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Biomimetic Strategies in Kinetic Architecture: A Comparative Analysis of Nature-Inspired Roof and Façade Designs

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ABSTRACT

Kinetic architecture enables buildings to adapt dynamically to environmental, functional, and aesthetic demands through responsive components. This method draws on the bionic principles of intelligent movement mechanisms found in nature, such as the phototropism of plant leaves. The paper investigates the influence of natural systems on the design of kinetic buildings, identifying three primary biomimetic design strategies: depiction or abstraction of the natural forms, imitation or response to natural motion, and environmentally driven control of movable components to enhance sustainability. Kinetic systems are classified as either passive, utilizing natural forces like wind and sunlight, or active, relying on sensors, actuators, and computational control. Through a comparative analysis of real case studies involving kinetic roofs and façades, the study highlights key variations in biomimetic application. The cases belong to different functional types and cover varied construction times, geographical locations, and climatic zones. The findings indicate that the use of nature as a formal reference is prevalent in all roof designs, while it is used in less than half of the facade designs. Natural forms are mostly abstracted in three-quarters of the roof cases and a quarter of the facade cases. Furthermore, the prevailing trend is to imitate the movement of natural reference in three-quarters of the roof cases, whereas the movements of nearly half of the facades are reactions to the movement of the natural reference. Nature as a tool for controlling building performance dominates both roof and façade designs. Roof cases applied active control systems only, while façade cases implemented both passive and active design strategies. These findings contribute to a deeper understanding of nature-informed kinetic architecture and its potential for sustainable building design.

1. INTRODUCTION

Kinetic architecture represents a type of adaptable architecture that enables buildings to modify their configuration to meet changing demands. Its applications include movable roofs, dynamic façades, and physically reconfigurable interior spaces and components, to enhance the building's functional, environmental, aesthetic, and economic performance. The functional characteristics are reflected in the building's ability to change its function to another, alter its form and configuration to host different events, and expand or reduce its space as needed. The environmental characteristics include improving natural ventilation, enhancing daylight, and increasing energy efficiency. The aesthetic characteristics make the building visually appealing, add a dynamic visual dimension, and create an attractive architectural presence. Moreover, movement can serve additional purposes depending on the project's context and design. As a result, the building's economic performance is improved. [1]. Kinetic buildings are characterized by the ability to change their geometries in response to the functional and spatial requirements of users or environmental conditions such as wind or sunlight. This adaptable architecture enhances the spatial quality of design spaces and creates environmentally responsive buildings [2].

Nature is recognized as one of the greatest sources of inspiration in the fields of architectural and artistic design. Biomimicry is defined as models inspired by nature to solve architectural design problems and enhance building sustainability by reducing CO_2 emissions and energy use [3]. The biomimetic patterns have inspired and influenced the formation of spatial structures in contemporary architecture. The biomimetic forms are new trends in architectural design, such as zoomorphism (the imitation of animal form) and biomorphism (implementing natural patterns) to imitate the natural shapes on a geometric level [4]. Furthermore, the element of nature, such as wind force, is a design driver of the architectural configuration of tower buildings [5].

Furthermore, nature has offered models of dynamism that can inspire innovative design solutions. It offers a valuable resource for the derivation of efficient designs, producing sustainable solutions, and achieving more innovative, artistic, and functional architectural outcomes. Biomimicry is the science that examines and imitates the adaptable strategies of nature's models to address human problems and improve the architectural design performance [6, 7]. Through the movements of plants, animals, and humans, nature reflects inspiring adaptive capabilities that can be transferred into architecture. Examples of kinetic design principles derived from nature include: mimicking the motion of plants such as stems, petals, or leaves that open and close in response to sunlight or other stimuli; using materials that change shape or properties in response to environmental conditions in a similar way to how natural organisms adapt; and adopting innovative solutions for systems inspired by nature, such as kinetic shading systems [8].

Designing kinetic buildings based on nature aims to enhance adaptability in building designs, making them more intelligent and responsive to the surrounding environmental stimuli. For example, plants offer effective strategies for light control through shape changes. The geometric and morphological shape of plants is a rich source for extracting interactive light strategies, employed in the design of kinetic shaded façades [6]. The biological responses to specific stimuli, such as sunlight, are studied, focusing on the mechanisms that trigger motion in parts of plants, such as their petals and leaves [8]. Hosseini et al. [6] have noted that design within biomimicry takes the ecosystem into account by mimicking plant movements to improve visual comfort and reduce the use of artificial lighting. Plants represent one of the key elements from which designers can learn biomimetic adaptation techniques in architectural design. They possess unique features that enable them to respond to environmental changes such as darkness, light, humidity, rainfall, temperature, freezing, air movement, or air quality. These characteristics position plants as a vital source of inspiration for developing adaptive movement strategies in responsive building design [9].

