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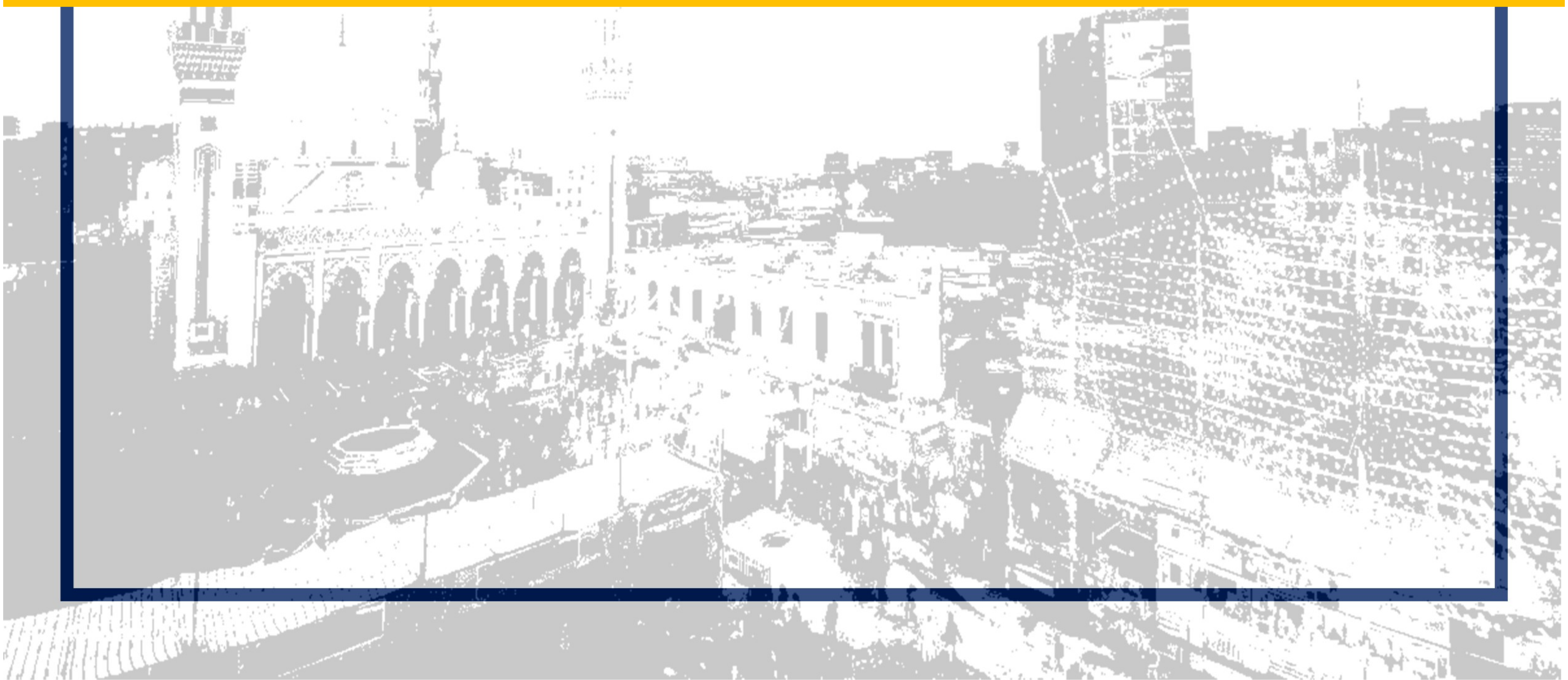

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APPLICATION OF BIOMIMETIC FACADES FOR A MORE SUSTAINABLE FUTURE

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ABSTRACT

A significant shift in thinking has been underway in the architecture and building industry, driven by growing concerns over excessive energy consumption and its environmental impact. This shift has transformed the early stages of building design, shifting the focus from geometry and form to performance, from structural considerations to the building's envelope, and from abstract aesthetics to bio-climatic aesthetics. In response, sustainable, intelligent, and adaptive building façades have been extensively researched and developed. The primary challenge for façade designers is identifying innovative and sustainable technologies that achieve high structural performance while maintaining aesthetic appeal. This paper reviews the performance and limitations of existing façade systems in sustainable building design.
Among contemporary façade technologies, Double Skin Façades (DSFs) are emerging as a promising solution for enhancing energy efficiency, indoor air quality, and visual appeal. Nonetheless, they come with certain drawbacks, including inter-floor sound transmission, elevated upfront costs, and vibrations in the external layer. Meanwhile, adaptive façades—designed to dynamically optimize energy use and occupant comfort—are becoming increasingly popular, though they remain challenged by intricate design processes, construction demands, and compliance with regulatory standards. Green wall systems enhance air quality and visual appeal, while photovoltaic façades contribute to lowering energy bills. However, both solutions often involve significant upfront investment and ongoing maintenance demands. For a building design to be genuinely sustainable, architects, engineers, and builders must implement façade systems that strike a balance between energy efficiency, affordability, user comfort, and ecological impact. Various typologies, strategies, and conceptual frameworks have been developed to enhance adaptive façade performance. This paper examines early-stage design approaches for adaptive façades and presents the theoretical foundations of three biomimetic frameworks. This analysis provides insight into the concepts, opportunities, and limitations of biomimetic adaptive façades in sustainable architecture.

KEYWORDS: façade; adaptive; biomimetic; methodology, Dual-Skin Façades ; green wall systems; photovoltaic façades; sustainable façade materials.

تطبيق الواجهات المستوحاة من الطبيعة من أجل مستقبل أكثر استدامة

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الملخص

تهدف هذه الورقة البحثية إلى استعراض التطورات في تصميم واجهات المباني، مدفوعةً بالتحول من الاعتبارات الجمالية والشكلية إلى الأداء الطاقي والبيئي. يركز البحث على تحليل أنظمة الواجهات الحديثة وأدائها في تحقيق الاستدامة، مع تسليط الضوء على أنواعها الرئيسية وقيودها. يُناقش البحث الواجهات ذات الطبقتين (DSFs) كحلٍ واعدٍ لتعزيز كفاءة الطاقة، ولكنه يُشير إلى عيوبها مثل التكلفة الأولية العالية ومشكلات انتقال الصوت. كما يستعرض الواجهات التكيفية التي تُحسّن استهلاك الطاقة وراحة المستخدم ديناميكيًا، مع الإشارة إلى تعقيدات تصميمها. بالإضافة إلى ذلك، يتناول البحث دور أنظمة الجدران الخضراء والواجهات الكهروضوئية في تحسين جودة الهواء وتوليد الطاقة، مع ذكر متطلباتها من حيث التكلفة والصيانة. وفي الختام، يؤكد البحث على ضرورة تحقيق توازن بين كفاءة الطاقة، التكلفة، وراحة المستخدم لتحقيق الاستدامة الحقيقية. ويُقدم إطارًا نظريًا لتصميم الواجهات التكيفية المُستوحاة من الطبيعة (البيوميميتك)، موفرًا بذلك فهمًا أعمق للمفاهيم والفرص والقيود المتعلقة بهذه الأنظمة في العمارة المستدامة.

الكلمات المفتاحية : واجهة؛ تكيفية؛ محاكاة الطبيعة (بيوميميتك)؛ منهجية؛ واجهات ذات طبقتين(Dual-Skin Façades) ؛ أنظمة الجدران الخضراء؛ الواجهات الفوتوفولطية؛ مواد الواجهات المستدامة.

INTRODUCTION

The building sector is responsible for around 40% of global energy use, playing a major role in greenhouse gas (GHG) emissions [1]. It also accounts for nearly 39% of worldwide carbon dioxide emissions and 50% of raw material consumption, highlighting the importance of energy-efficient practices in both construction and building operations [1,2]. Given the finite nature of Earth's resources and the growing challenges posed by climate change, mitigating the environmental footprint of the construction industry is vital for reducing energy demand and conserving natural resources.

In this context, the development of sustainable strategies in the building industry is critical for achieving energy efficiency and mitigating climate change [3]. As climate change and rising energy demands continue to shape the built environment, sustainability has become an increasingly important consideration in architectural design [4]. Sustainable buildings should be designed to minimize their environmental impact while optimizing the use of non-renewable resources.

