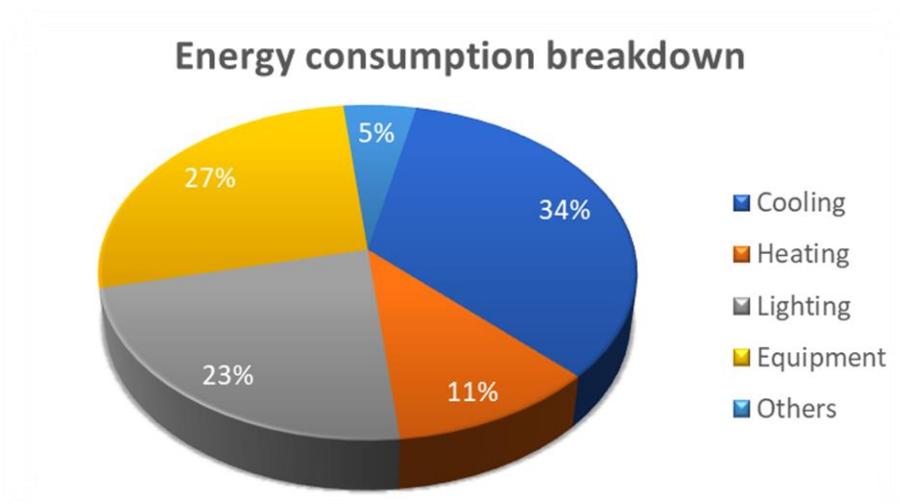


Figure 4.3: Energy consumption breakdown of SMME building

4.2 Results of PCAMs

The performance of the passive measure on building energy consumption is usually evaluated by comparing the energy consumption of the base case with that of passive measures. If any passive measures show energy reduction of the building, then it is energy efficient measure. Figure 4.4 represents the annual energy reduction by implementing the passive measures on the SMME building modeled in DesignBuilder. The base case consumes the 490,591 kWh per year to meet the energy demand of the building according to simulation results. It can be clearly seen from the figure that 2 °C increase in cooling setpoint is the most efficient passive measure as compared to others. Other than temperature setpoints, green wall is also very efficient passive measure as it reduces the approximately 10.05 % of the energy consumption. Similarly, green roof can reduce the energy consumption of the building up to 8.19 % approximately. Short-wave reflectivity is the least efficient measures in terms of reduction in energy consumption as it reduces the 5 % energy consumption approximately. This is because solar absorptance value has decreased and it reflects most of the solar radiations. By changing the window glass of 5 mm thickness with 8 mm and 12 mm thick window glass can help to save the 5.30 % and 6.47 % energy, respectively of the building. This reduction in energy consumption is due to decrease in solar heat gain coefficient (SHGC) as the thickness of a window glass increases. Similarly, by replacing the single glazing with double, triple and quadruple glazing can reduce the energy consumption of the building up to 7.73 %, 9.03 % and 9.33 % respectively. This reduction in energy consumption occurred because use of window glazing reduces the cooling energy consumption of the building significantly. Cooling energy consumption of the building decreases because window glazing reduces the number of radiations entering the building. Window shading also plays an important role in reducing the energy consumption as they are also cheaper measures as compared to some other passive measures. Among all window shading measures, window overhangs are the most effective. Window overhang of 1 m length is the most effective passive measure that can save about 8.4% energy of the SMME building. Window louvres and side fins can also reduce the energy consumption up to 7.93 % and 7.09 % respectively according to simulation results.

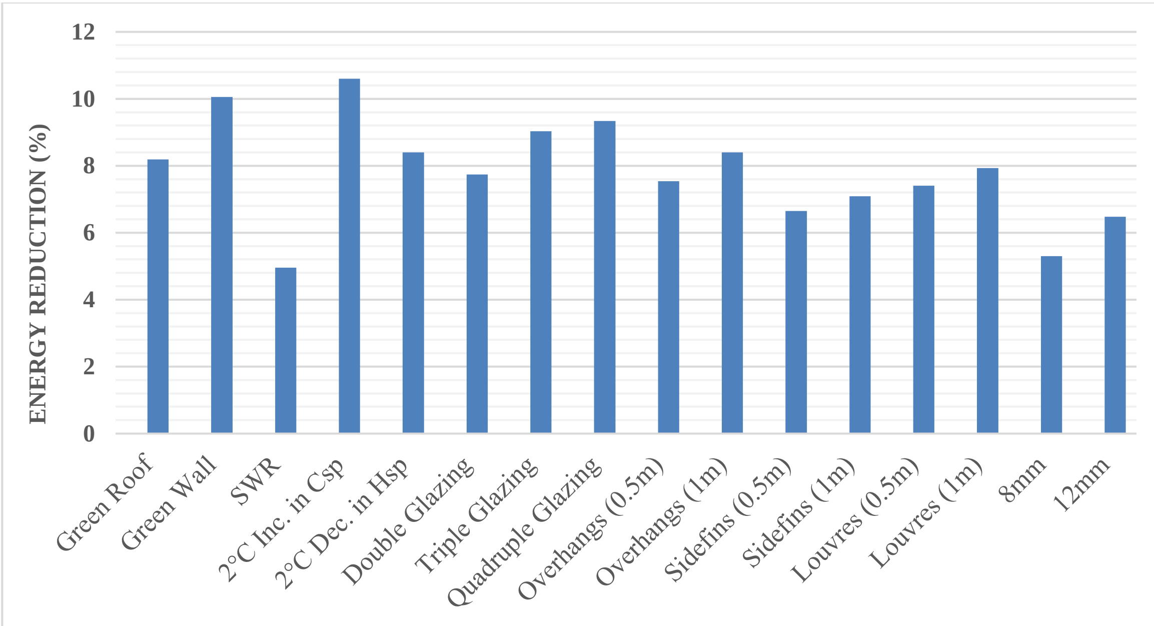


Figure 4.4: Percentage of energy reduction by implementing passive measures

Figure 4.5 represents the cooling consumption of the building in kWh/m^2 for base case as well as passive measures. The base case consumes 18.28 kWh/m^2 of energy to meet the cooling requirements. It is evident from the figure that decreasing the cooling setpoint of temperature by 2 °C results in minimum cooling energy consumption as compared to other passive measures. This measure can help us to save the cooling energy by 23 % approximately.

