

Technological Activation of Building Envelopes to Achieve Environmental Comfort

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ABSTRACT

With the rapid advancement of construction technologies, the architectural envelope of a building has evolved beyond a mere structural element into an integrated system designed to achieve comprehensive environmental comfort by controlling thermal, lighting, and acoustic factors within architectural spaces. This research focuses on the technological activation of building envelopes through modern innovations such as smart glass, adaptive walls, natural ventilation systems, and advanced insulation technologies, all of which contribute to enhancing building performance and promoting sustainability. The study explores key concepts and strategies related to the performance of building envelopes and examines how artificial intelligence, the Internet of Things, and smart materials can enhance energy efficiency while improving user comfort. Additionally, it reviews contemporary architectural applications that have successfully implemented innovative solutions in smart envelope design. Findings indicate that integrating dynamic shading technologies, smart ventilation systems, and phase-changing materials significantly reduces energy consumption and enhances indoor environmental quality. These strategies offer a sustainable solution for achieving environmental comfort in future buildings.

Keywords: Environmental comfort, Natural ventilation, Smart building envelopes, Smart technologies, Sustainability, Thermal insulation.

1. INTRODUCTION

Amid increasing environmental and climatic challenges, achieving sustainable environmental comfort within buildings has become a fundamental objective in contemporary architectural design. This goal necessitates the development of innovative solutions that ensure energy efficiency, improve air quality, and enhance thermal, visual, and acoustic comfort. The building envelope plays a crucial role in this context due to its ability to regulate heat exchange, control natural lighting levels, enhance sound insulation, and improve indoor air quality, thereby creating a comfortable and healthy indoor environment for building occupants. The construction sector has witnessed significant advancements in

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adopting smart materials and adaptive technologies that enable building envelopes to dynamically and effectively interact with external environmental factors (**ElAttar et al., 2022**).

Some of the key developments in this field are electrochromic glass, which controls light and heat transmission for maximum energy efficiency, breathing walls, which allow natural air exchange and provide maximum indoor environmental quality, and dynamic facades, which alter their response to climatic conditions in an attempt to provide minimum energy consumption. High-performance thermal insulation systems minimize thermal loads and artificial heating and cooling use (**Singh et al., 2021**). Besides, the application of IoT and AI in the building management system has revolutionized the process of climatic conditions monitoring and control in the building. Sophisticated sensor-based systems that self-regulate to prevailing climatic conditions through continuous control of ventilation, lighting, and shading according to occupants' requirements maximize climate control. The current work aims to address the use of smart technologies to activate building envelopes to achieve environmental comfort through the explanation of some of the most pertinent approaches and innovative ideas on the design of smart envelopes in constructive conversation with their surroundings. Additionally, it addresses brief future-oriented building design case studies that effectively adopted these ideas and future smart building designs that can design immaculate indoor conditions. Therefore, the current research provides an account of the broad application of high-tech in shaping architectural envelopes with the optimal combination of aesthetics, functional performance, and environmental sustainability. This contributes to enhancing buildings' capabilities to reduce their effect on the environment and meet green building and sustainable architecture requirements (**Singh et al., 2021**).

This research aims to examine and analyze the technological activation techniques of building envelopes to achieve environmental comfort within architectural spaces, by employing modern innovations such as smart glazing, adaptive walls, natural ventilation systems, and advanced insulation technologies. It also seeks to explore the integration of artificial intelligence, the Internet of Things, and smart materials to enhance energy efficiency and indoor environmental quality, as well as to evaluate contemporary architectural applications that successfully implement innovative smart-envelope solutions that provide sustainability and thermal, visual, and acoustic comfort for occupants—thereby supporting sustainability goals and improving the overall environmental performance of buildings.

2. BUILDING ENVELOPE

Building envelope technology is a qualitative jump in the field of architecture and interior design since it is founded upon the use of high-tech materials and technologies to ensure a pleasant indoor climate for occupants, regardless of the type and purpose of the area. This includes achieving thermal and acoustic comfort, managing the levels of light depending on functional purposes, and optimizing the users' sensory experience by integrating interior design with the exterior environment to enable more responsive and adaptive environments that dynamically respond to surrounding influences. The envelope in architecture plays a vital role in interior space development, enabling the achievement of human needs and fostering a unified environmental experience. Failing to respond to the design of the demand posed by man could lead to a monotonic response and one that does not relate to the environment. From this point of view, the continuous improvement of smart envelope



technologies not only facilitates the building's environmental performance but also has an impact on users' perception and response to the interior space **(Mustafa, 2016)**. As a result, this shift has led to the development of new design strategies taking into account dynamic interaction between the external envelope and the internal environment, enhancing the responsiveness of architectural space to users' needs and achieving sustainable functional and aesthetic integration **(Jarjat et al., 2020)**.

Accordingly, the building envelope can be defined as "the membrane surrounding the building, formed by employing a set of different elements in relationships that govern these elements according to aesthetic, sensory, and expressive standards. It reflects the architect's vision and the extent of success in achieving formal compatibility and visual harmony with the surrounding environment" **(ElAttar et al., 2022)**.

The architectural skin and the building envelope are both essential elements in shaping buildings; however, there is a fundamental difference between them in terms of function and their impact on both the internal and external environments. The architectural skin (Skin of Building) refers to the external façade or shell that surrounds the building. It is the dominant surface area visually that imparts the building's personality and expression of the designer's architectural identity. The skin plays a key role in aesthetic expression, forming the first impression of the building and defining its visual relationship to context without physically altering the internal environmental variables it is meant to control. On the other hand, the building envelope (Building Envelope) is the physical boundary between the external and internal building environment. It regulates thermal and acoustic insulation and determines indoor air quality by creating resistance to climatic parameters such as air, water, wind, and solar radiation. The envelope is seen as an architectural engineering technical specialist component in that it's made to increase efficiency within structures by controlling energy, lighting, and temperature, and is therefore mandated with facilitating coherence between environmental comfort and energy sustainability **(Al-Badri and Abdul Razzaq, 2008)**.

Thus, the key difference between the architectural skin and the building envelope is their orientation: while the skin is oriented toward aesthetic and design issues, the envelope is oriented toward environmental and performance ones. While the architectural skin strives to enhance the external look and visual coherence of the building, the building envelope optimizes the building's environmental performance and energy efficiency. Therefore, achieving integration of the envelope and the skin is a supreme challenge in modern architectural design, and it entails harmonization of an attractive exterior and functional efficacy that ensures user comfort and energy consumption optimization. Adaptive envelope construction is the focal point of enhancing thermal comfort in buildings using smart technologies with the least reliance on artificial heating and cooling systems. Controlled natural ventilation is arguably the most notable solution in this direction, making use of controllable vents and responsive materials to effectively control airflow within the building. The technique significantly minimizes summer cooling and winter heating needs. In addition, the envelope uses dynamic shading systems that automatically manage the movement of building facades according to the intensity of solar radiation. The system avoids the unwanted gain of heat in interior spaces. The other new technology employed in adaptive envelopes is phase change materials (PCMs), which can absorb daytime heat and dissipate it at night, hence maintaining indoor temperatures constant. These integrated solutions put the adaptive building envelope as a critical factor in enhancing energy



efficiency and indoor environmental quality for the occupants (**Al-Badri and Abdul Razzaq, 2008**).

2.1 In between Spaces

The in-between space can be defined as the architectural element that delineates spatial boundaries, granting the space its characteristics and making it perceivable through its physical limits, which materialize in elements such as openings, doors, windows, ceilings, and floors. Although space is defined by these physical elements, it remains an independent entity even in their absence, existing as a standalone void.

The in-between space is of various types depending on its role and location in the architectural environment. It may be a separator between zones, for example, doors, openings, and walls that regulate movements between spaces. It may also be a transitional space between two zones, for example, corridors and buffer zones that allow a dynamic interaction between the interior and exterior environments. Hence, the in-between space is an architectural part that denotes the space between more than one section of a building. The in-between space can be internal or external and serves the purpose of both appearance as well as function, and so it constitutes the building blocks of architectural composition. It determines the relationships within the spatial volume of a building and conditions perception by the user toward the built environment (**Mazloom, 2013; Al-Khaqani, 2022**).

2.2 Dynamic Efficiency

Efficiency in buildings is defined as the optimal use of resources and energy to achieve high performance while minimizing environmental impact and waste. Given the growing environmental challenges, building efficiency has become one of the primary objectives in architectural design. Multiple factors, such as façade materials, shading systems, and window distribution, play a crucial role in achieving indoor environmental comfort. With the advancement of architectural and construction technologies, efficiency is no longer a static concept but has become subject to time, operational costs, and maintenance, necessitating the adoption of a new approach known as Dynamic Efficiency (**Rasheed, 2022**). Dynamic efficiency refers to a building's ability to continuously adapt and interact with environmental changes through smart technologies and advanced materials, allowing it to respond instantly to fluctuating climatic conditions. These buildings rely on advanced sensor systems and adaptive materials, making them more sustainable and capable of achieving a balance between energy performance and environmental comfort. This approach represents a strategic shift in building design, transforming structures from static entities into dynamic systems that anticipate future changes, embrace proactive thinking (Thinking Ahead), and efficiently utilize available resources (**Chaix and Morel et Associés, 2013**).

This dynamism contributes to reinforcing the concept of smart buildings as an integrated system that effectively responds to environmental changes, highlighting the role of advanced technology in achieving energy sustainability. This has been shown through futuristic building designs, such as Origami Architecture, which draws its inspiration from adaptive structures with a capacity for response to climate. Dynamic efficiency can thus be seen as the future of green architecture since it includes adaptive design, intelligent technology, and climatic adaptability in order to achieve a holistic and sustainable performance in architecture (**Rasheed, 2022**).