The influence of nature on kinetic architecture is evident from the preceding discussion. Consequently, this paper focuses on exploring the role of nature in shaping kinetic buildings, specifically examining its impact on the movement of key architectural components such as roofs and façades. The study is structured as follows: the next section outlines the research problem, aims, and methodology, followed by the third section, which develops a theoretical framework defining nature-inspired design strategies in kinetic architecture. In the fourth section, the research applies this theoretical framework to a descriptive analysis of selected kinetic architectural projects, examining the specific application of the three identified strategies first in the design of roofs, and then in façades. The final section presents the study's results and conclusions.

2. RESEARCH PROBLEM AND METHODOLOGY

This paper examines the influence of nature on design strategies applied in kinetic buildings, with a particular focus on its role in developing kinetic roofs and facades. The study aims to build a comprehensive understanding of nature's contribution to kinetic architectural design through a conceptual analysis of the available literature. This analysis focused on two main aspects: the properties of kinetic buildings shaped by natural principles, and the roles of nature in informing the design process of such buildings. The study found three primary roles for nature in the design of kinetic buildings: the first as a reference for form, the second as a reference for movement, and the third as a controller of movement.

Following this, the paper conducted a descriptive analysis of selected case studies involving real kinetic buildings influenced by nature, to identify the similarities and differences in the nature roles between movable roofs and dynamic façades. The criteria for case selection are:

- They are well-known architectural practices.
- The selected cases belong to different functional types of buildings.
- They cover diverse geographical locations such as North America, Europe, and Asia with different climatic zones.
- The construction completion dates back to different time periods: 2 projects before 2000, 7 projects between 2000 to 2009, 15 projects from 2010 to 2019, and 4 projects from 2020 onward.
- There are numerous descriptions of them in architectural literature.

3. THE INFLUENCE OF NATURE ON THE DESIGN OF KINETIC BUILDINGS

Movement plays a fundamental role in the design of kinetic buildings inspired by nature, with biomimicry offering innovative technological solutions in both form and morphology. These designs often draw on biological mechanisms of motion, such as the movement of magnolia flower petals, exemplified in the kinetic roof of the Shanghai Sports Center. Biomechanical systems enable buildings to adapt to climatic conditions by emulating the transformative movements observed in living organisms, thereby enhancing both sustainability and aesthetic quality, particularly in kinetic façades [6]. Based on a review of previous studies, this research identifies three primary design strategies through which nature informs kinetic architectural design:

- Simulation of natural form
- Simulation of natural movement
- Performance control through interaction with natural ecosystems

The following sections of the research explore the defining characteristics of kinetic buildings and examine the role of nature in the architectural design process.

3.1 Characteristics of nature-influenced kinetic buildings

The characteristics of nature-influenced kinetic buildings can be analyzed through two key dimensions: the location of movement within the building structure and the type of movement exhibited.

In terms of movement location, it varies from specific internal components such as movable roofs and kinetic façades to the entire building that may change its shape. Kinetic transformations may occur within a single building component, span a portion of the building structure, or involve the entire building, either through interaction with external elements or by relying solely on the structure's internal capabilities [10]. Consequently, kinetic structural systems are defined as buildings or components capable of variable movement, encompassing elements such as roofs, façades, or other parts of the building envelope or structure [10, 11].

Regarding the types of movement in kinetic architecture, Stevenson categorizes kinetic transformations into several distinct forms: deformation, folding, expansion, stretching, sliding, and rotation. These movements may be implemented individually or as combinations of multiple transformation types, depending on the architectural and functional objectives of the design [12, 13].

Types of movement are decided based on the location of the movement within the building and the required environmental or aesthetic functions. The choice of movement type is almost related to the environmental function (improving shading, ventilation, energy saving), climate responsiveness (protection from sun, wind, rain), as well as aesthetic and interactive aspects with users.