An essential component of sustainable architecture is climate-responsive design, which focuses on passive strategies that harness natural elements like sunlight, heat, wind, and rainfall [4]. Through the implementation of environmentally conscious design solutions, buildings can significantly lower their carbon emissions and support the conservation of the environment [2,5]. Consequently, a paradigm shift in architectural design is underway, emphasizing environmentally conscious approaches [6].

One effective strategy for enhancing sustainability in buildings is the integration of adaptive façade systems. These systems respond dynamically to outdoor environmental conditions by regulating natural light, providing solar protection, and harnessing renewable energy, thereby improving overall building performance and sustainability [4,7].

Research methodology

This research seeks to examine existing literature on adaptive building façades, with a specific emphasis on biomimetic strategies. Over time, numerous types of adaptive façades have emerged, each characterized by distinct technical features, though many exhibit similar functional capabilities [8]. Central to these systems is their ability to adapt—an attribute that closely resonates with the core concepts of biomimicry [9]. The review will explore many methodological frameworks in biomimetic design to establish a comprehensive approach for the initial stages of adaptive façade development. These frameworks will be analyzed in terms of their potential to enhance façade performance and sustainability.

1. Literature review

1.1 Façades

The word "façade" is derived from the French term meaning "front" or "face" (Simpson 1989 a, b) and denotes the exterior surface of a building, encompassing its architectural elements and design features [10]. As a fundamental component of a building's envelope, the façade serves both functional and aesthetic purposes, influencing structural performance, energy efficiency, and indoor comfort. Façade materials have gradually transitioned from traditional options like clay, stone, wood, and brick to contemporary materials such as steel and glass, responding to different climatic conditions and functional requirements [5,11]. This ongoing advancement in both materials and construction methods has resulted in a wide range of façade types, each designed to meet particular architectural demands and environmental challenges [5,11].
With growing awareness of the building envelope's significance in managing energy and environmental conditions, façades have evolved from serving merely as passive protective barriers to functioning as active regulators of a building's energy performance [5,12].This transformation demands façades that are adaptable to changing environmental conditions, allowing them to optimize energy use and enhance occupant comfort [13]. In this context, the design and functionality of building façades are increasingly being inspired by natural systems.
Much like the skin of living organisms, which regulate body temperature through physiological, morphological, and behavioral thermoregulation mechanisms, façades must evolve to (respond dynamically) to environmental fluctuations while maintaining thermal comfort within buildings [14,15]. This concept aligns closely with biomimicry, a design approach that draws inspiration from nature to develop (innovative, sustainable architectural solutions) [16]. By integrating biomimetic principles, adaptive façades can (enhance resilience, improve energy efficiency, and reduce operational demands), making them a crucial component of next-generation sustainable buildings.

Façade performance can be evaluated through four key indicators: biological, climatic, biophilic, and energy factors [4,8,17,18].

- **Biological Factors:** Façades must adjust indoor lighting and thermal conditions to meet occupants' needs on a daily or seasonal basis for comfort and well-being.
- **Climatic Factors:** Façades should respond to outdoor climate elements like humidity, wind, solar radiation, and precipitation, optimizing the interaction between the indoor and outdoor environments.
- **Biophilic Factors:** Façades should incorporate natural features like light, air, acoustics, and design elements that connect occupants to nature, improving comfort and psychological well-being.
- **Energy Factors:** Energy efficiency is crucial, as façades regulate the amount of energy needed for heating and cooling, directly affecting building sustainability by controlling heat and light transfer [4,8,17,18].

These indicators highlight the role of façades in enhancing energy efficiency, comfort, and occupant well-being.

1.2 Biomimetics

Biomimetics involves the study of biological structures and processes to explore their possible applications in technology [18,19]. This interdisciplinary field connects biology, technology, and design, aiming not only to replicate living organisms but also to grasp the underlying biological principles to create innovative solutions [20,21]. As a fast-expanding area within engineering and architecture, biomimetics enables the development of multifunctional, sophisticated, and adaptive designs. By borrowing strategies from nature, it moves beyond static building façades, aiming to improve energy performance through adaptive designs [22].
Biomimetic typologies can be categorized into three levels:
Organism Level: Imitating organisms or parts of their systems.
Behavior Level: Translating how organisms interact with their environment.

Ecosystem Level: Replicating the principles of entire ecosystems [23–24].
The adaptation properties of organisms to environmental changes are particularly relevant to building façades, aiming to improve energy performance by creating adaptive systems that respond to changing conditions in nature [17,25]. Building façades have evolved from basic load-bearing components to more complex systems that regulate thermal, acoustic, and visual conditions. Examining nature's adaptable morphologies can inform the design of dynamic building envelopes, using smart materials to enhance performance and support building-environment interaction [25].
Recent technologies like adaptive façades allow buildings to adjust to environmental changes, improving energy efficiency and occupant comfort [26]. Biomimicry can be motivated by three key goals:
Innovation: Using biological systems to inspire modern technologies [27].
Sustainability: Enhancing environmental performance in both technology and the built environment.
Contributing to human psychological well-being through bio-inspired designs.
Advances in biology, particularly the application of thermodynamics, show how organisms maintain optimal temperature ranges despite environmental fluctuations. These principles can inform building thermal performance through adaptive, functional features [28].
Biomimetic architecture addresses the growing complexity of modern buildings by adopting interdisciplinary approaches to create functional and sustainable systems. This trend draws inspiration from biological mechanisms to control environmental conditions [15,29], transforming buildings into living, interactive systems that foster innovation and creativity in design [30]. Advances in digital design tools and composite materials have further enabled nature-inspired architecture [15,29].
Biomimetic architecture can be categorized into two main types:
Structural Biomimetics: Focuses on how organisms achieve material-efficient, multi-level structures with independent functions.
Process Biomimetics: Examines how biological systems control physical and chemical environments, particularly in regulating external climate and internal building conditions [30].
The primary advantage of biomimicry in architecture is the development of energy-efficient thermoregulatory systems for building façades [31]. However, a significant challenge lies in the gap between biosystems and human-made architecture, as biomimicry is a natural evolution process. This limited exchange of information between biologists and architects has been identified as a key barrier to applying biomimicry effectively in architectural design [32].

1.3 Design Considerations for Sustainable Biomimetic Façades

A building's façade, while primarily serving as the outer layer separating interior spaces from the external environment, also plays a crucial role in defining its visual identity. As façades directly respond to climatic factors and influence indoor comfort, sustainable design prioritizes material selection and energy efficiency (see Figure 1). To enhance façade performance, architects and engineers leverage thermal, optical, airflow, and electrical systems. Aksamija characterizes high-performance sustainable façades as building envelopes that minimize energy use while maintaining indoor comfort and supporting occupant Heath and productivité [33].

Biomimicry and biophilic design have long informed façade innovation, though not all nature-inspired solutions are inherently sustainable. For a façade to be truly sustainable, design decisions must align with ecological principles—examining how natural organisms manage heating, cooling, shading, and light regulation. In this light, sustainable design can interpret organic skin as dynamic and responsive to natural elements like wind, sunlight, precipitation, and temperature extremes.

Such façades may also replicate vital life-supporting functions such as respiration, carbon absorption, and water regulation, often through multi-layered systems.

Loonen highlights adaptability, multifunctionality, and evolvability as core principles of bio-inspired façade design [34]. Figure 2 illustrates the key concepts underpinning sustainable façade design. Therefore, achieving sustainability requires a holistic integration of energy performance, functionality, and structural optimization.