3. MATERIALS AND TECHNOLOGIES

Due to the growing development in the architecture and construction sector, there has been a constantly rising demand to enhance traditional materials to meet the aspects of sustainability and efficiency. Developing these materials is a critical revolution of their physical and chemical properties, thereby increasing thermal insulation, exterior factor resistance, and energy saving. Although they have preserved their original characteristics, these materials have become highly compatible with contemporary building activities in the sense that they can handle the weather patterns of today and facilitate green building activities.

This is known as "Advanced Traditional Materials," or traditional building material that has been subject to continuous scientific and technological progress, thus better positioned to fit the requirements of today's construction. History related to these materials enhances architectural efficiency because it is integrated into static and dynamic smart technologies. These technologies are based on the capability of smart materials to adapt to environmental changes either through internal change or controlled dynamic motion in an attempt to improve environmental and energy efficiency and render buildings more responsive to future demands of green architecture **(Abduljaleel, 2017)**.

Among the most significant material developments is nanomaterials, given that nanotechnology use in the construction industry is a significant evolution connecting material science and engineering, and enhancing innovation while supporting sustainability. Its greatest strengths are in its ability to evolve the properties of traditional materials and make them perform and function more efficiently. Studies indicate that nanomaterials play a huge role in resource conservation and saving energy since they improve the building's thermal envelope performance, providing improved indoor environmental quality and improved thermal comfort. Nanomaterials also include improved properties of mechanical strength, corrosion resistance, and reduced absorption of heat, making them even more efficient for use in building construction. Besides, contemporary nanocoatings contribute to attaining a pleasant indoor climate without mechanization, owing to their self-cleaning, scratch-resistance, and antibacterial properties, enhancing indoor air quality and reducing pollutants. Finally, these technologies help improve the durability of infrastructure, reducing the need for maintenance and rehabilitation, thus lowering resource and energy consumption **(Faal and Kammoona, 2021)**.

3.1 Smart Materials in Construction

Smart materials used in construction are categorized into different types based on their functionality and response to external stimuli. There are two primary types of smart materials:

1. Property-Changing Smart Materials, that alter their chemical, optical, mechanical, electrical, or thermal properties upon exposure to environmental stimuli without external control.
2. Energy-Changing Smart Materials alter the form of energy to provide a desired functional condition **(Al-Ousi, 2015)**.

3.1.1 Property-Changing Smart Materials

Such materials can respond to changing conditions in the environment through a change in their physical or chemical characteristics in response to conditions like temperature, sunlight, or electric currents.



- Photochromic Materials: These materials alter their optical characteristics because of exposure to light, heat, or an electric field, hermochromic, mechanochromic, chemochromic, and electrochromic materials. They also include thermo-liquid crystals, which alter between the solid and liquid states in order to modulate thermal insulation **(Dahlan, 2019)**.
- Rheological Materials: They change their viscosity and response to electric or magnetic fields by adjusting their microstructure **(Dahlan, 2019)**.
- Conductive Smart Materials: Thermal conductors, magnetic conductors, and optical conductors are included in this category, and they have extensive use in sensors and detection systems for the improved functioning of smart buildings **(Dahlan, 2019)**.

3.1.2 Energy-Changing Smart Materials

They function by converting energy from one form to another quite effectively. They are typically composite materials, such as piezoelectric quartz and magnetostrictive iron, and are therefore quite important when it comes to heating, cooling, and self-sustaining energy harvesting applications **(Al-Ousi, 2015)**.

The use of these intelligent materials in modern constructions significantly enhances energy efficiency, environmental comfort, and resource conservation, adhering to current trends of sustainable architecture.

3.2 Advanced Materials

As architecture and buildings developed rapidly, the necessity to upgrade conventional materials to achieve energy efficiency and sustainability has grown stronger. This has resulted in the development of advanced materials that can be divided into advanced opaque materials, advanced transparent materials, and advanced intermediate materials according to their physical and technical characteristics **(Jawad, 2015)**.

- Advanced Opaque Materials: These include concrete, bricks, and wood, which have been enhanced to improve thermal insulation, resist environmental factors, and reduce energy consumption.
- Advanced Transparent Materials: Examples include smart glass and nanoglass, which provide dynamic control over light and heat permeability, improving natural lighting and reducing the need for artificial cooling and heating.
- Advanced Intermediate Materials: These include transparent wood and transparent aluminum, which combine durability and transparency, allowing for uniform illumination while integrating functional and aesthetic performance **(Tariq, 2023)**.

In addition to advanced materials, smart construction technologies have emerged, categorized into static and dynamic construction techniques:

- Static Techniques: These rely on self-adaptive materials such as color-changing glass and smart insulating materials, which adjust to environmental conditions without requiring mechanical components.
- Dynamic Techniques: These involve interactive systems capable of adapting to changing environmental conditions, such as transformable facades and adaptive shading technologies, which enhance environmental comfort and optimize energy consumption **(ElAttar et al., 2022)**.



The integration of advanced materials with smart technologies forms the foundation for dynamic efficiency, enabling the creation of adaptive buildings that minimize environmental impact and comply with sustainable building standards. This paves the way for a smarter, more efficient, and sustainable architectural future (Ali, 2020).

Advanced materials can be categorized as follows in **Table 1**.

Table 1. Classification of Materials Based on Physical Properties and Environmental Interaction

Category	Examples of materials	Properties and uses
Advanced Opaque Materials	Glass fiber-reinforced concrete (GFRC), impermeable cement, aluminum foam, flexible concrete, bamboo-reinforced concrete, nano steel	Enhance thermal and acoustic insulation, reduce energy consumption, and provide high resistance to environmental factors.
Advanced Transparent Materials	Nano glass, fire-resistant glass, electrochromic glass, transparent concrete, transparent wood	Adjust transparency and light transmission in response to environmental conditions, improve natural lighting, and enhance energy efficiency.
Advanced Intermediate Materials	Aerogel, hydrogel, shape-memory alloys, smart polymers, bio-inspired materials (e.g., chameleon skin-like materials)	Interact with the surrounding environment, adapt to environmental changes, and improve dynamic building performance.

3.3 Responsive Technologies

Responsive environmental technologies represent an innovative approach in architecture and design aimed at enhancing the relationship between buildings and their natural environment. They are based on the principle of intelligent reaction to changes in environmental parameters, i.e., temperature, humidity, light, and ventilation. They assist in optimizing energy efficiency, indoor air quality, and overall thermal and environmental comfort for building occupants. They are founded upon the integration of intelligent technologies, property-changing materials, and adaptive structures. Their primary aim is to animate indoor spaces by targeting the building envelope, floor, ceiling, and walls to produce a comfortable indoor climate. Adaptive shading techniques are effective solutions for enhancing energy efficiency and indoor thermal comfort. This section highlights Pho'lliage, inspired by the movement of plant leaves using smart materials responsive to solar radiation, and Transformable Structure Technology, which employs mechanical components to modify building shape and function based on environmental or interior needs. These strategies represent advancements in environmentally responsive smart envelope design.

3.3.1 Adaptive Shading Techniques - Pho'lliage

This shape is biomimetically taken from flowers that execute opening and closing movements in a bid to provide responsive facades with dynamic performance under variations in the intensity of solar radiation. Here, one seeks to develop facade elements that can interact with environmental variation through the use of smart materials that could mimic the optical and thermal response of vegetation (Jarjat et al., 2020).

This is referred to as Pho'lliage, the concept of how plants enable control of light and heat transfer and dynamic and efficient shading depending on space conditions. The process has been utilized as a method to maximize thermal comfort and minimize energy consumption.

Fig. 1, Concepts have been borrowed from Nyctinastic movements through the integration

of thermal actuation with shape memory properties and curved geometry (DeLos et al., 2023) and even with external-stimulus-responsive bimetallic composite alloys.

One of the distinguishing characteristics of this system is that it can produce renewable energy using photovoltaic cells incorporated into the shading system, thus differentiating itself from other shading systems. The Pho'lliage system can reduce heating energy demand during winter by providing a natural dynamic light barrier, while in summer, the embedded photovoltaic cells prevent excessive heat gain by converting surplus solar energy into usable green electricity (Jarjat et al., 2020).

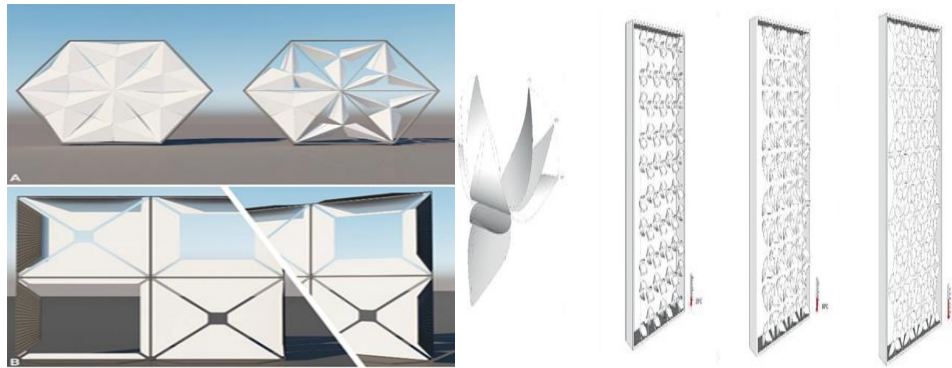


Figure 1. An adaptive facade system that mimics the floral movements

3.3.2 Transformable Structure Technology

Transformable structures refer to building systems that incorporate mechanical components, allowing the modification of a building's shape and function based on environmental needs or interior usage requirements. These technologies are not merely barriers protecting buildings from external factors but play a crucial role in defining both the architectural and functional character of a structure (Akgün, 2021).

This technology enables the transformation of a building's shape from one state to another. The morphological transformation process occurs through the following mechanisms:

1. Transfiguration of Outer Structure – Structural transformations occur along specific pathways, such as wall modifications or roof adjustments.
2. Transformation of Surrounding Architectural Elements – This involves modifications to interior architectural components within a space.
3. Rotational Transformations **Fig. 2.** These reconfigure external spaces and alter building orientations to enhance indoor comfort and environmental adaptability (Gnedina et al., 2019).