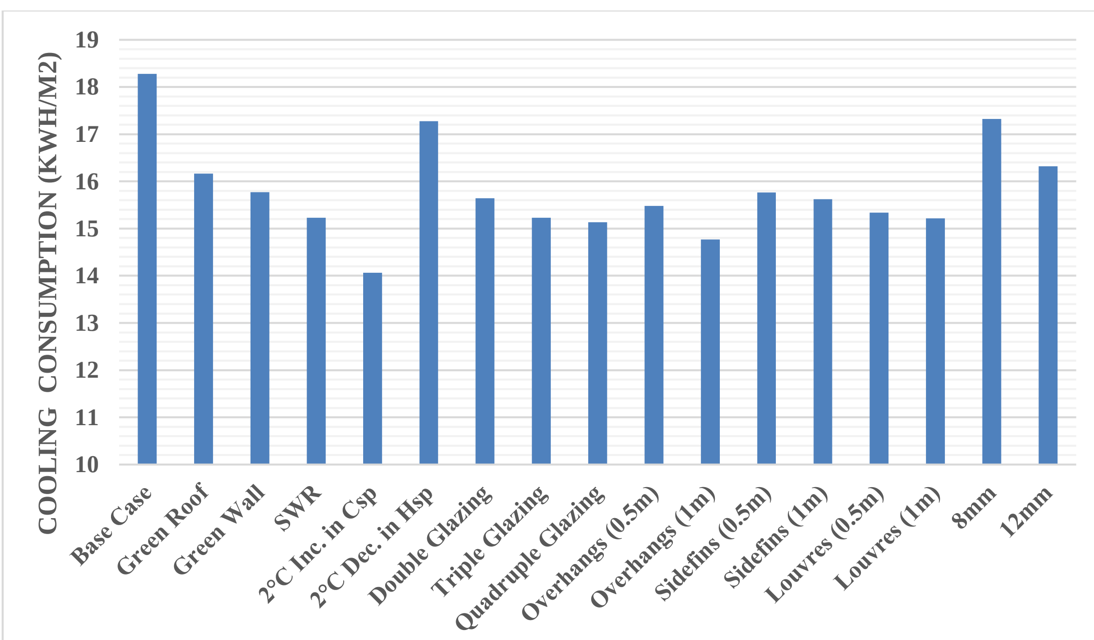


Figure 4.5: Annual cooling consumption (kWh/m^2) of base case and passive measures

Other than the variation in cooling setpoints, overhangs of 1 m and short-wave reflectivity also shows maximum reduction in cooling energy consumption as compared to other passive measures. Overhangs of 1 m length can save the cooling energy consumption by 19.20 % and the short-wave reflectivity helps us to reduce the cooling energy consumption of the building up to 16. 70 % approximately. The minimum reduction of cooling demand was observed in the case of 8 mm window glass. In this case cooling energy consumption was reduced to 5.22 % approximately. By changing the window glazing can also help us to save the cooling energy up to 17.21 % approximately by limiting the number of radiations entering the building.

Similarly, heating energy consumption is also important to analyze the energy efficiency of the building. The annual heating energy demand for the base case and different passive measures are shown in Figure 4.6. The significant reduction in heating energy consumption can be seen in the case of reducing the heating setpoint by 2 °C. This results in decrease of heating energy consumption up to 62 % approximately as compared to base case. Green Wall and Green Roof also results in significant reduction of heating energy consumption of about 42.21 % and 37.35 % respectively. But use of short-wave reflectivity as a passive measure eventually results in increase in heating energy consumption of about 8.47 % as compared to base case. Window shading shows the minimum effect on heating energy consumption as compared to other passive measures. The minimum reduction in heating energy consumption of about 13.12 % is observed in the case of louvres of 1 m projection.

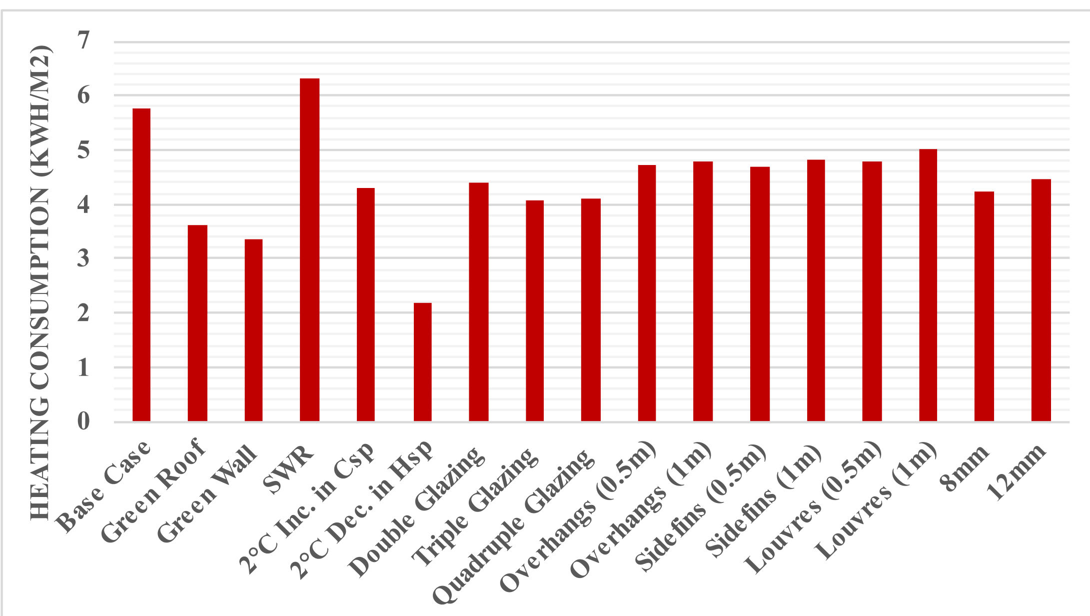


Figure 4.6: Annual heating consumption (kWh/m^2) of base case and passive measures

