

# **Smart Technology Integration in Industrial Architecture: Developing Smart Factory Buildings in Karachi**

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**Abstract:** This study investigates the planning and design of a factory building and users' level of understanding regarding smart buildings and their integration in the design of a factory, aiming to explore design guidelines for smart and energy-efficient industrial buildings in Karachi. The research employs mixed-method approaches, including quantitative and simulation, to analyze energy load in traditional factories vs smart factories, and its impact on users' comfort. Data were collected from a questionnaire survey and spatial analysis of the existing factory building, and through a random sampling process, 100 respondents were chosen for the study, including 2 factory owners, 20 architects, and 68 workers. Results were analyzed using Building Information Modeling (BIM) for calculating the energy consumption of a factory building, and descriptive analysis was performed for quantitative data. The findings reveal that integration of smart technologies into industrial buildings enhances energy efficiency and environmental sustainability, indicating that a smart building minimizes cooling energy load, with peak cooling load decreasing from approximately 790 kW in a non-insulated building to 600 kW in the proposed design, ensuring thermal comfort and a healthy indoor environment for the users. Despite this, inadequate technological infrastructure in Karachi hinders effective implementation. The paper concludes by presenting strategies to improve factory building energy efficiency, offering insights into sustainable and smart industrial architecture.

**Keywords:** Smart Buildings, Building Information Model (BIM), Energy Efficiency, Industrial Building, Indoor Environmental Quality, Karachi

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## **1. Introduction**

This study explores the design and performance of smart energy-efficient industrial buildings in Karachi, aiming to develop design guidelines for improving energy efficiency, indoor environmental quality, and worker comfort through the integration of BIM and smart technologies.

Climate change has given us an urgency to minimize our dependence on non-renewable sources of energy and shift towards sustainable alternatives. A significant contributor to climate change

is the construction sector, which emits 39% of total greenhouse gases through energy-intensive heating and cooling processes [1] [2]. Therefore, architects and urban designers are required to play the role of climate protectors through designing a variety of climate-sensitive buildings; for instance, sustainable buildings, eco-friendly buildings, and technology-driven smart and intelligent buildings, etc. Strategies used in these buildings help in enhancing thermal comfort, creating an eco-friendly environment, and reducing heating and cooling energy demands. Today, technological advancement shifted building design towards smart buildings, which are considered integrated building systems of interconnected components and act as mediums that process inputs and generate adaptive outputs, such as the regulation of indoor environmental conditions [3] [4].

Building systems have evolved from automation to responsiveness and finally to efficiency. During the automation phase (1981–1985), buildings focused on remote-controlled systems with Direct Digital Control (DDC), aiming to provide basic comfort, safety, and functional integration with minimal human intervention. This was followed by the response phase (1986–1991), in which building systems became more integrated and connected through emerging digital networks, and occupants started influencing building controls while also adapting to surrounding environmental conditions. Today, the efficiency phase has focused on performance optimization, minimizing costs, managing space effectively, and integrating environmental systems to support sustainable and intelligent building operations [5][6]. In sum, development started from the introduction of “automated buildings” which was later named “intelligent buildings” and has now evolved to “smart buildings” through the integration of the Internet of Things (IoT) and advanced automation systems [7].

Over the past two decades, smart buildings have combined intelligent control systems and connected technologies. These systems regulate indoor temperature, humidity, and airflow levels, and increase building efficiency, responsiveness, and adaptability based on environmental dynamics and user requirements. Moreover, building mass can be used as a thermal storage medium to enhance energy performance [8] [3].

Such advancements have transformed architectural design from rigid physical forms to flexible and responsive spaces that adapt to climatic factors such as daylight, airflow, heat gain, and cooling demands, as well as occupants’ needs. As noted by Ahmed et al. (2015) [9], sustainable smart façade applications, including energy-generating building skins and façades, include

energy-generating systems, kinetic façades, solar shading devices, double skin façades, and green building envelopes.

Although domestic architecture adopted the concept of smart technology globally, it now goes beyond residential buildings, and non-residential commercial buildings have transferred their design norms from typical buildings to smart structures. For instance, the concepts of smart building envelopes and smart factories have evolved in the post-Industrial Revolution era in developed countries, and automation is increasingly incorporated into building systems and machinery to improve energy efficiency, environmental responsiveness, and enhance productivity. These advancements have enabled smart technologies to be effectively utilized in both factory envelopes and interior spaces [10].

The concept of a “smart” factory is defined by the use of cyber-physical systems (CPS), which facilitate continuous communication between physical operations and digital systems. These systems support product development and more efficient operations. Technologies such as artificial intelligence, robotics, big data analytics, and IoT enable high automation and self-regulating processes. However, these systems have predominantly operated within the internal factory setting [10] [11] [12].

Smart factories are grounded in the principles of smart manufacturing, which facilitates integration with digital supply systems to optimize supply chain performance. In addition, digital manufacturing ensures digital connectivity of products across their lifecycle through digital twin technologies [13] [14]. The Industrial Internet further enables these processes through interconnected sensor networks and platforms managed by a centralized system that unifies overall operations (Figure 1) [15] [16].

In addition to operational efficiency, Smart factories also offer considerable benefits like improving the comfort and well-being of occupants. Intelligent HVAC systems facilitate real-time monitoring and precise control of thermal and humidity conditions and create a healthier indoor environment. Smart lighting systems enable adaptive illumination strategies to improve productivity and reduce eye strain. The continuous evolution of these technologies is increasing opportunities for performance optimization. Smart building envelopes further play an important role by dynamically responding to environmental changes, leading to energy savings, reducing the carbon footprint, and improving overall occupant comfort and productivity [14] [17].

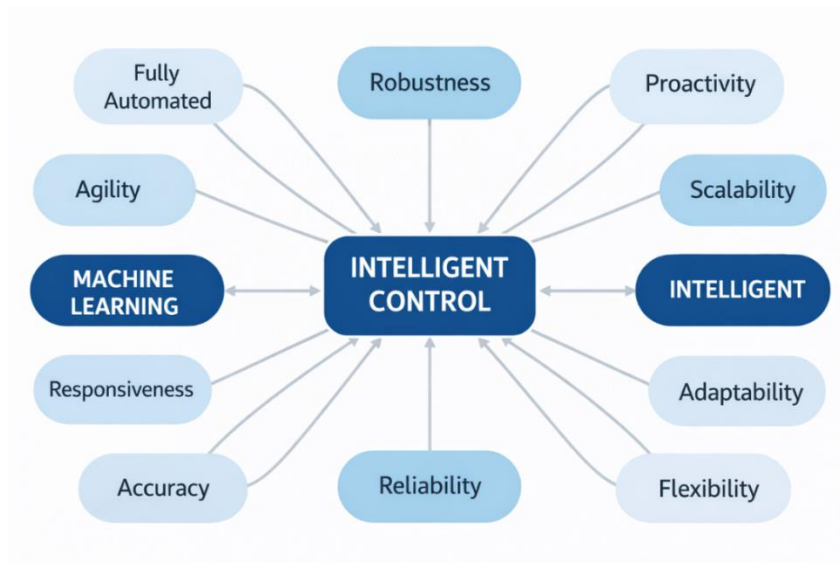
Pakistan, a low-middle-income country (LMIC), with limited energy sources, relies on the industrial sector, which is the backbone of the overall economy, with 64% of GDP share. In this sector, cotton and manufacturing industries export 65% of products with a large number of human workers [18].

In Pakistan, Karachi, the biggest city and economic hub of the country, is the home of different industries like paper, leather, cement, glass, steel, iron wool, and silk, located in different areas known as SITE, Korangi Industrial Area, Korangi Creek, Bin Qasim Industrial Park, and Landhi Industrial Area [19]. Therefore, for studying and designing a smart factory, Karachi was selected because it represents a major share of Pakistan's industrial sector, and the reason for selecting and converting factories to smart buildings is that the industrial architecture in Karachi lacks environmental and user-friendly design, and it negatively impacts the health of workers and reduces their work efficiency [20].