Figure 2 Sliding house with horizontal transformation



4. TECHNOLOGICAL ACTIVATION STRATEGIES

The method adopted follows the integrated building approach, one of the main theories of contemporary architecture, to create comfortable and sustainable indoor environments. It is interested in energy conservation through the intelligent coupling of the building with the outside environment by using intelligent environmental design solutions. These include the utilization of solar power, thermal insulation, natural ventilation, and the smart selection of innovative technology and materials as an attempt to decrease reliance on conventional energy sources. The strategy is realized through the design of Net Zero Energy Buildings (ZEBs) utilizing green building materials and renewable energy systems to balance energy consumption and production. Not only do the buildings attain thermal performance, but visual and acoustic comfort as well, providing the best conditions to occupants. Against the background of rapid advancements in the architecture field, the topic of Negative Energy Buildings (NEBs) has emerged. Rather than just being net-zero energy, these buildings generate surplus renewable energy that can be sold or fed to nearby buildings, thus being harbingers of the smart and sustainable architecture of the future. The overall goals are achieved through an integrated smart design that enhances interior spaces by leveraging advanced technologies and innovative, energy-efficient materials, hence creating a healthy and sustainable lifestyle **(Singh et al., 2021)**

Smart envelopes are optimal for achieving environmental performance and thermal comfort in buildings. Smart envelopes regulate the solar radiation insulation and enhance the natural ventilation to reduce the mechanical ventilation level necessary and conserve energy.

Solar panels can be incorporated into the envelope of buildings to generate electricity and minimize reliance on traditional energy sources. The envelopes consist of intelligent materials like adaptive glass and responsive heat materials that are capable of changing transparency and insulation capabilities towards ambient directions and user requirements. This generates multi-functional dynamic facades that dynamically respond to their environments **(Rasheed, 2022)**.

The concept of smart buildings is gaining more and more attention, with the smart envelope being the forerunner in achieving environmental and energy efficiency. The smart envelope approaches are founded on new materials and technologies designed to optimize energy performance, reduce consumption, and enhance thermal and visual comfort.

This is achieved by means of smart building management utilizing advanced control systems, artificial intelligence (AI), and the Internet of Things (IoT). The technologies enable data analysis and reaction to environmental change with increased flexibility in interaction between buildings and the environment **(Akgün, 2021)**. Some systems and mechanisms can be utilized to design a Smart Envelope building that is actively involved and interacts with its environment, as given in **Table 2**.

Table 2. Smart Envelope Strategies

Strategy	Objective	Technologies Used
Environmentally Adaptive Envelopes	Improve thermal insulation, ventilation, and reduce energy consumption	Smart materials, adaptive glass, and natural adaptive ventilation
Interactive Internet (IoT)	Enable devices to interact intelligently and adapt to environmental conditions	Smart device networks, MQTT, and COAP protocols
Biomimicry	Utilize nature-inspired mechanisms to enhance sustainability	Shape memory alloys, kinetic facades



4.1. Employing Environmentally Adaptive Envelopes

Environmentally Adaptive Envelopes, or Climate-Adaptive Facades, are Adaptive envelopes or facades of a building that can change their properties or shape as a reaction to environmental conditions around it in order to optimize building performance. In contrast to the traditional passive facades, adaptive envelopes integrate active and passive technologies in a way that they can adapt to short- and long-term climate changes under interior and exterior conditions (**Ergün and Aykal, 2022**). They are capable of adjusting light penetration, ventilation, and insulation against heat flexibly according to the strength of solar radiation, temperature, and wind speed, hence automatically attaining optimal indoor conditions for occupants. In general, this structure is to create facades that have a responsive connection with the environment, improved performance efficiency, and adaptability (**Kaarwan, 2023**). Adaptive envelopes are one of the most powerful ways of promoting sustainability in new buildings. They regulate heat and light transfer within the outer envelope and consume far less energy compared to traditional buildings. For example, the facades may regulate solar heat gain, hence minimizing the use of artificial cooling, which in warmer climates, where cooling accounts for a majority percentage of energy use, is paramount. As a result, carbon emissions are lowered by reducing reliance on air conditioning and artificial lighting.

Additionally, the intelligent control provided by this strategy optimizes indoor comfort factors, such as temperature regulation and glare reduction, which enhance occupant well-being and productivity by ensuring consistent natural lighting and moderate indoor temperatures. In summary, adaptive envelope strategies promote sustainability by saving energy and improving the living and working environment inside buildings (**Sridhar, 2023**).

4.2. Employing the Internet of Things (IoT)

The Internet of Things (IoT) is a modern technology that helps transform buildings into smart entities that automatically respond to their surrounding environment. This technology works by connecting various systems within the building to the internet, allowing them to be controlled remotely or activated based on data sensing (**Zarzycki, 2018**).

- Smart sensors are employed to measure environmental data such as temperature, humidity levels, air quality, lighting, and even the movement of individuals within different spaces (**Zarzycki, 2018**).
- This data is processed by artificial intelligence (AI) systems for real-time decision-making, such as turning heating and cooling devices on or off or adjusting lighting levels according to actual needs, thus achieving energy efficiency (**Zarzycki, 2018**).
- A few of the protocols used in this technology include MQTT and COAP, which are communication protocols that enable fast communication between sensors and real-time analysis of data (**Zarzycki, 2018**).
- Practical applications vary from managing smart lighting systems, ventilation, heating, and air conditioning (HVAC) systems, energy consumption management, and even smart security by using cameras and sensors to detect threats (**Zarzycki, 2018**).



4.3. Employing Biomimicry

Biomimicry relies on taking inspiration from nature to achieve functional efficiency and environmental sustainability in architecture. It has birthed sophisticated technologies, such as dynamic facades, that minimize solar radiation entering buildings through adaptive shading devices. These systems rely on intelligent materials that adapt to environmental states without the injection of additional operating energy, to the benefit of building energy efficiency as well as indoor thermal comfort (**Abdeljalil, 2016**).

- Biomimicry is a design philosophy that draws lessons and mimics the techniques and processes utilized by natural species in order to thrive in their environment. The grand design challenges of prime concern in philosophy are to solve sustainably and harmoniously with all living forms. There exist various types of biomimicry in architecture, where it can appear as a strategy of building, a function of a building, form copying, or as natural analog materials (**Novatr, 2023**). Therefore, the foundation of this strategy is to mimic living organisms or natural processes to create energy-efficient buildings. Below are some examples of biomimicry in architecture:
- Facade design inspired by reptile skin: Surface patterns are used that reduce heat absorption and help cool the building (**Ergün and Aykal, 2022**).
- Ventilation system inspired by termite nests: This concept involves designing buildings with natural ventilation systems that do not require air conditioning, directing air in a way that reduces internal temperatures (**Ergün and Aykal, 2022**).
- Insect eye-inspired intelligent glass: This relies on techniques that effectively reflect heat and light, thereby reducing the impact of direct sunlight inside the building (**Ergün and Aykal, 2022**).

These three strategies contribute to a more comfortable indoor climate, as well as to more energy-efficient and sustainable buildings. Environmentally responsive envelopes maximize building performance, IoT increases operational intelligence, and biomimicry provides nature-inspired solutions. Together, these elements are the path to smarter, more sustainable buildings that interact with their environment.

5. ANALYZING SMART STRATEGIES, THERMAL COMFORT, AND NATURAL LIGHTING IN BUILDING ENVELOPES: PRACTICAL FRAMEWORK

To identify the performance of natural light, thermal comfort, and smart strategies in building envelopes, this study presents a series of global case studies that demonstrate innovative applications in smart facade design. The studies were selected based on their architectural innovativeness, smart system compatibility, and efficiency in optimizing indoor environmental quality. These buildings rely on advanced technologies, including dynamic thermal control systems, smart glazing, adaptive natural ventilation, and sustainable natural lighting solutions, all contributing to balancing energy efficiency and user comfort in alignment with modern sustainability standards.

5.1 Thyssenkrupp Q1 Building

1. Employing Environmentally Adaptive Envelopes: This building implemented smart building strategies by utilizing environmentally adaptive envelopes, where smart glass was employed in the facades to enhance natural lighting and reduce heat gain. Self-responsive thermal materials were also applied to ensure the building's interaction with

climatic changes. Additionally, adaptive natural ventilation systems were integrated to improve thermal comfort and reduce the need for mechanical ventilation. The strategy achieved a rating of 4.3333 out of 5 (**Arch20, 2023**), see **Fig. 3**.

2. Employing the Internet of Things (IoT): The building relies on an Intelligent Building Management System (BAS), which monitors energy consumption and adjusts system operations automatically. It includes smart sensors that monitor temperature, lighting, and humidity, enabling automatic control to achieve higher energy efficiency. Additionally, predictive maintenance was implemented to reduce unexpected failures and optimize overall building performance, achieving a rating of 4.4444 out of 5. (**Wildeboer, 2010**)
3. Employing Biomimicry: The concepts of self-ventilation and self-conditioning were integrated, which aids in achieving a comfortable indoor environment while minimizing reliance on artificial energy. Nature-inspired ventilated facades were used to ensure airflow and minimize heat gain, and smart materials were utilized to enhance thermal and acoustic insulation, absorbing noise and reducing heat loss. The strategy achieved a rating of 4.5556 out of 5 (**Grimm, 2023**).