4.3 Results of PCAMs Combinations

The annual energy reduction that can be achieved by implementing the combinations of different passive measures on the modeled building are shown in Figure 4.7. The energy consumption of the base case in 490,591 kWh annually according to DesignBuilder simulation results. The most efficient combination was C_{10} in which 2 °C increase and decrease in cooling and heating setpoints was done. This measure resulted in reduction of energy consumption of approximately 14.4 %. This is the highest possible energy reduction among all the individually applied passive measures as well their combinations. By combining the green roof with green wall (C_1) can also reduce the energy consumption up to 11.9 % according to simulation results. The least efficient combination in terms of energy savings was C_8 in which window overhangs are combined with window side fins. This combination reduced the energy consumption of 8.5 % approximately. By combining the green wall with window overhangs of 0.5 m (C_4) also helps us to save the energy consumption of the building up to 11.06 % approximately.

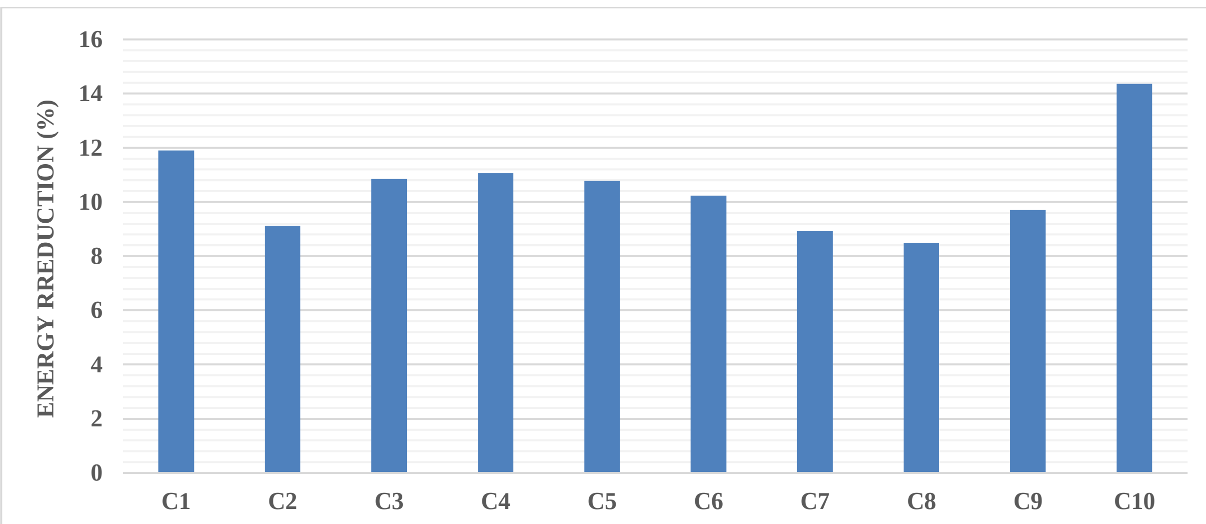


Figure 4.7: Percentage of energy reduction by implementing combinations of passive measures

Figure 4.8 indicates the energy consumption of the building to meet the cooling demands in kWh/m^2 for base case as well as different combinations of passive measures. It is crystal clear from the figure that by combining the window louvres and short-wave reflectivity of walls and roof (C_6) resulted in maximum reduction in cooling energy consumption of the building as compared to other combinations. It saves approximately 27.18 % of energy required for cooling demands. Another combination (C_5) in which short-wave reflectivity is coupled with double glazed windows, can reduce the 26 % cooling energy consumption. The least efficient combination in terms of cooling energy reduction is C_2 (Green Roof combined with window overhangs), that can save 15 % of energy required for cooling purpose.

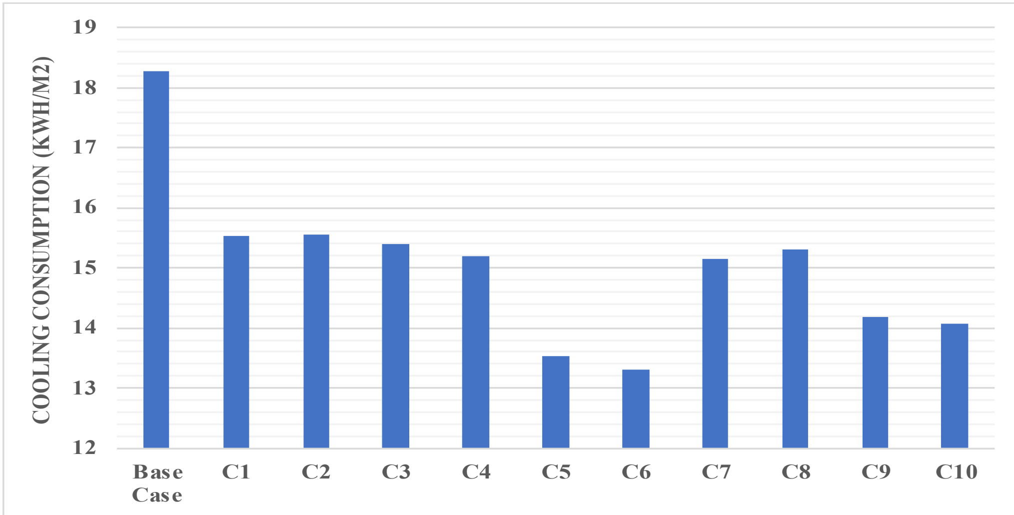


Figure 4.8: Annual cooling consumption (kWh/m^2) for combinations of passive measures

Figure 4.9 shows the annual energy consumption (kWh/m^2) to meet the heating demands for the base case as well as different combinations of passive measures. The significant reduction in heating energy consumption can be seen by combining the increase in cooling setpoint and decrease in heating setpoint by 2 °C (C_{10}). This combination helps us to decrease the heating energy consumption up to 60 % approximately as compared to base case.

