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Energy Efficient Office Buildings in Composite Climate

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Abstract
This research explores the integration of sustainable design strategies to enhance the energy efficiency of office buildings in composite climates, where climatic conditions vary significantly throughout the year. The study focuses on optimizing key architectural parameters, namely form, orientation, window-to-wall ratio (WWR), and building height, with a primary emphasis on achieving an optimal surface area volume (SA/V) ratio. The objective is to minimize energy consumption and improve overall building performance by considering the interplay between architectural design and energy efficiency.
The investigation employs a comprehensive approach, utilizing simulation tools and performance analysis to assess the impact of various design configurations. By strategically manipulating the building form, orienting it in relation to the sun's path, optimizing the WWR to balance daylighting and solar heat gain, and considering the influence of height on energy performance, the study aims to identify an ideal combination of these parameters. The SA/V ratio serves as a critical metric for evaluating the efficiency of the building envelope, contributing significantly to energy conservation.
The research also introduces the concept of the Energy Performance Index (EPI), a quantitative measure that encompasses various energy-related factors. The EPI is used to evaluate the overall energy efficiency of the proposed design solutions, providing a comprehensive perspective on the effectiveness of the implemented strategies.
Results from this study contribute valuable insights to architects, designers, and urban planners seeking to create sustainable and energy-efficient office buildings in composite climates. The findings emphasize the importance of a holistic approach in optimizing building design, considering the synergies between form, orientation, WWR, height, and the SA/V ratio to achieve superior energy performance. This research serves as a practical guide for the development of environmentally responsive and economically viable office buildings in regions characterized by diverse climatic conditions.

Keywords: *Form, Orientation, WWR, Height, SA/V ratio, Energy Performance Index (EPI)*

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I. INTRODUCTION

In an era marked by burgeoning urbanization and escalating energy demands, the imperative for sustainable architectural solutions has never been more pressing. Among these, the design and construction of energy-efficient office buildings emerge as a pivotal arena for innovation and transformation. This dissertation endeavors to dissect the intricate interplay of form, orientation, and WWR within the context of a composite climate, where challenges arise from the amalgamation of contrasting climatic conditions. As we confront the dual challenges of reducing energy consumption and mitigating environmental impacts, the quest for optimal building performance and occupant comfort becomes paramount.

Composite climates, characterized by their dynamic and often unpredictable weather patterns, pose a unique set of challenges for architects and engineers. These climates necessitate a comprehensive approach, one that recognizes the need for adaptable building forms, judicious orientation strategies, and sophisticated fenestration systems. The form of an office building serves as its initial interface with the external environment, dictating how it interacts with natural elements such as sunlight, wind, and precipitation. Concurrently, the orientation of a building exerts a profound influence on its thermal performance and energy efficiency, determining the extent to which it harnesses or mitigates climatic influences.

Among these factors, the WWR holds a position of particular prominence. Windows serve as conduits for both natural light and thermal energy, influencing the interior environment in multifaceted ways. Strategic window placement and the selection of appropriate glazing materials can significantly alter a building's energy consumption patterns, affecting heating, cooling, and lighting loads. Thus, a nuanced understanding of fenestration design within the context of a composite climate is essential for achieving a harmonious balance between energy efficiency and occupant well-being.

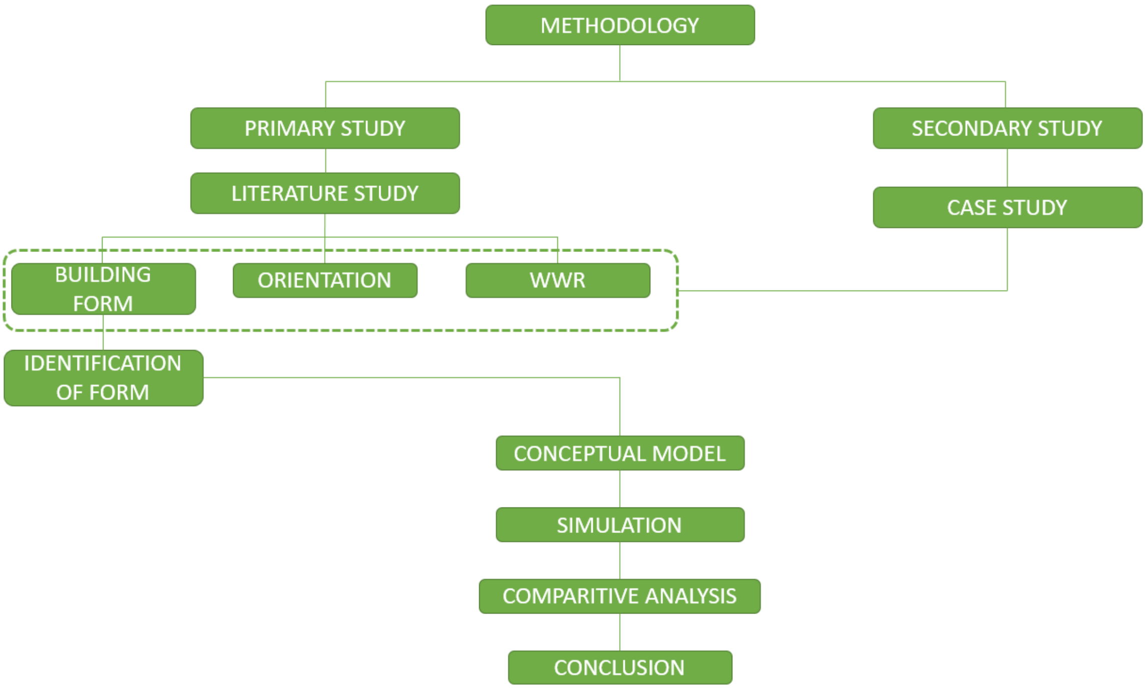
1.1 Aim

To study various building forms, window to wall ratio (WWR), and orientation in a composite climate in order to create energy-efficient office buildings.

1.2 Objectives

1. To understand the various building forms, orientation and WWR from literature study.
2. To analyze the various building forms, orientation and WWR through case study.
3. The comparison analysis based on energy efficiency in composite climate will be conducted through the simulation of various building profiles.
4. The window to wall ratio (WWR) and orientation are taken into consideration while designing office buildings with energy-efficient building forms.

1.3 Methodology



1.3 Scope & Limitation

Without considering the interior layout or the actual location, the main goal of this research is to increase the energy efficiency of office buildings through the use of forms, orientation, and WWR. The project will concentrate on brand-new building shapes that are designed to be the most energy-efficient buildings in a composite climate. The simulations will be run with the building orientated so that a comparison of each form may be made between base cases and final outcomes.

II. Literature Study

Conducting a literature review is a crucial component of a research study. This chapter discusses the important aspect that are related with the energy efficiency of a building. There are several parameters which contribute in making a building energy efficient, which are form, orientation and window to wall ratio (WWR). This literature study investigates different papers of office building in a composite environment. These parameters are discussed briefly below:

2.1 Form

Building forms can have a significant impact on energy consumption and urban sustainability. Different building forms can affect the amount of solar radiation that enters the building, the amount of heat that is retained or lost, and the amount of energy required for heating and cooling. By optimizing building forms, it is possible to reduce energy consumption, improve thermal comfort, and enhance the overall sustainability of urban environments.(Freewan, 2022)

The study found that different building forms can lead to variations in energy consumption in different climate zones. The slab-type is relatively energy-saving in most climate zones, while the block-type and E-shaped comb-type are more suitable for hot summer and warm winter zones. The building shape coefficient is an important parameter for reducing energy consumption in severe cold and cold zones, but the role of building depth is also sensitive. Therefore, comprehensive consideration should be taken to select a compact building form and maintain a suitable depth of building.(Deng et al., 2020)

Factors such as total wall surface area and shape coefficient affect the heat loss rate of buildings, leading to changes in energy consumption. Building floor and sky view factor influence ventilation corridors and shadows, which in turn affect ventilation efficiency and solar radiation, impacting energy use. Floor area ratio and building coverage ratio affect light and solar revenue of buildings, further influencing the energy use of building cooling, heating, and lighting. the research discusses the impact of different building types, such as courtyard buildings, slab-type buildings, and point-type buildings, on energy efficiency and consumption. The study also utilizes regression analysis to evaluate the impact of building form indicators on building energy use, revealing relationships between building coverage ratio and point-type building energy consumption.(Yang & Wang, 2022)

Building forms impact energy consumption in various ways. The shape of a building, particularly in office buildings, can significantly influence both lighting and thermal energy consumption. Research has shown that a more compact shape can lead to reduced heating demand by 6-10%. Additionally, the study found that a cubical shape resulted in a difference in lighting visual comfort of more than 30% compared to a rectangular shape. This suggests that building form plays a crucial role in optimizing energy usage for both lighting and thermal comfort.(Virgone et al., n.d.)

The actual amount of solar radiation on all facades of the building impacts the process of thermal convection, determining the thermal behavior and the level of thermal comfort of the occupants. Building form can also impact the extent of ventilation that passes inside the building and affects the amount of energy needed to meet the building's thermal requirements. The ratio of the volume-to-surface of a building is important in determining the amount of energy consumption. Smaller buildings with a low volume-to-surface ratio indicate controlled thermal load and have an architectural interaction with the sun, while larger buildings with a high volume-to-surface ratio require more energy to compensate for the temperature increase.(Sabah Haseeb et al., 2023)

The study found that building shape has a significant impact on energy consumption in different climate regions. The developed multi-linear regression models were used to predict the effect of building shape on total energy consumption in two different climate regions: cold-dry and warm-marine. The study considered seven building shapes, including H-shape, T-shape, rectangle, and others, and performed statistical analysis using R statistical analysis program to develop a set of linear regression equations predicting energy consumption for each design scenario. the study presented the total annual energy consumption, heating, and cooling loads for the same design and operational conditions in both climate zones, showing that T-shape buildings had the highest total energy consumption in both climate zones, while triangle buildings had the lowest total energy consumption.(Mottahedi et al., 2015)

The building form has a significant impact on energy performance. The study found that the orientation of the building, aspect ratio, and window-to-wall ratio (WWR) influence heat gain and loss through the building envelope. For example, buildings with a north-south orientation and a compact plan shape tend to have lower energy consumption. Additionally, the presence of a courtyard at the center of the building allows for effective daylighting, reducing the need for artificial lighting and subsequently lowering energy consumption. Dividing internal space into areas with different temperatures can also reduce the cooling or heating load of high-rise buildings. Overall, the building form plays a crucial role in determining energy performance, and optimizing design strategies can lead to significant energy savings.(Bano & Sehgal, 2020)