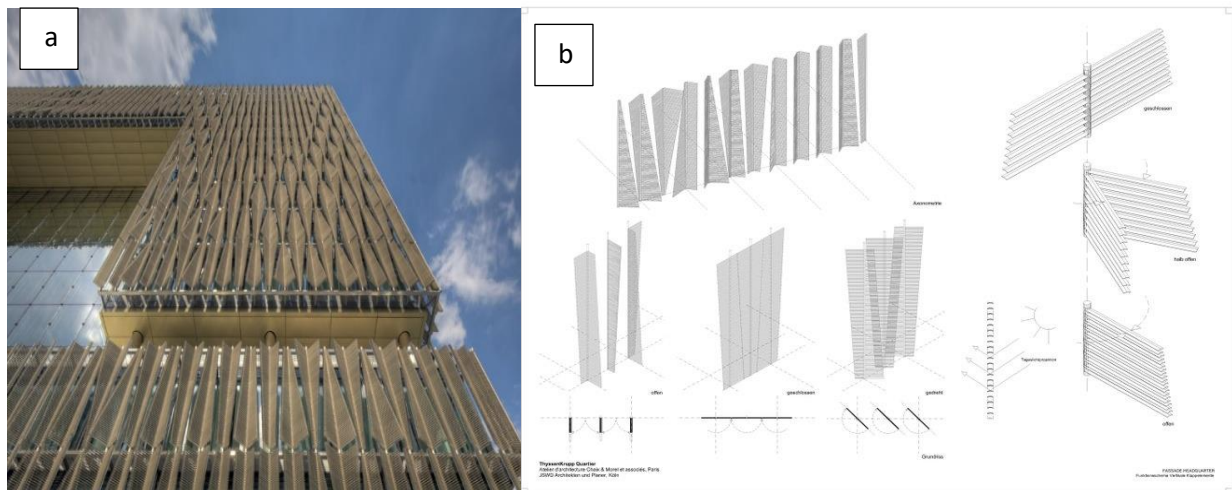


Figure 3. a) Thyssenkrupp Q1 Building, b) Environmentally Adaptive Envelopes for Building Envelope

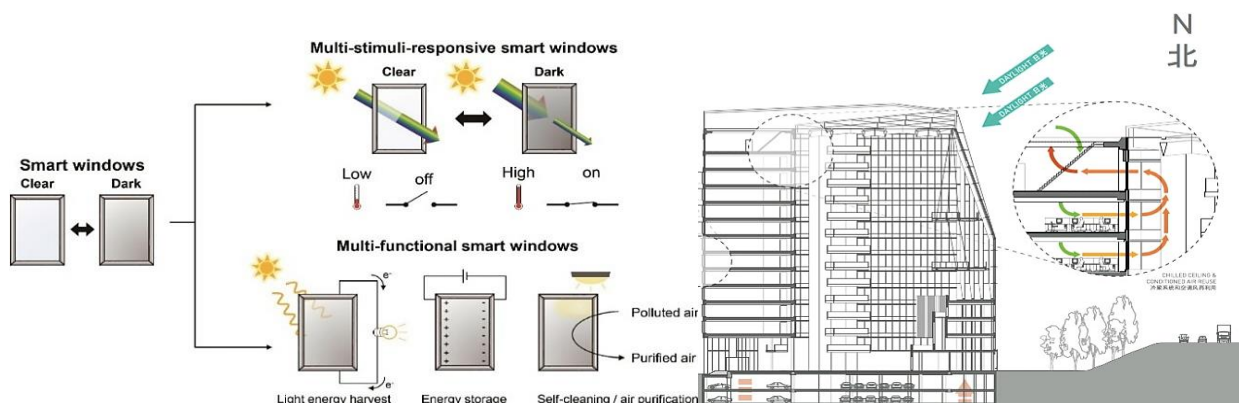


Figure 4. Use of Smart Glass in the Building Facade

5.2 The Edge Building

1. Using Environmentally Adaptive Envelopes: Smart glass responding to heat and light has been used to provide thermal comfort and conserve energy. Adaptive kinetic facades have also been included in order to reduce solar radiation while natural lighting remains intact. Smart thermal materials were also used, which can control heat absorption according to the external conditions. This method received a 4.3333 out of 5 (**Architect-US, 2017**), see **Fig.4**
2. Making use of the Internet of Things (IoT): The building incorporates an Intelligent Building Management System (BAS) that controls lighting, heating, and cooling via real-time information. It also uses smart sensors to control lighting and heating automatically depending on user presence. Big data analysis is also used to ascertain consumption patterns and maximize operational efficiency. This strategy was given a score of 4.1111 out of 5 (**Rob and Daniela, 2023**).
3. Applying Biomimicry: The ventilation system was designed to take advantage of natural air flow to reduce the use of mechanical air conditioning. The building also employs materials that mimic the thermal insulation and climate-adaptation abilities of living organisms, which assisted in achieving this strategy, earning a score of 4.4444 out of 5 (**ArchDaily, 2016**).

5.3 Bosco Vertical Forest (Vertical Forest)

1. Employing Environmentally Adaptive Envelopes: This building relies on environmentally adaptive envelopes by incorporating green facades, which play a key role in reducing temperatures and improving indoor and outdoor air quality. Additionally, environmentally adaptive plants contribute to reducing energy consumption and enhancing thermal insulation, achieving this strategy with a rating of 3.6667 out of 5 (**ArchDaily, 2015**), see **Fig.5**
2. Employing the Internet of Things (IoT): The use of integrated BAS systems was not explicitly mentioned, although there were some basic applications of smart systems in water management and irrigation. Therefore, this indicator was not clearly achieved.
3. Employing Biomimicry: The design of the building was inspired by the environmental integration between plants and architecture, with the strategy focusing on achieving thermal comfort through natural elements such as plants and organic shading. This approach resulted in a rating of 4.7778 out of 5 for this strategy (**ArchDaily, 2015**).



Figure 5. The impact of garden design on the envelope

4.4 Quadrant House

1. Employing Environmentally Adaptive Envelopes: This building relies on environmentally adaptive envelopes by using smart glass and thermal materials that assist in controlling temperatures, in addition to employing a kinetic facade system to regulate light and heat. However, this indicator did not achieve a high rating, with a score of 3.1111 out of 5 (**Designboom, 2019**), see **Fig. 6**.
2. Employing the Internet of Things (IoT): The building is equipped with sensors that help control temperature, air conditioning, and ventilation. However, it did not achieve a very high rating in this area, with a score of 3.4444 out of 5 (**Designboom, 2019**).
3. Employing Biomimicry: Natural systems were utilized for ventilation and lighting, but it was not one of the prominent buildings in this field, and the achievement of this indicator was not mentioned.

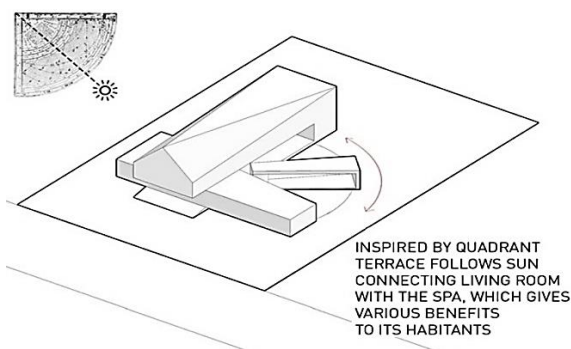


Figure 6. Kinetic facade system in the quadrant house

5.5 The Shed Building

1. Employing Environmentally Adaptive Envelopes: This building relies on environmentally adaptive envelopes with facades that can adjust to climatic conditions. However, its achievement of this indicator was limited, with a score of 3.0000 out of 5 (**Scofidio, 2019**), see **Fig. 7**.
2. Employing the Internet of Things (IoT): Big data analysis and predictive maintenance were utilized, contributing to a score of 4.0000 out of 5 for this indicator (**Scofidio, 2019**).
3. Employing Biomimicry: No clear details were mentioned regarding the application of this strategy in the building, and therefore, this indicator was not achieved.

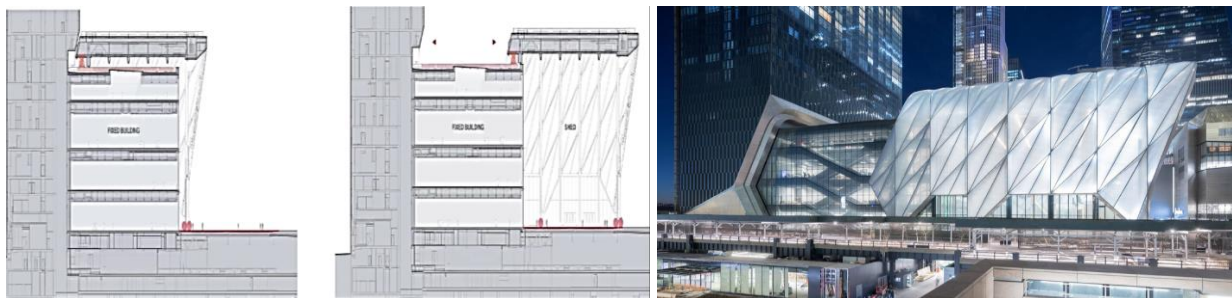


Figure 7. Adaptive Moving Structure as an Environmental Envelope

5.6 Mukaab Building

1. Employing Environmentally Adaptive Envelopes: This building relies on environmentally adaptive envelopes through the use of smart glass systems and dynamic shading, achieving a rating of 4.0000 out of 5 for this strategy (**Frank, 2024**), see **Fig.8**
2. Employing the Internet of Things (IoT): Big data analysis techniques and smart sensors were implemented to monitor the building's performance, resulting in a rating of 4.2222 out of 5 for this strategy (**Frank, 2024**).
3. Employing Biomimicry: No clear applications of this strategy were mentioned in the building.