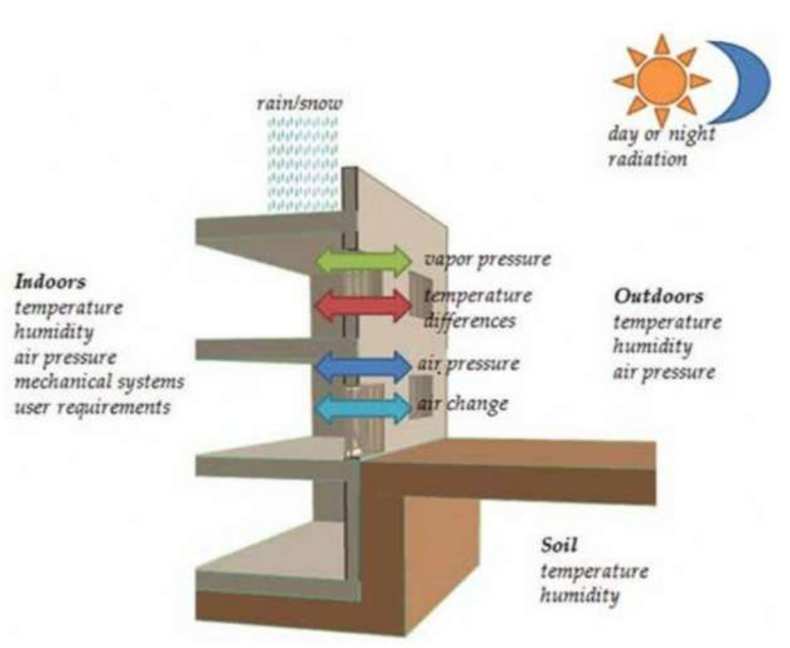


Figure 1. Design principles of a traditional facade, by TBT, 2017.

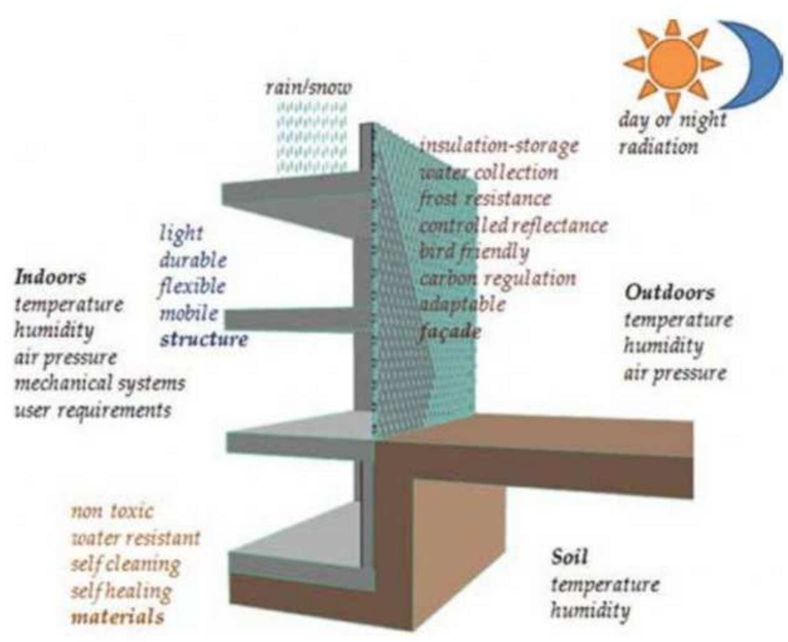


Figure 2. Design principles of a sustainable facade, by TBT, 2017.

1.3 Energy Requirements

Building sustainability is frequently assessed by the amount of energy needed to sustain comfortable indoor conditions. A large share of this energy use goes toward heating and cooling, which is largely impacted by the design of the façade. Serving as the main boundary for heat and light exchange between the interior and exterior, the façade's performance is influenced by factors such as solar radiation, outdoor temperature, wind speed, humidity levels, and sky temperature. Sustainable façade design generally focuses on three key aspects: thermal comfort, visual comfort, and the integration of renewable energy generation (see Table 1).

Table 1. Three Main Areas Sustainable Façade Design

Aspect	Description	Examples/Technologies	References
Thermal Comfort	The façade's ability to regulate heat transfer depends on material properties (e.g., thermal absorption, emissivity, density, specific heat, thermal conductivity) and design strategies like solar orientation, insulation, and shading. Advanced technologies enhance performance.	- Thermal mass - Dynamic insulation - Radiative cooling - Phase change materials - Energy storage - BioTRIZ-inspired open-cell honeycomb structure (4.5°C reduction in surface temperature)	[35]

Visual Comfort	Determined by optimal light levels and absence of glare. Façade design influences light transmission, transparency, translucency, color, and reflection. Innovative solutions dynamically adjust shading and lighting.	- Electrochromic glass - Homeostatic façade systems (e.g., Decker Yeadon's dielectric elastomer-based self-shading glass)	[36]
Renewable Energy Production	Façades can generate renewable energy by mimicking natural processes or integrating energy-harvesting technologies.	- Photovoltaic systems (artificial photosynthesis) - Bioactive façades (algae for biodiesel, bioethanol) - Building-integrated nano-wind turbines	[37, 38]

1.5 Form and Structural Efficiency

Biomimicry in architecture often involves drawing inspiration from natural forms and structures to enhance both aesthetics and functionality. While many biomimetic designs focus on surface morphology, some go beyond mere visual analogy to incorporate functional benefits. For example, the Esplanade Theaters in Singapore, designed by DP Architects, draw inspiration from the spiky texture of the durian fruit to develop a sun-shading system that lowers energy consumption and reduces the reliance on artificial lighting [39].

1.5.1 Form Generation:

Biomimetic design often uses computational methods like parametric modeling and evolutionary algorithms to generate complex geometries. Gruber et al. suggest a multi-step design approach involving the identification of design features, extraction of "feature genes," creation of evolved typologies (phenotypes), and adjustment of these genes to enhance the design [40].This approach allows for the creation of efficient, biomimetic structures that can be fabricated using digital technologies like CNC machining or 3D printing, ensuring material efficiency and ease of production.

1.5.2 Structural Systems Inspired by Nature:

Historically, structural systems have been influenced by natural forms, such as **Table 2**:

Table 2. Historically, structural systems have been influenced by natural forms

Masonry structures inspired by insect mounds (e.g., pyramids),	

Shell structures inspired by eggshells,	
Tensile structures inspired by spider webs,	
Cellular structures inspired by honeycombs,	
Pneumatic structures inspired by soap bubbles [41].	

Pioneers like Dischinger (reinforced concrete domes), Buckminster Fuller (geodesic domes), and Frei Otto (lightweight tensile structures) demonstrated how biomimicry can lead to innovative structural solutions. Contemporary examples include the One Ocean Pavilion by SOMA Architecture and Knippers Helbig Engineering, which draws inspiration from fish gills and the opening mechanism of the bird of paradise flower to develop a hinge-free, adaptive façade that controls light and airflow [42].

Bio-Kinematics:

The transfer of biological motion (bio-kinematics) to technical constructions enables the creation of dynamic, ever-changing surfaces. This approach aligns structural design with natural principles, ensuring stability, durability, and minimal environmental impact.

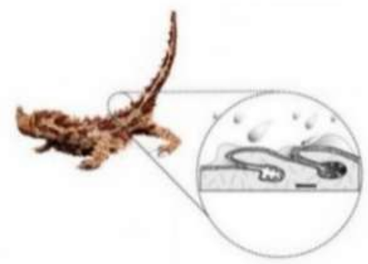
1.6 Sustainability considerations

Sustainability in architecture involves minimizing ecological footprints by optimizing resource use, reducing waste, and leveraging natural processes. Nature offers valuable insights for sustainable design, as it operates on principles like carbon utilization, zero waste, and energy efficiency through solar and gravitational energy. Façades play a critical role in sustainability by addressing air quality, water efficiency, carbon capture, and the use of non-toxic, low-energy materials. Biomimetic façades can also exhibit biological behaviors, such as responsiveness, adaptability, and self-regulation, to enhance environmental performance.