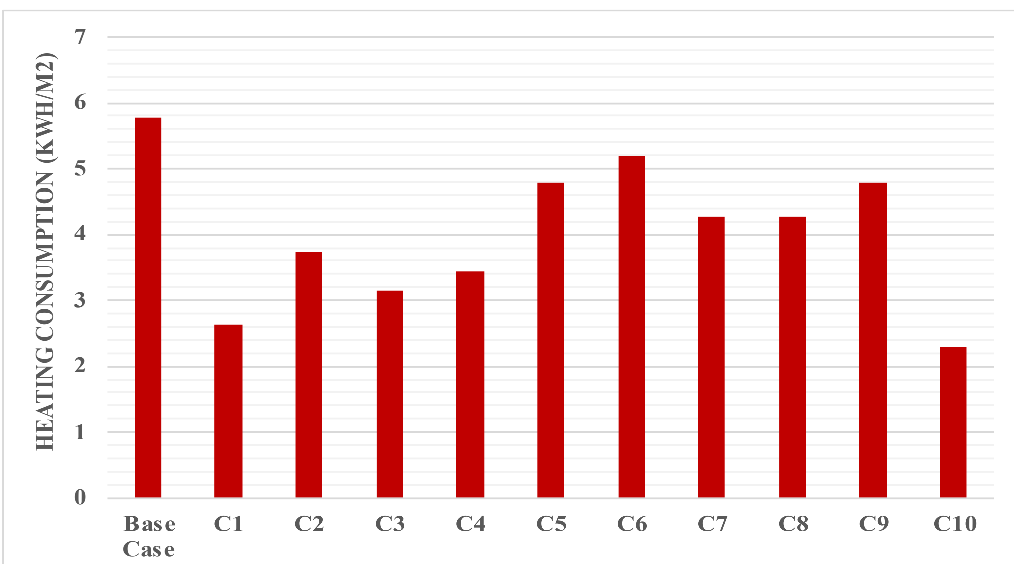


Figure 4.9: Annual heating consumption (kWh/m^2) for combinations of passive measures

The other significant performing combination was C_1 in which green wall and green roof are combined to reduce the heating energy consumption up to 54.57 %. And the least performing combination in terms of heating energy reduction is C_6 in which short-wave reflectivity is combined with window louvres. This helps us to save the energy required to meet the heating demands up to 10.15 % approximately.

4.4 Effect of PCAMs on Energy Consumption

In this section individual effects of different types of PCAMs on energy consumption was observed and are discussed below:

4.4.1 Effect of Window Glass Thickness

The base case consists of windows having 5 mm glass thickness. The energy consumption of base case is 490,591 kWh per year. By increasing the glass thickness to 8 mm can save the energy about 5.30 % as compared to base case. Similarly, by replacing the 5 mm glass with 12 mm glass, helps us to reduce the energy consumption by 6.47 % approximately. After that the effect of reducing the glass thickness as compared to base case is observed. In this case, 3 mm glass is used in place of 5 mm. This results in increase of energy consumption as compared to base case. So, by increasing the glass thickness, energy consumption reduces and by decreasing the glass thickness, energy consumption of the building is increased. This is because as we increase the glass thickness, solar heat gain coefficient (SHGC) decreases that helps us to reduce the energy consumption. So, window glass thickness and energy consumption have inverse relation between them. Figure 4.10 represents the annual energy consumption for different thicknesses of a window glass.

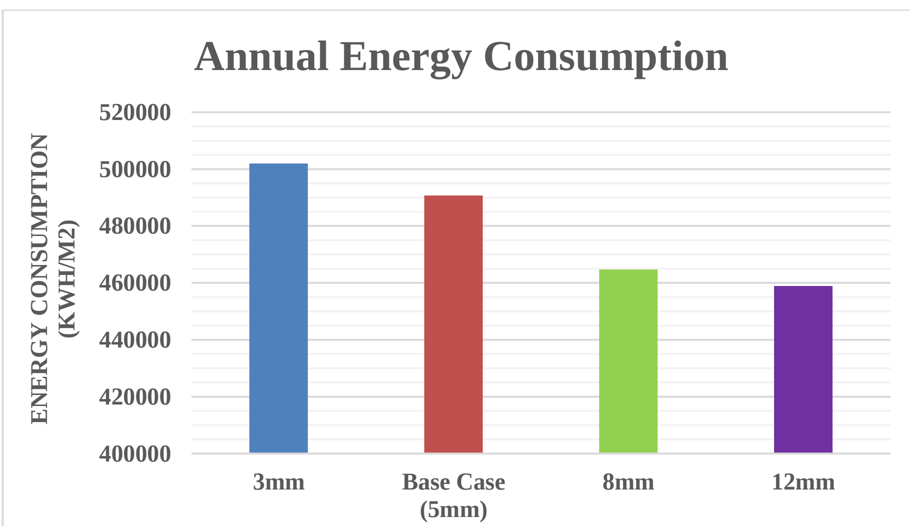


Figure 4.10: Effect of window thickness on annual energy consumption

4.4.2 Effect of Window Shading

Window shading plays a critical role in reduction of energy consumption of the building. So, it is important to select the best suitable window shading device for the building. In this study, overhangs, side fins and louvres are used to calculate their effect on annual energy consumption of the building. Figure 4.11 represents the effect of different window shading measures on annual energy consumption of a building as compared to base case. It can be clearly seen from the figure that window overhangs are the most effective window shading technique to save the annual energy usage as compared to other measures. It can help to save the annual energy consumption of the building up to 7.54 % approximately. Similarly, by using window louvres in the building can reduce the energy consumption about 7.4 %. But use of window louvres increases the heating energy consumption as it allows only a small number of radiations to pass through the openings of the building. The least effective window shading technique is window side fins among the other measures. But it can also help us to reduce the 6.65 % of the annual energy consumption of the building.

Windows overhangs are also effective in reduction of annual energy required to meet the cooling demands. But in terms of heating energy consumption, window side fins are most effective among other as they let some solar radiations to pass through the windows to reduce the heating demands. But overall, it is convenient to say that use of window overhangs in the building as compared to other window shading measures proves to be more suitable in terms of energy reduction of the building.

