European Research Studies Journal
Volume XXVI, Issue 4, 2023

pp. 391-404

High Performance High-Rise Buildings (HRB): A Case in Tropical Climate Construction

Submitted 01/09/23, 1st revision 16/10/23, 2nd revision 10/11/23, accepted 30/11/23

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Abstract:

Purpose: *The world's increasing need for energy comes with consequences like rising pollution and global warming. It is crucial to drastically cut back on energy use and completely stop using non-renewable energy sources. This research primary objective is to develop a commercial high-performance high-rise building for a tropical city like Chennai, India and to investigate the value of a sustainable building practice on the health, safety, and security of building occupants, the effects on ecological balance, and the requirements of high-performance high-rise buildings. This study investigates ways to include passive design elements into high-rise building plans, like natural lighting and ventilation, to significantly cut energy use and boost the residents' mental health. Numerous passive cooling techniques have been studied and incorporated within the building design to achieve a lower carbon footprint. This research emphasises optimal ways to design a building with lower electricity consumption.*

Design/Methodology/Approach: *The preliminary stages of building designs are indispensable and highly influence the performance of the building's energy consumption. By considering the cost of power, the amount of CO2 created by the building's use, and the size of the HVAC system needed for a specific building, SEFAIRA software was used to gain an early-stage analysis of the building's daylight and energy performance. Additionally, using SEFAIRA software, it was possible to comprehend how daylighting might affect a building's size and orientation.*

Findings: *According to the findings, energy is used more sparingly by high-performance building design models than by traditional building design models. The high-performance building model consumes 40% less power than the conventional building design, which is 4,580,998 kWh. Additionally, each year a High-Performance Building model saves 441,606 US dollars which is a 40% saving when compared to the conventional building model. The main principle of designing a sustainable building is to create a building that consumes lower power with providing a comfortable environment. The comfort analysis carried out using ASHRAE 55 standard and predicted mean vote (PMV) confirmed that the high-performance building model offers a better comfortable indoor environment than the conventional building design model, for more than 99% of the building's occupied hours. The*

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comfortable environment within the building is achieved by using an adequate amount of solar protection provided to the facades in the high-performance building design model.
Practical applications: *In conclusion, a proposed building management system can monitor the activity of the HRB and effectively regulate the power consumption, water consumption, and safety of the building occupants. Consequently, the high-performance high-rise building design suggested by this study effectively works sustainably and offers a comfortable both internal and external environment for building occupants in a tropical climate.*
Originality value: *The proposed design for a high-performance high-rise building effectively operates in a sustainable manner and offers a comfortable internal and outdoor environment for occupants in a tropical climate.*

Keywords: *High rise buildings, performance, construction.*

JEL codes: *R30, R32.*

Paper type: *Research article.*

1. Introduction

The phenomenon of urban population growth necessitates a corresponding expansion of both commercial and residential spaces, despite the constraints imposed by limited land resources. Individuals residing in urban regions are actively seeking expansive living spaces to support their daily lives. India is ranked as the second most populous country globally, and a significant number of individuals are migrating from rural to urban regions in order to improve their quality of life.

The escalating urban population contributes to the inflation of land resource prices and rental rates. In response to the phenomenon of fast urbanization, there has been a notable increase in the construction of high-rise buildings within urban areas (Jani *et al.*, 2021). The vertical dimensions of high-rise structures are steadily increasing in tandem with the modern advancements in the construction sector.

The objective of this study is to examine the specifications and architectural plan of a 30-story high-rise commercial building in a tropical climatic area, with a focus on implementing passive design principles to enhance its performance.

It aims to investigate strategies for creating a comfortable indoor and outdoor environment in the vicinity of the building, with a particular focus on reducing the carbon footprint associated with its operations.

The primary goal is to develop a building that ensures optimal thermal, psychological, and visual comfort for its tenants, while concurrently creating an appealing and inviting outdoor public area for pedestrians. The second goal is to explore potential approaches for utilising renewable energy sources to develop a sustainable building.

The inquiry involves analysing the climatic data of the selected site to gain insights into the most effective design techniques that can be used for the structure, considering the prevailing conditions.