Key Sustainability Considerations:

Table 3. Sustainability Considerations

Aspect	Description	Examples/Technologies	References
Carbon Sequestration and Air Quality	Façades can incorporate systems like photosynthesizing or fog-eating mechanisms to capture carbon and improve air quality. Greenery integrated into façades regulates heat, air, water, and electricity flows, enhancing energy efficiency and indoor air quality.	- Photosynthesizing façades - Fog-eating systems - Council House 2, Melbourne (tree-inspired multilayered façade with foliage, sunscreens, and microclimate management)	[43], [44]  Council House
Water Efficiency and Harvesting	Water management in buildings involves protection from water damage and efficient use of freshwater resources. Biomimetic designs, such as water-harvesting façades, can capture and utilize water sustainably.	- BioGen methodology for biomimetic design - Thorny Devil-inspired water-harvesting façade (bumpy surface, capillary grooves, storage chambers)	[45] 

			Thorny Devil-inspired 
Low-Impact Materials and Energy Efficiency	Sustainable façades prioritize materials with low embodied energy, non-toxicity, and minimal waste. Biomimetic processes, such as photosynthesis and water harvesting, reduce reliance on external energy sources.	- Low-embodied energy materials - Non-toxic materials - Biomimetic processes (e.g., photosynthesis, water harvesting)	[46]  Sustainable façades

1. **Biomimetic Building Materials and Techniques for Façade Applications**

Biomimetic façades have evolved beyond serving as mere protective barriers; they are now engineered to be adaptive, multifunctional, and visually appealing, all while improving energy efficiency, durability, and overall sustainability. By drawing inspiration from nature, interdisciplinary approaches have led to innovative materials and techniques that mimic biological processes such as self-healing, self-cleaning, and self-assembly. These advancements are transforming façades into living, responsive systems that interact with the environment.

Table 4. Key Biomimetic Solutions for Façades

Biomimetic Solution	Inspiration from Nature	Application in Façades	Benefits	References
Self-Cleaning Surfaces	- Lotus effect (hydrophobic surfaces) - Gecko feet - Pond skaters - Shark skin	- Self-cleaning paints and tiles - Photocatalytic TiO_2 nanoparticles for pollutant breakdown (e.g., NO_x)	- Reduces maintenance - Improves air quality - Enhances surface durability	[47-48]
Anti-Reflective Coatings	- Elephant hawk moth's eyes (nanostructured moth-eye arrays)	- Glazing for skyscrapers - Coatings for solar cells	- Reduces light reflection - Improves energy efficiency	[49, 50]

Phase-Changing Materials (PCMs)	- Organisms in arid climates (energy storage during phase transitions)	- Thermal insulation in façades	- Maintains indoor comfort - Reduces energy consumption	[51, 52]
Living Façades	- Photosynthesis in plants and algae	- Green walls - Microalgae photobioreactors	- Captures CO2 - Produces energy - Enhances energy efficiency	[53, 54]
Biomineralization and Self-Healing Materials	- Biocalcification (microbial-induced calcium carbonate precipitation)	- BioMason™ (bacteria-hardened sand) - Self-healing concrete	- Improves durability - Repairs cracks naturally - Eco-friendly	[55, 56]
Fungal Mycelium Insulation	- Fungal mycelium growth	- FungInsulation™ (thermal insulation from agricultural waste)	- Recycles waste - Provides energy-efficient insulation - Eco-friendly	[57]

Applications and Benefits:

- **Functional and Aesthetic Design**: Biomimetic façades combine form and function, offering solutions like self-cleaning, anti-reflective, and energy-efficient surfaces.
- **Sustainability**: By mimicking natural processes, these materials reduce waste, lower energy consumption, and improve durability.
- **Interdisciplinary Innovation**: Combining biology, architecture, and engineering has led to breakthroughs like microbial binders, living façades, and fungal insulation.

Future Directions:

- Biomimetic façades are evolving toward adaptive, living systems that mimic natural skins, offering enhanced functionality and sustainability.
- Ongoing research and development promise more energy-efficient, durable, and eco-friendly solutions for building envelopes.

Biomimetic materials and techniques are revolutionizing façade design, offering sustainable, functional, and innovative solutions that align with nature's principles. These advancements pave the way for smarter, more adaptive building skins that contribute to a sustainable built environment.

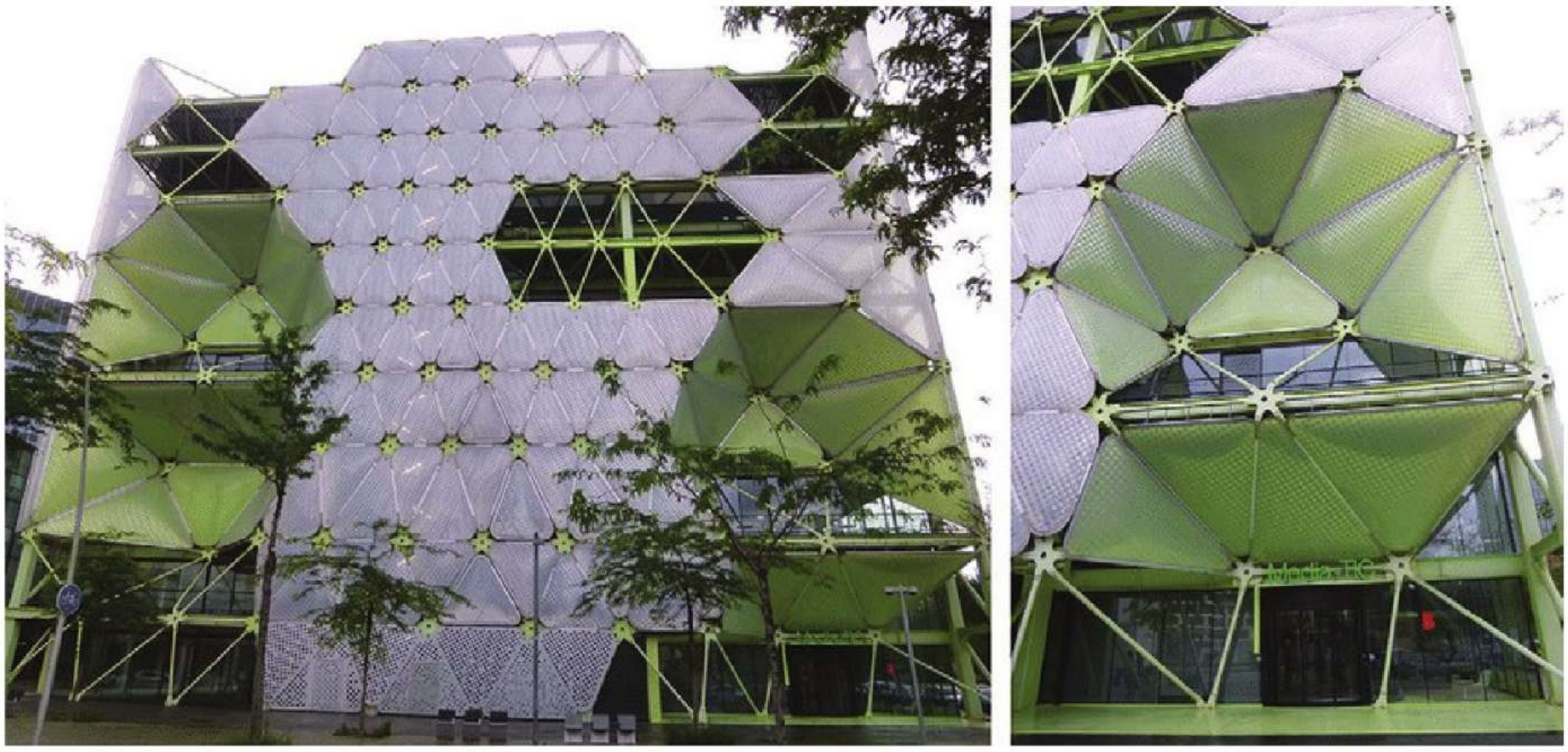
Modern Applications of Biomimetic Façades

Benyus categorizes biomimicry into two main types: mimicking natural forms and replicating natural processes. Designers may draw inspiration from the physical traits of organisms or emulate their behavioral patterns. Beyond these approaches, a more advanced form of biological inspiration—known as bio-collaborative design—involves integrating living organisms directly into the façade system. The following examples illustrate how natural principles and materials are employed to create diverse and innovative façade solutions [58].