The building form has a significant impact on energy performance, particularly in tropical climates like Penang, Malaysia. Research has shown that building form influences energy consumption through factors such as solar gain, thermal comfort, and natural daylighting. The shape and properties of a building are influenced by temperature, solar gain, wind, and humidity, making it a challenge for architects to establish a suitable relationship between buildings and climate. Studies have indicated that building form factors, especially those related to shading, play a crucial role in reducing energy consumption. The optimization of building shape can lead to a reduction in building energy demand by up to 36%, with the potential to improve energy performance by up to 19% in the study location. Additionally, the study found that a circular building shape with horizontal shading is better than that with vertical shading, contributing to the improvement of building energy performance by providing sufficient natural daylight and a comfortable indoor environment. The findings also suggest that passive solar building design through building form can aid energy efficiency in buildings. Overall, the research emphasizes the importance of considering building form as a key factor in optimizing energy performance and promoting sustainable building design.(Mohsenzadeh et al., 2021)

The building form with the least energy consumption is the cylindrical form. According to the research, the cylindrical building form resulted in the lowest energy consumption rate compared to other geometric forms such as the cube, cuboid, cone, and pyramid. It achieved energy savings of 7.6%, 7.7%, 18.3%, and 40.4% respectively. Additionally, the research also found that using brick as the wall material and marble as the flooring material further enhanced energy efficiency in buildings.(Onome et al., 2018)

The form of a building can has a significant impact on the thermal comfort of the building. The shape and orientation of a building can affect the amount of solar radiation that enters the building, which in turn affects the amount of heat gain or loss. For example, a building with a compact form and a low surface area to volume ratio will have less exposure to solar radiation and therefore less heat gain. On the other hand, a building with a complex form and a high surface area to volume ratio will have more exposure to solar radiation and therefore more heat gain.("Effect of Window Wall Ratio (WWR) on Heat Gain in Commercial Buildings in The Climate of Lahore," 2016)

In the central European region, non-compact forms are more suitable than compact forms because they allow for using larger window surfaces and therefore allow more solar heat gain to be received. The impact of facade on energy-efficient buildings was much lower than that of conventional buildings. The overall energy consumption of the building is highly dependent on changing the indoor heat load and the shading system.(Shaeri et al., 2019)

2.2 Orientation

The life cycle of energy consumption is not significantly impacted by the orientation of a building. When it comes to heating energy, its influence on energy usage is greater. Because they self-shade, south-tilted facades are effective at minimizing cooling demand. The most energy-efficient building styles have balanced facades slanted north and south. The best-performing buildings have 30-degree angles formed by their south-tilted façade, which save 20% on average on energy. Structures with 10-degree north and 30-degree south facade tilts can cut energy use by about 23% when compared to the base scenario. Reducing the cooling load by 15% to 23% on average can be achieved by tilting walls up to 30 degrees. The configuration of the south facade has a greater impact on cooling load than the configuration of the north façade.(Freewan, 2022)

The building orientation has a significant impact on energy consumption in different climate zones. In the severe cold zone, heating energy consumption is the main energy consumption, accounting for about 74.1% of the total energy consumption. The smaller the building shape coefficient, the lower the building energy consumption will be. In the hot summer and warm winter zone, north-south oriented building models effectively reduce cooling energy consumption by avoiding excessive solar radiation caused by an east-west direction. The depth of the building and the organization of internal functional space affect natural lighting conditions, which in turn impact lighting energy consumption. Models with increased lighting area facing south and reduced building depth through embedding in inner or outer courtyards improve natural lighting conditions and reduce lighting energy consumption.(Deng et al., 2020)

The building orientation can have a significant impact on energy consumption. By strategically positioning and orienting buildings, solar radiation can be harnessed or minimized to affect heating and cooling loads. For example, buildings with large windows facing south can take advantage of passive solar heating during the winter, reducing the need for heating energy. Conversely, buildings with extensive east and west-facing windows may experience increased cooling loads due to solar heat gain during the hottest parts of the day. Proper orientation can also optimize natural ventilation and daylighting, further influencing energy consumption for heating, cooling, and lighting. Therefore, the careful consideration of building orientation is crucial for maximizing energy efficiency and minimizing energy consumption.(Yang & Wang, 2022)

The orientation of a building can has a significant impact on its energy consumption. According to the research discussed in the article, the orientation of a building can affects its exposure to solar radiation, which can in turn affect its heating and cooling demands. Buildings that are oriented to maximize solar gain in the winter can reduce their heating demand, while buildings that are oriented to minimize solar gain in the summer can reduce their cooling demand. Additionally, the orientation of a building can affects its exposure to wind, which can impact its ventilation and air conditioning needs. Therefore, the orientation of a building is an important factor to consider when designing for energy efficiency.(Sabah Haseeb et al., 2023)

The orientation of a building can has a significant impact on its energy consumption. The study suggests that the process of determining the proper orientation for a building begins with an evaluation of the project’s geographical location, including determining the city’s longitude and latitude as well as studying the local climate conditions. The orientation of the building should be optimized to take advantage of natural light and ventilation while also reducing the building’s energy consumption. the optimum orientation for achieving thermal comfort in a dwelling is one that receives the most sunshine in the winter and the least in the summer. The orientation of the building facets is preferably turned towards the north for places with a hot climate to reach the least solar radiation in the summer, and the opposite for locations with a cold climate to reach the most solar radiation on the building in the winter. Wind direction and speed should also be studied in a location throughout the year, and the building should be oriented so that the wind flow is more in the building during the wet season than in other seasons.(Sabah Haseeb et al., 2023)

The study investigates the effect of building orientation on energy consumption. The results indicate that building orientation is one of the key building parameters that influence annual energy consumption. In the context of this study, the orientation of the building has a significant impact on the total energy consumption, particularly in different climate regions. The multi-linear regression model developed in the study provides insights into how building orientation, along with other parameters, contributes to the overall energy consumption of office buildings in various climate zones. The findings suggest that understanding and optimizing building orientation can be crucial for reducing energy consumption and improving the overall energy performance of office buildings. By considering the impact of building orientation on energy consumption, designers and stakeholders can make informed decisions to enhance the energy efficiency of buildings in different climate regions.(Mottahedi et al., 2015)

The building orientation has a significant impact on energy consumption. In the study of office buildings in Lucknow, it was found that the orientation of the building plays a crucial role in energy usage. The buildings oriented in the east-west direction were noted to absorb heat from the low-angled morning and afternoon sun, leading to increased cooling and lighting loads. On the other hand, buildings with a north-south orientation were found to have lower energy consumption, likely due to reduced heat absorption. Therefore, it is recommended to install large-area windows in the north-south direction to avoid heat absorption into the building and decrease energy consumption.(Bano & Sehgal, 2020)

The building orientation has a significant impact on energy consumption. Studies have shown that the orientation of a building affects its exposure to solar radiation, which in turn influences the building's cooling loads and energy demand. In hot-humid climates like Penang, Malaysia, the proper orientation of a building can helps control solar heating and reduce the amount of cooling energy required. Additionally, the shape and form of a building, including its orientation, play a crucial role in reducing energy consumption, with specific building shapes and shading strategies being identified as effective in improving energy performance. Furthermore, the study found that the amount of solar gain contributed to an increase in the energy efficiency index (EEI), indicating a direct relationship between solar gain and energy consumption. The research also revealed that optimizing building shape can lead to a reduction in energy demand of up to 19% in the study location, highlighting the importance of building orientation and form in achieving energy efficiency. Building orientation significantly influences energy consumption by impacting solar radiation exposure, cooling loads, and overall energy performance. Therefore, proper building orientation and form are crucial considerations in the design and construction of energy-efficient buildings in hot-humid climates.(Mohsenzadeh et al., 2021)

The building orientation can have a significant impact on energy efficiency. In the study it was found that variation in openings and orientation plays a vital role in energy consumption. For example, using 20% openings for N/S façade and 30% openings for E/S façade indicated a higher energy demand than when it was reversed as 20% openings for E/S and 30% openings for N/S. Additionally, the orientation of the building can affect the amount of solar radiation that enters the building, which can impact the cooling load and energy consumption.(Onome et al., 2018)

The orientation of a building has a significant impact on energy efficiency. According to the information from multiple sources, the orientation of windows plays a crucial role in determining energy consumption. For example, continuous horizontal windows on the west and east orientations are found to be better than separate horizontal or other types of windows. The optimal window design for the south orientation of an office building is a square window with 40% window-to-wall ratio (WWR) in the central position. Additionally, the study suggests that a window with 30% WWR and a horizontal shape in the upper position is the best design choice for the west orientation. Overall, the orientation and design of windows can greatly affect energy consumption in buildings.(Maleki & Dehghan, 2021)

According to the study, the simulated office building in the study was oriented east to west to take advantage of the wind direction. The thermal comfort scores varied in different months, with the best thermal comfort conditions observed mostly in May and October in category B. In September, 49% (PPD < 10% full open window) and 51% (PPD < 15%–0.1% open window) thermal comfort scores were obtained when the WWR is 10%.(Alibaba, 2016)

The orientation of a building has a significant impact on heat gain and the optimal window wall ratio. In the study "Effect of Window Wall Ratio (WWR) on Heat Gain in Commercial Buildings in The Climate of

Lahore," it was found that the heat gain through windows varies on different orientations. The research conducted for the climate of Lahore, which has a hot climate for 8 months and mild winter for the rest of 4 months, showed that the impact of the south façade is highest on energy consumption, while the impact of the north façade is the lowest. The study also revealed that the heat gain generally decreases with the decrease in the size of windows on all orientations, leading to a decrease in cooling load in hot climates like that of Lahore. Additionally, larger windows are suggested on the north side in hot climates compared to other orientations, while smaller windows with a window wall ratio (WWR) of 0.20 - 0.30 or appropriate shading devices are recommended for the south side to handle heat gain.("Effect of Window Wall Ratio (WWR) on Heat Gain in Commercial Buildings in The Climate of Lahore," 2016)

The building orientation plays a significant role in the energy consumption of buildings. The research found that by choosing the right orientation, heating energy demand can be reduced by up to 13.73% and cooling energy demand can be reduced by up to 13.26%. For predominantly south orientation, even a small change in building orientation could result in a decrease in energy consumption. The study also suggests that shading systems should be installed to improve cooling energy performance without affecting the heating one.(Vasov et al., 2018)

It was discovered that in the moderate climate, a bigger WWR is more advantageous in the winter in the south, east, and west facing zones, but not on the north side, which received less direct solar light. The purpose of this is to promote the increased use of passive solar heating. The research findings indicate that the maximum WWR in highland and mild regions can be 40%, 35%, and 35% in the north, east, and south, respectively. In hot, arid locations, the recommended sequence of orientations is 30%, 25%, and 25%.(Alwetaishi & Benjeddou, 2021)

The building orientation has a significant impact on energy efficiency. In the case of the mixed-mode office building studied in a high-altitude tropical climate, the south-facing facade was found to have the lowest energy consumption for all Window-to-Wall Ratios (WWRs). This is due to lower solar heat gains on the south facade compared to other orientations (north, east, and west). Therefore, large window areas should be avoided in the north, east, and west facades to reduce energy consumption. On the other hand, the north, east, and west facades with larger WWRs (80%) were classified as having the highest energy consumption. Despite their high daylight autonomy, these orientations also had a higher risk of glare. Therefore, it is recommended to avoid large window areas in these orientations as well. The south-facing facade offers the best energy efficiency in the studied building, while the north, east, and west facades with larger WWRs have higher energy consumption and a higher risk of glare. Proper design considerations, such as choosing the appropriate WWR and solar orientation, can help achieve a balance between energy consumption, daylight autonomy, and the risk of glare.(Brugnera et al., 2019)

The orientation of a building determines the amount of solar radiation it receives throughout the day. Buildings with a south-facing orientation receive more direct sunlight, which can be beneficial in colder climates as it helps to naturally heat the building during the winter months. On the other hand, buildings with a north-facing orientation receive less direct sunlight, resulting in lower heating loads. In warmer climates, a building with a north-facing orientation can help reduce cooling loads as it receives less direct sunlight. South-facing buildings, on the other hand, may require additional cooling measures to counteract the increased solar heat gain. Building orientation also affects natural ventilation and daylighting. By strategically positioning windows and openings, buildings can take advantage of prevailing winds for natural ventilation, reducing the need for mechanical cooling. Additionally, proper orientation can maximize natural daylighting, reducing the reliance on artificial lighting and further reducing energy consumption.(Badawy et al., n.d.)