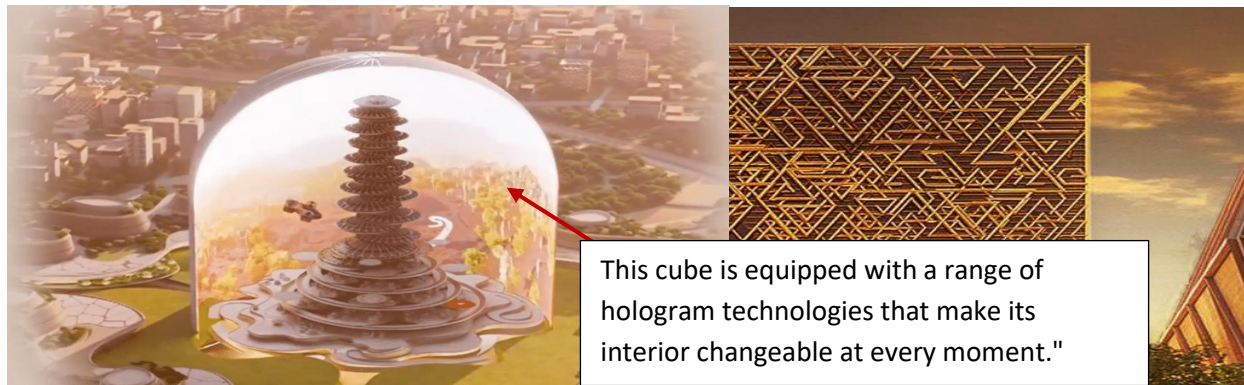


Figure 8. Use of Hologram Technologies Inside the Building

5.7 Turn to The Future

1. Employing Environmentally Adaptive Envelopes: This building relies on environmentally adaptive envelopes through the use of smart glass and adaptive thermal materials, in addition to utilizing technologies that allow each floor to move independently to provide an adaptive living environment. This strategy achieved a rating of 3.5556 out of 5 (**Kuo, 2015**), see **Fig. 9**.
2. Employing the Internet of Things (IoT): Sensors and smart systems were implemented to monitor and improve the building's environmental performance, with the building responding to sunlight, wind, and other factors to provide the necessary movement for each floor. This strategy achieved a rating of 3.6667 out of 5 (**Kuo, 2015**).
3. Employing Biomimicry: This technique was not widely used in the building. While some parts of the building are inspired by nature, they were not specifically identified.



Figure 9. Application of environmentally adaptive technologies

5.8 Santiago Bernabéu Stadium

1. Employing Environmentally Adaptive Envelopes: This building relies on environmentally adaptive envelopes by utilizing kinetic facades that can open and close, achieving a rating of 3.2222 out of 5 for this strategy (**ArchDaily, 2023**), see **Fig. 10**.
2. Internet of Things (IoT): Smart sensors were employed to control lighting and ventilation, but no clear details were provided regarding the achievement of this indicator (**ArchDaily, 2023**).
3. Employing Biomimicry: No details were provided regarding the application of this strategy in the building, and therefore, this indicator was not achieved.

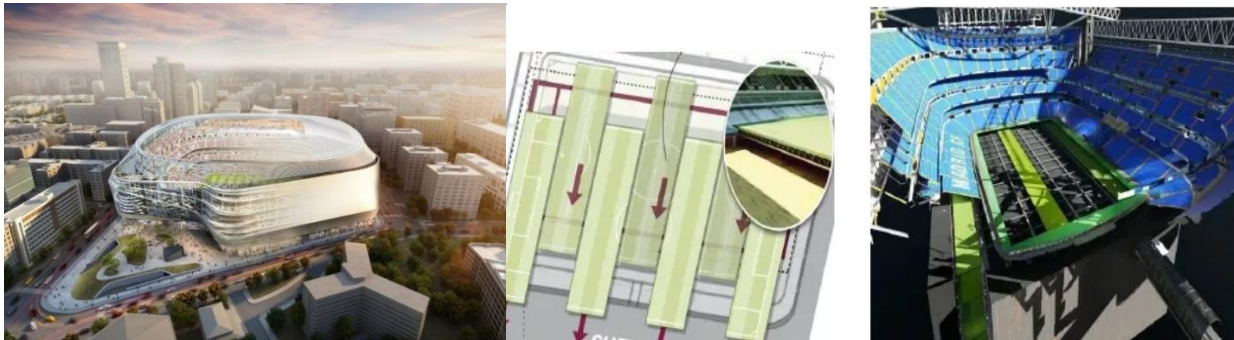


Figure 10. Adaptive Technologies in the Building

5.9 MORPHotel – Gianluca Santosusso

1. Application of Environmentally Responsive Envelopes: Dynamic in relation to variations in environmental conditions has been the basis of the project, with a building that can adapt to climatic change and the seas it encounters. Thermally responsive materials have been used in indoor temperature control and environmental sustainability, as well as other natural ventilation systems that decelerate the pace of energy consumption. This approach reached a 4.2222 out of 5 (**Santosuosso, 2016**), see **Fig. 11**.
2. Internet of Things (IoT) adoption: The building features the latest in smart technologies that constantly monitor and sense climatic and environmental information and modify building performance accordingly. Energy, water level, and ventilation are constantly monitored using advanced sensors as part of the quest for maximum efficiency of operations and long-term sustainability. It scored 4.1111 out of 5 (**Santosuosso, 2016**).

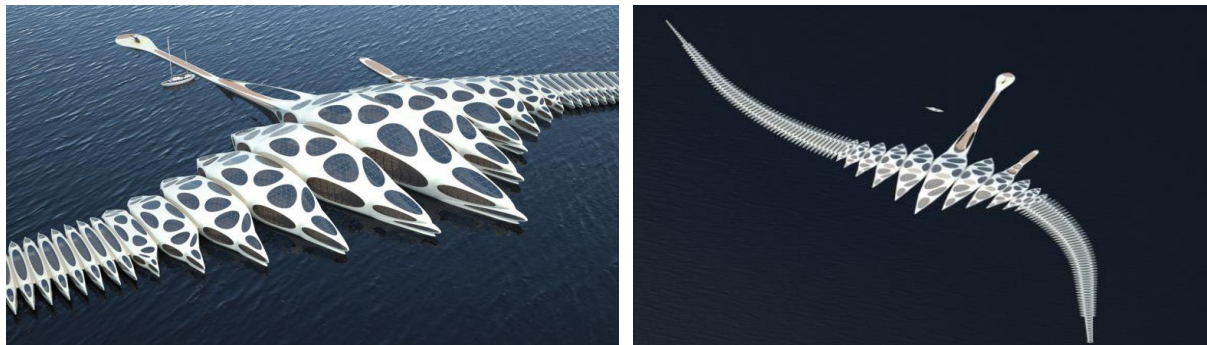


Figure 11. MORPHotel – Gianluca Santosusso



3. Using Biomimicry: The building's design has been modeled on some principles from sea animals and living organisms, being sensitive to the surroundings. It employs strategies that mimic nature in how air and heat flow are managed, achieving thermal balance within the interior spaces. The structural composition is inspired by the shapes of marine creatures, enabling them to adapt to ocean currents and changing weather conditions. This strategy achieved a rating of 4.5556 out of 5 (**Santosuosso, 2016**).

6. APPLYING FOR THEORETICAL FRAMEWORK INDICATORS TO GLOBAL BUILDING

In this study, the impact of smart building strategies on improving thermal, visual, and acoustic comfort in multifunctional buildings was analyzed through a set of design indicators. These indicators were studied and statistically analyzed using SPSS software, where the data were interpreted according to a five-level rating scale, as follows:

- 1) Met (●): Implementation of advanced modern technology
- 2) Partially Met (●): Implementation of advanced technology
- 3) Partially Met (●): Implementation of advanced traditional technology
- 4) Partially Met (●): Implementation of traditional technology
- 5) Partially Met (●): Not achieved

This statistical analysis (**Table 3**) contributes to providing a precise understanding based on reliable data, enabling the evaluation of how well various design indicators are achieved. It also helps measure the efficiency of the designs used and identifies areas that require development to improve acoustic privacy and enhance indoor environmental quality in buildings.

- S1: Thyssenkrupp Q1
- S2: The Edge Building
- S3: Bosco Vertical Forest
- S4: Quadrant House
- S5: The Shed
- S6: Mukaab Building
- S7: Turn to The Future
- S8: Santisgo Bernabeau Stadium
- S9: MORPHotel – Gianluca Santosusso

Table 3. The testing of selected global buildings based on the theoretical framework indicators.

Paragraphs			Project								
Planning strategies			S1	S2	S3	S4	S5	S6	S7	S8	S9
Smart Envelope Strategies	Environmentally	Smart Glass	●	●	●	●	●	●	●	●	●
		Kinetic Facades	●	●	●	●	●	●	●	●	●
		Thermal Response Materials	●	●	●	●	●	●	●	●	●
		Adaptive Natural Ventilation Systems	●	●	●	●	●	●	●	●	●
		Use of Smart Materials	●	●	●	●	●	●	●	●	●
	Internet of Things (IoT)	Integrated Building Management Systems	●	●	●	●	●	●	●	●	●
		Provision of Smart Sensors	●	●	●	●	●	●	●	●	●
		Big Data Analysis	●	●	●	●	●	●	●	●	●
		predictive maintenance	●	●	●	●	●	●	●	●	●
		Smart Security Systems	●	●	●	●	●	●	●	●	●

	Biomimicry	Energy Consumption Management									
		Natural Ventilation and Self-conditioning									
		Ventilated Facades									
		Thermal and Acoustic Insulation									

Each of these colored points represents one of the criteria for the implementation of technologies in the selected buildings, which have been numbered as S1, S2, S3, and so on for each strategy.

7. RESULTS AND DISCUSSION

7.1 Environmentally Adaptive Facades

The thermal and visual comfort criteria were assessed in nine different buildings from a functional perspective, aiming to analyze the efficiency of smart building strategies and their impact on the quality of indoor environments and user behavior. An analytical methodology based on statistical measurement was used to determine the extent to which these criteria were achieved, contributing to a better understanding of the relationship between smart design, comfort levels, and operational efficiency.

The discussion presents the results of these measurements, focusing on the differences between the buildings studied and evaluating the success of the applied solutions in improving indoor environmental conditions and enhancing the user experience.

Smart glass met efficiency criteria in 44.4% of cases, partially met in 33.3%, and relied on traditional methods in 22.2%, showing progress but needing further integration **Fig. 12 a**.