The analysis seeks to ascertain the feasibility of applying comparable tactics in the design of the present structure. The research project has selected Chennai, the capital of the state of Tamil Nadu in South Asia, as the tropical city of interest. Chennai ranks 36th in terms of worldwide population and is the 6th most densely inhabited city in India and is situated on the eastern coast of the Bay of Bengal. Chennai is situated at a latitude of 13° 5' O" N and a longitude of 80° 17' O" E, with an average height of 6 meters above sea level.

It serves as the prominent industrial and economic centre in the southern region of India, often referred to as ‘The gateway of South Asia’. The rapid process of industrialization in India has resulted in a significant increase in job prospects, leading to a substantial influx of individuals to Chennai, a prominent metropolitan area (Krishnamurthy and Desouza, 2004).

2. Literature Review

2.1 Passive Strategies

The term passive design refers to utilising natural resources such as natural ventilation or air movement, heating, and cooling to provide a pleasant environment for the building occupants instead of using the mechanical HVAC system and other sources which uses non-renewable energy resources (Passive building design, 2022).

By adopting a passive strategy, the electricity consumed by the building can be significantly reduced. Using several passive design methods, including self- shading envelope, recessed spaces, core position, etc., 40% of the solar radiation gains in a high-rise building can be eliminated (Ahmad *et al.,* 2004). Designing a building aligned with the prevailing wind direction improves natural ventilation within a building, which helps to improve air quality and remove pollution.

It is also important to remove hot air from the building, using the convection airflow method whereby raised hot air can be removed from the top window, which eventually draws cool air from the lower windows. The performance of this system is more effective if the drawn air is from a shaded area (according to the Sustainable Tropical Building Design Guidelines for Commercial Buildings, 2011).

Natural ventilation enhances the sustainability of the building by reducing the requirement of mechanical systems such as air conditioners, and this can be based on cross ventilation or stack ventilation. Cross ventilation is effective for horizontal air movements and stack ventilation of effective for vertical air movements (Wahab *et al.,* 2019).

2.2 Building Materials

Latha *et al.* (2015) points out that, the external surface of a building transfers the external heat into the building through walls and ceilings. The utilisation of materials possessing high thermal mass, such as marble and concrete, which exhibit excellent heat conductivity, can result in the absorption and retention of heat. Consequently, this can lead to elevated internal temperatures within a building, thereby causing thermal discomfort among its occupants.

According to the Sustainable Tropical Building Design Guidelines for Commercial Buildings (2022) and Architropics' publication on Best Wall Materials For Staying Cool In Tropical Climates (2022), it is recommended to avoid the use of materials with high thermal mass as an exterior skin of the building. These sources propose that materials with lower thermal mass tend to exhibit greater efficiency in hot climates.

This is due to the ability of low thermal mass materials to expeditiously dissipate accumulated heat through natural ventilation. The limitation of the low thermal mass materials used in the building envelope is that they will rapidly heat up when exposed to solar radiation. This, however, can be mitigated by protecting the materials with insulations or by shading techniques.

Furthermore, the study conducted by Latha *et al.* (2015) suggests that building materials such as ‘autoclaved aerated concrete, vacuum insulated panels, window glazing, phase changing building materials, polymer building skin, with good thermal properties’ can be used in a tropical environment.

Moreover, according to the Sustainable Tropical Building Design Guidelines for Commercial Buildings (2011), it is recommended that construction materials employed in sustainable buildings possess specific attributes such as being non-polluting, recycled, renewable, recyclable, environmentally friendly, and energy-efficient, among others.

2.3 Building Envelope

The building envelope of high-rise buildings in tropical regions is exposed to direct solar radiation and high external temperature, causing overheating within the building. Low- rise buildings are comparatively less exposed because the roof of the low-rise buildings provides shading to a larger extent of the building. Therefore, it is essential to address the solar radiation on a high-rise building in a tropical climate (Ahmad *et al.*, 2004).

To protect the building from direct and indirect solar radiation, especially in east and west-facing facades, solar protection can be utilized. Some of the solar protection can be controlled mechanically depending on the building requirements and weather conditions. Solar protection can be placed as a secondary facade system attached to the external facade to control light levels and heat gains from solar radiation (Lee *et al.,* 2002).