Media-TIC Building

The Media-TIC Building, designed by architect Enric Ruiz-Geli and located in Barcelona, exemplifies the integration of biomimetic principles within a performative architectural framework. Recognized with the World Building of the Year Award in 2011 and awarded LEED Gold certification, the project stands as a benchmark for sustainable and technologically responsive design. A defining feature of the building is its innovative façade system, composed of inflatable ETFE (ethylene tetrafluoroethylene) cushions arranged in three layers. These cushions are modulated by the injection of air or nitrogen to dynamically alter their opacity, thereby emulating the functional behavior of plant stomata—natural microstructures that regulate the exchange of heat and light in response to environmental stimuli. This adaptive façade enables passive ventilation, dynamic solar shading, and efficient thermal regulation, aligning the building's environmental performance with biological analogs. It is estimated that such strategies contribute to an energy consumption reduction of approximately 20%. In elevation, the envelope presents as a translucent, responsive "second skin," functioning as a climatic interface between the interior and exterior—a conceptual and functional parallel to the respiratory function of plant epidermis.

The Media-TIC Building exemplifies a sophisticated application of biomimicry within contemporary architectural practice, demonstrating how biologically inspired systems can enhance both environmental performance and design innovation. Through the implementation of a responsive ETFE façade that mimics the adaptive behavior of plant stomata, the building successfully merges aesthetic expression with functional efficiency. Its performative envelope not only reduces energy consumption but also fosters a dynamic interaction between the built environment and natural forces. As such, the Media-TIC Building stands as a paradigmatic case of biomimetic and performative architecture, offering a compelling model for future sustainable design strategies that aspire to emulate the intelligence, adaptability, and resilience inherent in natural systems.



Elevation: Shows the modular, inflatable ETFE cushions in detail, illustrating how they act as an adaptive outer layer.

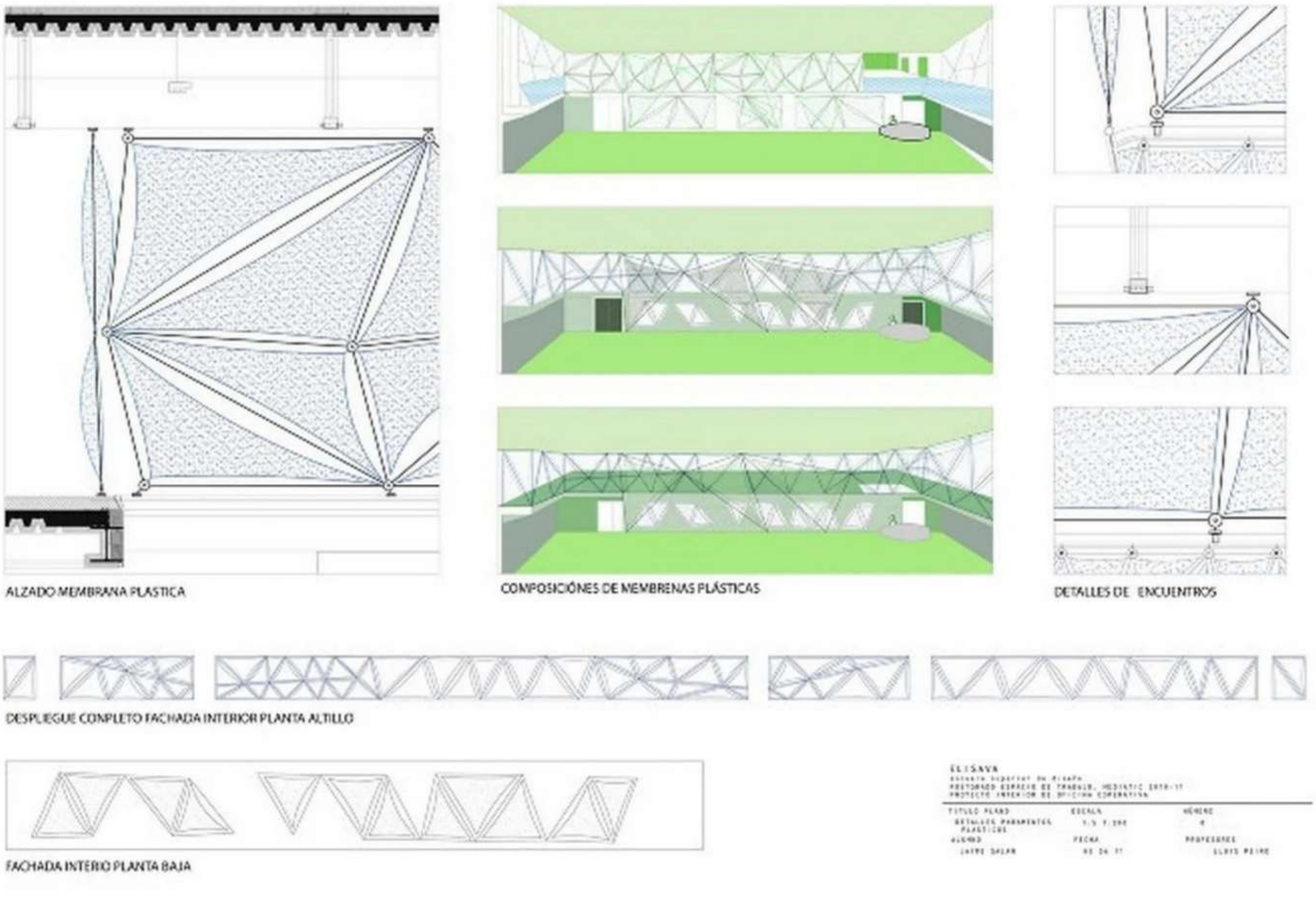


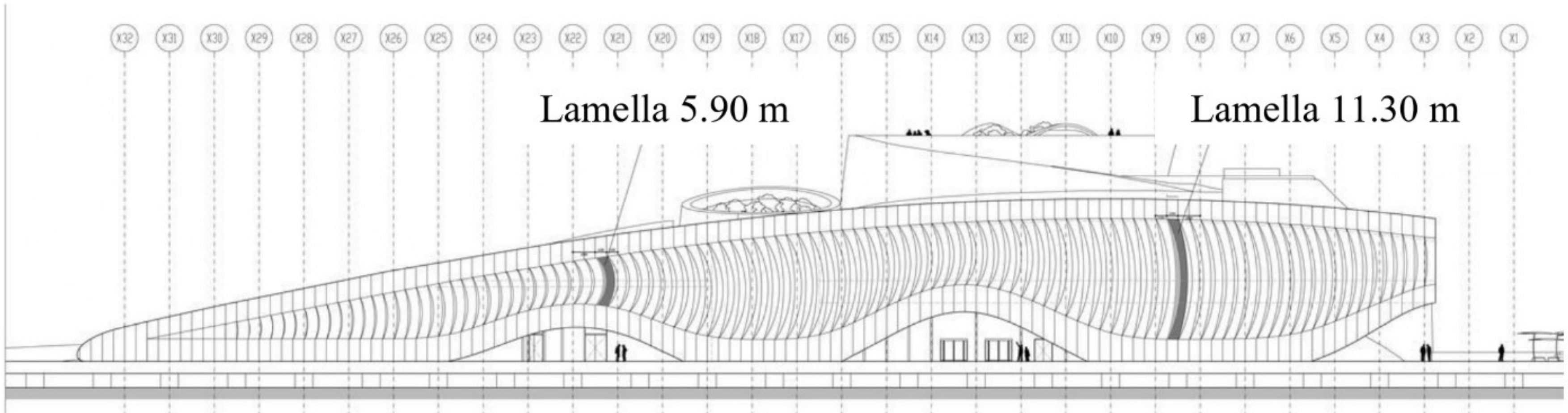
Figure 3. Section: Clearly reveals the external steel frame system, open floor plans, and central atrium. The galleries and lightweight structure optimize both functionality and energy use.