Movement in roofs is often folding or rotating around a central axis, inspired by the motion of wings or petals, to achieve control of shading, protection from weather, or ventilation, such as the UAE Pavilion in Expo Dubai 2020, Starlight Theater, and Shanghai QiZhong Stadium. Movement in façades occurs through opening and closing panels, rotating or swinging, usually to provide dynamic shading and adapt to sunlight and wind, either by mechanical movement, such as the Arab Institute Building in Paris, and Al Bahr Towers, or natural kinetic movement without mechanical control, such as Wind Arbor façade and the Wind Veil façade.

Integrated movement systems combining roofs and façades, or the entire structure, rely on advanced control with sensors and software to adjust the building's response to environmental factors and improve energy efficiency, such as HelioTrace façade and Kiefer Technic Showroom. Uncontrolled natural movement, such as panels or rods moved by wind, is often used in applications focusing on aesthetics and environmental interaction with reduced technical complexity, such as Wind Arbor and Moving Goalposts façades.

3.2 The role of nature in the strategies of kinetic architecture design

The role of nature in the design of kinetic buildings can be understood through three primary strategies. In each, nature serves as a foundational reference—either for form, movement, or performance control. Specifically, nature may be utilized: (1) as a reference for the geometric form of the moving elements; (2) as a model for the dynamic action or behavior of movement; or (3) as a mechanism for regulating movement to achieve performance-based goals. The following sections provide definitions and explanations for each of these three nature-inspired design strategies.

3.2.1 The role of nature as a reference for the geometry of movable components

The role of nature as a reference for form in kinetic architecture can be attributed to two distinct strategies: literal imitation and abstraction of natural forms.

• **Literal imitation of natural form:** This approach aims to replicate nature in an iconic way that the building or architectural element directly mirrors the shape of a natural reference as a recognizable representation, such as mimicking the shape of a bird's wing or the literal imitation of a mangrove flower. This approach creates a clear visual link with the natural reference, such as the direct imitation of falcon wings in the UAE Pavilion at Expo Dubai 2020.

• **Abstraction of natural form:** In this approach, the natural form is symbolized by simplifying or reinterpreting it to capture its essence or core characteristics. The conceptual qualities of the natural reference are preserved while embodying it in a geometric representation, such as the abstraction of the shape of magnolia petals or fish scales.

Some projects have combined both iconic and symbolic strategies, such as the Zoomlion Center in California, which mimics the shapes of butterfly or eagle wings on some façades, while using the abstraction of other animals like frogs in other parts. This achieves a balance between iconic and symbolic imitation of natural forms.

From the analyses of design cases, certain guidelines can be drawn: when there is a strong need for iconic representation or cultural expression, direct imitation of natural reference is preferred. In situations that require precise environmental performance or efficient mechanical solutions, symbolic representation and abstraction of natural reference is the better choice.

3.2.2 The role of nature as a model for the dynamic action of movement

Many designers incorporate natural movements in their designs by either simulating motion in nature or by designing components that respond dynamically to natural forces. The first approach involves mimicking specific natural motions, while the second approach represents the design's responsiveness to environmental changes, thereby enhancing the interaction of the building with its surroundings.

Accordingly, the second role of nature as a reference for movement can be classified into two strategies: the first is that the design mimics the movement of the natural reference, and the second is that the design movement is a reaction to the dynamic environment.

Mimicking natural motion in design components: This strategy enhances the interaction between the building and its surrounding environment by implementing the movement patterns of nature in architecture. The kinetic principles of living organisms have inspired the geometric formations and mechanical behavior of design components such as the flapping of bird wings or the opening and closing of flower petals. In addition, the motion of natural phenomena such as sea waves serves as a reference for movable design [6].

Design elements responding to environmental movement: In this responsive design strategy, movable elements respond directly to their surrounding environmental actions, such as wind movement, and natural variables such as solar position and natural lighting. This approach reflects the design's ability to real-time and interact to its environment to improve environmental performance and user comfort. Examples include movable aluminum fins or wooden panels that rotate in response to wind flow, or design elements that track the path of the sun to optimize daylight penetration and shading.

3.2.3 The role of nature as a control mechanism for regulating movement to achieve performance-based goals

Applying biological principles in architecture considers environmental factors such as temperature, lighting, humidity, and carbon dioxide. Kinetic building structures are characterized by their ability to modify shape in response to climatic changes. Ochoa and Capeluto defined active dynamic façades as systems that interact with environmental variables through sensors and control devices to regulate energy use, shading, and ventilation to gain performative adaptation [14].

Adaptive kinetic façades and roofs represent advanced architectural systems that immediately respond to changing environmental factors via movable components that enhance the transfer of energy, air, and information. These systems rely on technologies such as sensors, software, and electromechanical actuators powered by natural sources, including the sun, wind, and gravity, to reconfigure design elements to improve occupant well-being, thermal comfort, and energy efficiency [15].