Kinetic facades fully met criteria in 33.3% of cases, partially met in 44.4%, and were not applied in 11.1%, highlighting adoption inconsistencies and the need for more investment **Fig. 12 b**.

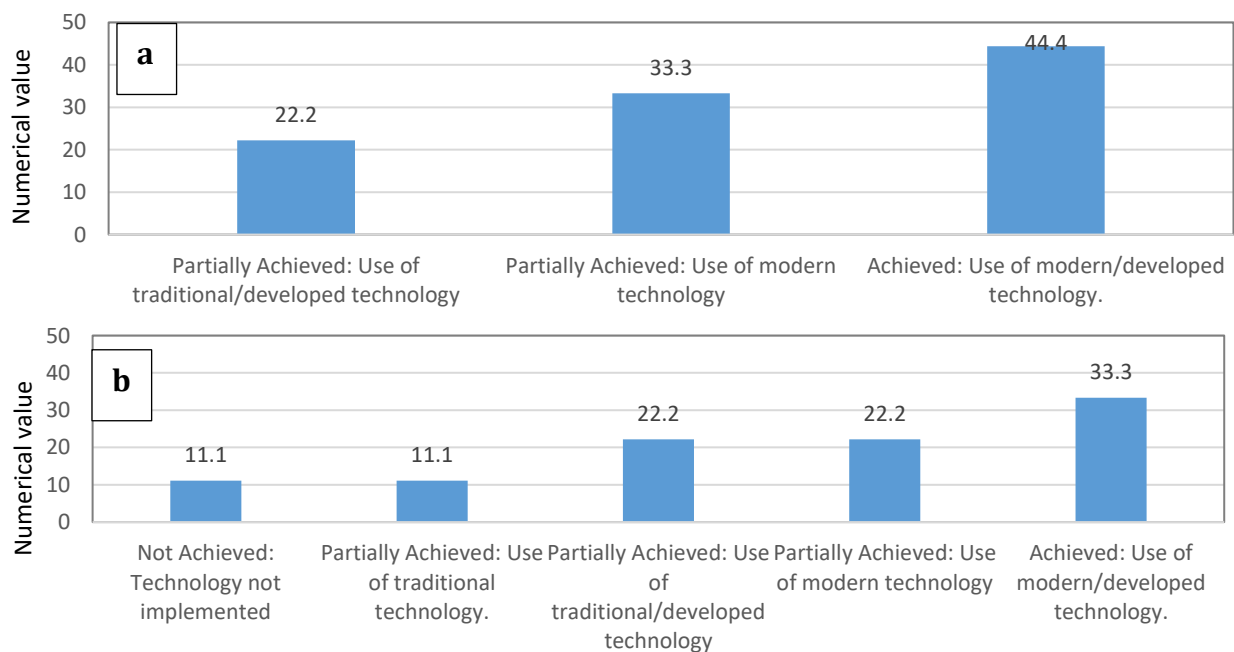


Figure 12 (a) Smart Building Strategies - Implementing Environmentally Adaptive Envelopes - Use of Smart Glass. (b) Smart Building Strategies - Employing Environmentally Adaptive Envelopes - Kinetic Facades

Adaptive natural ventilation systems achieved full efficiency in 44.4% of cases, partial efficiency in 44.4%, and relied on traditional methods in 11.1%, highlighting their effectiveness but the need for further integration. **Fig. 13 a**. Thermal responsive materials fully met criteria in 55.6% of cases, while 44.4% partially met them, showing progress in thermal regulation with room for optimization. **Fig. 13b**.

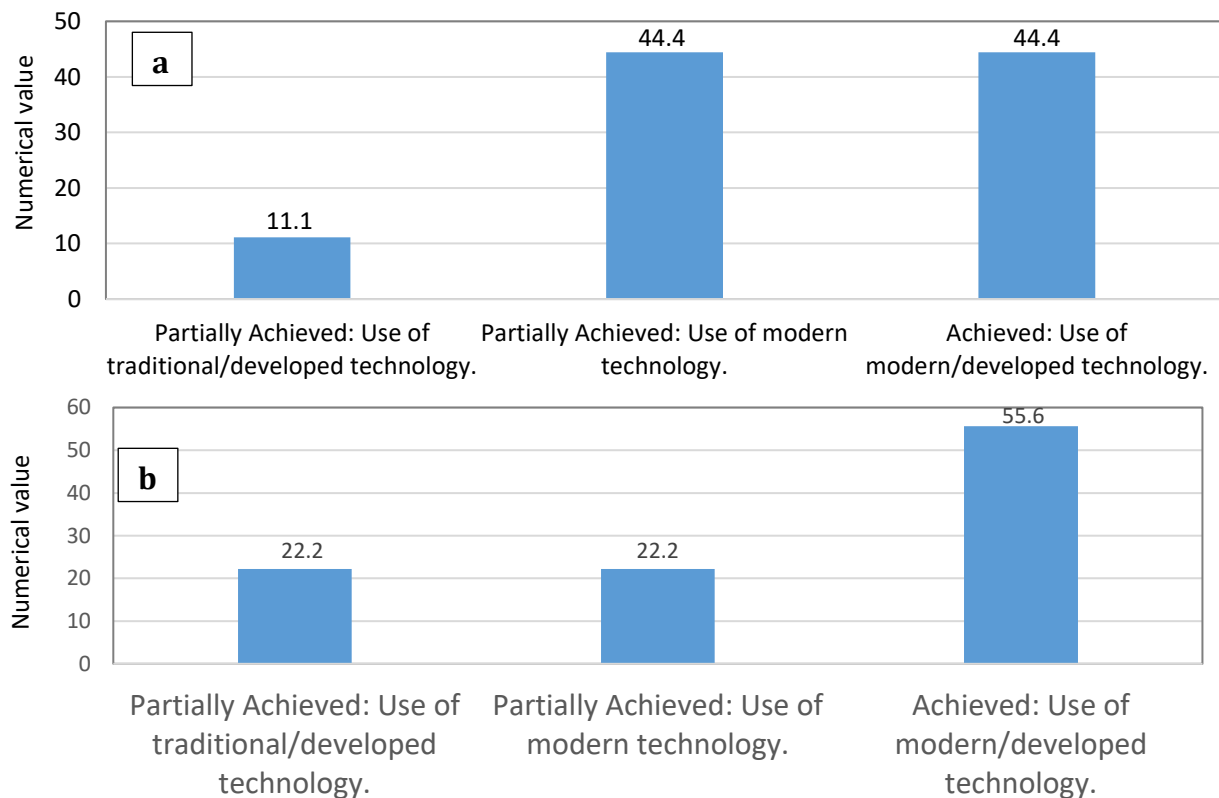


Figure 13 (a) Smart Building Strategies - Employing Environmentally Adaptive Envelopes - Kinetic Facades, **(b)** Smart Building Strategies - Employing Environmentally Adaptive Envelopes - Use of Thermally Responsive Materials

7.2 Internet of Things

Integrated building management systems met criteria in 66.7% of cases, while 33.3% partially applied them, **Fig. 14a** showing high efficiency but requiring further enhancement for full adoption. Smart sensors met criteria in 55.6% of cases, with 44.4% partially adopting them, **Fig. 14 b** indicating strong progress but a need for deeper integration to maximize efficiency and sustainability.

Big data analysis met criteria in 44.4% of cases, while 55.6% partially applied it, **Fig. 15a** showing progress but requiring stronger integration for optimal efficiency and sustainability. Predictive maintenance met criteria in 33.3% of cases, with 66.7% partially adopting it, indicating progress **Fig. 15b** but highlighting the need for better technological integration and infrastructure support. Smart security systems fully met criteria in 44.4% of cases, while 55.6% partially met them, showing progress **Fig. 16a** but requiring further integration for safer and more responsive smart buildings. Smart energy management met criteria in 33.3% of cases, with 55.6% partially adopting it and 11.1% relying on traditional methods, **Fig. 16b** emphasizing its role in efficiency and the need for better integration.

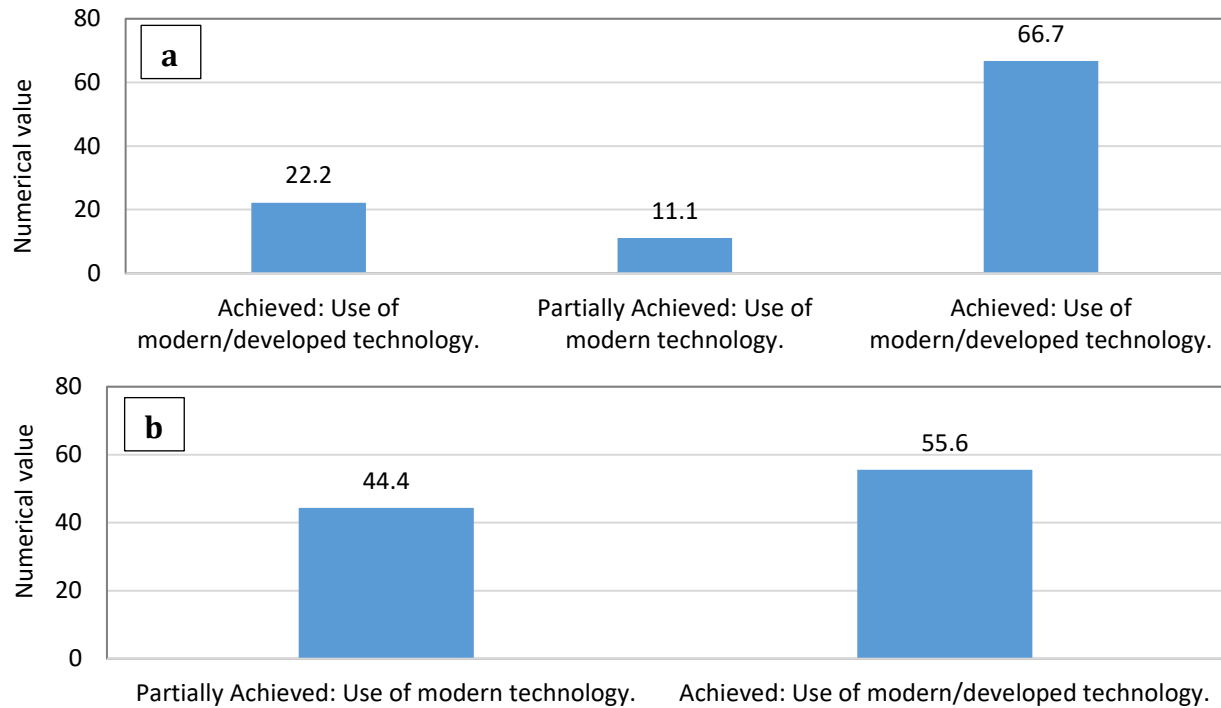


Figure 14 (a) Smart Building Strategies - Employing the Internet of Things - Use of Integrated Building Management Systems **(b)** Smart Building Strategies - Employing the Internet of Things - Provision of Smart Sensors