Hensen *et al.* (2002) argue that the external shading devices are very effective compared to internal shading devices. Solar protection can be in the form of fins, overhangs, louvers, etc. In a hot tropical environment, the efficiency of the louvers is enhanced when placed externally. Combinations of these strategies can be adapted to provide a better shading effect (Lee *et et al.,* 2002). To achieve a lower internal temperature shading devices must be installed in all the openings to reduce the incoming solar radiation.

Using light colour paints on the walls and roof minimizes heat absorption within the building (Matthew *et al.*, 2017). In a tropical environment, roof and external walls should be protected using insulation. Insulation is the most effective method to reduce the heat gain within the building. Bulk insulation and reflective insulation are the two types of insulation commonly used in tropical regions.

In a tropical climate where there is a high amount of humidity, one should avoid insulation that absorbs moisture to avoid mould growth. Ventilating this insulation with a help of a cavity could avoid growing mould (Sustainable Tropical Building Design Guidelines for Commercial Buildings, 2011).

3. Research Methodology

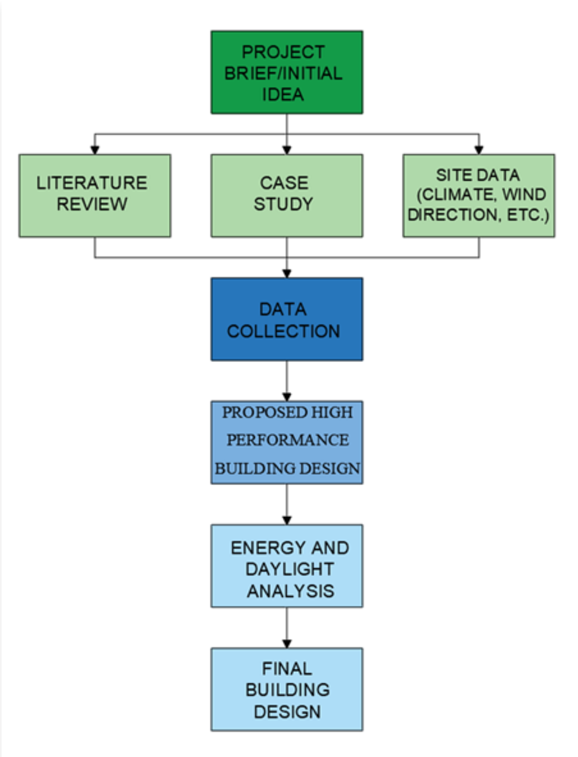
In this study, quantitative anlaysis was used to carry out comfort level analysis between basic building model design and high-performance building design. Comfort is the most critical factor to be measured in building design. Pre-design conditions were set before the analysis commenced. Sefaira software used ASHRAE Standard 55 to determine whether the area provided for the analysis satisfied the required conditions or not.

American Society of Heating, Refrigerating and Air-Conditioning Engineers, also known as ASHRAE (Ashrae, 2022) was a standard measure used for the study. Predicted mean voltage, also known as PVM, is widely recognized as a unit to measure thermal comfort where -2 is very cold, 2 is very warm, and 0 is a neutral condition. The scope is to ascertain where building users have a comfortable environment. The analysis made use of PMV criteria (per the ASHRAE 55 standard).

The predicted mean voltage (PMV) is set between -0.5 and 0.5, for more than 98.0 % of occupied hours for each floor zone to pass. A scaling system is used to show the amount of discomfort caused in relation to the PMV scale. The zones that satisfied sepcific conditions appear green and the failed zones appeared red. Meteonorm 8 software has been utilised for the purpose of gathering climate and weather data. The Meteonorm software provided users with the capability to retrieve historical data pertaining to radiation, precipitation, temperature, sunshine, and wind for a specific user-selected region.

The program has a comprehensive database of over 8000 weather stations, encompassing a worldwide aerosol climatology, and harnessing the capabilities of five geostationary satellites to ensure the delivery of precise and reliable outcomes. The Meteonorm program incorporates international standards to facilitate global user accessibility. Figure 1 is a schematic layout of how the research method evolved.