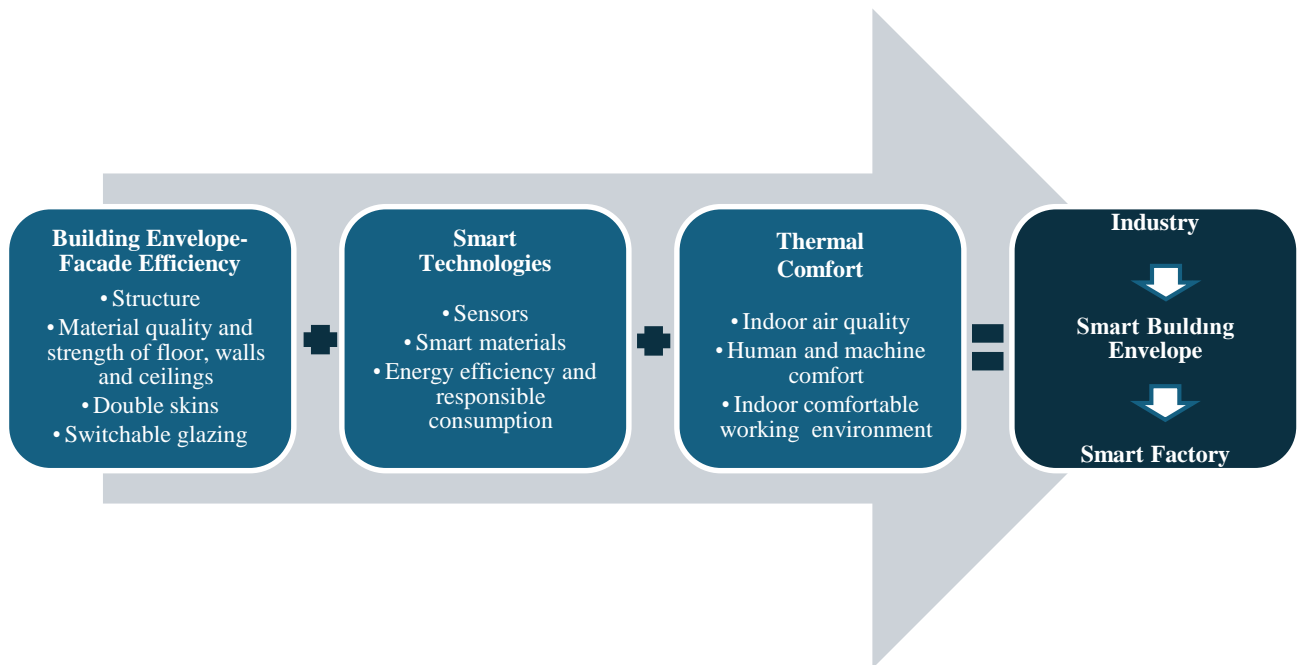
Hence, it is the need of the hour to revisit the design of factories in the city and consider its role as more than serving a building to run the machines; a place where laborers spend more than half of a day, and a building that is required to be climate-responsive. Many factory workers are frequently affected by chronic illnesses due to multiple factors, including poor indoor comfort levels, insufficient airflow, inadequate building maintenance, and poor sanitation practices.

Hence, the question arises: how can the design of a factory building be environmentally and user-friendly, and energy-efficient? This question has addressed two main objectives: 1) to explore the planning and design of factory building and users' level of understanding regarding smart buildings and its integration in the design of a factory, and 2) to propose a smart factory design proposal that combines technology with architectural design to minimize cooling energy demand, optimize indoor conditions to ensure healthy environment for labors, and enhance environmental responsiveness.

Hence, by examining energy consumption patterns, indoor environmental quality, and smart building integration through BIM-based simulation, this research seeks to uncover the impact of BIM-based design on building energy performance and indoor thermal conditions in industrial buildings. Through this investigation, the research aims to contribute to sustainable industrial architecture and smart building design practice by providing evidence-based design guidelines and recommendations for improving energy performance and occupant well-being.



**Figure 01: Integration of Sensors and Machinery to a Central Controller for Regulating Operations (Mittal et al., 2017)**



**Figure 02: Conceptual Frameworks (Author)**

## 2. Methodology

### 2.1 Research Setting

Karachi, the most populous and largest metropolitan city of Pakistan and the province of Sindh, extends over 3,527 km<sup>2</sup>, located along the coastline of the Arabian Sea (24.56'00" N, 67.01'00" E); it is the main seaport of Pakistan and a major centre for commerce and industry (Figure 3).

The city experiences persistently high relative humidity year-round, with relative humidity peaking at 85% in August, its wettest month, to 58% in December, its driest month. Karachi generally experiences dominant southwesterly to westerly winds for roughly half of the year, including monsoon season. In winter, winds shift toward the east and northeast, contributing to an average temperature of around 21°C. The highest temperatures occur in May and June, characterized by average maximum temperatures around 35°C, while January remains the coldest month [19]. Karachi, being Pakistan's sole seaport, is also a major industrial hub, with around 4,500 industrial units in the formal sector. A large share of these sectors contributes to export-driven economic activities. Although formal statistics for the informal sector are lacking, it mainly consists of activities in garment, leather, textile, carpet, and light engineering industries within low-income settlements, employing about 75% of the working population [21]. The selected study area is the Sindh Industrial Trading Estate (SITE) (Figure 3), recognized as one of Karachi's oldest industrial areas. Located in the southern region, SITE Town takes its name from the Sindh Industrial and Trading Estate [22]. For in-depth analysis, a single factory—Printech Packages (Pvt) Ltd., located on Fakhruddin Valika Road in Metroville, SITE, Karachi—was selected as the case study.

## ***2.2 Research Design***

This mixed-method research approach, quantitative and simulation, is used for data collection, and data is collected through a structured questionnaire and physical survey. For technical performance evaluation, the design of a factory was proposed and simulated for assessing users' comfort and energy efficiency.

For surveys, questionnaire tools were designed for understanding the perception of different stakeholders about smart buildings, their concept, benefits, and use of smart technology in the design of a factory. There were five main parts to the questionnaire.

1. Basic information on respondents and their socio-economic status
2. Understanding and awareness regarding the basic concept of smart buildings and technologies
3. Perception of smart building envelopes and their role in industrial architecture
4. Impact of the current working environment on the thermal comfort of the workers
5. Opinion regarding the improvement to the existing building

Surveys were conducted in the summer of 2023, and questionnaires were distributed among 100 people, which included 2 owners of factories, 20 architects, and 68 industrial workers. Two people were trained to gather data from the people who carried out surveys in a factory building in Karachi's SITE area to identify user issues, natural ventilation issues, availability of daylighting, space planning issues, and energy usage patterns in the production areas. The factory building's floor plans were prepared on AutoCAD for understanding and communicating spatial qualities. After analysis of the floor plans and spatial qualities of the existing building, a new building was proposed to address the issues identified by the respondents and highlighted by the spatial analysis.

To evaluate indoor comfort conditions and energy usage of the proposed building, we used Building Information Modelling (BIM). The proposed G+4 industrial building was modeled using Autodesk Revit, where physical and thermal properties were assigned to the components of the building, like floors, roofs, walls, and glazing systems.

The simulation collected data on:

1. Peak cooling and heating loads
2. Energy consumption patterns
3. Indoor operative temperature
4. Impact of insulation and façade systems on thermal performance
5. Contribution of solar panels to energy generation

For this purpose, building materials were generated in Autodesk Revit through the "Family Creation Tool," and assigned relevant physical and thermal properties within the model. After completing the model, thermal loads were simulated by defining material thermal properties along with inputs such as power and lighting loads. The simulation included multiple environmental and energy-related parameters, including:

1. Occupancy levels and schedules
2. Lighting load density
3. Equipment power loads
4. Ventilation and infiltration rates
5. HVAC system operation
6. Building material thermal properties (U-values)