Table 5. Adaptive ETFE Façade of Media-TIC Building

Aspect	Description	Key Features/Technologies	Benefits	References
Adaptive ETFE Façade	Inspired by breathing organisms, the building features a dynamic envelope made of ethylene tetrafluoroethylene (ETFE), a lightweight and flexible material that adapts to external conditions like sunlight and weather.	- **Southeast façade**: 104 inflatable ETFE cushions with three air chambers to control solar radiation. - **Southwest façade**: ETFE sheets filled with nitrogen and oil for variable shading. - **2,500 m² ETFE cladding**: Nonstick surface, fire-safe, and low maintenance.	- Reduces heat gain. - Improves thermal insulation. - Contributes to 20% energy savings.	[59]
Sustainability Features	The building integrates renewable energy systems and smart technologies to minimize environmental impact and resource use.	**Photovoltaic Roof:** Produces half of the building's energy needs. **Rainwater Harvesting:** Collects and stores rainwater for flushing toilets. **Smart Sensors and ETFE Sun Filters:** Cut CO_2 emissions by 55%.	- Significant CO2 reduction. - Energy efficiency. - Resource conservation.	[60, 61]
Biomimetic Interior Design	Inspired by jellyfish, the interior design incorporates self-sustaining lighting systems.	- **Interior Paint:** Captures solar energy throughout the day and emits a green luminescence at night.	- Provides self-sustaining lighting. - Reduces external energy consumption.	[62]
Biomimetic Principles	The building's design mimics natural systems to achieve sustainability, adaptability, and energy efficiency.	- **Form and Function**: ETFE façade mimics natural adaptability. - **Energy Efficiency**: Integrates renewable energy and adaptive shading. - **Sustainability**: Reduces CO2 emissions and resource use.	- Combines biomimicry with advanced technology. - Sets a benchmark for sustainable design.	[63]

Kinetic Façade of the One Ocean Building

The One Ocean Building, a thematic pavilion for the EXPO 2012 in Yeosu, South Korea, designed by SOMA architects in collaboration with Knippers Helbig Advanced Engineering, presents a compelling case study in kinetic and biomimetic architecture. Its defining feature is a large-scale, adaptive façade composed of 108 kinetic lamellas made from glass fiber-reinforced polymers (GFRP). This innovative system directly references biological movement, specifically the gill structures of marine life or the rippling surface of the ocean, to dynamically control light, airflow, and visual connection with the surroundings. Through a computer-controlled bus system, individual lamellas can be articulated to create wave-like choreographies, allowing the building to "breathe" and modulate its interaction with natural forces. This performative envelope not only enhances energy efficiency by regulating solar gain and natural ventilation but also transforms the building's aesthetic into a living, responsive entity, demonstrating how mimicking natural mechanisms can lead to both functional optimization and expressive design in contemporary architecture.



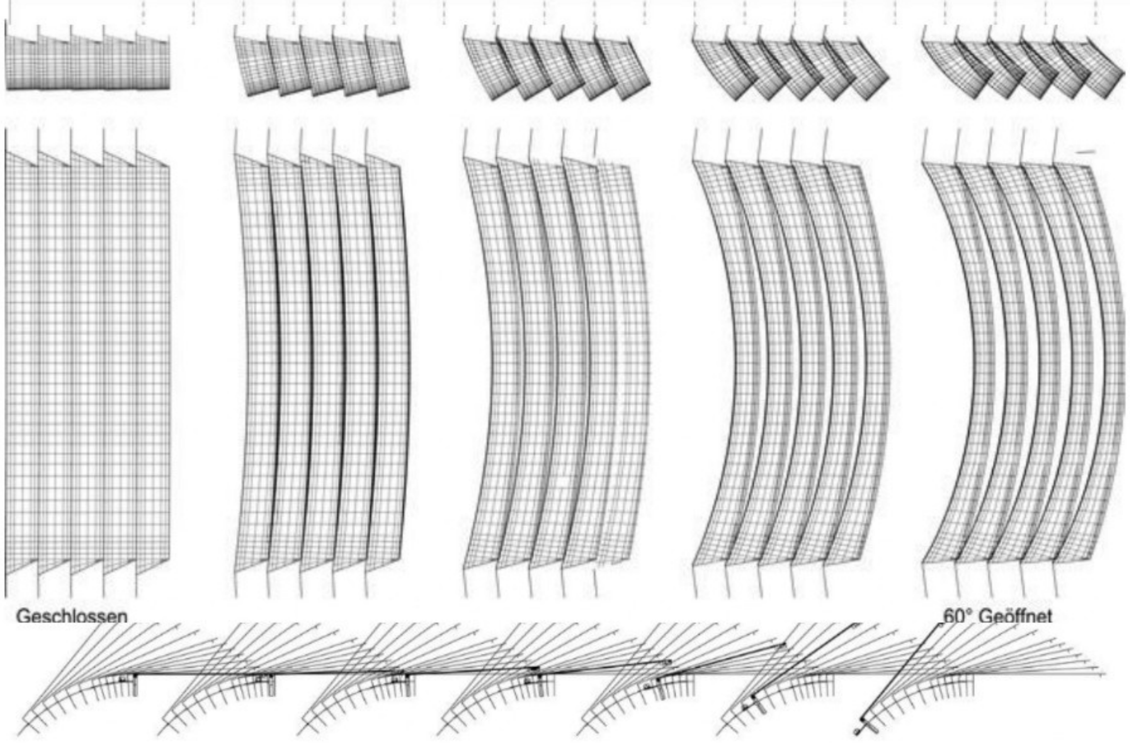


Figure 4, Lamella façade - movement from closed to 60° opening - cut through the middle of a lamella with different length of the 108 kinetic lamellas made from glass fiber-reinforced polymers

Table 6 Kinetic Façade of the One Ocean Building

Aspect	Description	Key Features/Technologies	Benefits	References
Biomimetic Inspiration	The façade mimics the **bird of paradise flower** (torsional buckling to open/close petals) and **fish gills** (wave-like movement).	- **Bird of paradise flower**: Controlled buckling and elastic deformation. - **Fish gills**: Wave-like patterns on the façade.	- Dynamic, adaptive movement. - Aesthetic appeal.	[64]
Material and Design	The façade consists of **108 fiberglass lamellas** made of **glass fiber-reinforced polymers (GFRP)**.	- **GFRP lamellas**: 9 mm thick, up to 14 m long. - Combines high strength and flexibility. - Lateral-torsional buckling for doubly curved shapes.	- High durability. - Reversible elastic deformation without fatigue.	[65]
Mechanism and Functionality	The lamellas are moved by **actuators** powered by **solar panels** on the roof. Compression forces induce elastic deformation, causing bending and rotation.	- **Actuators**: Located at top and bottom edges. - **Solar-powered**: Energy-efficient operation. - **Elastic deformation**: Controls light and airflow.	- Energy efficiency. - Improved indoor environmental conditions.	[66]
Aesthetics and Functional Benefits	The façade creates **animated, wave-like patterns** and regulates light and airflow.	- **Wave-like patterns**: Enhances visual appeal. - **Light and airflow regulation**: Improves energy efficiency and indoor comfort.	- Combines aesthetics with functionality. - Sustainable design.	[67]

Innovative façade combines biomimicry: Manuel Gea Gonzalez Hospital, Mexico City

The Manuel Gea González Hospital in Mexico City stands as a pioneering example of how architecture can actively contribute to urban environmental health through biomimicry. Designed with an innovative façade system by Elegant Embellishments, the building incorporates hexagonal tiles coated with titanium dioxide (TiO2), a photocatalytic material. This "smog-eating" skin is inspired by natural processes, particularly the way certain organisms or systems interact with their environment to purify or regulate.
When exposed to ambient ultraviolet light, the TiO2 reacts with urban air pollutants like nitrogen oxides (NOx) and volatile organic compounds (VOCs), breaking them down into less harmful compounds. This dynamic surface, resembling a vast, porous organism, not only mitigates local air pollution, equivalent to the daily emissions of numerous vehicles, but also serves as a striking visual statement. The Gea Hospital exemplifies a direct and impactful application of biomimetic

principles, showcasing a performative envelope that integrates ecological function with aesthetic design, offering a compelling model for future urban development in polluted environments. [68]