The most energy-efficient orientation for glazing the conditioned office building when solar shading is not applied is the north while east and west orientations are the worst, according to the analyzed results. Energy efficient WWR (window-to-wall ratio) values differ for different facades and are 20% for the south, east and west oriented facades and 20-40% for the north.(Motuziene & Juodis, 2010)

The orientation towards the sun has a moderate importance in increasing the indoor temperature for the window size, so there is no significant change in the amount of energy obtained by rotating houses 180◦. For each climate with a certain orientation, there is no optimal ratio for the window size, but in all cases, the minimum energy consumption in samples was for those with a window area of 30–45%. The southern facade of the cold climate and the very hot climate were exceptions in this case. However, the impact of facade on energy-efficient buildings was much lower than that of conventional buildings.(Shaeri et al., 2019)

2.3 WWR

Windows are more susceptible to heat gain and loss compared to walls. Therefore, a higher WWR can result in increased heat gain during hot weather, leading to higher cooling energy consumption, and increased heat loss during cold weather, leading to higher heating energy consumption. While windows provide natural daylighting, they also allow solar heat to enter the building. A higher WWR can lead to excessive solar heat gain, especially in hot climates, which in turn increases the cooling load of the building. A higher WWR can reduce the need for artificial lighting during daylight hours, potentially reducing lighting energy consumption. However, this benefit needs to be balanced with the potential for increased heat gain and loss through the windows. The WWR affects the overall performance of the building envelope, including insulation, air leakage, and thermal bridging. A higher WWR can impact the effectiveness of the building envelope in controlling heat transfer, potentially leading to increased energy consumption for heating and cooling.(Deng et al., 2020)

The window to wall ratio (WWR) of a building also has a significant impact on energy consumption. In the study of office buildings in Lucknow, it was found that the selected government office buildings had a low WWR range of 20%–25%, with a recessed window of 450 mm depth, whereas the selected private offices had a high WWR range of 50%–60%, without any shading devices. The study also found that a WWR of 25% was found to be optimum for horizontal fenestrations and 35% for vertical fenestrations for daylight optimization in high-rise office buildings. The WWR of the BOB building was found to be optimum (31%) as per Mahoney's recommendations for the climate of Lucknow, which restricted heat gain and allowed sufficient daylight to enter the interiors. Moreover, the compact plan and low plan depth (5 m) because of the presence of a courtyard at the center of the BOB building reduced the electricity consumption by artificial lighting. Therefore, it is recommended to optimize the WWR of a building to reduce energy consumption while ensuring sufficient daylight and ventilation.(Bano & Sehgal, 2020)

The window to wall ratio (WWR) has a significant impact on the energy efficiency of a building. In the study, it was found that the smaller the opening (i.e., the lower the WWR), the lesser the energy consumption and the more effective the use of thermal mass. This indicates that a lower WWR can contribute to reduced energy consumption and improved energy efficiency. Additionally, the percentage of fenestration should not exceed 40% of the façade area for the comfort of occupants, according to ASHRAE-IESNA's research. Therefore, controlling the WWR is an important factor in designing energy-efficient buildings.(Onome et al., 2018)

The impact of the window to wall ratio (WWR) on the energy efficiency of high-rise office buildings with photovoltachromic (PVC) windows is significant. Optimal WWR values depend on various factors such as lighting power density, climate, window orientation, and insulation features of the building envelope. Studies have shown that the WWR values can reduce or increase energy consumption. It has been conducted to evaluate the optimal WWR ranges of PVC windows in different climate conditions. Simulation results have indicated that PVC windows can reduce energy consumption of high-rise office buildings by up to 16.31% in Kermanshah, 19.69% in Tehran, 18.59% in Yazd, and 17.36% in Bandar Abbas. The optimal WWR range of PVC windows was found to be 80-90% in Kermanshah and 70-80% in Tehran, Yazd, and Bandar Abbas. By optimizing the WWR and incorporating PVC windows, high-rise office buildings can achieve improved energy efficiency and reduce their environmental impact. The combination of PVC windows with their adaptive transparency and BIPV systems offers a promising solution for enhancing the thermal and optical performance of windows in high-rise office buildings.(Fathi & Kavoosi, 2021)

The optimal window design for the south orientation of an office building is a square window with 40% window-to-wall ratio (WWR) in the central position. Additionally, the study suggests that a window with 30% WWR and a horizontal shape in the upper position is the best design choice for the west orientation. Overall, the orientation and design of windows can greatly affect energy consumption in buildings.(Maleki & Dehghan, 2021)

The building's energy demand increased in direct proportion to the increase in window-to-wall area; however, the distribution pattern varied depending on the size of the building. Specifically, for structures greater than 3600 m2, WWR could not determine the building's energy use. Energy sensitivity tests using SHGC and U-value for a mid-sized structure revealed no effect at 20% WWR. It was demonstrated that keeping SHGC below 0.4 resulted in great energy performance in the instance of a mid-sized structure with a significant WWR. Different material qualities of the window appeared to have a significant impact in the case of a mid-sized building, as WWR increased from the energy sensitivity study with respect to WFR.(Kim et al., 2021)

The study found that the window to external wall ratio (WWR) had a significant impact on thermal comfort in a hot and humid climate. For example, in May, thermal comfort scores of 45% (PPD < 6%–0.7% open window), 93% (PPD < 10–0.2 open window), and 97% (PPD < 15%–0.1% open window) were obtained when the WWR was 10%. In October, thermal comfort scores of 43% (PPD < 6%–0.7% open window), 86% (PPD < 10–0.2 open window), and 92% (PPD < 15%–0.1% open window) were obtained when the WWR was 10%. These findings highlight the importance of WWR in achieving thermal comfort in hot and humid climates.(Alibaba, 2016)

The "Effect of Window Wall Ratio (WWR) on Heat Gain in Commercial Buildings in The Climate of Lahore" revealed that the heat gain generally decreases with the decrease in the size of windows on all orientations, leading to a decrease in cooling load in hot climates like that of Lahore. This indicates that a lower WWR can contribute to improved thermal comfort by reducing heat gain and the associated cooling demand. The research suggested that larger windows are recommended on the north side in hot climates compared to other orientations, while smaller windows with a WWR of 0.20 - 0.30 or appropriate shading devices are recommended for the south side to handle heat gain. This orientation-specific approach to WWR can help optimize thermal comfort based on the building's orientation. The impact of the south façade was found to be highest on energy consumption, while the impact of the north façade was the lowest. This underscores the importance of considering WWR in relation to building orientation to effectively manage energy consumption and enhance thermal comfort.("Effect of Window Wall Ratio (WWR) on Heat Gain in Commercial Buildings in The Climate of Lahore," 2016)

The window to wall ratio (WWR) has a significant impact on the energy consumption of a building. The study found that the size of windows, as indicated by the WWR, influences the energy needs of the building. It was concluded that highly glazed single skin buildings are likely to consume more energy, but the most energy-efficient 100% glazed alternative results in only 15% higher total energy use compared with the reference building with 30% WWR. This suggests that the WWR is an important factor to consider in the design of energy-efficient buildings.(Vasov et al., 2018)

The document indicates that the window to wall ratio (WWR) has a significant impact on the energy efficiency of the building. It states that adjusting the WWR can lead to a considerable impact on energy consumption compared to adjusting the external walls' thickness. The influence of WWR on energy consumption and internal thermal conditions varies based on the orientation and climatic zone. Specifically, the document provides recommendations for the maximum WWR in different orientations and climatic zones. For example, in higher altitude locations located in hot regions, the recommended maximum WWR is 40%, 35%, and 35% in the north, east, and south, respectively. In hot dry locations, the recommended maximum WWR is 30%, 20%, and 20% in the same sequence of orientations. These recommendations suggest that the percentage of WWR can have a substantial impact on energy efficiency, with different percentages being optimal for different orientations and climatic conditions. Therefore, the specific percentage of WWR can significantly influence the energy efficiency of the building, and it should be carefully considered in building design and construction.(Alwetaishi & Benjeddou, 2021)

The Window-to-Wall Ratio (WWR) of a building has a significant impact on its energy efficiency. As the WWR decreases, there is less availability of natural light, resulting in a smaller room area with daylight autonomy. This means that more artificial lighting and mechanical cooling are required, leading to higher energy consumption. On the other hand, as the WWR increases, there is more natural light available, reducing the need for artificial lighting and mechanical cooling, thus improving energy efficiency. The north, east, and west facades with larger WWRs (80%) were classified as having the highest energy consumption. Despite their high daylight autonomy, these orientations also had a higher risk of glare. Therefore, it is recommended to avoid large window areas in these orientations as well.(Brugnera et al., 2019)

The research findings indicate that the WWR (Window-to-Wall Ratio) has an impact on the energy efficiency of the building. In the case of the north façade, it is observed that the energy consumption is not significantly affected by the WWR, except when the WWR decreases to 10%. At this point, the decrease in WWR starts to harm natural lighting, resulting in increased energy consumption. On the other hand, for the south façade, the research suggests that a WWR of 20% leads to the best energy consumption, which differs from the Egyptian code that recommends a WWR of 30% for ventilated buildings. Therefore, it can be concluded that the WWR plays a role in determining the energy efficiency of the building, particularly in relation to natural lighting and ventilation.(Badawy et al., n.d.)