The design of these systems is based on biomimicry principles of biological adaptability, incorporating flexible and smart materials [6]. The operation of these systems is managed by a computerized control system composed of a central processing unit, sensors, and software to detect environmental changes or user interactions and execute the required movements based on the input data [16]. Furthermore, smart building envelopes, made of materials capable of changing their shape in response to environmental changes, facilitate movement without relying on computer control. These systems can also integrate with building intelligence systems, acting as both sensors and moving components [10].

Control systems in kinetic buildings can be classified into passive and active systems:

Passive systems: These systems offer sustainable solutions for dynamic architecture by relying on natural conditions such as wind or sunlight to manage the movable elements of a building without the need for complex control systems [17].

Active systems: These systems, in contrast, rely on mechanical or electronic actuators to real-time control the movement of building elements in response to environmental data or user needs. These systems are typically integrated with embedded computerized controls that collect, process, and analyze environmental inputs, such as temperature, solar radiation, and wind speed, to optimize interior conditions and enhance occupant comfort [18]. The performance of active kinetic systems is further improved through the use of parametric design strategies and digital simulation tools. Software platforms such as Rhino, Grasshopper, and Ladybug facilitate the development of responsive façades by enabling real-time environmental analysis, supporting sustainability objectives, and improving both design efficiency and adaptability of movable architectural elements [19].

Based on the foregoing, the role of nature in the design of kinetic buildings can be summarized in Table 1.

Table 1. Variables of nature's role in the design of kinetic buildings

The Role of Nature in the Design of Kinetic Buildings	Form simulation: as a reference for the geometric form of the moving elements	Literal imitation of natural form	
		Abstraction of Natural Form	
	Motion simulation: as a model for the dynamic action or behavior of movement	Mimicking natural motion in design elements	
		Design Elements Responding to Environmental Movement	
	Performance control: as a control mechanism for regulating movement to achieve performance-based goals	Direct control	
		Indirect control	Computer
			Algorithm
			Sensors
			Actuators

The subsequent sections of this paper examine the specific application of nature-inspired design strategies in kinetic architecture through two groups of case studies. The first group focuses on real projects of kinetic building roofs, while the second group analyzes kinetic building façades. Each case is evaluated to identify how the three nature-based design strategies: form simulation, motion simulation, and performance control, are implemented in practice.

4. NATURE-INSPIRED DESIGN STRATEGIES FOR GENERATING KINETIC ROOFS

In light of technological advancements and the growing emphasis on sustainability, kinetic roofs and dynamic structures have become an essential part of contemporary architectural design. Architectural surfaces are no longer static; instead, they have evolved into intelligent, responsive kinetic systems that interact with the environment to enhance comfort and reduce energy consumption. These systems vary from retractable roofs, movable canopies, to kinetic roof structures inspired by nature, such as bird wings and flower petals, aiming to achieve a balance between functionality and aesthetics.

This paper adopts a descriptive-analytical approach to examine eight case studies of nature-inspired kinetic roof designs. The analysis reveals that kinetic roofs represent innovative solutions that go beyond aesthetics to enhance sustainability and environmental comfort. They effectively contribute to energy production using solar panels that adapt to climatic conditions such as heat, rain, and sandstorms. These systems enable precise control of a building's response to environmental factors such as sunlight and ventilation. Kinetic roofs are redefining how buildings are designed to meet changing climate requirements.

Advanced computational techniques facilitate the transformation of roofs, enabling them to open for ventilation in appropriate weather conditions and seamlessly transition between open and closed states when needed. This suggests that movable roofs are not merely functional elements, but rather dynamic designs capable of enhancing the user experience based on environmental changes.

In the following sections, the paper presents real-world examples of movable roof designs inspired by nature.

4.1 UAE Pavilion for expo 2020, Dubai, by Santiago Calatrava

The roof was designed to mimic the movement of a falcon’s wings in flight, consisting of 28 movable wings that all rotate around a single pivot point. These wings, powered by 46 hydraulic actuators, can open and close using a dynamic folding mechanism [20]. Integrated carbon fiber photovoltaic panels generate energy [21], offering protection from rain and sandstorms when closed and harvesting solar energy when opened. Solar, wind, and shading analyses supported by 3D modeling optimized the roof's environmental performance [22], allowing the building to actively contribute to energy conservation by supplying power to the main grid (Figure 1) [23].