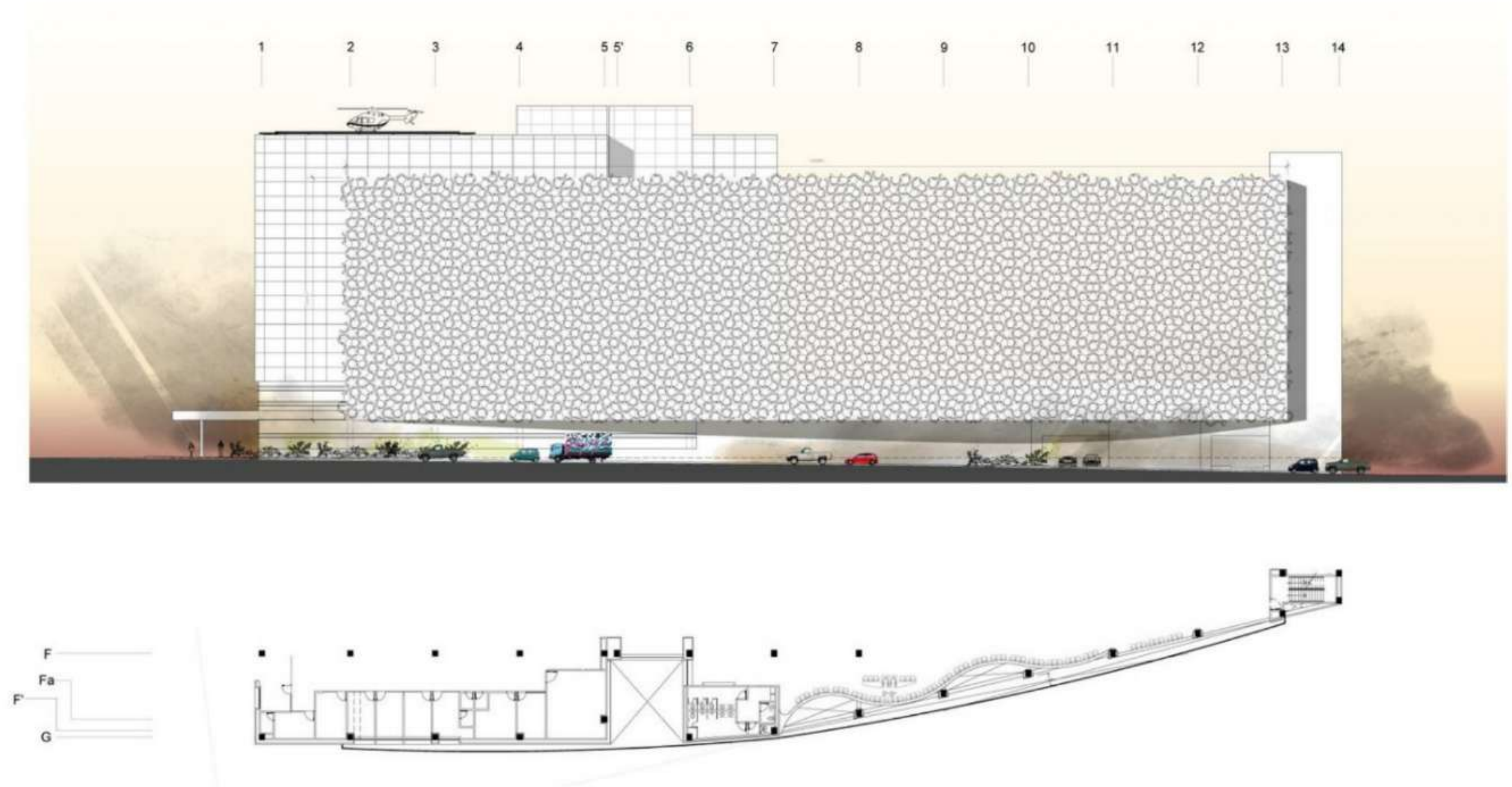
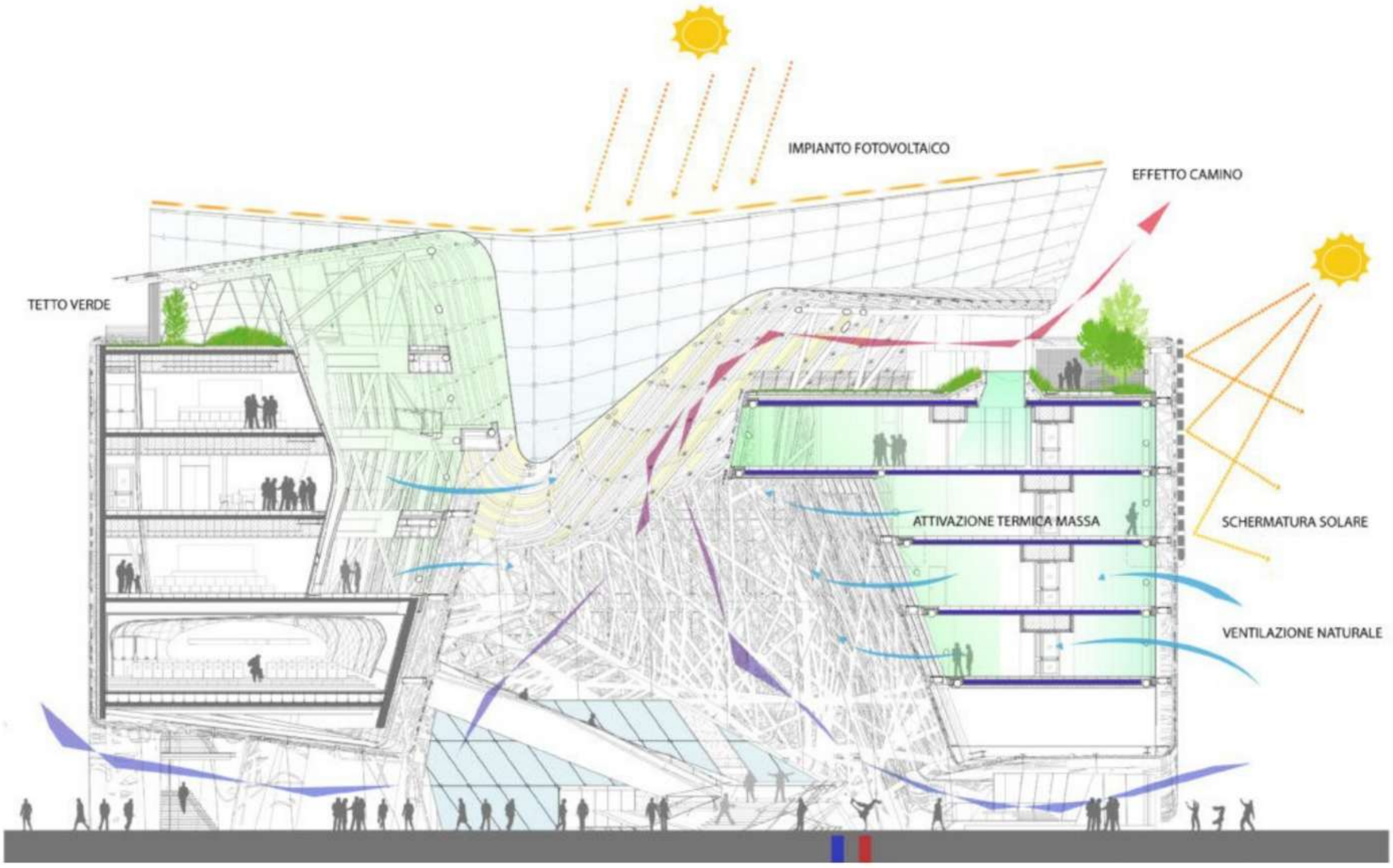


Figure 5. Innovative environmentally sustainable construction techniques, technologies and materials, as well as infrastructures. materials used According to recent studies of the technology, the facade at Torre de Especial is reducing pollution by 1,000 cars per day. **[69]**

Innovative façade combines biomimicry: Expo 2015 Italian Pavilion, Milan

The Expo 2015 Italian Pavilion, "Palazzo Italia," designed by Nemesi & Partners, stands as a profound architectural embodiment of biomimicry, drawing direct inspiration from the concept of an "urban forest" and an "osmotic organism." Its most striking feature is the intricate, branched external envelope, composed of over 700 unique, pre-cast concrete panels made from a special "i.active BIODYNAMIC" cement. This innovative material, containing titanium dioxide (TiO_2), functions as a photocatalyst. Much like the process of photosynthesis in plants, when this "smog-eating" skin is exposed to sunlight, it actively breaks down air pollutants, converting them into inert salts and thereby helping to purify the surrounding atmosphere. Beyond its air-cleaning capabilities, the building's design, with its interplay of solids and voids and its "canopy" inspired roof with integrated photovoltaic glass, functions as a high-performance, energy-efficient structure. The Italian Pavilion thus exemplifies a holistic biomimetic approach, where the building's form, materials, and environmental performance are deeply intertwined with the regenerative and adaptive qualities observed in natural ecosystems.