The analysis of energy demand shows that in most cases, energy efficient WWR (window-to-wall ratio) for the conditioned office building in cool climate zones like Lithuania is 20% for the south, east and west oriented façades and 20-40% for the north. For highly fenestrated conditioned office buildings of any orientation, cooling energy demand is 2 to 3 times higher than that for heating (except north oriented). Energy efficient WWR values do not satisfy standard hygienic requirements for daylighting, meaning the most energy efficient fenestration does not satisfy minimum daylighting standards, hence recommended WWR must be equal to the minimum required by daylighting standard.(Motuziene & Juodis, 2010)

The findings indicate that, in all climates, 20–30% of the north building front should be made up of windows. This amounts to 20–30%, 10–30%, and 20–50% for the southern facades of the buildings in Bushehr, Shiraz, and Tabriz, respectively. For the eastern and western building facades in Bushehr, the ideal window area is between 30 and 50%; in Tabriz, it is between 40 and 70%; and in Shiraz, it is between 20 and 60% and 40 and 70%, respectively. In Bushehr and Shiraz, there is a 20–100% difference in the highest and minimum energy usage with varied window areas; in Tabriz, there is a 16–25% difference.(Shaeri et al., 2019)

The WWR (Window to Wall Ratio) analysis was performed to determine the daylight intensity in offices for visual comfort and lighting intensity boundaries in office buildings. Visual comfort is satisfied if the lighting intensity holds a constant value between 350 and 500 lx throughout the occupied working schedule which in this study is set from 8.00 to 16.00 hours. The lighting quality is demonstrated through daylight intensity analysis where the illumination scale was set from 0-1000 lx. The simulation outputs showed that the 30% WWR had shown the best dispersion performance. In correlation with its luminance performance, the demand for heating and cooling energy compared with the base case presents an effective solution. The base case 50% WWR had in most orientations higher interior lighting intensity than the upper limit of 500 lx which is inadequate for a working environment. Finally, the 20% WWR presented a lighting intensity lower than the demanded 350 lx in most of the simulated orientations. Hence, it can be concluded that the WWR has a significant impact on the energy efficiency of the building and selecting an appropriate WWR can lead to better energy performance.(Harmati et al., 2016)

2.4 Conclusion

The facade with its balanced north-south tilt conserved the most energy. The energy consumption of point-type buildings is positively correlated with the building coverage ratio (BCR). The model with a T-shape used the least energy. The lighting visual comfort of a rectangular and cubic shape is more than thirty percent, and if a more compact shape is chosen, the heating demand is lowered by six to ten percent. In terms of energy efficiency, e-shaped comb-type are more suited for hot summers and warm winters. Building locations, shapes, and energy consumption levels are highly correlated.

Out of cube, cuboid, cone, and pyramid construction forms, the cylindrical building form used the least amount of energy. Energy consumption was significantly impacted by the wwr. The most energy-efficient office building in terms of WWR is 20%. This indicates that higher WWR will result in less energy-efficient buildings, and in certain circumstances, orientation is disregarded due to compact planning and reduced solar radiation exposure. Furthermore, the building with an east-west orientation enjoys the best wind direction. During the hottest times of the day, solar heat gain may cause buildings with large east and west facing windows to have higher cooling demands.

III. Case Study

In the pursuit of sustainable and energy-efficient architecture, the case study of [Aranaya Bhawan, Income Tax Building, Divisional Office Building IOCL, Indira Paryavaran Bhawan, and Bhamashah State Data Centre] stands as a noteworthy example of thoughtful design and innovative strategies. This study delves into the building's distinctive features, emphasizing key parameters such as form, orientation, Window-to-Wall Ratio (WWR), and its consequential Energy Performance Index (EPI). These elements collectively contribute to the building's ability to harmonize with its environment, minimize energy consumption, and create a conducive indoor environment.

Form and Aesthetic Integration: [Aranaya Bhawan, Income Tax Building, Divisional Office Building IOCL, Indira Paryavaran Bhawan, and Bhamashah State Data Centre] boasts a unique architectural form that not only serves aesthetic purposes but also plays a crucial role in optimizing energy performance. The design principles take into consideration the local climate, cultural context, and functionality, resulting in a structure that seamlessly integrates with its surroundings while prioritizing sustainability.

Strategic Orientation: The orientation of a building plays a pivotal role in harnessing natural resources effectively. This case study explores how [Aranaya Bhawan, Income Tax Building, Divisional Office Building IOCL, Indira Paryavaran Bhawan, and Bhamashah State Data Centre] strategically aligns itself to maximize solar gain during the colder months and mitigate heat gain during warmer periods. The orientation not only influences the building's thermal performance but also enhances the occupants' comfort and well-being.

Window-to-Wall Ratio (WWR): An essential factor in achieving a balance between natural light, views, and energy efficiency is the Window-to-Wall Ratio (WWR). [Aranaya Bhawan, Income Tax Building, Divisional Office Building IOCL, Indira Paryavaran Bhawan, and Bhamashah State Data Centre] case study investigates how the careful selection of WWR contributes to optimizing daylighting, reducing artificial lighting needs, and influencing the overall energy demand of the building.

Energy Performance Index (EPI): The effectiveness of the building's sustainable design is quantified through the Energy Performance Index (EPI). This metric encapsulates the overall energy efficiency, considering factors such as insulation, HVAC systems, lighting, and renewable energy integration. The case study meticulously analyzes [Aranaya Bhawan, Income Tax Building, Divisional Office Building IOCL, Indira Paryavaran Bhawan, and Bhamashah State Data Centre] EPI, shedding light on its performance against established benchmarks and its impact on the broader sustainability goals.

Through a comprehensive exploration of these parameters, this case study aims to unravel the intricacies of [Aranaya Bhawan, Income Tax Building, Divisional Office Building IOCL, Indira Paryavaran Bhawan, and Bhamashah State Data Centre] design and its implications for sustainable architecture. By dissecting the interplay of form, orientation, WWR, and EPI, valuable insights will be gained for architects, designers, and policymakers striving for a greener and more energy-efficient built environment.

3.1 Identification and Selection Criteria

The identification and selection of buildings for sustainable development require a meticulous evaluation of various parameters to ensure an environmentally conscious and energy-efficient approach. In this context, the criteria of climate, form, orientation, Window-to-Wall Ratio (WWR), and Energy Performance Index (EPI) emerge as pivotal factors. Understanding and scrutinizing these aspects contribute to a comprehensive strategy for sustainable building practices.

3.1.1 Climate

The first step in identifying a suitable building for sustainable design involves a meticulous climate analysis. The local climate influences a building's energy demands, heating and cooling requirements, and overall performance. Areas with extreme temperature variations or specific climatic challenges may necessitate unique design strategies. A building situated in a temperate climate may require different considerations than one in a tropical or arid region.

3.1.2 Form

The architectural form of a building is a fundamental element influencing its energy efficiency and aesthetic integration. When identifying and selecting buildings for sustainability considerations, attention is given to designs that embrace innovative and contextually responsive forms. Buildings with thoughtful shapes that maximize passive solar gain, encourage natural ventilation, and minimize heat loss are prioritized. The form should not only be visually appealing but also possess inherent features that contribute to sustainable performance.

3.1.3 Orientation

The orientation of a building plays a crucial role in its response to the local climate and its ability to harness or mitigate solar radiation. Sustainable buildings are identified based on their strategic orientation, aligning with the sun's path to optimize daylighting and reduce the reliance on artificial lighting. Selecting buildings that showcase a conscious effort to minimize solar heat gain during hot seasons and maximize it during colder periods is paramount. This criterion ensures a holistic approach to energy efficiency through passive design strategies.

3.1.4 Window-to-Wall Ratio (WWR)

Efficient use of glazing is integral to sustainable design, emphasizing the importance of the Window-to-Wall Ratio (WWR). Buildings selected for sustainable development exhibit a balanced WWR, allowing for ample natural light while minimizing excessive heat gain or loss. The identification criteria include a careful evaluation of the distribution and size of windows, considering factors such as insulation, shading devices, and the overall impact on the building's energy demand.

3.1.5 Energy Performance Index (EPI)

To quantify the overall energy efficiency of a building, the Energy Performance Index (EPI) is a key metric. During the identification and selection process, buildings with lower EPI values are prioritized, indicating superior energy performance and reduced environmental impact. The EPI serves as a comprehensive indicator, considering factors like insulation, HVAC efficiency, renewable energy integration, and overall energy consumption. Sustainable building initiatives focus on selecting structures that align with or surpass established EPI benchmarks.

3.2 Comparative Analysis of the Buildings in Composite Climate

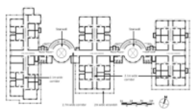
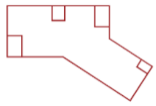
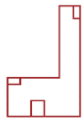
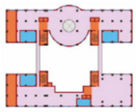
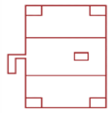
	Aranya Bhawan Case-1	Income Tax Building Case-2	Divisional Office for IOCL Case-3	Indira Paryavaran Bhawan Case-4	Bhamashah State Data Centre Case-5
Location	Jaipur	Lucknow	Kanpur	New Delhi	Jaipur
Climate	Composite	Composite	Composite	Composite	Composite
Orientation	North-South	North-South	NE-SW	North-South	East-West
Form					
WWR	15%	70%	20%	20%	70%
No. of floors	G+4	G+7	Stilt+4	G+7	2B+G+6
Height	18m	24m	15m	31.2m	21m
EPI (kWh/m²/year)	43	60	72.6	24.13	82.86
Total Built-up Area	10,000 m²	13,576 m²	1390 m²	31,400 m²	23,920.94 m²
Images					

Table 1.Comparative Analysis of the Building in Composite Climate

3.3 Conclusion

In conclusion, the meticulous consideration of shape and orientation in the design of the IPB office building for the Ministry of Environment and Forests emerges as a key factor in optimizing daylight utilization and overall energy efficiency. The intentional placement of the building in a north-south direction, complemented by a large linear open court, creates a porous block form that facilitates optimal air movement. This not only enhances the visual and thermal comfort of the building's occupants but also contributes significantly to sustainability goals.

The strategic layout results in a noteworthy 67.5% of regularly occupied spaces meeting the prescribed daylight factor by NBC 2005, attesting to the successful integration of design principles that prioritize natural light. Moreover, 57.67% of the total living area benefits from effective daylighting, surpassing the NBC 2005 standards and minimizing reliance on artificial lighting.

The commitment to energy efficiency is further underscored by the project's low Lighting Power Density (LPD) of 6.37 W/m2, which is below the specified ECBC limit for office buildings. Additionally, the thermal efficiency of the building envelope at 420.06 sq. ft./TR surpasses the higher threshold, demonstrating a keen focus on insulation and thermal performance.

Notably, the careful consideration of the building's shadow ensures that neighboring structures maintain unobstructed solar access, fostering a harmonious coexistence within the environment.