Figure 3: Study Area Map with Karachi’s District and Town Boundaries

### 3. Findings and Analysis

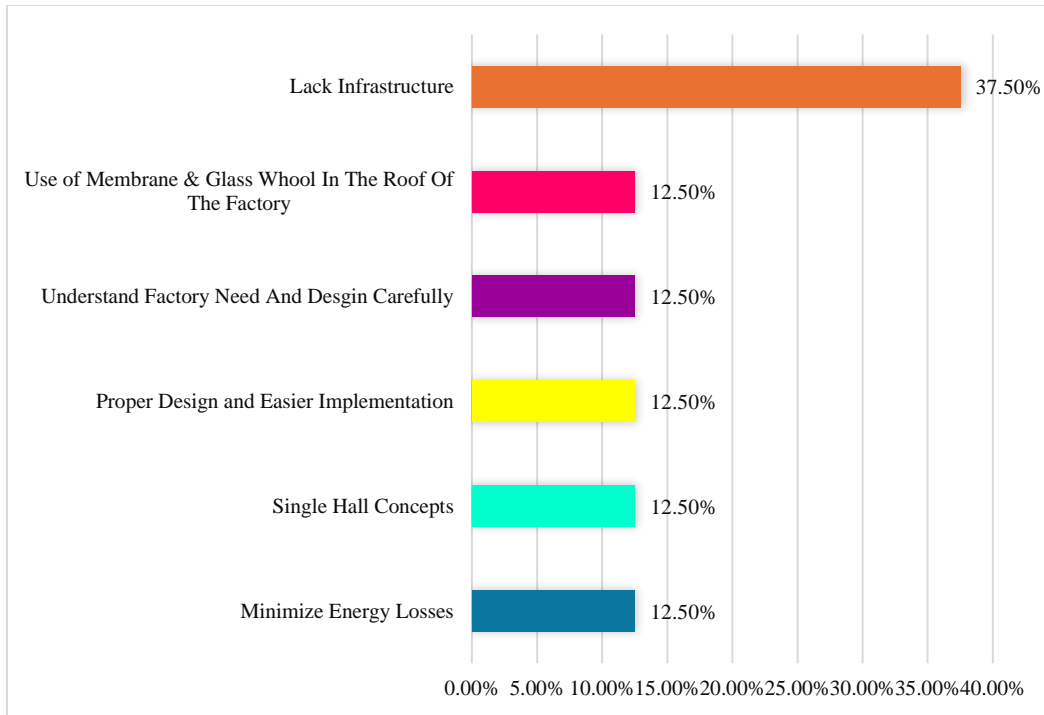
#### 3.1 Survey Results

Findings showed that 12% of respondents consider smart façade design an effective approach for reducing energy losses. The same proportion also considered it as a strategy for creating flexible spaces where multiple functions can be accommodated within a single area instead of relying on multi-storey configurations. Around 38% of participants believed that smart building concepts can be implemented in factory design. However, limited technological infrastructure in Karachi

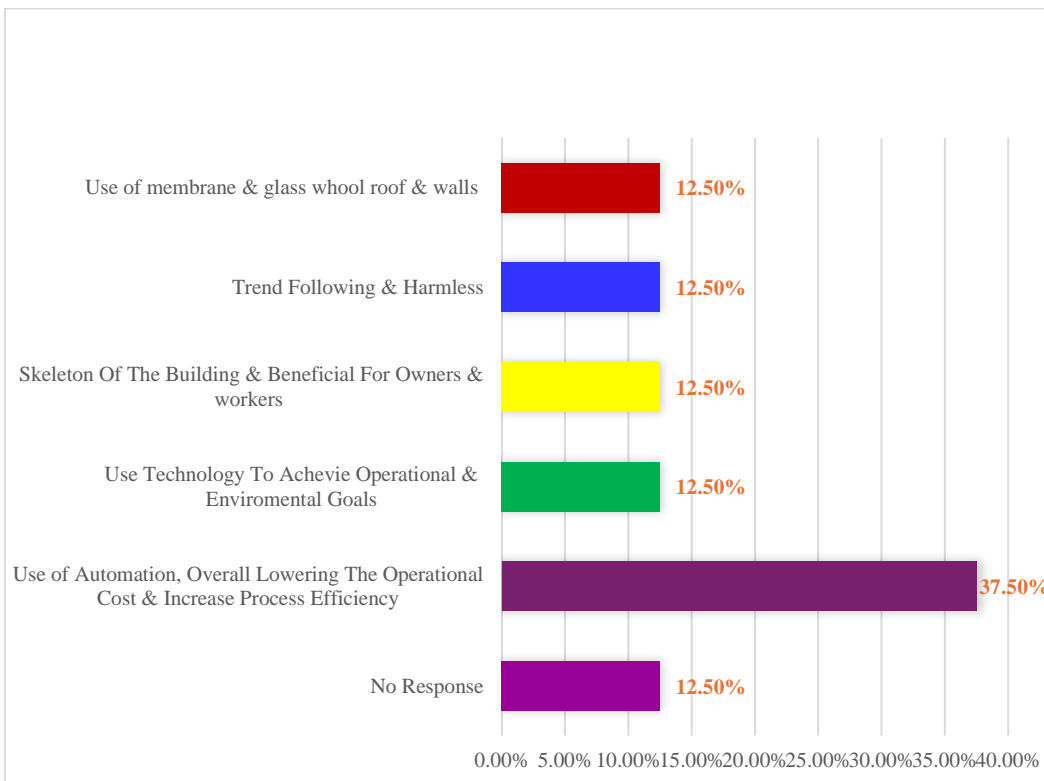
remains a major barrier to implementation. In addition, 12% viewed smart buildings as a major advancement not only in design but also in enabling building envelopes to be responsive within contextual environments. In addition, 13% highlighted that the application of membrane materials and glass wool in factory roofs is supporting the integration of smart building principles in Karachi's industrial sector (see Figure 4A).

Regarding smart buildings and their perceived benefits, 37% of people reported the improvement in efficiency of factory buildings, with lowering operational costs and decreasing energy use. 13% described the envelope of smart buildings as the structural framework of the factory that can provide advantages for both occupants and owners. For 12%, smart buildings represent the application of technology aimed at reducing costs, enhancing environmental conditions, and delivering other advantages. Meanwhile, 12% of respondents were unfamiliar with the concept of smart buildings or smart envelopes (see Figure 4B).

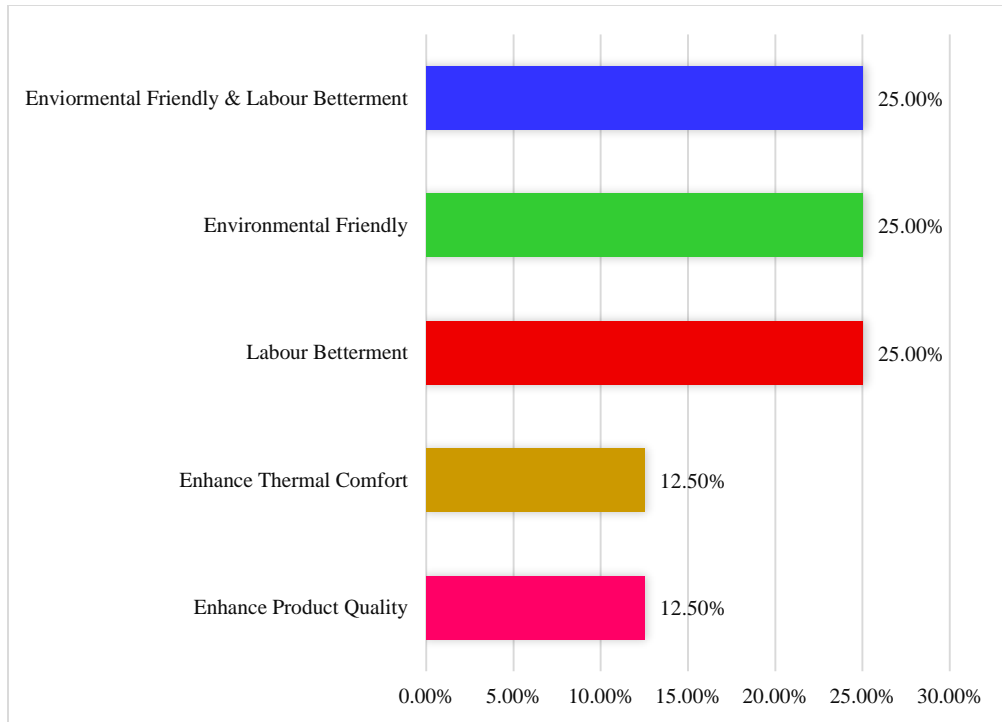
Regarding the effect of smart building envelope on user health and indoor environmental quality, 13% of respondents indicated that thermal comfort would improve, as the envelope adapts to climatic conditions to regulate indoor comfort. 25% believed technology would benefit labor conditions, and 12% reported that it would improve product quality by maintaining stable environmental conditions for workers and machines (see Figure 4C). Moreover, 52% of respondents believed that Pakistan would adopt smart building technologies within the next 15 years. However, the remaining participants were uncertain about its adoption, believing that adoption relies on both technological readiness and national economic circumstances (see Figure 4D).