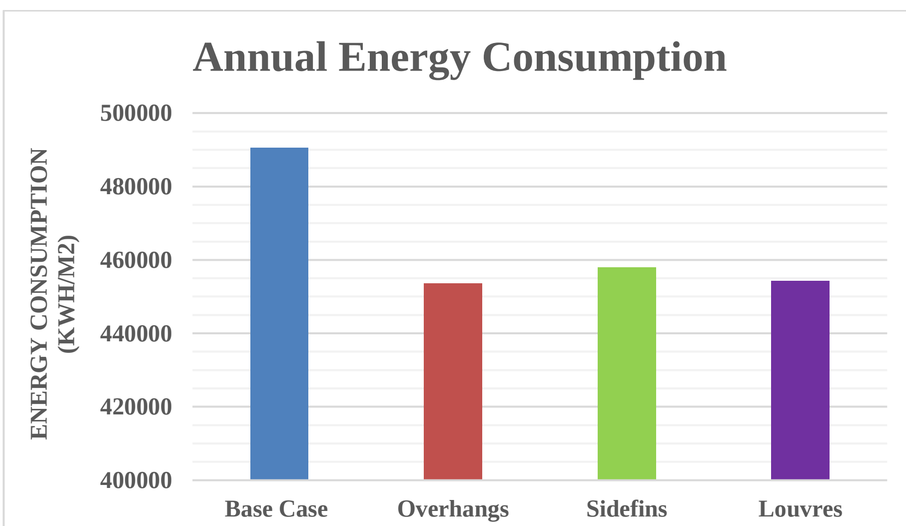


Figure 4.11: Effect of window shading on annual energy consumption

4.5 Cost Benefit Analysis

To implement the passive climate adaptation measures, cost effectiveness is necessary requirement. So, to select the most suitable passive measure, cost benefit analysis is important to be performed. Payback period is important factor for the investors, so it is necessary to be calculated. The cost of each passive measure for the specific area and energy savings cost are required to calculate the payback period for every passive measure. The formula to calculate the payback period is given below:

$$Payback\ Period\ (Years) = \frac{Total\ Cost\ of\ Additional\ Investment}{Annual\ Savings}$$

The cost of the electricity for commercial buildings which is approximately 0.1 USD/kWh was used to calculate the payback period of PCAMs and their combinations. The per unit cost of each passive measure was collected from local markets and PMO office. Table 4-1 and Table 4-2 represents the payback period of passive measures and their combinations respectively.

Table 4-1: Payback period of passive measures

Passive Measure	Area (ft^2)	Cost/ft^2 ($)	Total Cost ($)	Annual Savings ($)	Payback Period (Year)
Green Roof	25941	1.315	34112.42	3976.34	8.58
Green Wall	23842	1.315	31352.23	4883.86	6.42
SWR	67091	0.1	6709.14	2408.12	2.79
Overhangs (0.5 m)	2534.45	2.72	6893.70	3661	1.88
Overhangs (1 m)	5068.9	2.72	13787.41	4120.20	3.35
Louvres (0.5 m)	4635	4.95	22943.25	3594.55	6.38
Louvres (1 m)	7169.45	4.95	35488.78	3890.40	9.12
Side fins (0.5 m)	3359.63	2.72	9138.19	3228.32	2.83
Side fins (1 m)	6719.16	2.72	18276.12	3479.80	5.25
Double glazing	6000	6	36000	3759.21	9.58
8mm Glass	8391.85	1.5	12587.78	2575.15	4.89
12mm Glass	8391.85	2.23	18713.83	3144.75	5.95
2°C Inc. in C_{SP}	-	0	0	5148.32	0
2°C Dec. in H_{SP}	-	0	0	4078.51	0

Table 4-2: Payback period of combination of passive measures

Combination	Total Cost ($)	Annual Savings ($)	Payback Period (Year)
GR + GW	65464.65	5780.59	11.32
GR + WO	41006.12	4429.50	9.26
GW + DGW	67352.23	5271.78	12.78
GW + WO	38245.93	5370.89	7.12
SWR + DGW	42709.15	5235.54	8.15
SWR +WL	29652.40	4969.31	6
WO + WL	29836.95	4332.65	6.89
WO + WS	16031.89	4124.50	3.89
WO + WL +WS	38975.14	4709.21	8.28
2°C Inc. and Dec. in C_{SP} and H_{SP}	0	6973.56	0

The classification of the no, low and medium cost passive measures is done in Table 4-3. The measures that have zero payback period are referred as no-cost measures. The measures having payback period of less than five years are low-cost measures. Medium-cost measures are the one that have less than 10 years of payback period. Based on the calculated payback period of different passive measures and their combinations, the no-cost, low-cost and medium-cost passive climate adaptation measures are suggested.

Table 4-3: Classification of no, low and medium cost passive measures

Scenario	Passive Measure	Payback Period (Year)
No-cost measure	2 °C increase in C_{sp}, 2 °C decrease in H_{sp}, C_{10}	0
Low-cost measure	Short-wave reflectivity Window overhangs and side fins, 8 mm window glass, C_8	<5
Medium-cost measure	Green roof & Green wall, Window louvres, Double glazed windows, 12 mm window glass C_2, C_4, C_5, C_6, C_7, C_9	<10

Combinations of all these passive measures were used to perform energy simulations. But only those combinations were considered in study that can be classified into low-cost and medium-cost passive measures. When all lost-cost measures were considered at the same time, their payback period increased more than 10 years, hence classified into high-cost measures. Similar trend was observed in the case of passive measures. Thus, they were not considered in this study.

4.6 EUI of SMME Building

The energy use intensity of the SMME building is calculated using the DesignBuilder. In DesignBuilder EUI of the building can be calculated by normalizing the energy consumption of the building by floor area. It is observed that energy use intensity of the SMME building is 154.71 kWh/m^2/year. Unfortunately, there are no EUI or BEI standards for buildings in Pakistan. So, for the sake of comparison, it is compared with the standards for educational buildings of other countries. Less EUI represents the more energy efficient building.