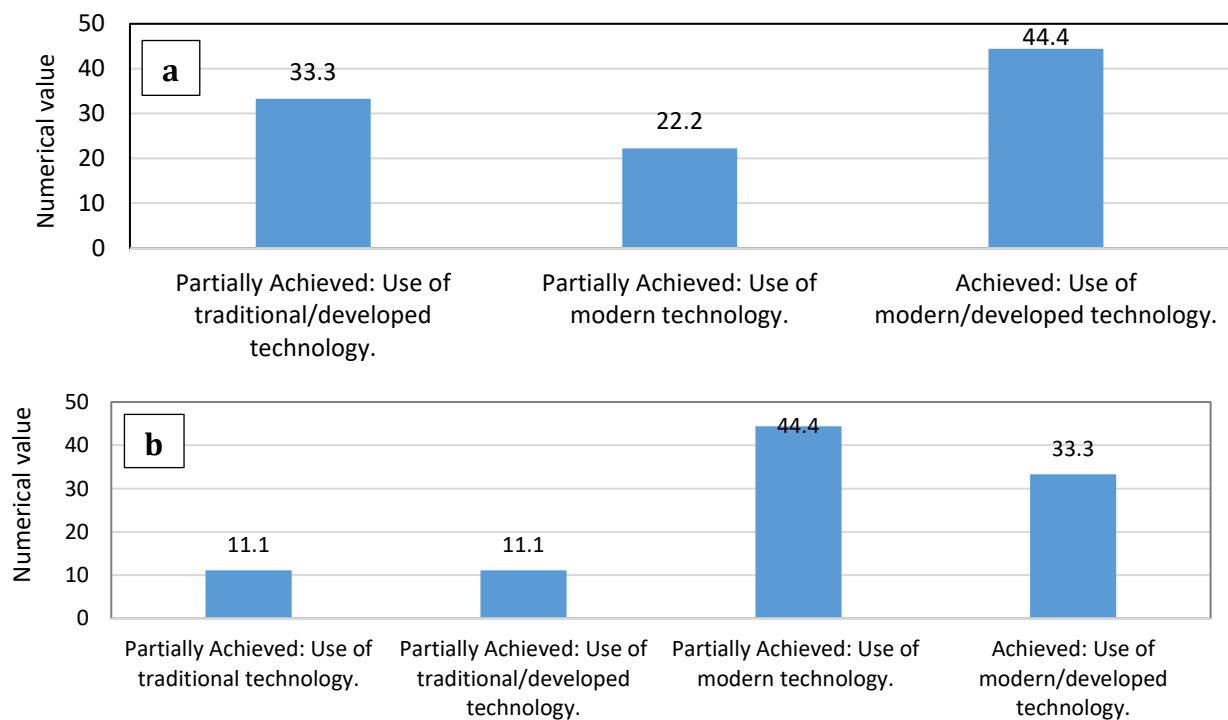


Figure 15 (a) Smart Building Strategies - Employing the Internet of Things - Big Data Analysis **(b)** Smart Building Strategies - Employing the Internet of Things - Predictive Maintenance

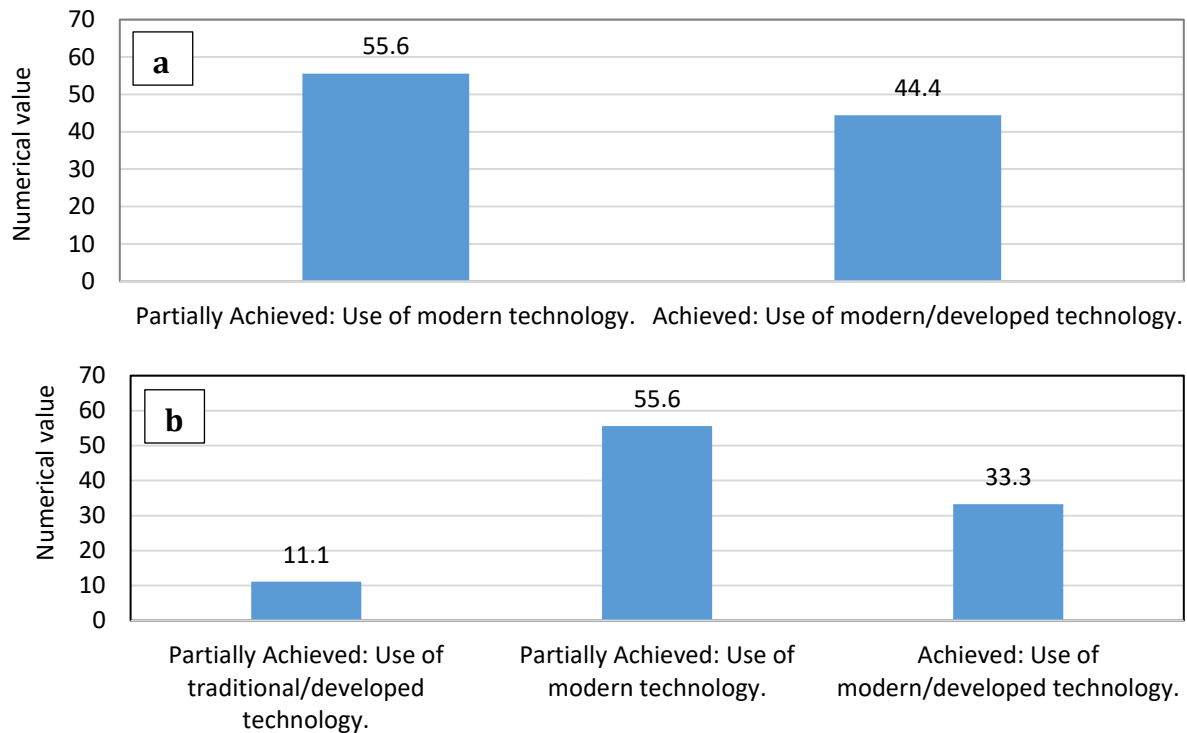


Figure 16. (a) Smart Building Strategies - Employing the Internet of Things - Use of Smart Security Systems **(b)** Smart Building Strategies - Employing the Internet of Things - Smart Energy Management

7.3 Biomimicry

Energy consumption management via biomimicry met criteria in 66.7% of cases, while 33.3% partially adopted it, **Fig. 17a** showing strong progress but requiring further integration for broader sustainability. Natural ventilation and self-conditioning via biomimicry met criteria in 55.6% cases, with 33.3% partially adopting it and 11.1% relying on traditional methods, **Fig. 17b** highlighting progress but needing full integration for optimal efficiency.

Ventilated facades via biomimicry remain underutilized, with 44.4% not implementing them, 33.3% partially adopting advanced traditional methods, and only 11.1% fully applying modern technologies. **Fig. 18a** greater investment in research and development is needed to enhance adoption and maximize sustainability benefits. The findings of the study showed an evident disparity in the level of implementation and performance of the three adopted smart strategies for the building envelope activation to achieve environmental comfort in the selected case studies **Table 4**. It was found that the first strategy (Environmentally Adaptive Envelopes) proved the most successful in achieving thermal comfort needs. This is because it is capable of controlling the management of solar radiation, ventilation, and insulation—particularly through smart glazing, adaptive facades, and advanced thermal materials. Its effectiveness was proven in structures such as The Edge and Al Bahr Towers, wherein it contributed extensively to energy reduction and indoor climate stability. Conversely, the second strategy (IoT Integration Systems) helped to improve the efficiency of building operations and internal environmental conditions intelligent control through smart building management systems and adaptive sensors.