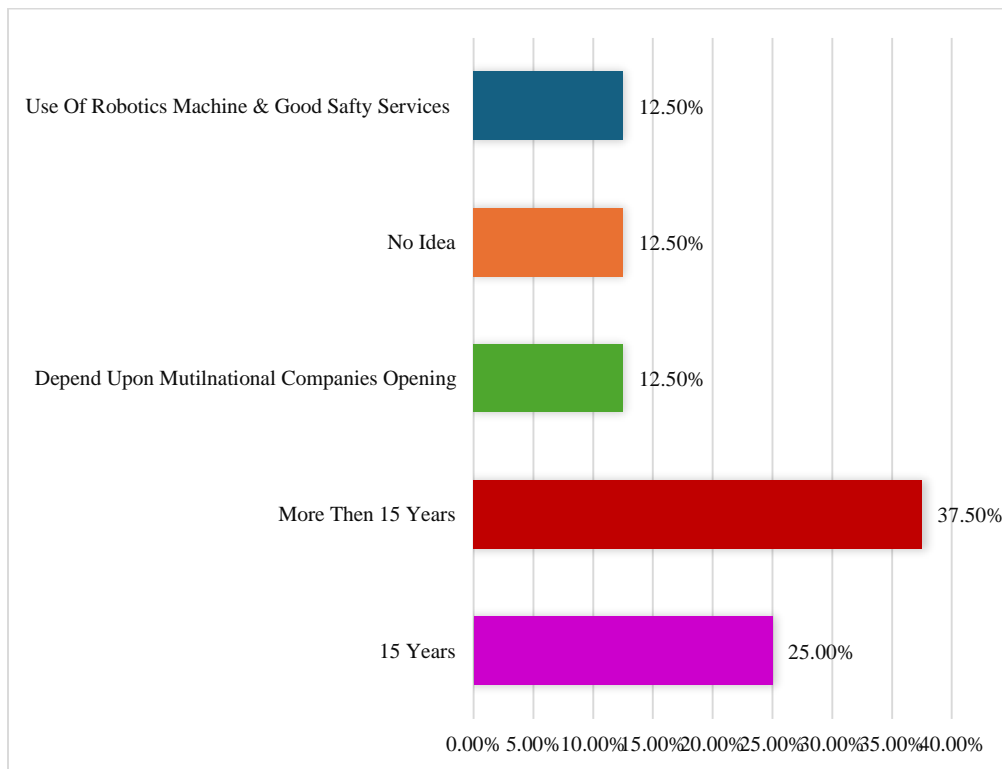
**Figure 4 (A) Understanding the Smart Building Concept and Its Implementation in Industrial Buildings (N = 100)**



**Figure 4 (B) Concept of Smart Building Envelope and Its Impact in Industrial Sector (N = 100)**



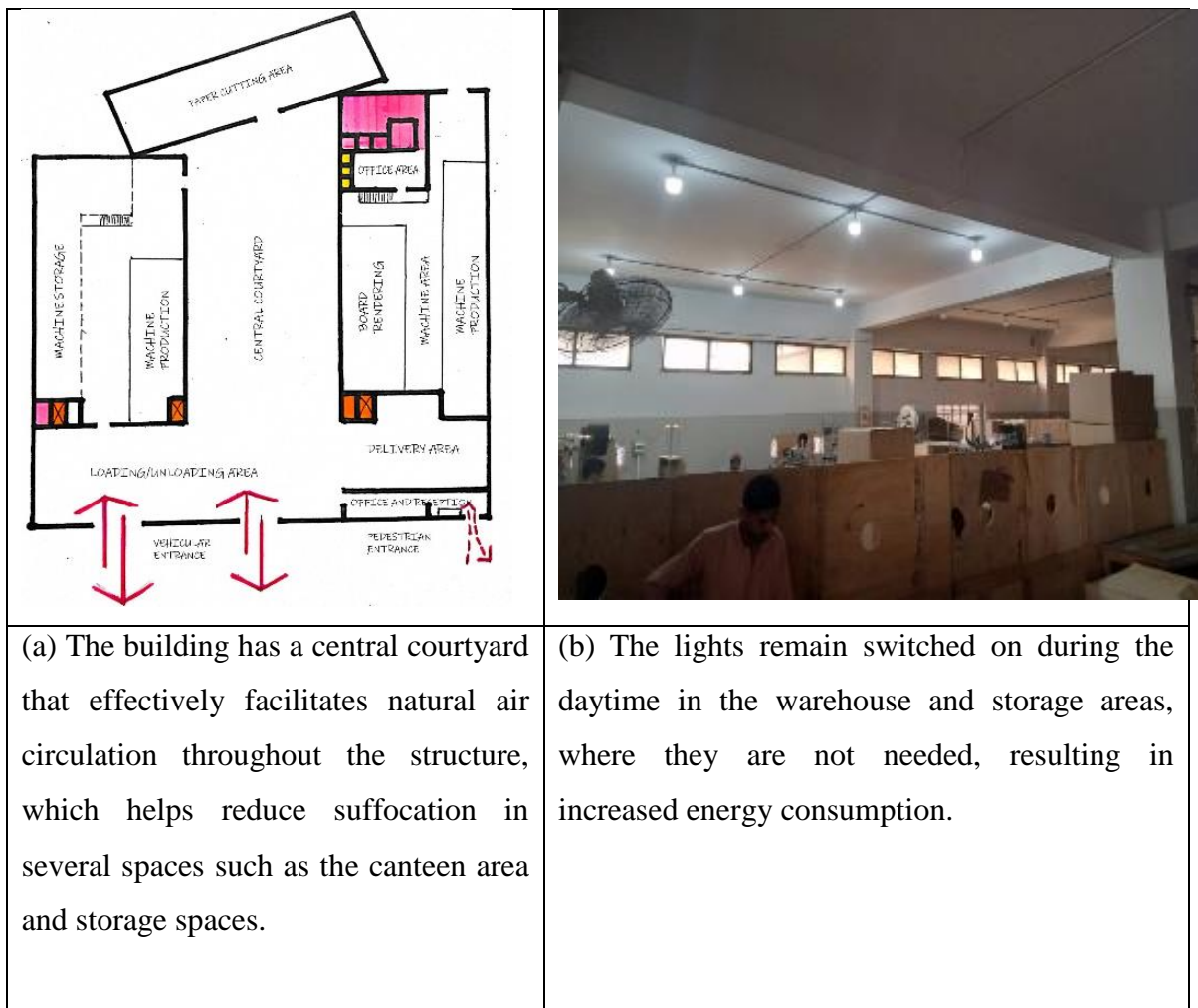
**Figure 4 (C) Assessment of Smart Building Envelope Impact on Environment and Occupant Health in an Industrial Building (N = 100)**