The Malaysian standard MS 1525 suggests the best BEI of 135 kWh/m^2/year for commercial buildings. Similarly, the average energy use intensity for universities in Taiwan is 120.8 kWh/m^2/year [57]. So, the EUI of the SMME building is higher than these standards. The median value of the site EUI for the universities and colleges in US is 265.9 kWh/m^2/year (84.3 kBtu/ft^2) according to the Energy Star portfolio manager. Table 4-4 represents the EUI of university buildings for multiple countries.

Table 4-4: Energy use intensity (EUI) of different buildings in various countries

Country	Climate	Building Type	Sample Size	EUI	Reference
Pakistan	Sub-tropical	SMME, NUST	1	154.71	This study
Taiwan	Sub-tropical	University	51	79	[58]
Australia	Sub-tropical	Griffith University	1	170	[59]
USA	Humid sub-tropical	Cornell University	1	265	[60]
Brazil	Humid, Sub-tropical	University of Passo Fundo	1	49	[61]

CHAPTER 5: CONCLUSION AND FUTURE RECOMMENDATIONS

5.1 Conclusion

This study aimed to investigate the effect of passive climate adaptation measures and their combinations on annual energy consumption of the four-story SMME building. These passive measures are analyzed to suggest some low and medium cost passive measures that can reduce the energy consumption of the SMME building. This is done by performing energy simulations on the base model by implementing these passive measures and calculating their annual energy consumption. After that cost analysis is performed to suggest some low and medium cost passive measures for annual energy savings of the building. Following conclusions can be made after performing annual energy simulations on the SMME building:

- The objective was to suggest some low and medium cost passive measures and the most efficient passive measures in terms of energy reduction are 2 °C increase in C_{sp} and Green Wall. These measures can reduce the energy consumption up to 10.6 % and 10.05 % respectively.
- The most effective combinations are C_{10} (2 °C inc. in C_{sp} and 2 °C dec. in H_{sp}) and C_1 (Green roof and green wall) that can save the 14.36 % and 11.9 % energy consumption, respectively of the building.
- The cooling and heating demand of the building is higher in the base case as compared to passive measures. 2 °C increase in C_{sp} can save the cooling energy consumption up to 23 % approximately. Similarly, by combining SWR and window louvres (C_6) can reduce the cooling energy consumption by 27.18 %. Heating energy consumption of the building was reduced by 62 % by reducing the 2 °C in H_{sp}. The most efficient combination in terms of heating energy consumption is C_{10} (2 °C inc. in C_{sp} and 2 °C dec. in H_{sp}). It can save the heating energy consumption of the building up to 60 % approximately.
- Short-wave reflectivity is the only passive measure that increase the heating energy consumption of the building by 8.47 % approximately. It was due to reflection of most the solar radiations, thus increasing the heating energy demand in winters.
- The result shows that the window thickness has inverse relation with the energy consumption of the building. Increase in window thickness can reduce the energy consumption of the building.

- The energy use intensity (EUI) of the SMME building is 154.71 kWh/m^2/year. It is higher than the EUI standard for the university buildings in most countries. Thus, it is not an energy efficient building.
- The payback period is calculated for each of the passive measure and their combinations. After that classification of passive measures is done into no-cost, low-cost and medium-cost passive measures. It is concluded that variation in cooling and heating setpoints are the most efficient measure having zero payback period. Short-wave reflectivity, window overhangs (0.5 m), window side fins (0.5 m) have payback period of 2.79 %, 1.88 % and 2.83 % respectively. They are suggested as low-cost passive measures that can reduce the energy consumption of the building significantly. C_{10}, C_8 and C_6 are the most effective combinations in terms of payback period.

5.2 Future Recommendations

Every study has its limitations that can be addressed in future works. Some of the limitations that can be studied in future are:

- This study is only limited to low and medium cost passive measures. In future, different high-cost passive measures such as thermal mass, thermal insulation, replacing HVAC, etc. can be implemented to check the possible reduction in energy consumption of the building.
- This study only focuses on passive measures that mostly helps to reduce the cooling and heating energy consumption of the building. As lighting is the third major electricity consuming parameter of this building, so different techniques like lighting control should be implemented to reduce the lighting energy consumption of the building.
- In the SMME building, the energy demand is met by the grid. By implementing the renewable energy resources such as solar photovoltaic systems, electricity demand can be reduced that will eventually help in annual savings.
- This study was done for the climate of Islamabad only. This building model can be used to investigate the effects of PCAMs in other climates of Pakistan such as northern part of the country which lies in cold and freezing weather conditions.
- The effect of different window to wall ratios (WWR) on annual energy consumption of the building can be studied.