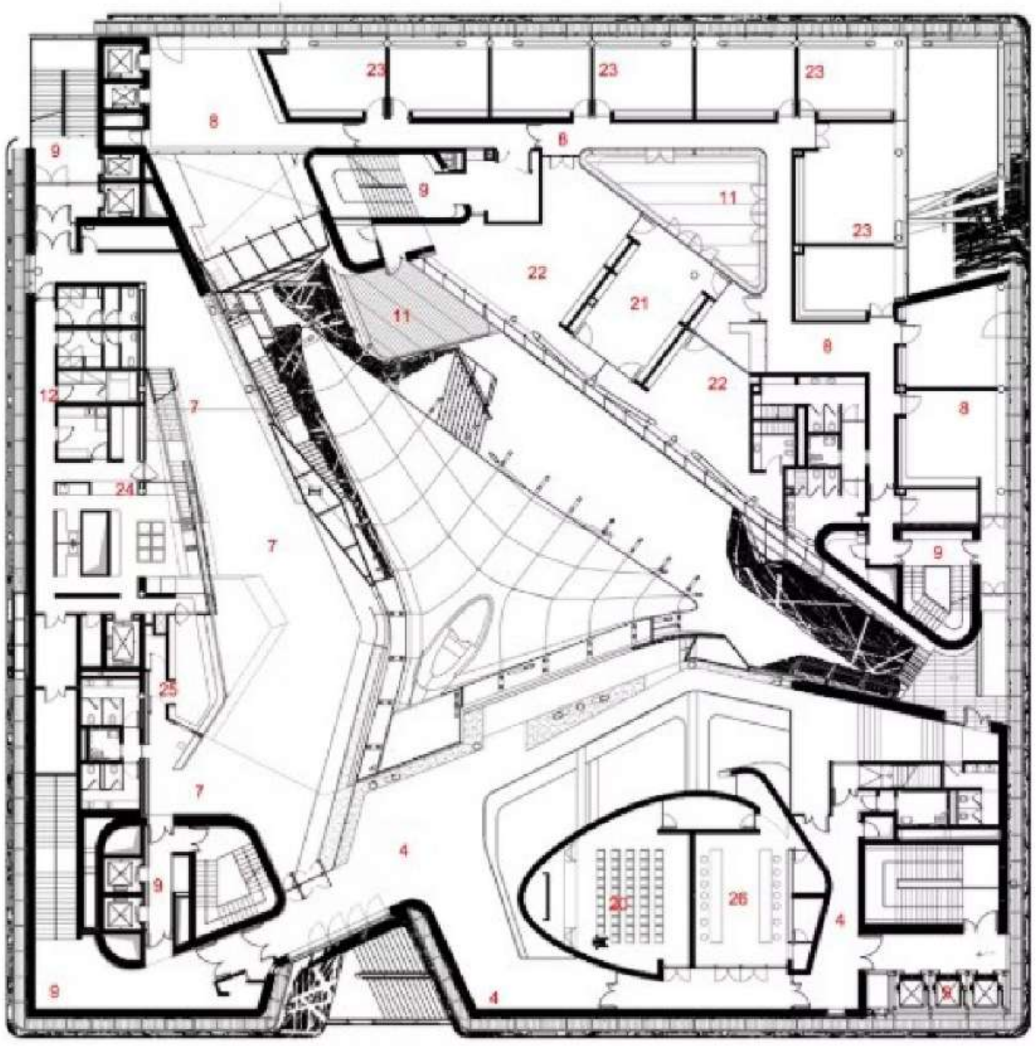


Figure 6. This space is the starting point for the exhibition route, in the midst of the four volumes that make up Palazzo Italia. These four volumes house the Exhibition zone (West), the Auditorium and Events zone (South), the Office zone (North) and the Conference and Meeting zone (East).

The façade of Palazzo Italia is clad in more than 700 I. Active BIODYNAMIC concrete panels with Italcementi's patented TX Active technology. **[72]**

Table 7. innovative façade combines biomimicry

Aspect	Description	Key Features/Technologies	Benefits	Ref.
Photocatalytic TiO2 Technology	Developed by Italcementi, TiO2 acts as a catalyst when activated by sunlight, converting harmful pollutants like NOx into inert substances (e.g., calcium nitrate, water, and CO2).	- **Self-cleaning effect** (since 1995). - **Air-cleaning property** (TX Active® technology, 2006). - Durable and long-lasting.	- Reduces smog levels. - Improves air quality. - Low maintenance.	[70]
Manuel Gea Gonzalez Hospital, Mexico City	A 2,500 m² façade designed by Elegant Embellishments, featuring biomimetic tiles inspired by sponges and corals.	- **Biomimetic tiles**: Quasicrystal line pattern based on sponges and corals. - **TiO2-coated ABS-polycarbonate plastic**: Increases surface area and creates turbulence for better pollutant capture. - **Pollution reduction**: Neutralizes pollution equivalent to 1,000 cars per day.	- Improves local air quality. - Provides cleaner air for hospital surroundings.	[71]
Expo 2015 Italian Pavilion, Milan	A 9,000 m² façade with 900 biodynamic concrete panels, designed by Nemesi and Partners. The design mimics a "petrified forest" with branching patterns inspired by the tree of life.	- **Biodynamic concrete panels**: Made from 80% recycled materials (e.g., Carrara marble scraps). - **NOx reduction**: 20–80% (average 45%). - **Aesthetic design**: Resembles tree branches, symbolizing urban forests.	- Reduces urban pollution. - Combines aesthetics with functionality. - Uses sustainable materials.	[72]
Biomimetic Design Principles	The façades mimic natural structures (e.g., sponges, corals, and trees) to enhance pollutant capture and air purification.	- **Form and Function**: Mimics natural adaptability. - **Sustainability**: Uses recycled materials and renewable energy. - **Innovation**: Integrates TiO2 for active air purification.	- Combines biomimicry with advanced technology. - Sets a benchmark for sustainable design.	[73]

RESULTS:

Integrating biomimetic principles into façade design is a transformative approach for sustainable architecture. By drawing inspiration from nature, biomimetic adaptive façades significantly enhance energy efficiency, occupant comfort, and overall environmental performance. We've observed a clear evolution from passive to active façade systems, with notable advancements in:

- Double-skin façades: Improving thermal insulation and natural ventilation.
- Green walls: Contributing to thermal regulation, air quality, and biodiversity.
- Photovoltaic panels: Generating renewable energy.
- Self-regulating materials: Adapting dynamically to changing environmental conditions, optimizing performance without constant human intervention.

These developments demonstrate the significant potential for responsive building envelopes that actively adapt to their surroundings.

RECOMMENDATIONS:

Despite the promising advancements, several challenges need to be addressed to facilitate the widespread adoption of biomimetic façades:

- Cost Reduction: Focus on developing more cost-effective biomimetic solutions to overcome the barrier of high initial investment.
- Regulatory Simplification: Streamline regulatory processes to encourage innovation and implementation of these advanced systems.
- Interdisciplinary Collaboration: Foster stronger collaboration among architects, engineers, and biologists from the early stages of design to integrate diverse expertise effectively.
- Material Performance Enhancement: Prioritize future research on improving the durability, efficiency, and sustainability of biomimetic materials.
- Smart Technology Integration: Invest in research and development to seamlessly integrate smart technologies, further enhancing the adaptability and functionality of biomimetic façades.

By addressing these points, the architecture and construction industries can fully leverage biomimicry in early-stage design processes. This will lead to façade systems that not only minimize environmental impact but also contribute significantly to the resilience and sustainability of the built environment, fostering a deeper connection between architecture and nature.

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