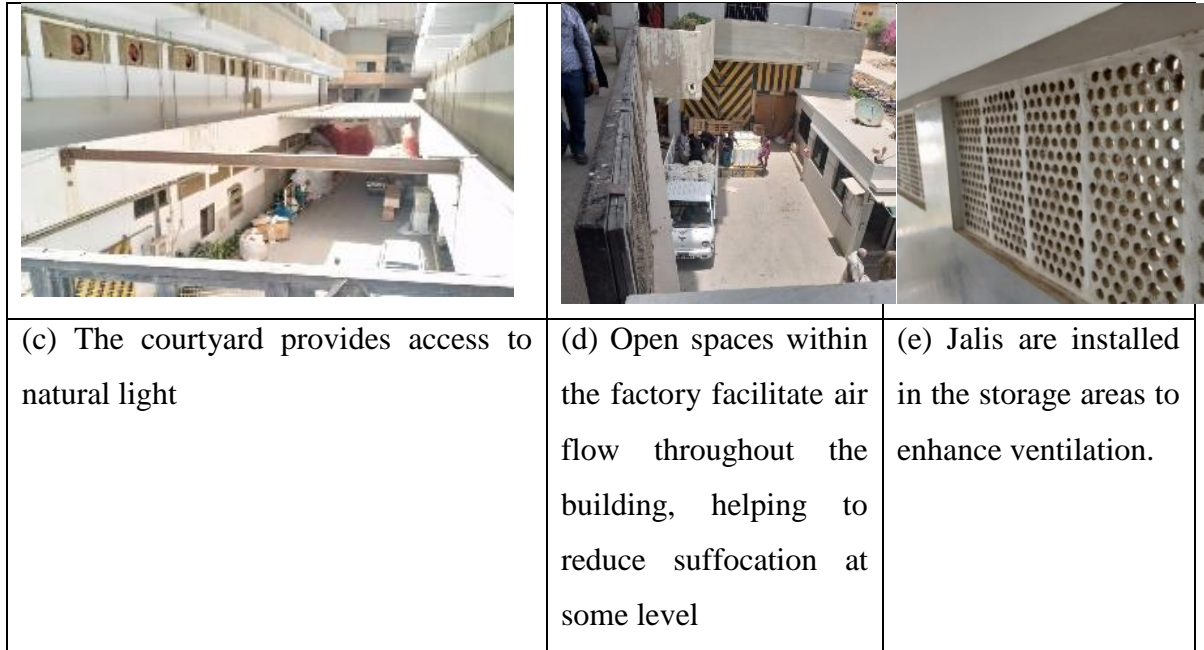


**Figure 4 (D) Users' Opinion About the Advancement of Industrial Sector in Terms of Smart Technology Application Over the Next Decade to 15 Years (N = 100)**

### 3.2 Spatial Analysis

An analysis of the factory floor plans and interior spaces with their spatial organization and circulation patterns, natural ventilation, and light availability in the factory showed that the existing building has a central courtyard to provide natural light and ventilation, but the ratio of height to the size of the courtyard is not appropriate to ventilate or light the interior spaces (see Figure 5). Due to the absence of air conditioning, the production areas experience high indoor temperatures, and they are already suffering from limited natural light and ventilation. As a result, workers are exposed to uncomfortable conditions that can lead to chronic health problems. This environment also slows productivity and reduces production volume. Moreover, frequent power breakdowns further disrupt the workflow. Hence, the factory must be redesigned to address these challenges and create healthier indoor environments while reducing dependence on non-renewable energy and reducing environmental impacts.

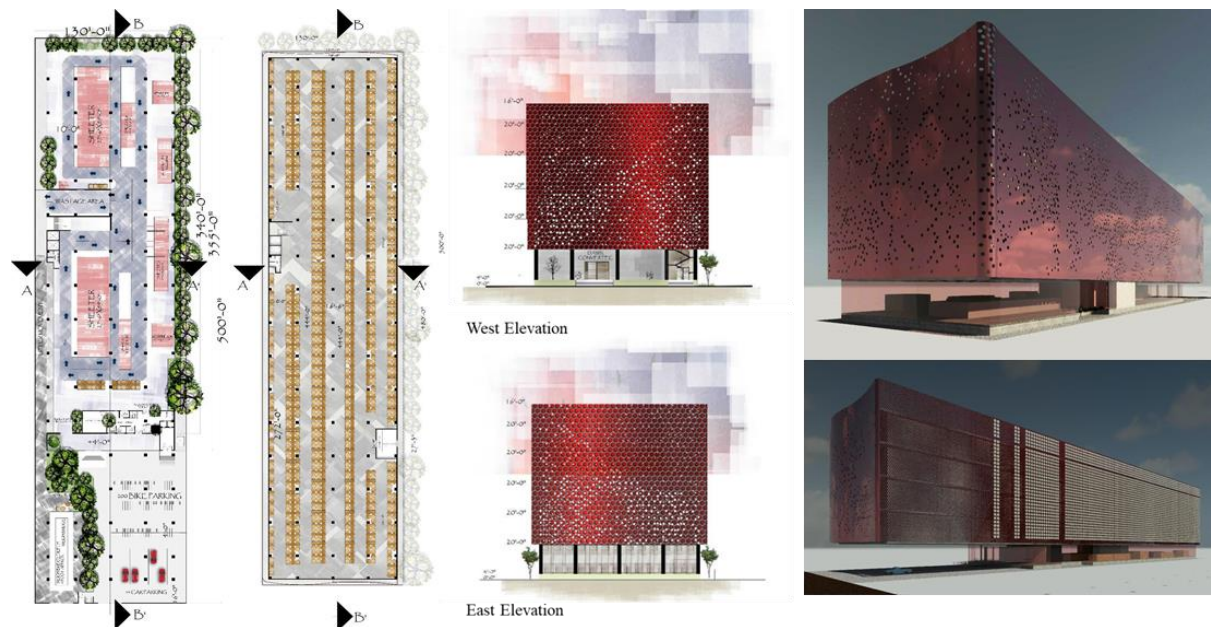




**Figure 5 (A-E) Existing Plan and Different Spaces of Selected Case Study of a Factory Building in Karachi**

**3.3 Building Information Model (BIM) of the Proposed Factory**

A new factory is proposed to address the issues indicated by the results of surveys and spatial analysis: 1) Thermal comfort and 2) High energy consumption, which were considered in the development of the new factory building design (Figures 6 & 7 a,b).



**Figure 6 Proposed Floor Plans of Factory with the Simulation and 3D Models (Author)**



Figure 7a Section at AA'



Figure 7b Section at BB'

### 3.4 Computational Thermal Simulation on Autodesk Revit

Energy simulation was performed to analyze the effect of the proposed HVAC on energy requirements for cooling in the factory building. It further analyzed thermal insulation effects through a solar-shaded smart façade and installing solar panels on the roof of the building. Autodesk Revit was used to model the energy demand of the proposed industrial building (Figures 8 & 9), including major contributors such as HVAC systems, lighting, machinery, and occupants. Internal loads from occupants and equipment were calculated on an hourly basis, as well as for building control operations such as blinds and ventilation. The results of the energy simulation are presented in Table 1.

A full-year simulation was performed, with load parameters derived from a two-week measurement period (two shifts, excluding weekends and national holidays) assumed to represent typical yearly conditions (see Table 2). While actual load profiles may vary with production demand and use of equipment, this is taken as a baseline assumption. The peak cooling load for the proposed factory building is 600 kW, necessary to maintain indoor summer temperatures of 27–28°C and to counter heat gains. In comparison, the solar panel system generates 850 kW; the results showed that the energy generated through renewable means is sufficient to meet peak cooling needs, with an additional 250 kW available for other uses (see Figure 10).

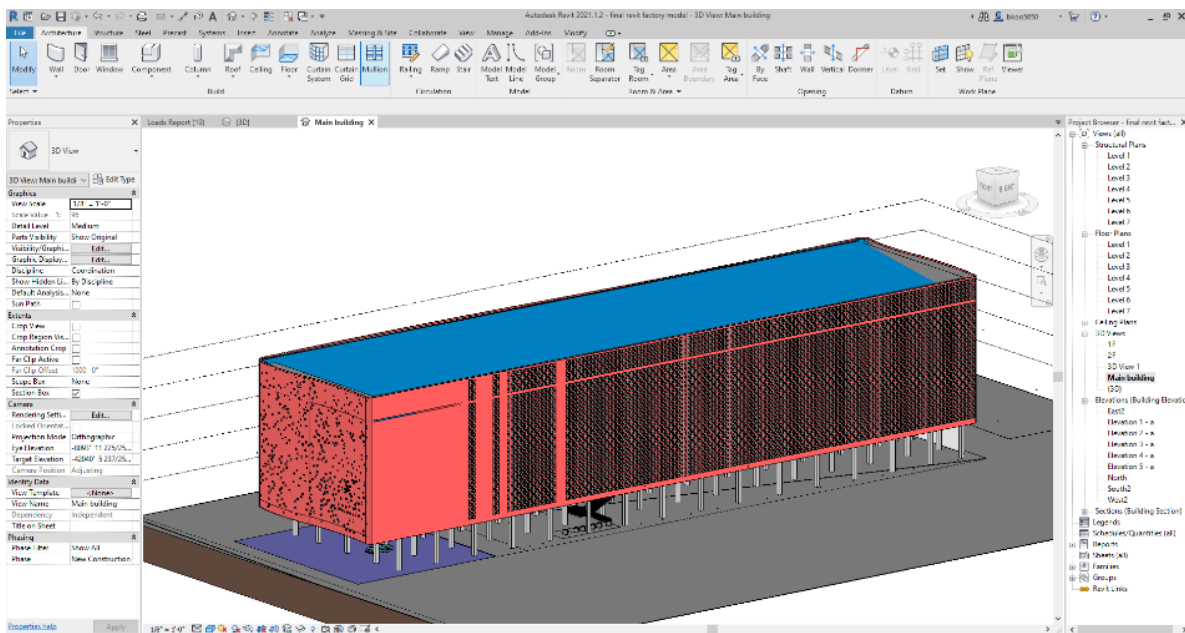
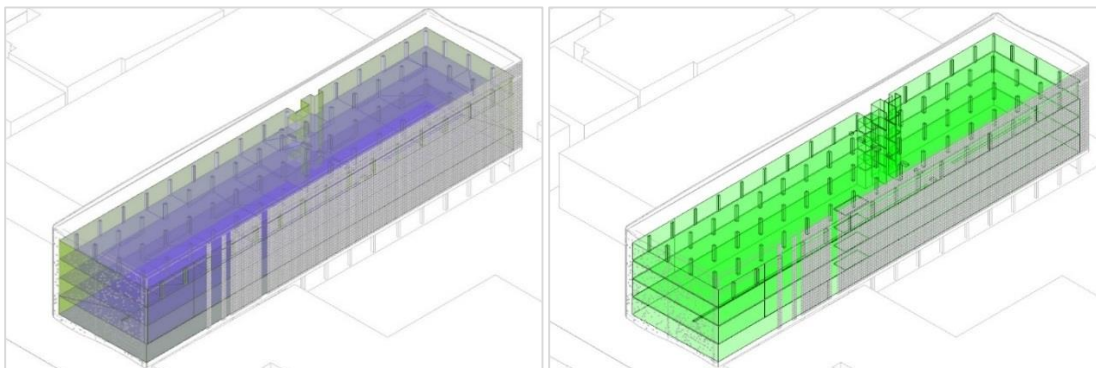