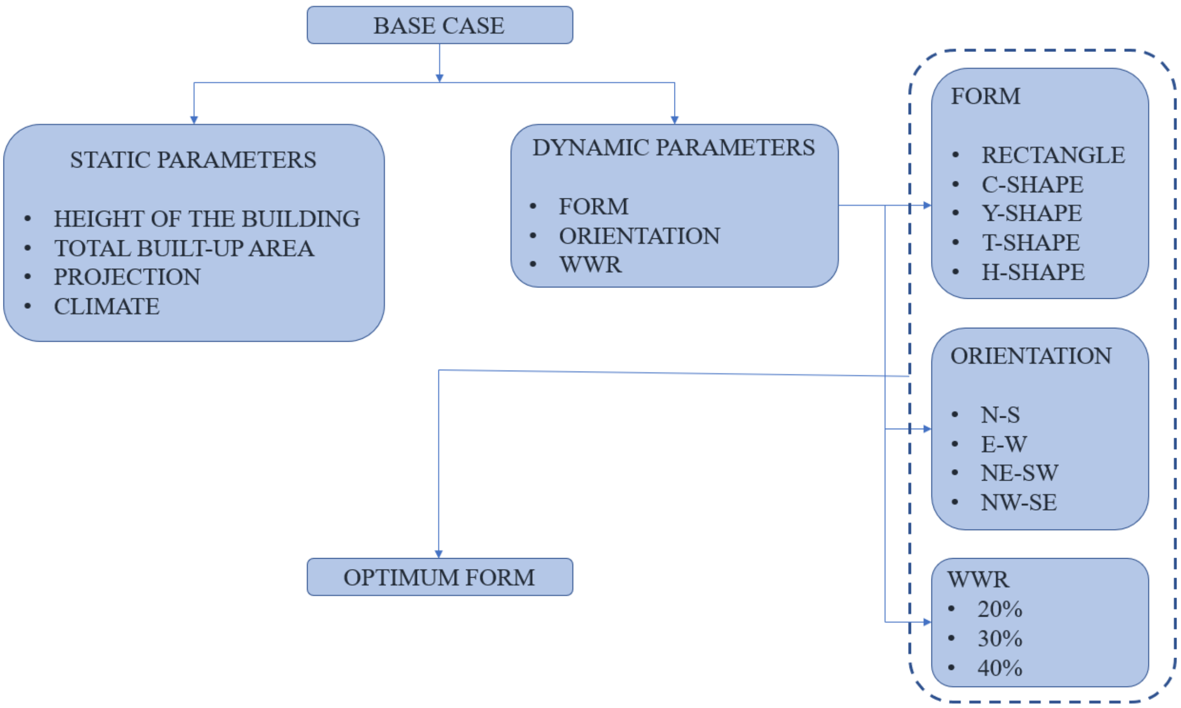
In summary, the culmination of thoughtful design choices in shape and orientation results in a sustainable, energy-efficient, and occupant-friendly building that aligns with contemporary standards and regulations, setting a commendable example in the realm of environmentally conscious architecture.

IV. Simulation Methodology

The integration of simulation methodology into the design and evaluation of buildings marks a paradigm shift in the approach to achieving sustainability and energy efficiency. This delves into the significance of simulation methodologies, focusing on key architectural parameters such as form, orientation, Window-to-Wall Ratio (WWR), and Energy Performance Index (EPI). The focus shifts to the four key architectural parameters under investigation: form, orientation, WWR, and EPI. Each parameter plays a pivotal role in determining the overall sustainability and energy efficiency of a building. Form and orientation impact daylighting and thermal performance, while WWR influences natural light penetration, and EPI quantifies the energy performance of the building.

4.1 Methodology

In this chapter, two types of parameters are determined: dynamic parameters, such as form, orientation, and window to wall ratio (WWR), which vary depending on the situation, and static parameters, such as height, total built-up area, and climate, which are fixed. The goal is to determine the optimal form with the lowest energy performance index (EPI).



4.2 Simulations

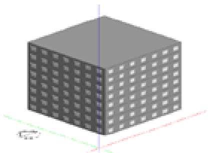


Figure 1.Square

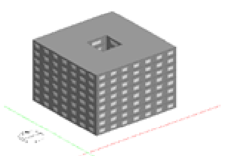


Figure 2.Square with Courtyard

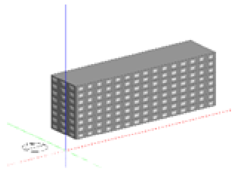


Figure 3.Rectangle

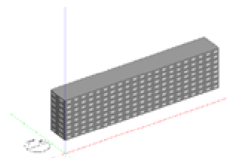


Figure 4.Rectangle 1

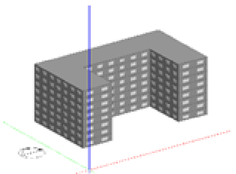


Figure 5.C-shape

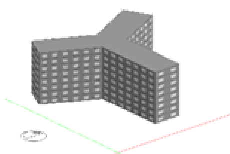


Figure 6.Y-shape

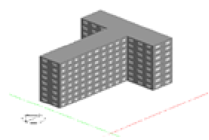


Figure 7.T-shape

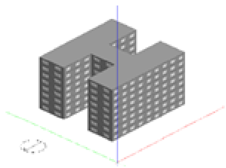


Figure 8.H-shape

Building Forms	**WWR**	**Orientation**	**Height**	**SA/V**	**Projection**	**Total Built-up Area**	**Lighting (Kwh/m²/y)**	**Heating (Kwh/m²/y)**	**Cooling (Kwh/m²/y)**	**EPI (Kwh/m²/y)**
Square (Base Case)	20%	N-S	26.4 M	17:100	0.5M	12,800	23.00	0.294	32.32	55.62
Square with Courtyard	20%	N-S	26.4 M	17:100	0.5M	12,800	21.17	0.403	33.00	54.57
Rectangle	20%	N-S	26.4 M	20:100	0.5M	12,800	21.73	0.250	32.63	54.62
Rectangle 1	20%	N-S	26.4 M	22:100	0.5M	12,800	20.62	0.242	33.73	54.59
C-shape	20%	N-S	26.4 M	22:100	0.5M	12,800	20.74	0.378	34.51	55.64
Y-shape	20%	N-S	26.4 M	22:100	0.5M	12,800	19.64	0.392	35.15	55.19
T-shape	20%	N-S	26.4 M	22:100	0.5M	12,800	20.47	0.366	34.55	55.39
H-shape	20%	N-S	26.4 M	23:100	0.5M	12,800	21.29	0.402	34.02	55.72

Table 2.Comparative chart N-S

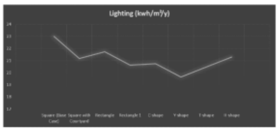


Figure 1.Lighting

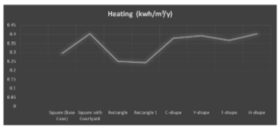


Figure 2.Heating

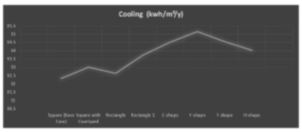


Figure 3.Cooling

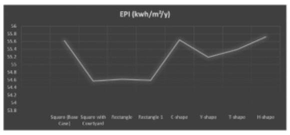


Figure 4.EPI

Inferences

According to the analysis above, the square with courtyard has the highest energy efficiency (EPI: 54.57 kwh/m²/y) because of low surface area volume ratio with WWR 20% and compact planning. The building is naturally ventilated in summers in which cooling (33.00 kwh/m²/y) which reduces the energy usage of the building. Following that rectangle 1 is the most energy efficient (EPI: 54.59 kwh/m²/y) because the longer side of the building is orientated towards north side which makes the building naturally ventilated and the cooling load (33.73 kwh/m²/y) is comparatively high because the longer façade lies on south direction which needs more cooling in summers. The rectangle with the highest energy efficiency, with an (EPI of 54.62 kwh/m²/y), has a cooling load of (32.63 kwh/m²/y). This is because its longer face faces north, providing diffused light and reducing artificial light.

The C-shape has the greatest (EPI of 55.64 kwh/m²/y) because it has more exposed surface area to the south which needs more cooling (34.51 kwh/m²/y) in summer season and lighting (20.74 kwh/m²/y) load is low because the larger portion lies on north direction and some part is mutually shaded which reduces the artificial light during the day time and get natural light.

Building Forms	WWR	Orientation	Height	SA/V	Projection	Total Built-up Area	Lighting (Kwh/m²/y)	Heating (Kwh/m²/y)	Cooling (Kwh/m²/y)	EPI (Kwh/m²/y)
Square (Base Case)	20%	E-W	26.4 M	17:100	0.5M	12,800	23.00	0.294	32.32	55.62
Square with Courtyard	20%	E-W	26.4 M	17:100	0.5M	12,800	21.17	0.403	33.00	54.57
Rectangle	20%	E-W	26.4 M	20:100	0.5M	12,800	20.63	0.406	34.98	56.02
Rectangle 1	20%	E-W	26.4 M	22:100	0.5M	12,800	19.74	0.461	37.56	57.77
C-shape	20%	E-W	26.4 M	22:100	0.5M	12,800	19.83	0.404	34.89	55.12
Y-shape	20%	E-W	26.4 M	22:100	0.5M	12,800	20.43	0.376	35.17	55.99
T-shape	20%	E-W	26.4 M	22:100	0.5M	12,800	20.82	0.403	35.33	56.56
H-shape	20%	E-W	26.4 M	23:100	0.5M	12,800	20.97	0.471	34.72	56.17

Table 3.Comparative chart E-W

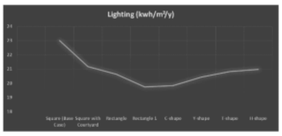


Figure 5.Lighting

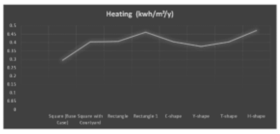


Figure 6.Heating

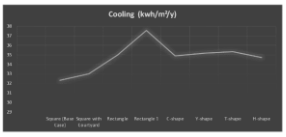


Figure 7.Cooling

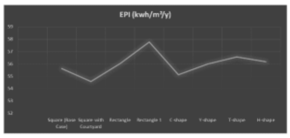


Figure 8.EPI

Inferences

According to the analysis above, the square with courtyard has the highest energy efficiency (EPI: 54.57 kwh/m²/y) because of low surface area volume ratio with WWR 20% and compact planning. The building is naturally ventilated in summers in which cooling (33.00 kwh/m²/y) which reduces the energy usage of the building. Following that C shape is the most energy efficient (EPI: 55.12 kwh/m²/y) because the longer side of the building is orientated towards east side which makes the building naturally ventilated and the cooling load (34.89 kwh/m²/y) is comparatively high because the longer façade lies on west direction which needs more cooling in summers because of direct glare. The square (base case) with the highest energy efficiency, with an (EPI of 55.62 kwh/m²/y), has a cooling load of (32.32 kwh/m²/y). This is because its faces north, providing diffused light and reducing artificial light.

The Rectangle 1 has the greatest (EPI of 57.77 kwh/m²/y) because it has more exposed area to the west which needs more cooling (37.56 kwh/m²/y) in summer season and lighting (19.74 kwh/m²/y) load is low because the larger portion lies on east direction which reduces the artificial light during the day time and get natural light.