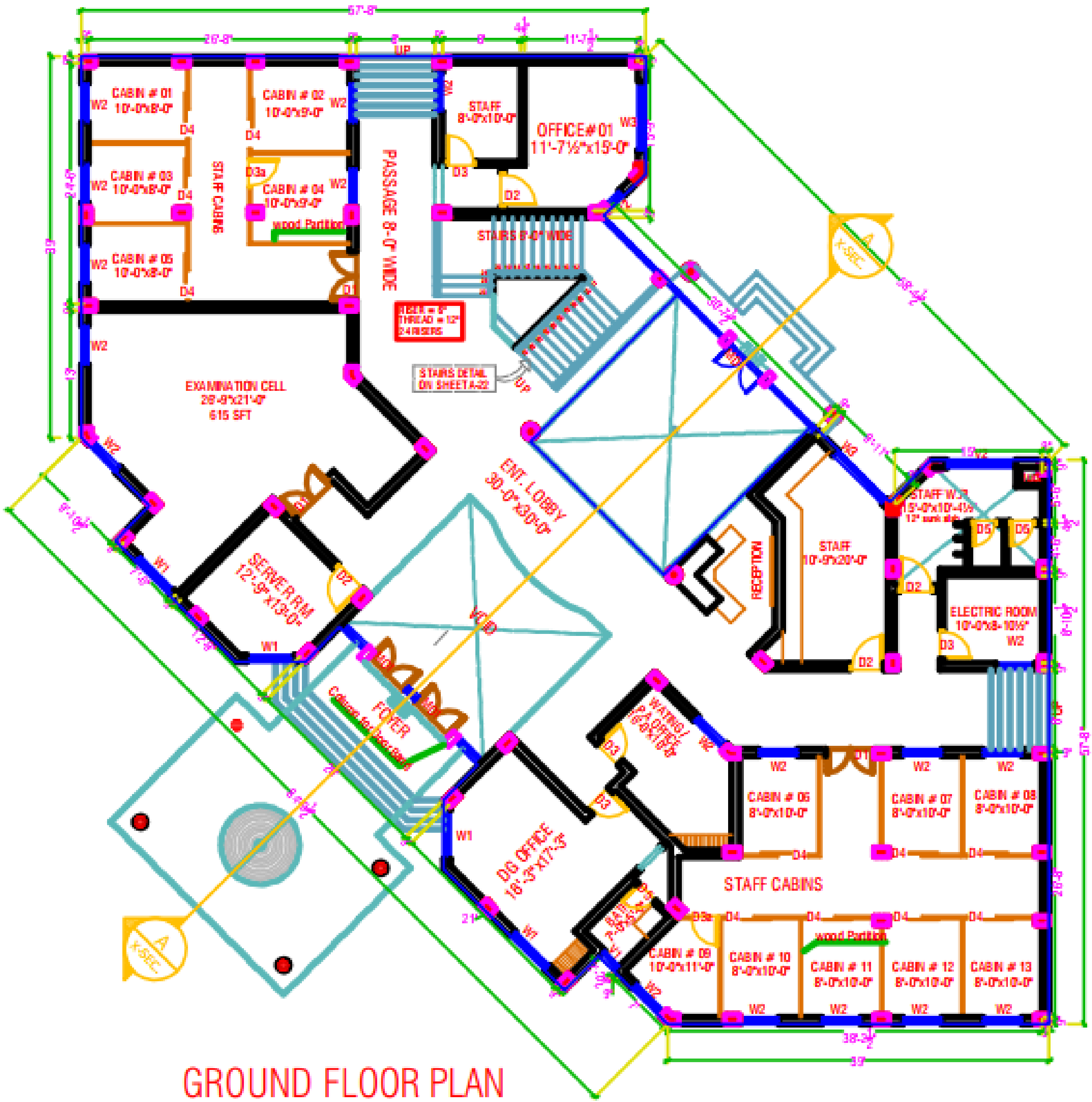
Symbols Used

Symbol	Description
°C	Centigrade
CO_2	Carbon Dioxide
U-value	Thermal Transmittance

Abbreviations

Abbreviation	Description
GHGs	Greenhouse gases
PCMs	Phase Change Materials
PCAMs	Passive Climate Adaptation Measures
CFD	Computational Fluid Dynamics
DB	DesignBuilder
HVAC	Heating, Ventilation, and Air Conditioning
VRF	Variable Refrigerant Flow
CBECS	Commercial Building Energy Consumption Survey
SMME	School of Mechanical & Manufacturing Engineering
SNS	School of Natural Sciences
PMO	Project Management Office
BOQs	Bills of Quantities
BEI	Building Energy Index
EUI	Energy Use Intensity
TMY	Typical Meteorological Year
LAI	Leaf Area Index
SWR	Short-wave Reflectivity
DGW	Double Glazed Windows
GR	Green Roof
GW	Green Wall
WO	Window Overhang
WS	Window Side fin
WL	Window Louvre
C_{sp}	Cooling Setpoint
H_{sp}	Heating Setpoint
RCC	Reinforced Cement Concrete
P.C.C	Plain Cement Concrete
SHGC	Solar Heat Gain Coefficient