Figure 8 BIM Model of the Proposed Factory Building (Source: Author)



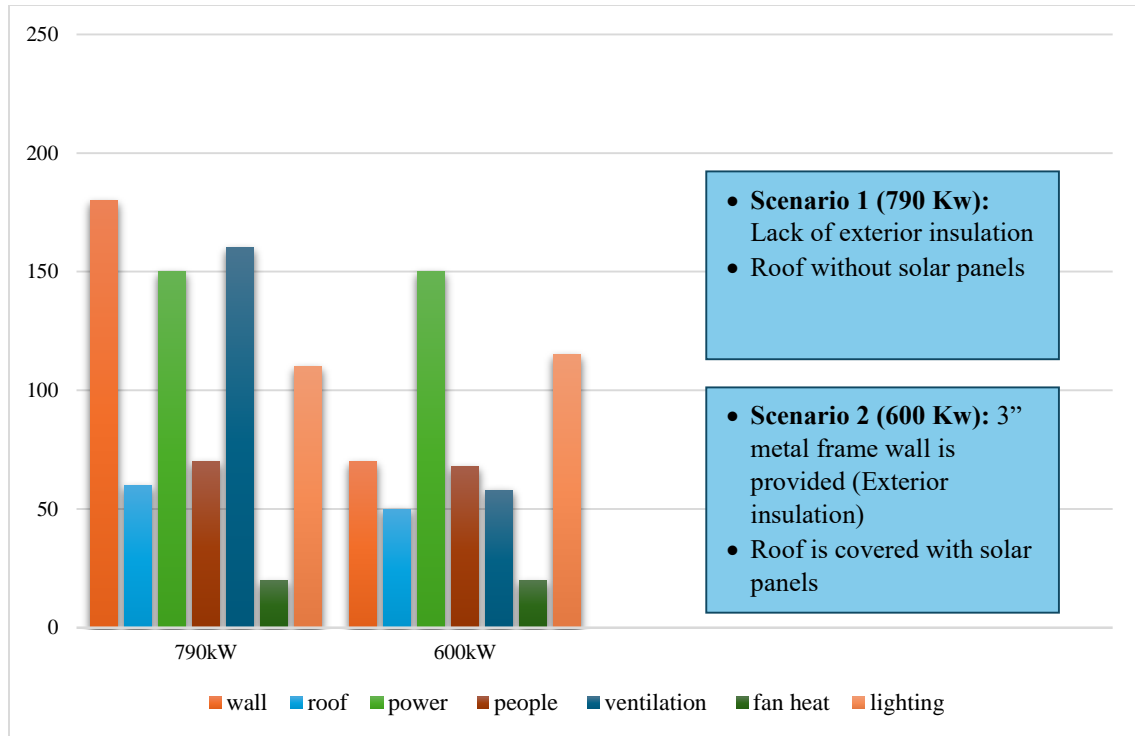
**Figure 9 Computational Simulations on Autodesk Revit (Source: Author)**

**Table (1) Material Parameters of Factory Building for Analysing the Thermal Load (Source: Author)**

<b>Analysis Properties</b>		
By default, properties are normally generated from conceptual type inputs; however, when override is selected, schematic type properties are used instead.		
<b>Category</b>	<b>Override</b>	<b>Analytic Construction</b>
Roofs	<input checked="" type="checkbox"/>	PV panels installed on the inclined roof (U=0.1589 W/m <sup>2</sup> .K)
External Walls	<input checked="" type="checkbox"/>	Curtain wall constructed with metals and 1 ft thermal insulation (U=0.5149 W/m <sup>2</sup> .K)
Internal Walls	<input checked="" type="checkbox"/>	Lightweight framed partition finished with ¾ inch gypsum board (U=1.4733 W/m <sup>2</sup> .K)
Ceilings	<input checked="" type="checkbox"/>	8 -inch concrete slab (lightweight) used as ceiling assembly (U=1.3610 W/m <sup>2</sup> .K)
Floors	<input checked="" type="checkbox"/>	8-inch lightweight concrete floor slab system (U=1.3610 w/m.k0)
Slabs	<input type="checkbox"/>	Perimeter slab insulation (R-10) applied at edges (U=0.1160 W/m <sup>2</sup> .K)
Door	<input checked="" type="checkbox"/>	Metal entry door assembly ( U=3.7021 W/m <sup>2</sup> .K)
External Windows	<input checked="" type="checkbox"/>	Large-scale double-glazed units with reflective coating suitable for industrial use
Internal windows	<input checked="" type="checkbox"/>	Single-glazed internal glazing system (U=3.6869W/m <sup>2</sup> .K) SHGC=0.86
Skylights	<input checked="" type="checkbox"/>	Double-glazed skylight system with reflective coating for industrial applications
<input type="button" value="All"/> <input type="button" value="None"/> Shading factor for external window <input type="text" value="0"/>		
<input type="button" value="OK"/> <input type="button" value="Cancel"/>		

**Table (2) Simulation Outcomes of the Factory Building's Required Indoor Operative Temperature alongside Corresponding Energy Demand (Source: Authors)**

<b>Building Summary</b>	
Inputs	
Building Type	Manufacturing
Area (S.F)	203,129
Volume (CF)	3,848,475.39
<b>Calculated Results</b>	
Overall Cooling Load for peak time (kW)	<b>600.3</b>
Peak period for Cooling Load (Month and Hours)	July 3:00 pm
Peak Sensible Load of Cooling	534.2
Peak Latent Load of Cooling (kW)	203.3
Maximum Capacity for Cooling (kW)	619.3
Peak Airflow requirements for Cooling (CFM)	68.107
Peak Load of Heating (kW)	110.5
Peak Airflow of Heating (CFM)	16,090
<b>Checksums</b>	
Density of Cooling Load (Btu/[h.ft <sup>2</sup> ])	12.39
Density of Cooling Flow [CFM/SF]	0.34
Cooling Flow / Load (CFM/ton)	324.79
Cooling Area / Load (SF/ton)	968.68
Density of Heating Load (Btu/[h.ft <sup>2</sup> ])	1.86
Density of Heating Flow (CFM/SF)	0.08



**Figure 10 Comparative Analysis of Cooling Loads under Insulated and Non-Insulated Conditions**

(Source: Author)

In the connected production zone, spanning 203,129 square feet, indoor environmental conditions are regulated by a central HVAC system with an evaporative humidifier. The system is set to maintain temperature and humidity at 22°C and 46%, respectively, with air exchange rates ranging from three to six times per hour (see Table 3). A complete rooftop solar panel is installed, and thermal load analysis is performed through simulation. The material properties used in the building model are listed in Table 1. For exterior wall insulation, a 1'-0" air gap within the cavity wall and a 3-inch metal cladding are used to assess wall heat gain. Peak cooling loads are also calculated for both insulated and non-insulated scenarios for walls and roofs and compared with a non-insulated building. The simulation results revealed that uninsulated buildings have higher energy consumption (790 kW) compared to the insulated building (600 kW), as shown in Figure 10. This demonstrates that proper insulation can significantly reduce building energy consumption.