Figure 1. *Research Methodology Diagram,*



Source: *Authors' own.*

4. Results, Analysis and Discussion

The following section will discuss the data extracted from testing stages and software development:

1. Positioning Study: Site and Orientation

The project site is surrounded by low, medium, and high-rise buildings, and thirty percent of the area is covered by greenery and the site is on a flat terrain. The site location consisted of mixed residential and commercial areas. The important characteristic of designing a sustainable building in a tropical climate is to reduce the solar heat gain in a building. Taking this into consideration, the proposed high-rise building has a rectangular-shaped design. The building’s longest axis is aligned in the east and west directions or the longest façade faces the North and South directions.

By adopting this approach, the proposed high-rise commercial building can receive higher daylight while minimizing heat gain, which reduces the electricity load on the HVAC system to keep the building cool. Additionally, the edge of the building is chamfered to improve the building’s aerodynamic performance.

The study conducted by Kwok *et al.* (1988) shows that the building with the chamfered edges reduces the wind load for the across and along wind response. One of the aspects of the high-performance building is to provide a comfortable indoor and external space surrounding the building. Pedestrians are the most impacted by the high-rise buildings. The velocity of the wind increase near a high-rise building due to the downdraught effect (Cammelli and Stanfield, 2017), therefore adequate protection must be given to the pedestrians at street level.

The proposed high-rise building provides a protected pedestrian path from downdraft, rain and solar radiation. To protect the pedestrians the proposed lobby is set back from the building’s outer profile, the South façade’s shading device helps to reduce the impact of the downdraft, East, West and North direction canopies are added to mitigate the issue.

To improve the comfort level of the pedestrians, landscaping is placed at the ground level, which act a wind barrier, and sound barrier from street traffic and create an enhanced microclimate by isolating the building site from the urban area.

2. Energy Simulation: Climate and Weather Data and analysis

Meteonorm allowed the user to access the historical data of radiation, precipitation, temperature, sunshine, and wind for a particular location of the user’s preference. This research output was centered on optimal ways to design a building with lower electricity consumption. The preliminary stages of building designs were crucial and highly influenced the performance of the building's energy consumption.

SEFAIRA software enabled the researchers to acquire an early-stage analysis of the building's daylight and energy performance, acknowledging the electricity cost, amount of CO2 produced from the building's function, and size of the HVAC systems required for the building. The impact of daylight was assessed, and software produced suggestions on how the design of the building had to be modified to attain satisfactory thermal comfort within the building with a highly energy-efficient design.

3. *Output and Results: Energy Harness*

Building-integrated photovoltaics (BIPV), commonly referred to as BIPV panels, are strategically positioned at a 37˚ inclination above the southern façade glazing. This arrangement serves the dual purpose of optimizing solar radiation absorption and offering shading capabilities for the glazing.

On each floor, the overhanging BIPV panels sum up to 68.34m². In total, the overall south façade overhanging BIPV panels sum up to 1708.5m². Also, BIPV panels are installed on a part of the East and West façades of the high-rise building. The limitation of having the BIPV panels on the East and West façades is that the energy generation duration is lower than the south façade BIPV panels. The East façade receives sunlight during the morning hours and the West façade receives sunlight during the afternoon hours.

Each floor consists of 82m² of BIPV panels combining both east and west façades. The overall BIPV panels installed on the East façade are 1025m², and on the West façade is 1025m². As stated in the section on shading tactics, the top of the high-rise building is equipped with Building-Integrated Photovoltaic (BIPV) panels, which serve the dual purpose of generating electricity and offering shading capabilities.

The HRB has a roof area measuring 1917m², upon which BIPV panels are mounted at a 17˚ angle. This angle is chosen to be perpendicular to the equinox, ensuring optimal harnessing of solar energy by facing the south direction. The cumulative surface area of Building Integrated Photovoltaic (BIPV) and Photovoltaic (PV) panels on the high-rise structure amounts to 5593 square meters.