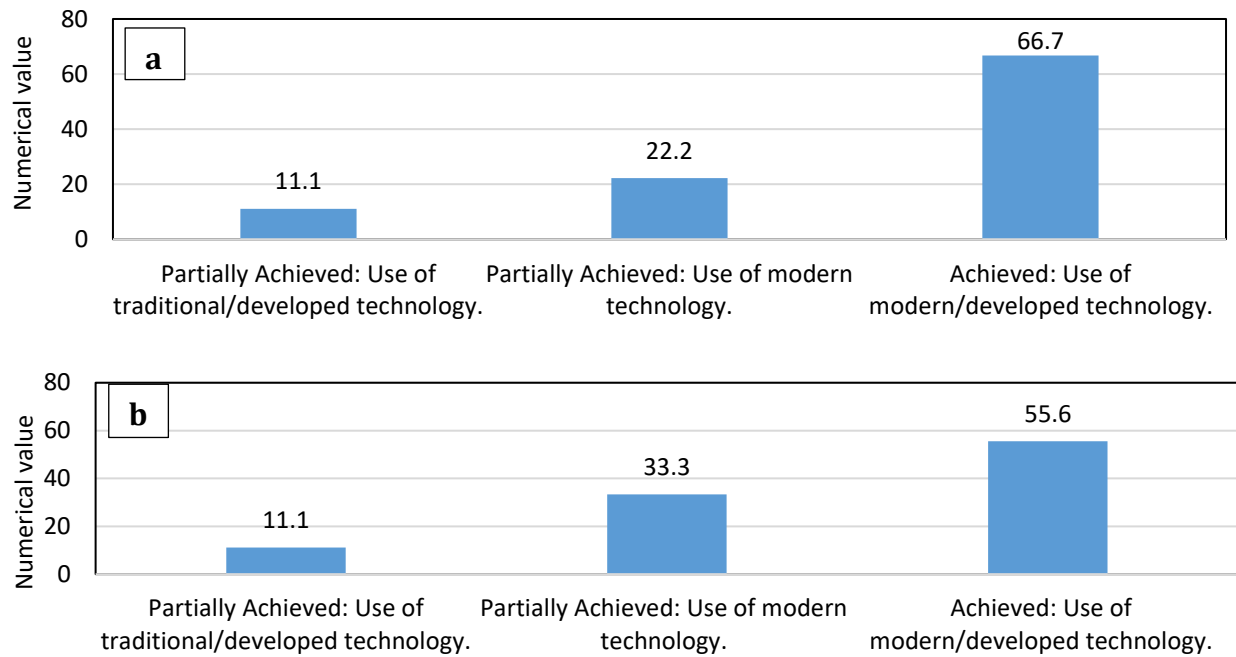


Figure 17. (a) Smart Building Strategies - Employing Biomimicry - Energy Consumption Management **(b)** Smart Building Strategies - Employing Biomimicry - Natural Ventilation and Self-Conditioning.

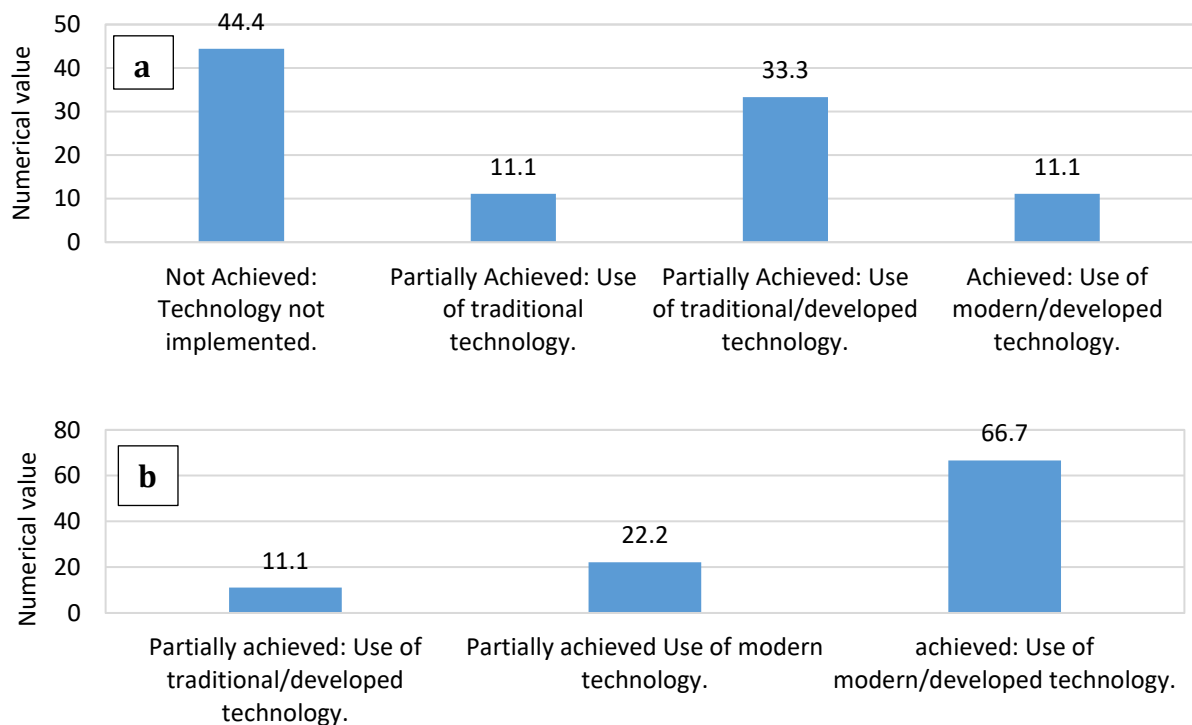


Figure 18. (a) Smart Building Strategies - Employing Biomimicry - Ventilated Facades **(b)** Smart Building Strategies - Employing Biomimicry - Providing Thermal and Acoustic Insulation



Yet its degree of utilization differed across the case studies because of the necessity for high digital infrastructure. As for the third strategy (Biomimicry), it was lowest in practical application, although theoretically it was robust as an innovative and progressive strategy based on nature. Its current implementations are still limited to some dynamic facade systems and biomaterial-based materials, as seen in initiatives like BIQ House. Nevertheless, the author is of the view that it is one viable strategy with high prospects of further implementation in subsequent architecture practices. As such, it can be asserted that the Environmentally Adaptive Envelope Strategy is the most holistic and effective strategy for achieving environmental comfort in whatever form it may take, seconded by smart IoT systems, while biomimicry is an emerging strategy that needs to be advanced and applied.

Table 4. Comparative Summary of the Three Adaptive Envelope Strategies Based on Implementation, Features, and Effectiveness

Strategy	Level of Implementation	Key Features	Strengths	Limitations	Notable Examples
Environmentally Adaptive Envelopes	High (widely applied in selected cases)	Smart glazing, adaptive facades, thermal insulation materials	Excellent thermal performance and energy efficiency	May require complex integration in retrofitting	The Edge, Al Bahr Towers
IoT Integration Systems	Moderate (varies based on infrastructure)	Smart sensors, automated systems, energy management platforms	Enhanced control and operational intelligence	Dependent on advanced technical infrastructure	The Edge (smart systems), Media-TIC
Biomimicry	Low (limited real-world applications)	Nature-inspired facades, passive ventilation, bio-materials	Innovative and sustainable long-term potential	Limited current application and high development cost	BIQ House, Eden Project

8. CONCLUSIONS

This research has investigated the impact of activating building envelopes by emerging and advanced technologies for enhancing environmental comfort, sustainability, and energy efficiency. The findings demonstrate the great potential of incorporating smart materials, dynamic systems, and biomimetic principles in building envelope design in order to accomplish responsive and sustainable built environments. The major findings can be summarized as follows:

1. Integration of Smart Technology in Building Envelopes: The research confirmed that the activation of building envelopes with new technologies, such as smart materials and the Internet of Things (IoT), is crucial in achieving environmental comfort through improved ventilation, thermal insulation, and natural light control.



2. Role of Advanced Materials in Enhancing Sustainability: The results demonstrated that the use of smart materials and materials with variable properties, such as electromagnetic and photochromic materials, can contribute to higher energy efficiency and more comfortable indoor environments, with reduced environmental impact.
3. Applications of Dynamic and Transformable Envelopes: The study showed that transformable or adaptive facades can increase the efficiency of buildings by responding to climatic and environmental changes, improving thermal performance and natural lighting inside buildings.
4. Achieving Environmental Comfort through Interactive Design Strategies: The research indicated that using interactive design strategies, such as automatic shading systems and smart natural light orientation, helps achieve thermal comfort and reduce energy consumption.
5. Role of Smart Systems in Reducing Energy Consumption: The findings revealed that the integration of smart envelopes with smart systems, such as adaptive ventilation and lighting systems, can reduce energy consumption and improve the performance of sustainable buildings.
6. Potential of Biomimicry in Envelope Design Development: The study confirmed that biomimicry in envelope design can provide effective and sustainable solutions, such as systems that mimic tree leaves in regulating heat and lighting.

NOMENCLATURE

Symbol	Description	Symbol	Description
A	area, m ² .	α	Altitude angle, deg.
t	time, s	β	factor of variation, dimensionless.
T _a	ambient temperature, °C		

Credit authorship Contribution Statement

Zainab Mohammed Ahmed: Conceptualization, Methodology, Data collection and analysis, Writing – original draft, Writing – review and editing.
Amjad Al-Badri: Supervision, Review, and academic guidance.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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تفعيل اغلفة المباني تقنياً لتحقيق الراحة البيئية

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الخلاصة

مع التقدم السريع في تقنيات البناء، تطور الغلاف المعماري للمبنى من مجرد عنصر إنشائي إلى نظام متكامل مصمم لتحقيق الراحة البيئية الشاملة من خلال التحكم في العوامل الحرارية والإضاءة والصوت داخل الفراغات المعمارية. يركز هذا البحث على تفعيل التكنولوجيا لأغلفة المباني من خلال الابتكارات الحديثة مثل الزجاج الذكي، والجدران التكميفية، وأنظمة التهوية الطبيعية، وتقنيات العزل المتقدمة، والتي تسهم جميعها في تعزيز أداء المباني وتعزيز الاستدامة. يستكشف البحث المفاهيم والاستراتيجيات الرئيسية المتعلقة بأداء أغلفة المباني ويفحص كيف يمكن للذكاء الاصطناعي وإنترنت الأشياء والمواد الذكية تحسين كفاءة الطاقة مع تعزيز راحة المستخدمين. بالإضافة إلى ذلك، يستعرض الدراسة التطبيقات المعمارية المعاصرة التي نجحت في تنفيذ حلول مبتكرة في تصميم الأغلفة الذكية، تشير النتائج إلى أن دمج تقنيات التظليل الديناميكي، وأنظمة التهوية الذكية، والمواد متغيرة الطور يقلل بشكل كبير من استهلاك الطاقة ويحسن جودة البيئة الداخلية. تقدم هذه الاستراتيجيات حلاً مستداماً لتحقيق الراحة البيئية في مباني المستقبل.

الكلمات المفتاحية: أغلفة المباني الذكية، الراحة البيئية، الاستدامة، التقنيات الذكية، التهوية الطبيعية، العزل الحراري