APPENDIX A


CABIN # 01
CABIN # 02
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STAFF CABINS
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OFFICE# 01
STAIRS 8'-0" WIDE
STAIRS DETAIL ON SHEET A-22
EXAMINATION CELL
ENT. LOBBY 30'-0"x30'-0"
SERVER RM
VOID
FOYER
RECEPTION
STAFF
ELECTRIC ROOM
CABIN # 06
CABIN # 07
CABIN # 08
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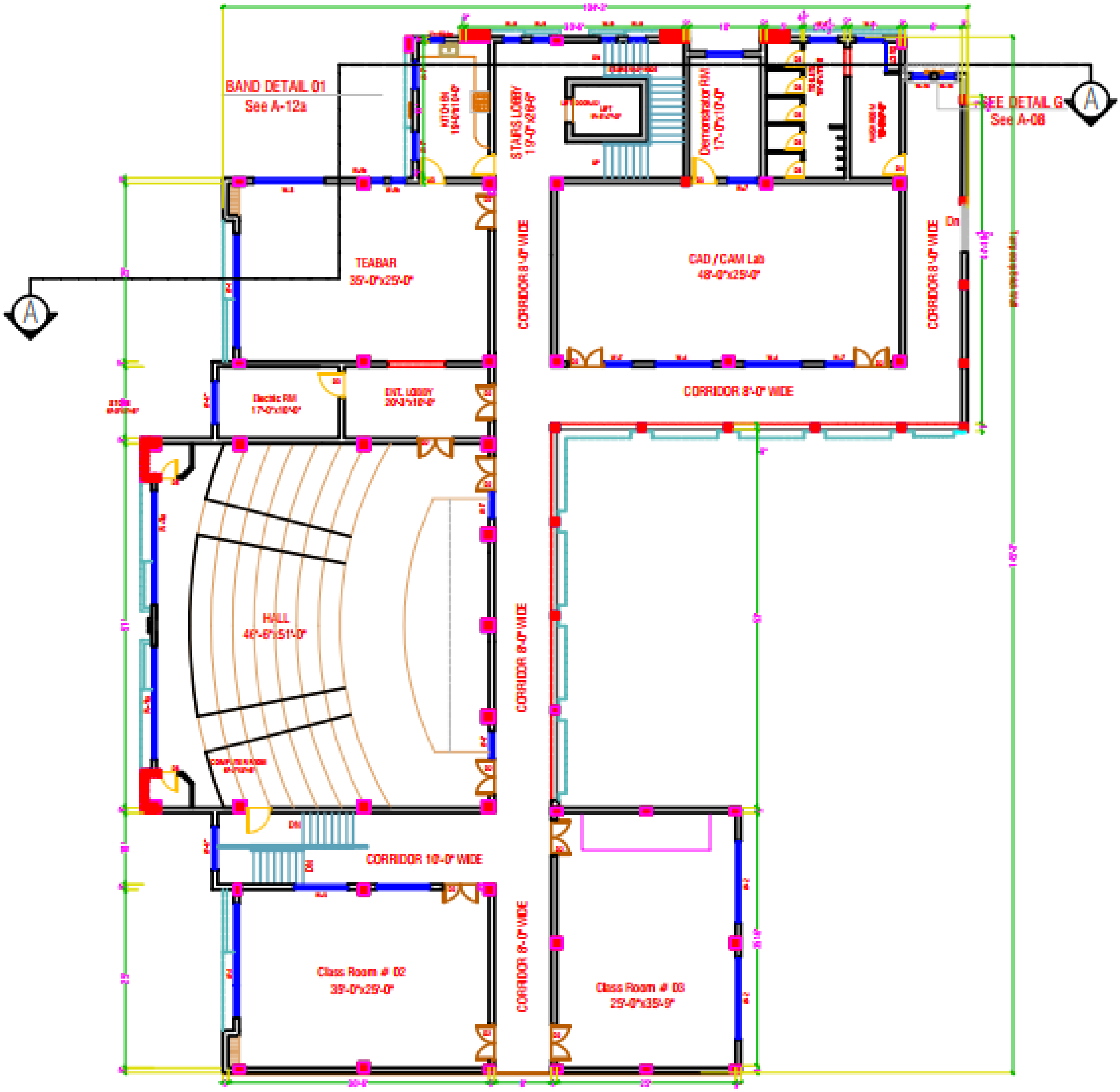
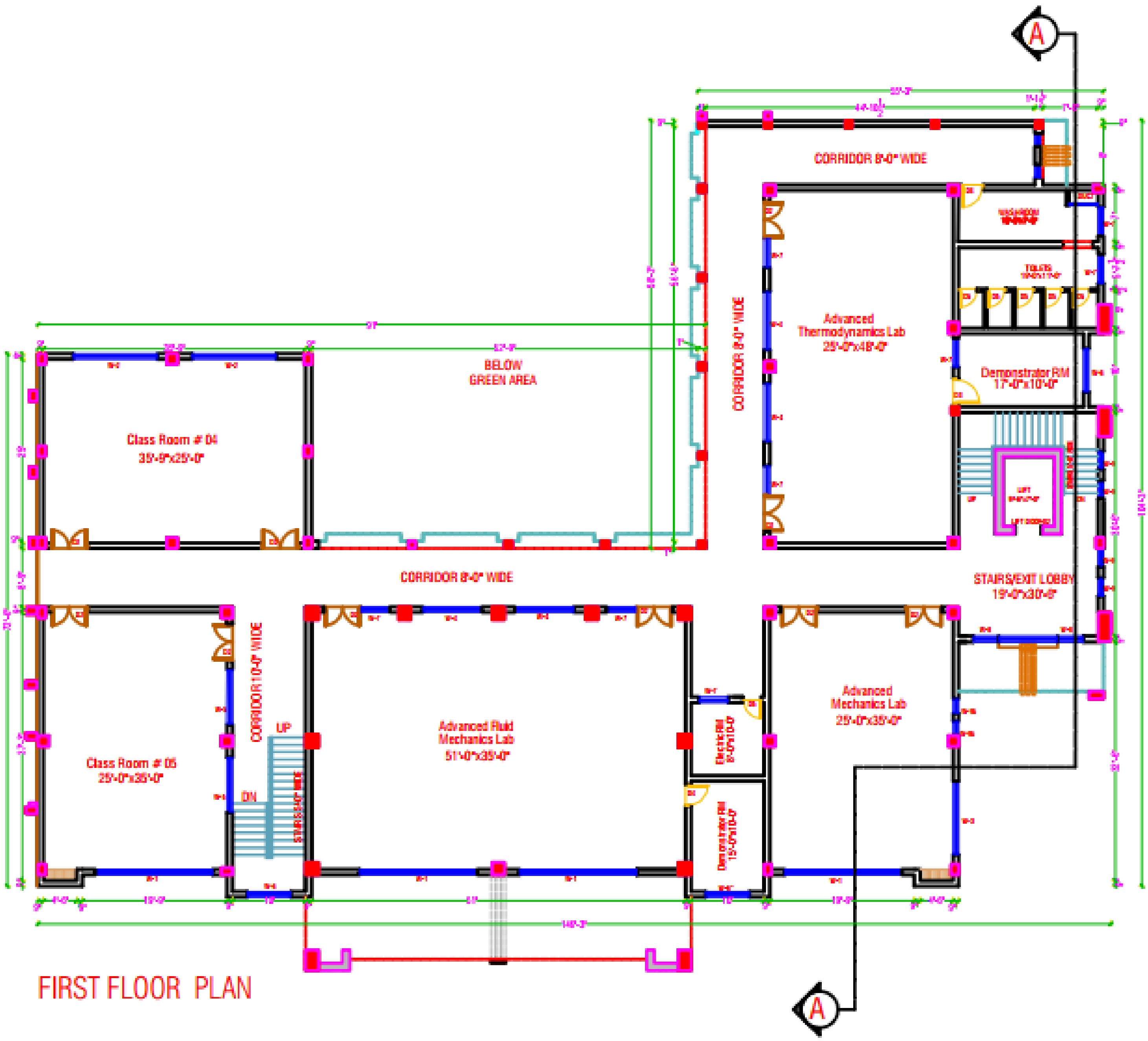
wood Partition
GROUND FLOOR PLAN



THIRD FLOOR WORKING PLAN



FIRST FLOOR PLAN

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