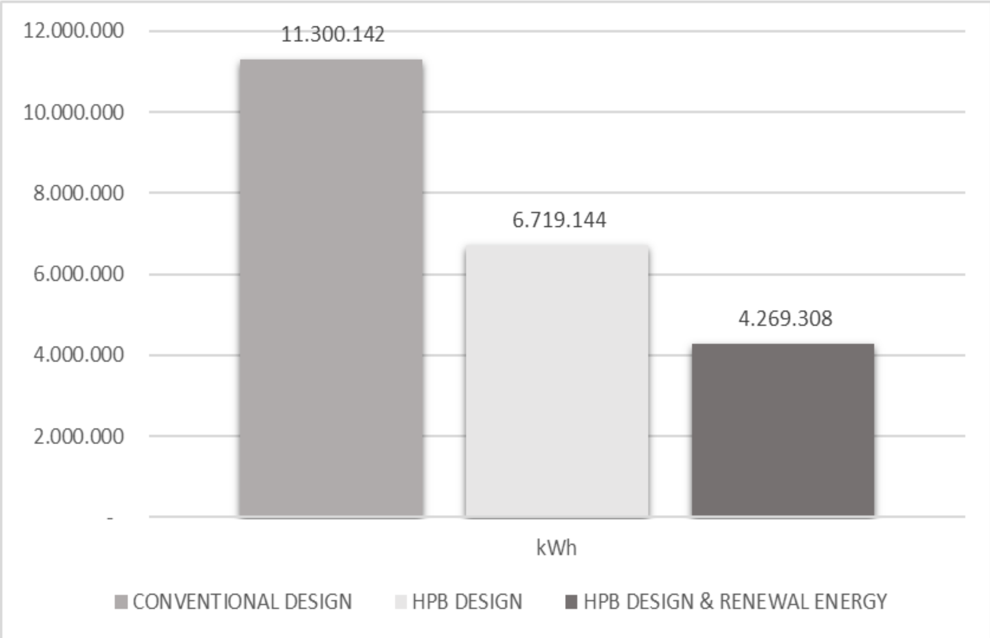
4. *Analysis of Energy Consumption*

Based on the analysis of the data, it has been determined that the high-performance building design model demonstrates a lower energy consumption compared to the traditional building design model. The high-performance building model demonstrates a 40% reduction in power consumption compared to the conventional building design, resulting in a total energy savings of 4,580,998 kWh.

In addition, the HPB model demonstrates an annual cost reduction of $441,606, representing a 40% decrease in expenses when compared to the conventional building type. The present analysis provides confirmation that the proposed high-rise construction exhibits characteristics of sustainability.

The illustration given depicts the energy consumption patterns of three building models, the conventional model, the HPB model, and the HPB model integrated with renewable energy generated from BIPV and PV panels.