Figure 1. UAE Pavilion for expo [22]

4.2 Milwaukee Art Museum "Quadracci Pavilion", 2001, Wisconsin, U.S., by Santiago Calatrava

The Quadracci Pavilion draws inspiration from the flight of seagulls, blending architecture with nature. Its 72-steel wing-like fins form a movable sunshade that adjusts to sunlight and weather via a computer-controlled hydraulic system [24]. Guided by environmental sensors, the wings close automatically in high winds and take about 3.5 minutes to fully retract. The sensors on the fins continuously monitor wind speed and direction, so when the wind speed exceeds 23 miles per hour for more than 3 seconds, the wings automatically close, allowing the building to adapt dynamically to changing conditions (Figure 2) [25, 26].

Figure 2. Milwaukee Art Museum [25]

4.3 Florida Polytechnic University, 2014, Florida, U.S., by Santiago Calatrava

This kinetic roof, inspired by bird wings and oak trees, includes solar canopies made of aluminum panels that move linearly via a hydraulic system. Controlled by environmental sensors or computer programming, the panels adjust to the sun's position to provide shading, natural ventilation, and thermal comfort. A surrounding pergola reduces solar impact by 30%, enhancing the building's passive environmental performance (Figure 3) [14, 24, 27, 28].

Figure 3. Florida Polytechnic University [14, 28]

4.4 Zoomlion Main Exhibition Center of Amphibians, 2011, California, U.S., by AmphibianArc

This transformable building features a kinetic roof and façades that mimic the movements of insect and bird wings, including those of an eagle, butterfly, dragonfly, and frog. Operable steel and glass panels, mounted on hydraulic arms, allow the structure to shift shape, such as the north façade forming an eagle or butterfly, and the south folding into a frog. Parametric modeling was used to optimize daylight entry and light diffusion across the site (Figure 4) [29].

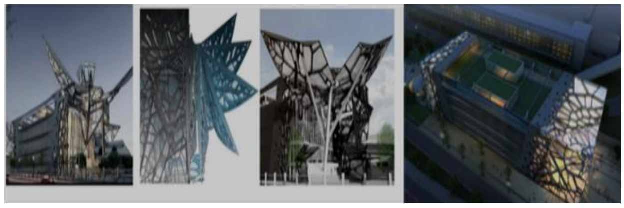

Figure 4. Zoomlion's main exhibition center of Amphibians [29]

4.5 Starlight Theater, 2003, Rockford, Illinois, U.S., by Studio Gang Architects

This open-air summer theater features a transformable roof inspired by potato flower petals and origami folds. Made of wood and steel, the roof consists of six hinged triangular panels that open upward in a helical sequence via a computerized control system. Operable with a single click and guided by environmental sensors, the roof provides shelter when closed and natural ventilation with sky views when open, ensuring performance continuity in various weather conditions (Figure 5) [7, 25, 26, 30, 31].

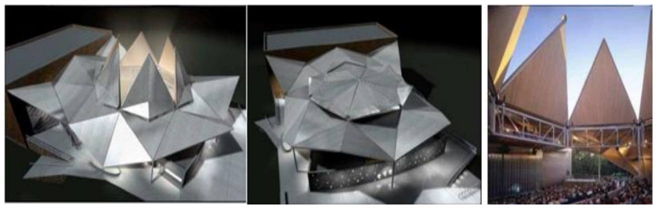

Figure 5. Starlight Theater [25]

4.6 The Shanghai Qizhong Forest Sports City, 2005, China, by a Chinese company

The stadium features a dynamic roof with eight movable petals inspired by the magnolia flower. Designed to adapt to Shanghai's variable climate, the petals open for shading in sunlight and close during rain to retain warmth. Each pedal rotates around a single pivot, supported by three structural arms. The system was developed using numerical simulations and advanced design tools (Figure 6) [7, 25, 31].

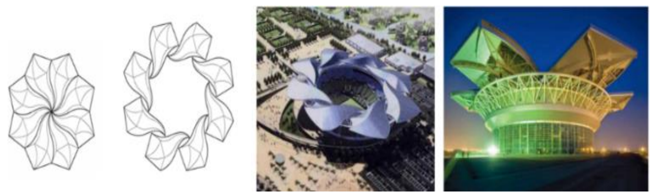

Figure 6. The Shanghai Qizhong [25]

4.7 The Kuwait Pavilion of Expo, 1992, Seville, Spain, by Santiago Calatrava

The roof design mimics palm fronds, featuring two rows of foldable, tapered "fingers" with seventeen ribs each, operated by electric motors. Controlled by a computerized system, the roof adjusts to fifteen pre-programmed positions, opening vertically for sunlight or overlapping to form a closed canopy (Figure 7) [25, 32, 33].