Building Forms	**WWR**	**Orientation**	**Height**	**SA/V**	**Projection**	**Total Built-up Area**	**Lighting (Kwh/m²/y)**	**Heating (Kwh/m²/y)**	**Cooling (Kwh/m²/y)**	**EPI (Kwh/m²/y)**
Square (Base Case)	20%	NE-SW	26.4 M	17:100	0.5M	12,800	23.04	0.313	32.56	55.92
Square with Courtyard	20%	NE-SW	26.4 M	17:100	0.5M	12,800	21.06	0.499	33.67	55.24
Rectangle	20%	NE-SW	26.4 M	20:100	0.5M	12,800	21.14	0.374	33.75	55.27
Rectangle 1	20%	NE-SW	26.4 M	22:100	0.5M	12,800	20.18	0.416	35.53	56.13
C-shape	20%	NE-SW	26.4 M	22:100	0.5M	12,800	20.16	0.425	34.89	55.48
Y-shape	20%	NE-SW	26.4 M	22:100	0.5M	12,800	20.17	0.389	35.30	55.87
T-shape	20%	NE-SW	26.4 M	22:100	0.5M	12,800	20.58	0.409	35.08	56.07
H-shape	20%	NE-SW	26.4 M	23:100	0.5M	12,800	21.06	0.476	34.52	56.05

Table 4.Comparative chart NE-SW

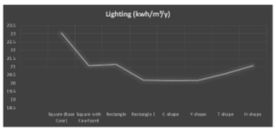


Figure 9.Lighting

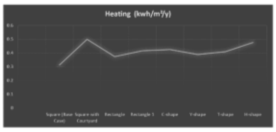


Figure 10.Heating

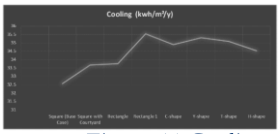


Figure 11.Cooling

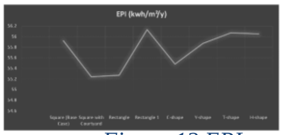


Figure 12.EPI

Inferences

According to the analysis above, the square with courtyard has the highest energy efficiency (EPI: 55.24 kwh/m²/y) because of low surface area volume ratio with WWR 20% and compact planning. The building is naturally ventilated in summers in which cooling (33.67 kwh/m²/y) which reduces the energy usage of the building. Following that rectangle is the most energy efficient (EPI: 55.27 kwh/m²/y) because the longer side of the building is orientated towards NE side which makes the building naturally ventilated and the cooling load (33.75 kwh/m²/y) is comparatively high because the longer façade lies on SW direction which needs more cooling in summers. The C shape is the most energy efficient (EPI: 55.48 kwh/m²/y) because the longer side of the building is orientated towards NE side which makes the building naturally ventilated and the cooling load (34.89 kwh/m²/y) is comparatively high because the longer façade lies on SW direction which needs more cooling in summers because of direct glare.

The Rectangle 1 has the greatest (EPI of 56.13 kwh/m²/y) because it has more exposed area to the SW which needs more cooling (35.53 kwh/m²/y) in summer season and lighting (20.18 kwh/m²/y) load is low because the larger portion lies on NE direction which reduces the artificial light during the day time and get natural light.

Building Forms	WWR	Orientation	Height	SA/V	Projection	Total Built-up Area	Lighting (Kwh/m²/y)	Heating (Kwh/m²/y)	Cooling (Kwh/m²/y)	EPI (Kwh/m²/y)
Square (Base Case)	20%	NW-SE	26.4 M	17:100	0.5M	12,800	23.04	0.313	32.56	55.92
Square with Courtyard	20%	NW-SE	26.4 M	17:100	0.5M	12,800	21.06	0.499	33.67	55.24
Rectangle	20%	NW-SE	26.4 M	20:100	0.5M	12,800	21.07	0.317	34.36	55.74
Rectangle 1	20%	NW-SE	26.4 M	22:100	0.5M	12,800	19.91	0.331	36.33	56.57
C-shape	20%	NW-SE	26.4 M	22:100	0.5M	12,800	20.22	0.425	34.89	55.54
Y-shape	20%	NW-SE	26.4 M	22:100	0.5M	12,800	20.09	0.383	35.23	55.70
T-shape	20%	NW-SE	26.4 M	22:100	0.5M	12,800	20.75	0.409	35.08	56.25
H-shape	20%	NW-SE	26.4 M	23:100	0.5M	12,800	20.90	0.466	34.68	56.05

Table 5.Comparative chart NW-SE

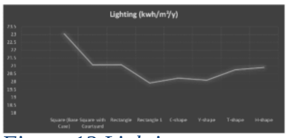


Figure 13.Lighting

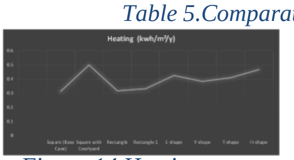


Figure 14.Heating

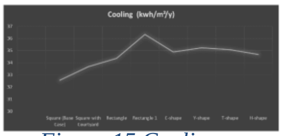


Figure 15.Cooling

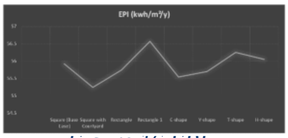


Figure 16.EPI

Inferences

According to the analysis above, the square with courtyard has the highest energy efficiency (EPI: 55.24 kwh/m²/y) because of low surface area volume ratio with WWR 20% and compact planning. The building is naturally ventilated in summers in which cooling (33.67 kwh/m²/y) which reduces the energy usage of the building. Following that C shape is the most energy efficient (EPI: 55.54 kwh/m²/y) because the longer side of the building is orientated towards NW and SE which makes the building naturally ventilated and the cooling load (34.89 kwh/m²/y) is comparatively high because the longer façade lies on NW and SE direction which needs more cooling in summers. Rectangle shape having the (EPI: 55.74 kwh/m²/y) is the most energy efficient because the longer façade lies on NW and SE direction which gets some diffuse light and with the lighting (21.07 kwh/m²/y) reduces the energy consumption of the form.

The Rectangle 1 has the greatest (EPI of 56.57 kwh/m²/y) because it has more exposed area to the SE which needs more cooling (36.33 kwh/m²/y) in summer season and lighting (19.91 kwh/m²/y) load is low because the larger portion lies on NW and SE direction which reduces the artificial light during the day time and get natural light.

Building Forms	WWR	Orientation	Height	Projection	Total Built-up Area	Lighting (Kwh/m²/y)	Heating (Kwh/m²/y)	Cooling (Kwh/m²/y)	EPI (Kwh/m²/y)
Square (Base Case)	30%	N-S	26.4 M	0.5M	12,800	20.76	0.219	34.56	55.54
Square with Courtyard	30%	N-S	26.4 M	0.5M	12,800	19.90	0.302	35.80	56.01
Rectangle	30%	N-S	26.4 M	0.5M	12,800	20.22	0.154	35.39	55.77
Rectangle 1	30%	N-S	26.4 M	0.5M	12,800	19.48	0.143	37.29	56.91
C-shape	30%	N-S	26.4 M	0.5M	12,800	19.62	0.267	38.03	57.92
Y-shape	30%	N-S	26.4 M	0.5M	12,800	18.82	0.273	38.91	58.01
T-shape	30%	N-S	26.4 M	0.5M	12,800	19.36	0.256	38.10	57.73
H-shape	30%	N-S	26.4 M	0.5M	12,800	20.02	0.298	37.18	57.50

Table 6.Comparative chart N-S

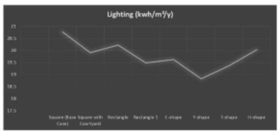


Figure 17.Lighting

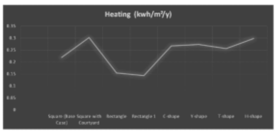


Figure 18.Heating

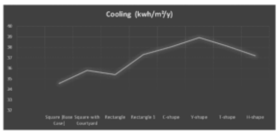


Figure 19.Cooling

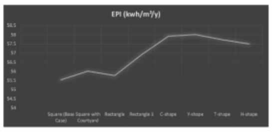


Figure 20.EPI

Inferences

According to the analysis above, the square (base case) has the highest energy efficiency (EPI: 55.54 kwh/m²/y) because of low surface area volume ratio and compact planning. The building is naturally ventilated in summers in which cooling (34.56 kwh/m²/y) which reduces the energy usage of the building. Following that rectangle is the most energy efficient (EPI: 55.77 kwh/m²/y) because the longer side of the building is orientated towards north side which makes the building naturally ventilated by reducing the cooling (35.39 kwh/m²/y) which reduces the energy usage of the building. Due to building height, squares with courtyards have higher cooling and energy efficiency (EPI: 56.01 kwh/m²/y) than squares (base case) and rectangles. The middle floors have less ventilation due to their height, which increases energy consumption during the heat.

The Y-shape has the greatest (EPI of 58.01 kwh/m²/y) because it has more exposed surface area to the south and west which needs more cooling (38.91 kwh/m²/y) in summer season and lighting (18.82 kwh/m²/y) load is low because the larger portion lies on north direction and some part is mutually shaded which reduces the artificial light during the day time and get natural light.

Building Forms	WWR	Orientation	Height	Projection	Total Built-up Area	Lighting (Kwh/m²/y)	Heating (Kwh/m²/y)	Cooling (Kwh/m²/y)	EPI (Kwh/m²/y)
Square (Base Case)	30%	E-W	26.4 M	0.5M	12,800	20.76	0.219	34.56	55.54
Square with Courtyard	30%	E-W	26.4 M	0.5M	12,800	19.90	0.302	35.80	56.01

Rectangle	30%	E-W	26.4 M	0.5M	12,800	19.41	0.314	38.60	58.32
Rectangle 1	30%	E-W	26.4 M	0.5M	12,800	18.84	0.363	42.18	61.39
C-shape	30%	E-W	26.4 M	0.5M	12,800	18.90	0.287	38.56	57.75
Y-shape	30%	E-W	26.4 M	0.5M	12,800	19.39	0.261	38.87	58.52
T-shape	30%	E-W	26.4 M	0.5M	12,800	19.65	0.288	39.04	58.98
H-shape	30%	E-W	26.4 M	0.5M	12,800	19.76	0.375	38.13	58.27

Table 7.Comparative chart E-W

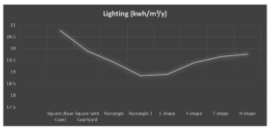


Figure 21.Lighting

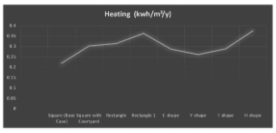


Figure 22.Heating

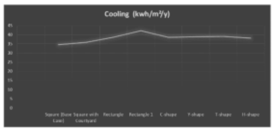


Figure 23.Cooling

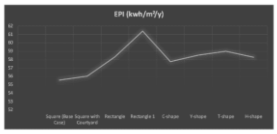


Figure 24.EPI

Inferences

According to the analysis above, the square (base case) has the highest energy efficiency (EPI: 55.54 kwh/m²/y) because of low surface area volume ratio and compact planning. The building is naturally ventilated in summers in which cooling (34.56 kwh/m²/y) which reduces the energy usage of the building. Following that square with courtyard is the most energy efficient (EPI: 56.01 kwh/m²/y) because of courtyard it is naturally ventilated having cooling (35.80 kwh/m²/y) which reduces energy consumption in summers. C shape having the (EPI: 57.75 kwh/m²/y) is the most energy efficient because it has less lighting (18.90 kwh/m²/y) because the surface area is more and most of the part is mutually shaded which gets diffuse light.