Figure 3. *Comparison of Energy Consumption Levels in kwH*



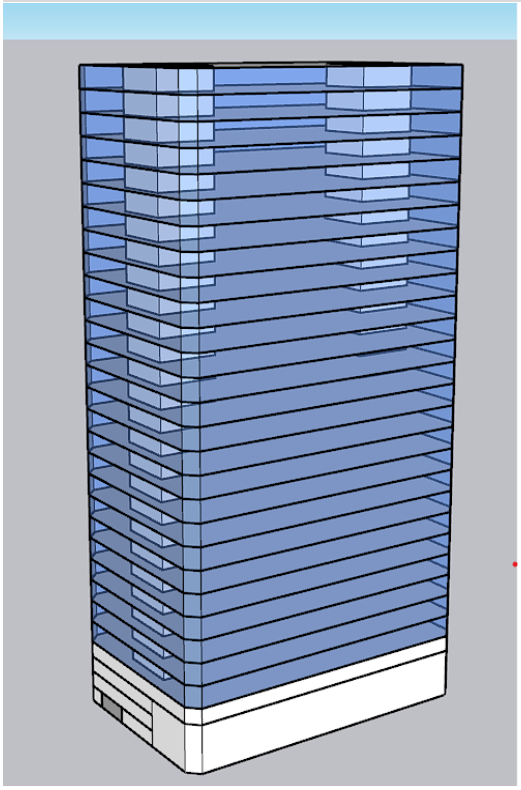


Figure 4. *Conventional model*

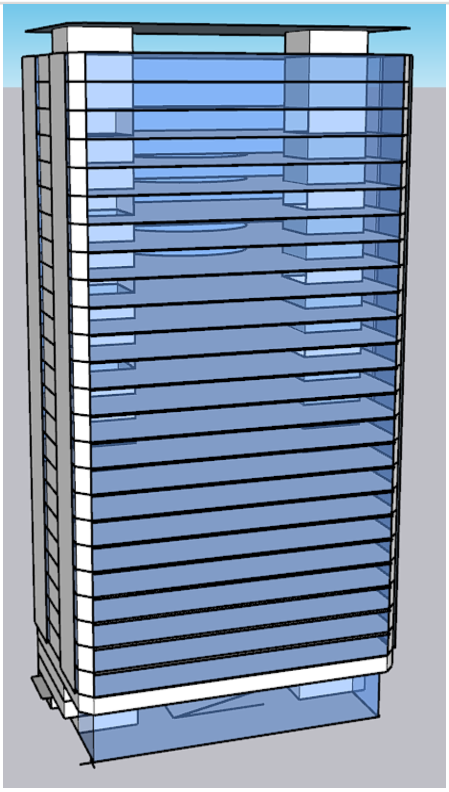


Figure 5. *HPB model*

5. *Daylight Settings*

To improve the daylight and to have a better view of the external environment glass facades are being used in several places on the proposed high-rise building. The North and South façades are the longest façades of the building. Even though huge glass façade help to maximize the daylight intake, a large portion of the building is exposed to solar radiation, which will cause a significant amount of negative impact on the comfort and energy performance of the building.

6. *South Façade System*

To reduce the heat intake from the North and South directions, double skin façade systems are utilized. The south façade which encounters direct solar radiation, is protected by horizontal fixed shades. Due to this reason, every floor is isolated from the other. Therefore, the South façade is equipped with a corridor double-skin façade. Most of the working spaces are located near the south façade. The cavity introduced between the building and the external skin provides better thermal insulation and acoustics performance for the proposed high-rise building's productive area.

7. *Building Management Systems*

To reduce power consumption and to provide a pleasant environment to the building users, the proposed high-rise building is installed with the building management system. The building management in the proposed high-rise building monitors all the activities using sensors and predefined programs. It effectively operates the HVAC system using a demand control system, depending on the activity, operates the lighting system of the building based on the amount of natural daylight available at that particular instance.

All the water fittings are connected to the BMS to limit water wastage. The green screening layer on the external facades are installed with a watering system to water the plants. This watering system is connected to the BMS, which provides adequate water required for the plants and shrubs. This watering system also detects rain and avoids overwatering the vegetation. This method helps save water substantially.

To protect the building from solar radiation, automated louvers are installed between the double skin façade. This louver system is connected to the BMS, which automatically adjusts the louver's angle depending on the sun's position. This method enhances the comfort of the building user by eliminating solar heat gain. All of the fire sensors are connected to the building management system. During a fire, the building management system takes control of several systems, such as water sprinklers, smoke extractors, etc., which significantly reduce the destruction caused by a fire accident.

BMS can effectively collaborate with the renewal of energy harnessed from the building and electricity from the power grid to power the high-rise building effectively, depending on the power requirement.

5. Conclusions

The literature and analysis of case studies yielded valuable insights into sustainable construction practices, passive ventilation and lighting solutions, and the use of a high-rise building design strategy in tropical climates with the aim of minimizing power usage.

Based on the findings of this study, it has been ascertained that the primary constraint in architectural design inside tropical regions pertains to the effects of solar radiation and subsequent heat accumulation. In order to address this concern, it is imperative to ensure that the building envelope is equipped with sufficient shade or other protective measures to effectively limit solar heat gain.

The optimization of vegetation and natural light in commercial building design has the potential to greatly boost workers' productivity through the provision of psychological and ecological advantages. The Meteonorm 8 and Sefaira predesign software can be utilized to analyse the prevailing climatic conditions in a specific geographical location as performed in this research.

In order to mitigate the effects of solar radiation, the southern side of the structure is outfitted with a projecting shade apparatus that incorporates a Building Integrated Photovoltaic (BIPV) panel. In order to enhance thermal comfort, the installation of a corridor displacement ventilation system (DSF) has been implemented. The northern side of the building does not experience direct exposure to solar radiation.