**Table (3) Thermal Load Parameters for Hourly Energy Performance Analysis in the Designed Building (Source: Author)**

Parameter	Value
<b>Energy Analysis</b>	
Area / Person	260.00SF
Sensible Heat Gain/ person	250.00Btu/h
Latent Heat Gain/ person	200.00Btu/h
Density of Lighting Load	1.20 W/ft <sup>2</sup>
Density of Power Load	1.00 W/ft <sup>2</sup>
Infiltration Airflow/ area	0.04CFM/SF
Plenum Lighting Contribution	20.0000%
Schedule of Occupancy	Warehouse Occupancy – 7 AM to 4 PM
Schedule of Lighting	Office lighting - 6 AM to 11 PM
Schedule of Power	Office lighting - 6 AM TO 11 PM
Outdoor Air/ Person	5.00 CFM
Outdoor Air/ Area	0.06 CFM/SF
Air changes/ hour	0.000000
Outdoor air method	By people and by area
Heating set point	21.11 °C
Cooling set point	28.00 °C
Humidification set point	0.0000 %
Dehumidification set point	70.0000%

**Table (4) Zone-Based Summary of How the Proposed Air Conditioning Installation Influences Cooling Energy Requirements of the Building (Source: Author)**

<b>Zone Summary</b>	
Inputs	
Area (SF)	203,129
Volume (CF)	3,848,475.39
Cooling Setpoint	23°C
Heating Setpoint	21°C
Supply Air Temperature	12°C
Number of People	781

Infiltration (CFM)	0
Air Volume Calculation Type	VAV – Dual Duct
Relative Humidity	46.00% (Calculated)
<b>Psychometrics</b>	
Psychometric Message	None
Cooling Coil Entering Dry-Bulb Temperature	27°C
Cooling Coil Entering Wet-Bulb Temperature	18°C
Cooling Coil Leaving Dry-Bulb Temperature	10°C
Cooling Coil Leaving Wet-Bulb Temperature	10°C
Mixed Air Dry-Bulb Temperature	27°C
<b>Calculated Results</b>	
PPeak Cooling Load (kW)	<b>600.3</b>
Peak Cooling Month and Hour	June 3:00 pm
Peak Cooling Sensible Load (kW)	564.7
Peak Cooling Latent Load (kW)	54.6
Peak Cooling Airflow (CFM)	68.107
Peak Heating Load (kW)	110.5
Peak Heating Airflow (CFM)	16,090
Peak Ventilation Airflow (CFM)	16,090
<b>Checksums</b>	
Cooling Load Density (Btu/[h.ft <sup>2</sup> ])	10.40
Cooling Flow Density (CFM/SF)	0.34
Cooling Flow / Load (CFM / ton)	386.79
Cooling Area / Load (SF/ton)	1,153.61
Heating Load Density (Btu/[h.ft <sup>2</sup> ])	1.86
Heating Flow Density (CFM/SF)	0.08
Ventilation Density (CFM/SF)	0.08
Ventilation/Person (CFM)	21

**Table (5) Result Summary of Thermal Analysis (Source: Author)**

Components	Cooling		Heating	
	Loads(kW)	Percentage of Total	Loads(kW)	Percentage of Total
Wall	83.8	12.46	18.8	16.98
Windows	0.0	0.00	0.0	0.00
Door	0.0	0.00	0.0	0.00
Roof	50.0	9.00	0.0	0.00
Skylight	0.0	0.00	0.0	0.00
Partition	0.0	0.00	0.0	0.00
Infiltration	0.0	0.00	0.0	0.00
Ventilation	62.6	10.25	91.7	83.02
Lighting	120.7	29.18		
Power	151.0	24.55		
People	78.9	12.74		
Plenum	0.0	0.00		
Fan Heat	12.3	1.98		
Reheat	0.0	0.00		
<b>Total</b>	600.3	100	110.5	100%

Operative temperature in the factory is evaluated in relation to wall construction techniques and the use of solar-shaded smart façades, under conditions with and without ventilation. Simulation results indicated that the building has walls without cavities and lacks sunshades, experience significant high operative temperatures, and has a reduced duration of indoor thermal comfort. Under ventilated conditions, the combination of block masonry walls with cavities, a solar-shaded smart façade, and solar panels installed on the rooftop resulted in increased hours of adaptive thermal comfort. Further, energy consumption is reduced by up to 28% by using cavity walls with a metal curtain façade instead of a standard 0'-6" concrete wall and concrete facade (see Table 5). On a peak summer day, a factory's interior operative temperature rises to 29.1°C without ventilation but decreases to 28.4–23.7°C with ventilation, reaching 26.9°C on average (see Table 4). Figure 11 compares the yearly factory performance, demonstrating operative temperatures maintained within the adaptive thermal comfort range year-round when equipped

with solar-shaded smart skin and metal curtain walls. Figure 12 presents simulation results for relative humidity and operative temperature; relative humidity rises proportionally with ventilation. Temperature falls as humidity increases; occupants often use fans for comfort, indicating how higher energy demand contributes to climate change.

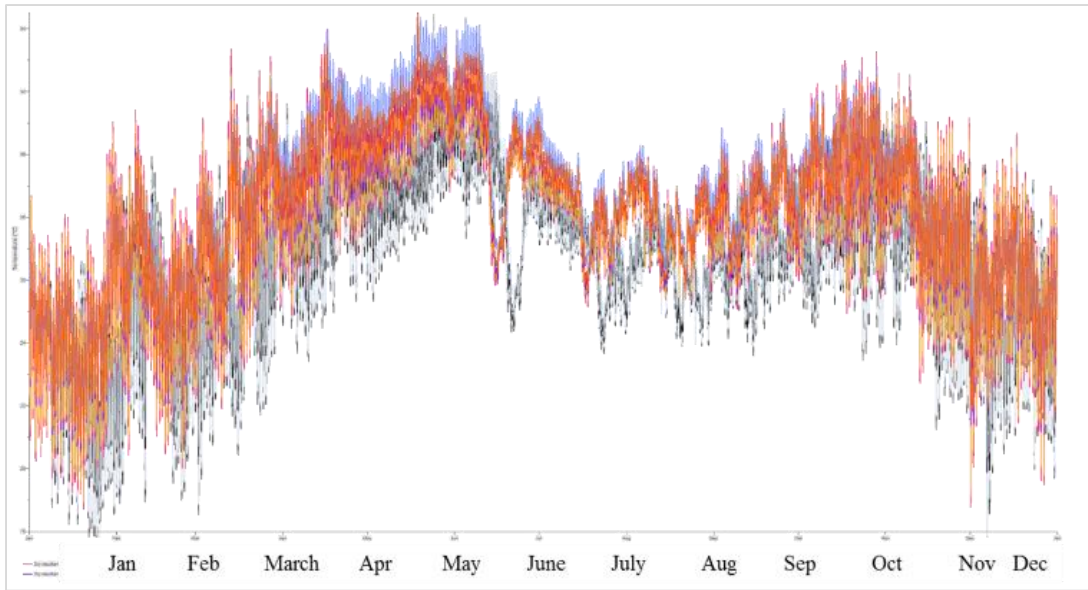


Figure 11 Adaptive Comfort Zone Temperature Range: 23.7–29.1°C (Source: Author)