The Rectangle 1 has the greatest (EPI of 61.39 kwh/m²/y) because it has more exposed area to the west which needs more cooling (42.18 kwh/m²/y) in summer season and lighting (18.84 kwh/m²/y) load is low because the larger portion lies on east direction which reduces the artificial light during the day time and get natural light.

Building Forms	WWR	Orientation	Height	Projection	Total Built-up Area	Lighting (Kwh/m²/y)	Heating (Kwh/m²/y)	Cooling (Kwh/m²/y)	EPI (Kwh/m²/y)
Square (Base Case)	30%	NE-SW	26.4 M	0.5M	12,800	20.86	0.244	34.86	55.97
Square with Courtyard	30%	NE-SW	26.4 M	0.5M	12,800	19.76	0.394	36.53	56.69
Rectangle	30%	NE-SW	26.4 M	0.5M	12,800	19.74	0.285	36.85	56.88
Rectangle 1	30%	NE-SW	26.4 M	0.5M	12,800	19.13	0.305	39.40	58.84
C-shape	30%	NE-SW	26.4 M	0.5M	12,800	19.22	0.307	38.48	58.01
Y-shape	30%	NE-SW	26.4 M	0.5M	12,800	19.10	0.273	39.00	58.38
T-shape	30%	NE-SW	26.4 M	0.5M	12,800	19.45	0.292	38.67	58.41

H-shape	30%	NE-SW	26.4 M	0.5M	12,800	19.81	0.367	37.74	57.93

Table 8.Comparative chart NE-SW

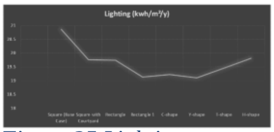


Figure 25.Lighting

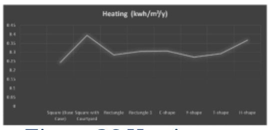


Figure 26.Heating

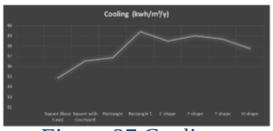


Figure 27.Cooling

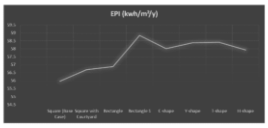


Figure 28.EPI

Inferences

According to the analysis above, the square (base case) has the highest energy efficiency (EPI: 55.54 kwh/m²/y) because of low surface area volume ratio and compact planning. The building is naturally ventilated in summers in which cooling (34.86 kwh/m²/y) which reduces the energy usage of the building. Following that square with courtyard is the most energy efficient (EPI: 56.69 kwh/m²/y) because of courtyard it is naturally ventilated having cooling (36.53 kwh/m²/y) which reduces energy consumption in summers. Rectangle shape having the (EPI: 56.88 kwh/m²/y) is the most energy efficient because the longer façade lies on NE direction which gets diffuse light and with the lighting (19.74 kwh/m²/y) reduces the energy consumption of the form.
The Rectangle 1 has the greatest (EPI of 58.84 kwh/m²/y) because it has more exposed area to the SW which needs more cooling (39.40 kwh/m²/y) in summer season and lighting (19.13 kwh/m²/y) load is low because the larger portion lies on NE direction which reduces the artificial light during the day time and get natural light.

Building Forms	WWR	Orientation	Height	Projection	Total Built-up Area	Lighting (Kwh/m²/y)	Heating (Kwh/m²/y)	Cooling (Kwh/m²/y)	EPI (Kwh/m²/y)
Square (Base Case)	30%	NW-SE	26.4 M	0.5M	12,800	20.86	0.244	34.86	55.97
Square with Courtyard	30%	NW-SE	26.4 M	0.5M	12,800	19.76	0.394	36.53	56.69
Rectangle	30%	NW-SE	26.4 M	0.5M	12,800	19.75	0.226	37.63	57.61
Rectangle 1	30%	NW-SE	26.4 M	0.5M	12,800	19.03	0.225	40.65	59.91
C-shape	30%	NW-SE	26.4 M	0.5M	12,800	19.23	0.306	38.44	57.99
Y-shape	30%	NW-SE	26.4 M	0.5M	12,800	19.17	0.267	38.97	58.41
T-shape	30%	NW-SE	26.4 M	0.5M	12,800	19.58	0.293	38.64	58.52
H-shape	30%	NW-SE	26.4 M	0.5M	12,800	19.75	0.356	38.02	58.13

Table 9.Comparative chart NW-SE

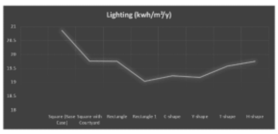


Figure 29.Lighting

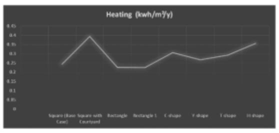


Figure 30.Heating

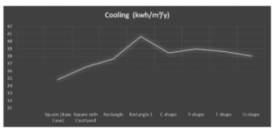


Figure 31.Cooling

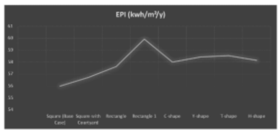


Figure 32.EPI

Inferences

According to the analysis above, the square (base case) has the highest energy efficiency (EPI: 55.97 kwh/m²/y) because of low surface area volume ratio and compact planning. The building is naturally ventilated in summers in which cooling (34.86 kwh/m²/y) which reduces the energy usage of the building. Following that square with courtyard is the most energy efficient (EPI: 56.69 kwh/m²/y) because of courtyard it is naturally ventilated having cooling (36.53 kwh/m²/y) which reduces energy consumption in summers. Rectangle shape having the (EPI: 57.61 kwh/m²/y) is the most energy efficient because the longer façade lies on NW and SE direction which gets some diffuse light and with the lighting (19.75 kwh/m²/y) reduces the energy consumption of the form.

The Rectangle 1 has the greatest (EPI of 59.91 kwh/m²/y) because it has more exposed area to the SE which needs more cooling (40.65 kwh/m²/y) in summer season and lighting (19.03 kwh/m²/y) load is low because the larger portion lies on NW and SE direction which reduces the artificial light during the day time and get natural light.

Building Forms	WWR	Orientation	Projection	Height	Total Built-up Area	Lighting (Kwh/m²/y)	Heating (Kwh/m²/y)	Cooling (Kwh/m²/y)	EPI (Kwh/m²/y)
Square (Base Case)	40%	N-S	0.5M	26.4 M	12,800	19.89	0.152	37.36	57.40
Square with Courtyard	40%	N-S	0.5M	26.4 M	12,800	19.29	0.460	39.05	58.81
Rectangle	40%	N-S	0.5M	26.4 M	12,800	19.49	0.087	38.63	58.21
Rectangle 1	40%	N-S	0.5M	26.4 M	12,800	18.89	0.070	40.96	59.93
C-shape	40%	N-S	0.5M	26.4 M	12,800	19.07	0.190	41.76	61.02
Y-shape	40%	N-S	0.5M	26.4 M	12,800	18.44	0.193	42.91	61.55
T-shape	40%	N-S	0.5M	26.4 M	12,800	18.85	0.178	41.97	61.00
H-shape	40%	N-S	0.5M	26.4 M	12,800	19.35	0.219	40.67	60.24

Table 10.Comparative chart N-S

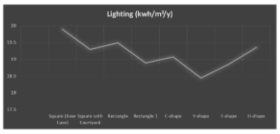


Figure 33.Lighting

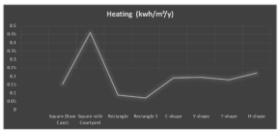


Figure 34.Heating

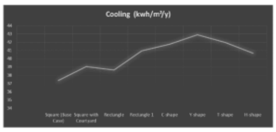


Figure 35.Cooling

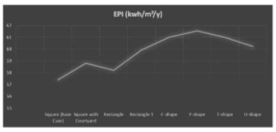


Figure 36.EPI

Inferences

According to the analysis above, the square (base case) has the highest energy efficiency (EPI: 57.40 kwh/m²/y) because of low surface area volume ratio and compact planning. The building is naturally ventilated in summers in which cooling (37.36 kwh/m²/y) which reduces the energy usage of the building. Following that rectangle is the most energy efficient (EPI: 58.21 kwh/m²/y) because the longer side of the building is orientated towards north side which makes the building naturally ventilated by reducing the cooling (38.63 kwh/m²/y) which reduces the energy usage of the building. Due to building height, squares with courtyards have higher cooling and energy efficiency (EPI: 58.81 kwh/m²/y) than squares (base case) and rectangles. The middle floors have less ventilation due to their height, which increases energy consumption during the heat.

The Y-shape has the greatest (EPI of 58.01 kwh/m²/y) because it has more exposed surface area to the south and west which needs more cooling (38.91 kwh/m²/y) in summer season and lighting (18.82 kwh/m²/y) load is low because the larger portion lies on north direction and some part is mutually shaded which reduces the artificial light during the day time and get natural light.

Building Forms	WWR	Orientation	Projection	Height	Total Built-up Area	Lighting (Kwh/m²/y)	Heating (Kwh/m²/y)	Cooling (Kwh/m²/y)	EPI (Kwh/m²/y)
Square (Base Case)	40%	E-W	0.5M	26.4 M	12,800	19.89	0.152	37.36	57.40
Square with Courtyard	40%	E-W	0.5M	26.4 M	12,800	19.29	0.460	39.05	58.81
Rectangle	40%	E-W	0.5M	26.4 M	12,800	18.87	0.235	42.57	61.68
Rectangle 1	40%	E-W	0.5M	26.4 M	12,800	18.36	0.268	46.99	65.62
C-shape	40%	E-W	0.5M	26.4 M	12,800	18.58	0.208	42.52	61..31
Y-shape	40%	E-W	0.5M	26.4 M	12,800	18.81	0.184	42.84	61.84
T-shape	40%	E-W	0.5M	26.4 M	12,800	19.05	0.209	43.03	62.30
H-shape	40%	E-W	0.5M	26.4 M	12,800	19.12	0.280	41.73	61.14

Table 11.Comparative chart E-W

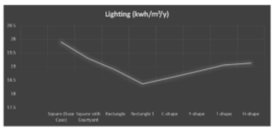


Figure 37.Lighting

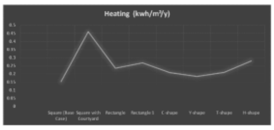


Figure 38.Heating

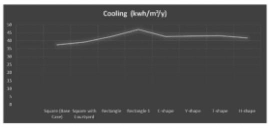


Figure 39.Cooling

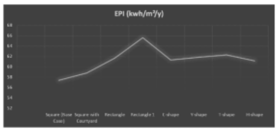


Figure 40.EPI

Inferences

According to the analysis above, the square (base case) has the highest energy efficiency (EPI: 57.40 kwh/m²/y) because of low surface area volume ratio and compact planning. The building is naturally ventilated in summers in which cooling (37.36 kwh/m²/y) which reduces the energy usage of the building. Following that square with courtyard is the most energy efficient (EPI: 58.81 kwh/m²/y) because of courtyard it is naturally ventilated having cooling (39.05 kwh/m²/y) which reduces energy consumption in summers. C shape having the (EPI: 61.31 kwh/m²/y) is the most energy efficient because it has less lighting (18.58 kwh/m²/y) because the surface area is more and most of the part is mutually shaded which gets diffuse light.