However, to safeguard the external structure of the building from the effects of a tropical environment, a multi-story shading system has been installed on this facade. The East and West facades experience significant sun radiation over a limited duration of the day. Consequently, an external green screening layer has been implemented at the openings to mitigate this exposure.

The implementation of green screening layers serves the dual purpose of shielding the building from solar radiation while also offering psychological and ecological advantages. In addition, the central part of the East and West facades are installed with BIPV panels, and the roof is installed with PV panels. These strategies adopted act as a screening layer to the building envelope from high solar radiation.

The HPB is designed to take advantage of the local climate conditions. The building's 3.7m floor-to-ceiling height, and the 12m floor-to-ceiling height central sky garden enhance the daylight to pass more profoundly into the building. The daylight analysis carried out for the proposed HRB resulted as well-lit, this reduces the artificial lighting requirement. The building's north multi-story DFS uses the stack effect to extract air from the building. This draws fresh air from the South facade, where office spaces are located, then this is passed to the recreation area near the sky garden and extracted from the North facade. These passive strategies significantly reduce the HVAC power consumption.

The high-rise building's rectangle shape and orientation reduces the impact of solar radiation from the East and West directions. The proposed base isolation system in the HRB will protect the building users from earthquakes, which the HRB might encounter due to Chennai's Zone-III moderate seismic zone category. The chamfered edge design provides better aerodynamic performance and minimizes the structural damage caused by the wind load.

The cut-out on the top floor enhances the aerodynamic performance of the building. The plant room is located in this cut-out area which is exposed to constant high-speed airflow. This method improves the performance of the equipment by removing the heat. This also saves a significant amount of energy which would have been used to precool the equipment.

The proposed above-ground car park does not necessitate the utilization of a mechanical HVAC system or an artificial lighting system in order to operate. The proposed design for an elevated car park capitalises on the utilisation of natural light and ventilation in its functioning. The parking lot is equipped with a green screening layer as a measure to mitigate solar heat gain. The green screening layer serves as a means of filtering the observations made by the general public, while the flora within this layer enhances air quality by effectively mitigating airborne pollutants.

In order to enhance the efficacy of vertical mobility inside the proposed HRB, each core is outfitted with three high-speed gearless traction elevators. Additionally, the floors are segregated into three distinct zones, as seen in table 14. Every elevator is designated to serve a specific range of floors by intentionally bypassing certain levels. These tactics are implemented to effectively manage high traffic periods.

To generate renewal energy, BIPV panels are installed on the South, East, and West facades, and PV panels are installed on the roof of the HRB. In total, the building generates 2,449,836kWh of renewal energy. This generated renewal energy will offset 36% of the energy required to operate the proposed high-performance high-rise building. Based on the analysis carried out under section 4.3.17., the proposed high- performance building requires 6,719,144kWh of power to run the building.

In contrast, conventional building design (basic building design) requires 11,300,142kWh of energy to operate the building. Conventional building design uses 68% more power compared to the HPB design. Considering the renewable energy generated from the HPB model, the conventional building design requires 164% more electricity to operate the building.

This energy analysis shows that the HPB can save 7,030,834kWh of power each year, which is $681,355. Hence, this provides sufficient evidence that the proposed high- performance high-rise building is sustainable compared to the conventional buildings.

Several strategies have been adopted to address the well-being of the building occupants. The main principle of designing a sustainable building is to create a building that consumes lower power with providing a comfortable environment. The comfort analysis carried out using ASHRAE 55 standard and PMV confirms that the high-performance building model offers a better comfortable indoor environment than the conventional building design model for more than 99% of the building's occupied hours.

The comfortable environment within the building is achieved by using an adequate amount of solar protection provided to the facades in the high-performance building design model. The proposed building management system monitors the activity of the HRB and effectively regulates the power consumption, water consumption, and safety of the building occupants.

The proposed design for a high-performance high-rise building effectively operates in a sustainable manner and offers a comfortable internal and outdoor environment for occupants in a tropical climate.

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