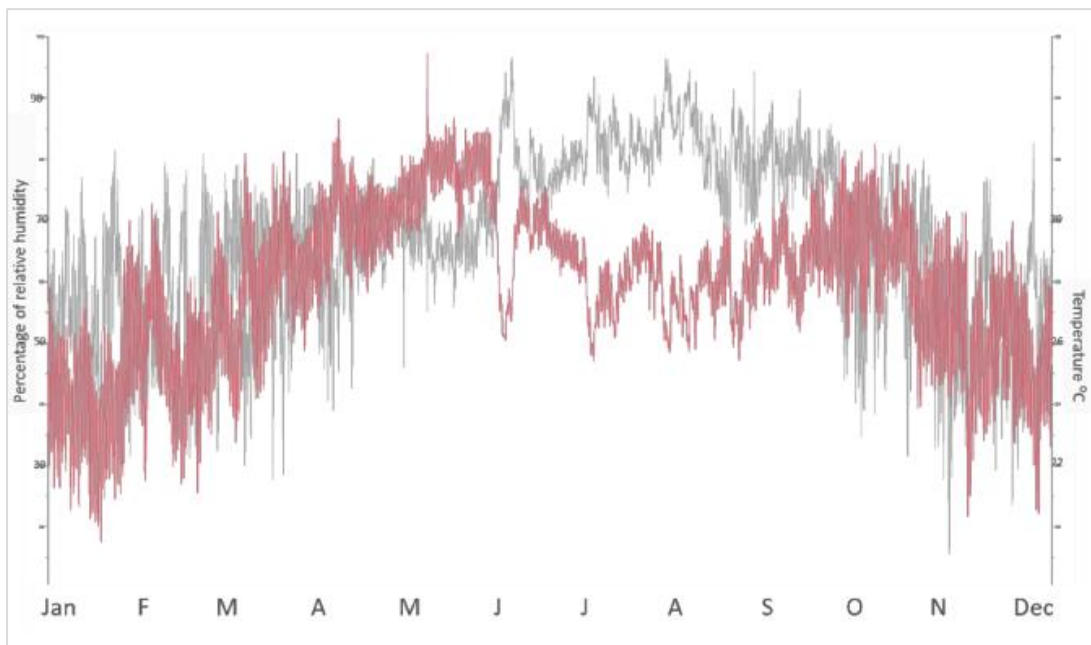


Figure 12a Comparison between Temperature Levels and Relative Humidity Conditions (Source: Author)

#### 4. Discussion

This study has explored the design and performance of smart, energy-efficient industrial buildings in Karachi, with a focus on optimizing energy performance, indoor environmental quality, and thermal comfort. The trend in building design is shifting toward automation, energy efficiency, and user-oriented design. The results of the simulation clearly highlighted the reduction of energy load and the creation of a comfortable environment with the use of smart technologies. In factories, energy consumption is a key issue because production areas demand substantial amounts of electricity. However, in the energy-deficient country of Pakistan, the requirement of energy is fulfilled by load shedding that negatively affects production, and industries suffer a billion-rupee-per-year loss due to failures in the power grid. Hence, the adoption of smart technologies within building interiors can help in addressing energy issues, enhance ventilation and comfort, and offer effective solutions for spaces like warehouses and production zones where natural ventilation is inadequate and conventional systems like air conditioners are ineffective.

Smart energy generation, such as rooftop solar panels, can reduce reliance on the grid and provide a continuous energy supply for critical operations, complementing energy-saving strategies within the building. Further, the integration of Building Control Systems (BCS) and smart sensors allows precise monitoring and control of HVAC, lighting, and internal climate conditions, which improves both efficiency and user comfort. Furthermore, integrating automated lighting, adaptive solar shading devices, cavity wall systems, and automated door operations can significantly reduce energy consumption. Evidence suggests that a reduction of 50–60% in energy use is possible, based on building performance and HVAC features. These results confirm that combining smart building envelopes with adaptive technology and energy-efficient systems provides a viable solution for industrial sustainability and occupant comfort in Pakistan's factories.

Further, by improving the design of building envelopes, the simulated model addresses issues of poor indoor conditions and indicates that smart buildings can effectively adjust to changes in external and internal conditions, leading to improved energy efficiency, minimized carbon footprint, and better comfort for occupants. A well-regulated thermal environment for workers is essential for sustainable industrial development, as it enhances employee well-being and productivity. Thermal comfort remains a significant challenge in factories, particularly in areas

like storage and packaging. Limited ventilation in such spaces often leads to discomfort and dizziness among workers. Additionally, most factories lack adequate insulation and thermal control measures, which often create oppressive indoor conditions, which worsen during the summer months in Karachi when temperatures reach 40°C. According to the study of Panjwani et al. (2014), thermal comfort for Karachi residents is between 24°C and 27°C, with humidity levels of 50% to 60% (Panjwani et al., 2014). The survey findings also highlighted that the indoor environment of the factories is not user-friendly and environmentally friendly and favors the use of smart technology in the design of factories. Therefore, smart technologies in factory buildings can help maintain and precisely monitor thermal comfort and ventilation, as well as improve fire prevention measures and occupant comfort. Buildings integrated with smart technologies also allow residents to adjust their spaces according to their needs and preferences, using elements such as adaptive solar blinds and seasonally adjustable partitions. The use of a solar-shaded smart skin or adaptive façade can reduce heat gain, improve natural lighting, and provide dynamic control over indoor environmental conditions, which directly impacts worker productivity and energy efficiency. These results are aligned with the study of Premier (2019) that solar shading, often referred to as "solar control" or "solar protection," helps in improving the indoor environment and the comfort of building occupants (Premier, 2019). Additionally, the integration of smart lighting systems, smart HVAC, and real-time monitoring ensures the use of energy as per the requirements, reducing waste and lowering operational costs.

This study has several limitations. It is confined to a single factory case study in Karachi, which may limit the applicability of the findings to other industrial buildings in Pakistan, due to differences in climate conditions, building types, and operational practices. The study also focuses mainly on energy efficiency, thermal comfort, and ventilation, while other smart building parameters such as structural performance, cost evaluation, and worker behavior were not comprehensively analyzed. Additionally, limitations related to sample size, high capital costs, and technical complexities of BIM and smart systems may have influenced the study outcomes.

Future studies should focus on investigating multiple factories across various industrial zones and by implementing long-term evaluations of indoor environmental quality, energy efficiency, and worker productivity. Additional research is required to conduct cost–benefit analysis and cross-context implementation of advanced technologies to enhance existing design models.

Overall, this research supports sustainable industrial architecture by proposing actionable strategies and encouraging further innovation.

## **5. Conclusion and Recommendations**

As electricity production continues to depend largely on fossil fuels, energy conservation is increasingly important to reduce total energy demand. Major determinants of building energy use include envelope design and materials, along with external environmental features such as vegetation that promote natural ventilation. Efficient lighting, heating, ventilation, and air conditioning (HVAC) systems also play an important role. In tropical environments like Karachi, climate-responsive cooling technologies and energy-efficient appliances are necessary. Maintaining thermal comfort through natural ventilation with reduced energy use should be considered an important design objective. The results demonstrate that smart technologies can effectively decrease cooling energy demand while improving occupant comfort in industrial settings.

The study suggests a range of design strategies to promote environmental efficiency and occupant comfort in Pakistani factories. First, a solar-responsive smart skin is proposed to respond to climatic variations and manage heat gain and natural lighting under changing conditions. Secondly, thermal comfort, a major issue in industrial settings, can be addressed through chillers with intelligent control systems capable of regulating temperature, controlling humidity in storage facilities, reducing dust in production areas, and maintaining optimal conditions for product quality. Additionally, energy costs can be minimized through the incorporation of solar energy systems. Apart from industrial machinery loads, the building's energy demand may be met by adopting a smart building approach involving the installation of 400 W photovoltaic panels with dimensions of 2024 mm × 1024 mm × 40 mm. Furthermore, the adoption of DALI (Digital Addressable Lighting Interface), a network-based lighting control system developed by Philips Lighting in 1984 (Mahmoud, 2021), is proposed for the factory building. The integration of sensor-based monitoring of temperature, water, and humidity is also advantageous. Such strategies can contribute to improved sustainability, operational efficiency, and occupant comfort in industrial buildings in Pakistan, in accordance with smart building design principles.

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**Data Availability:**

The authors confirm that the data supporting the conclusions of this article will be readily available without delay.

**Author's Contribution:**

**Humaira Nazir:** Supervision, Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Bushra Khan:** Writing – review & editing, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Dr. Ubaid Ullah:** Writing – review & editing, Visualization, Validation. **Hassaan Bilal Rashid:** Methodology, Software, Formal analysis

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