The Rectangle 1 has the greatest (EPI of 65.62 kwh/m²/y) because it has more exposed area to the west which needs more cooling (46.99 kwh/m²/y) in summer season and lighting (18.36 kwh/m²/y) load is low because the larger portion lies on east direction which reduces the artificial light during the day time and get natural light.

Building Forms	WWR	Orientation	Projection	Height	Total Built-up Area	Lighting (Kwh/m²/y)	Heating (Kwh/m²/y)	Cooling (Kwh/m²/y)	EPI (Kwh/m²/y)
Square (Base Case)	40%	NE-SW	0.5M	26.4 M	12,800	19.96	0.173	37.61	57.75
Square with Courtyard	40%	NE-SW	0.5M	26.4 M	12,800	19.09	0.308	39.75	59.15
Rectangle	40%	NE-SW	0.5M	26.4 M	12,800	19.12	0.206	40.38	59.71

Rectangle 1	40%	NE-SW	0.5M	26.4 M	12,800	18.63	0.224	43.53	62.39
C-shape	40%	NE-SW	0.5M	26.4 M	12,800	18.79	0.225	42.32	61.34
Y-shape	40%	NE-SW	0.5M	26.4 M	12,800	18.62	0.195	43.01	61.83
T-shape	40%	NE-SW	0.5M	26.4 M	12,800	18.89	0.211	42.56	61.67
H-shape	40%	NE-SW	0.5M	26.4 M	12,800	19.17	0.290	41.26	60.73

Table 12.Comparative chart NE-SW

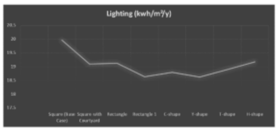


Figure 41.Lighting

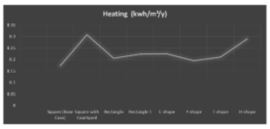


Figure 42.Heating

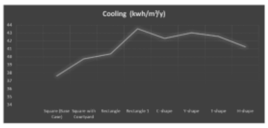


Figure 43.Cooling

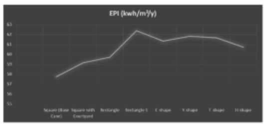


Figure 44.EPI

Inferences

According to the analysis above, the square (base case) has the highest energy efficiency (EPI: 57.75 kwh/m²/y) because of low surface area volume ratio and compact planning. The building is naturally ventilated in summers in which cooling (37.61 kwh/m²/y) which reduces the energy usage of the building. Following that square with courtyard is the most energy efficient (EPI: 59.15 kwh/m²/y) because of courtyard it is naturally ventilated having cooling (39.75 kwh/m²/y) which reduces energy consumption in summers. Rectangle shape having the (EPI: 59.71 kwh/m²/y) is the most energy efficient because the longer façade lies on NE direction which gets diffuse light and with the lighting (19.12 kwh/m²/y) reduces the energy consumption of the form.

The Rectangle 1 has the greatest (EPI of 62.39 kwh/m²/y) because it has more exposed area to the SW which needs more cooling (43.53 kwh/m²/y) in summer season and lighting (18.63 kwh/m²/y) load is low because the larger portion lies on NE direction which reduces the artificial light during the day time and get natural light.

Building Forms	WWR	Orientation	Projection	Height	Total Built-up Area	Lighting (Kwh/m²/y)	Heating (Kwh/m²/y)	Cooling (Kwh/m²/y)	EPI (Kwh/m²/y)
Square (Base Case)	40%	NW-SE	0.5M	26.4 M	12,800	19.96	0.173	37.61	57.75
Square with Courtyard	40%	NW-SE	0.5M	26.4 M	12,800	19.09	0.308	39.75	59.15
Rectangle	40%	NW-SE	0.5M	26.4 M	12,800	19.09	0.152	41.41	60.66
Rectangle 1	40%	NW-SE	0.5M	26.4 M	12,800	18.54	0.149	45.07	63.76
C-shape	40%	NW-SE	0.5M	26.4 M	12,800	18.79	0.224	42.24	61.26
Y-shape	40%	NW-SE	0.5M	26.4 M	12,800	18.60	0.188	42.94	61.74
T-shape	40%	NW-SE	0.5M	26.4 M	12,800	19.00	0.214	42.48	61.70

H-shape	40%	NW-SE	0.5M	26.4 M	12,800	19.11	0.269	41.59	60.97

Table 13.Comparative chart NW-SE

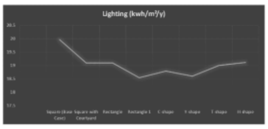


Figure 45.Lighting

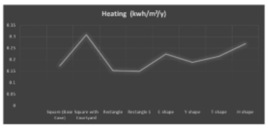


Figure 46.Heating

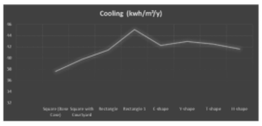


Figure 47.Cooling

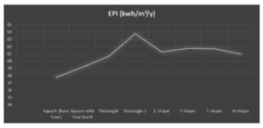


Figure 48.EPI

Inferences

According to the analysis above, the square (base case) has the highest energy efficiency (EPI: 57.75 kwh/m²/y) because of low surface area volume ratio and compact planning. The building is naturally ventilated in summers in which cooling (37.61 kwh/m²/y) which reduces the energy usage of the building. Following that square with courtyard is the most energy efficient (EPI: 59.15 kwh/m²/y) because of courtyard it is naturally ventilated having cooling (39.75 kwh/m²/y) which reduces energy consumption in summers. Rectangle shape having the (EPI: 60.66 kwh/m²/y) is the most energy efficient because the longer façade lies on NW and SE direction which gets some diffuse light and with the lighting (19.09 kwh/m²/y) reduces the energy consumption of the form.

The Rectangle 1 has the greatest (EPI of 63.76 kwh/m²/y) because it has more exposed area to the SE which needs more cooling (45.07 kwh/m²/y) in summer season and lighting (18.54 kwh/m²/y) load is low because the larger portion lies on NW and SE direction which reduces the artificial light during the day time and get natural light.

V. RESULT AND DISCUSSION

The energy simulations reveal several key findings regarding the impact of orientation, form, and window-to-wall ratio (WWR) on the energy efficiency of the building designs.

Impact of Orientation

Orientation has a significant influence on energy performance. Across all forms and WWRs, buildings oriented with their longer facades facing north-south perform better than buildings facing east-west. For example, with 20% WWR, the north-south oriented rectangle has an EPI of 54.62 kWh/m^2/year compared to 57.77 kWh/m^2/year for the east-west oriented rectangle. This is likely because north-south orientation allows for greater passive solar design with ample diffused northern light and reduced western solar gain.

Additionally, orientations with oblique solar exposure, such as northeast-southwest and northwest-southeast, enable some passive solar benefit. For instance, with 30% WWR, the northeast-southwest oriented rectangular building has an EPI of 56.88 kWh/m^2/year, lower than the east-west oriented rectangle at 61.39 kWh/m^2/year.

Impact of Form and Compactness

Compact forms with low surface area to volume ratios, such as the square and courtyard, demonstrate high energy efficiency across orientations. For example, with 40% WWR in a north-south orientation, the square has an EPI of 57.40 kWh/m^2/year compared to 58.21 for the rectangle. The central courtyard enhances ventilation and daylight access.

Additionally, elongated forms with narrower profiles oriented on the east-west axis tend to perform better than those oriented north-south. For instance, with 30% WWR, the east-west oriented C-shape has an EPI of 57.75 kWh/m^2/year versus 58.01 kWh/m^2/year for the north-south oriented Y-shape. This indicates passive solar design is aided by proportional surface exposure.

Impact of Window-to-Wall Ratio

Increasing WWR decreases energy efficiency substantially for all forms. However, at higher WWRs the courtyard, rectangle, and C-shape maintain lower EPI relative to other shapes. For example, at 40% WWR in a north-south orientation, the courtyard has an EPI of 58.81 kWh/m^2/year, the rectangle 58.21 kWh/m^2/year and the C-shape 61.31 kWh/m^2/year, while the Y-shape has 65.12 kWh/m^2/year. This exemplifies the interplay between WWR, form, and orientation - compact and/or appropriately oriented forms can partially offset high WWR energy loads.

In summary, orientation, form, and WWR each impact energy use. Optimal energy efficiency is achieved through a north-south elongation, compact form factors with courtyards, and minimized WWR. Careful consideration of these architectural parameters is necessary for enhanced building performance. Further optimization may be possible through additional energy modeling investigations.

VI. CONCLUSION

Based on the above analysis here is a conclusion:

N-S Orientation (20% WWR)

- Square with courtyard has highest energy efficiency (EPI: 54.57 kwh/m²/y) due to low surface area, compact shape and natural ventilation.
- Rectangle 1 (longer side north) is next most energy efficient (EPI: 54.59 kwh/m²/y) due to natural ventilation and diffuse north light.
- C-shape has highest EPI (55.64 kwh/m²/y) due to more south exposure needing cooling.

E-W Orientation (20% WWR)

- Square with courtyard most efficient (EPI: 54.57 kwh/m²/y).
- C-shape next most energy efficient (EPI: 55.12 kwh/m²/y) with east side exposure for natural ventilation.
- Rectangle (longer west side) has highest EPI (56.02 kwh/m²/y) due to more west exposure needing cooling.

NE-SW Orientation (20% WWR)

- Square with courtyard most efficient (EPI: 55.24 kwh/m²/y).
- Rectangle (longer NE side) next most energy efficient (EPI: 55.27 kwh/m²/y) for natural ventilation.
- Rectangle 1 (longer SW side) has highest EPI (56.13 kwh/m²/y) due to more SW exposure needing cooling.

NW-SE Orientation (20% WWR)

- Square with courtyard most efficient (EPI: 55.24 kwh/m²/y).
- C-shape next most efficient (EPI: 55.54 kwh/m²/y) with NW/SE exposure for some diffuse light.
- Rectangle 1 (more SE exposure) has highest EPI (56.57 kwh/m²/y) due to more cooling needed.

N-S Orientation (30% WWR)

- Square (base case) most efficient (EPI: 55.54 kwh/m²/y) for compact shape and natural ventilation.
- Rectangle (longer north side) next most efficient (EPI: 55.77 kwh/m²/y) for natural ventilation and reducing cooling load.
- Y-shape has highest EPI (58.01 kwh/m²/y) due to more south/west exposure needing cooling.

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