Figure 7. The Kuwait Pavilion [25]

4.8 Mobile hybrid chassis, 2022, Germany, by Paul Marker of Brandenburg University of Technology

This hybrid movable roof combines flexible kinetic motion with rigid body mechanics, using sensors, algorithms, and actuators for stability and adaptability. Inspired by the Fin Ray® effect in fish fins and butterflies, the radial design allows flexible components to rotate around a circular structure. A linear actuator opens the roof in 15 seconds, with motors controlled together or independently to adjust shape and flexibility (Figure 8) [34].

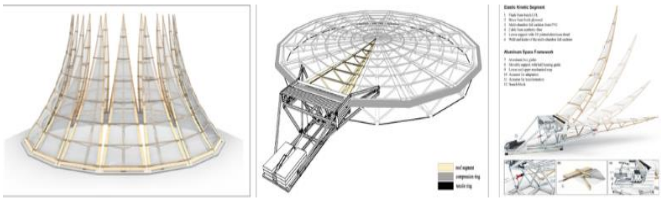

Figure 8. Mobile hybrid chassis [34]

Based on the descriptive analysis of buildings with movable roofs, the nature-inspired design strategies adopted in their designs can be identified, as shown in Table 2.

Table 2. Nature-inspired design strategies for the generation of kinetic roofs

Case Studies	Building Specifications						The Role of Nature in the Design of Kinetic Buildings							
	Position of Movement		Movement Style				As a Reference to the Shape		As a Reference for the Movement		As a Tool for Controlling Building Performance			
												Indirect control		
	Part of the roof	The roof as a whole	Transformation	Rotation	Deployment and folding	Openness and closure	Literal imitation of a shape as a reference	Abstraction of the reference shape	Imitation of the reference movement	Reaction to the reference movement	Direct control	Computational Algorithm	Sensors	Actuators
UAE Pavilion at Expo 2020 Dubai		●		●	●		●		●			●		●
Milwaukee Art Museum "quadracci pavilion" In Wisconsin, U.S.	●					●		●	●			●	●	●
Florida Polytechnic University, in the US	●				●			●	●			●	●	●
Zoomlion's Main Exhibition Center of Amphibians in California	●				●	●	●		●					
The Bengt Sjostrom/Starlight Theater- in the USA	●					●		●	●			●	●	●
The Shanghai Qizhong Forest Sports City in China		●		●		●		●				●	●	●
Kuwait Pavilion for Expo 92, Seville		●				●		●				●		●
Mobile Hybrid Chassis		●		●	●			●	●			●	●	●

5. NATURE-INSPIRED DESIGN STRATEGIES FOR GENERATING KINETIC FACADES

Biology has been integrated with architecture through biomimicry, which considers nature as a vast repository of mechanisms and strategies that can be applied in the design of buildings. Biological solutions can be multifunctional, complex, and highly responsive, thus offering a transformative alternative to traditional static building envelopes for adaptive energy performance [9]. Biomimetic design approaches enhance the adaptability of building facades to diverse environmental conditions, thereby improving sustainability by emulating principles found in nature. Thus, these nature-inspired methodologies enable building envelopes to be more responsive to both external and internal conditions while meeting comfort levels [9]. They focus on developing adaptive architectural façades, wherein building envelopes—modeled after living organisms—respond dynamically to external stimuli through complex, multi-level kinetic systems [9, 10].

This approach can replace static building envelopes with intelligent, interactive skins that sustainably enhance energy performance. By the integration of multifunctional biological solutions, future building envelopes will become more responsive to both internal and external environmental conditions, thereby achieving higher levels of comfort and efficiency [9]. A kinetic façade represents a dynamic envelope system that interacts with environmental stimuli using sensors and actuators [9]. For instance, responsive façades optimize the use of natural light and enhance natural ventilation. The developed building skins adjust their shape and movement in response to external light intensity and sun angles, providing dynamic control of daylighting and reducing unwanted glare and heat gain [6]. However, adaptability alone does not render a responsive envelope as biomimetic; rather, kinetic envelope technologies can emerge from various theories proposing principles for generating responses to external environmental stimuli [10].

Nature, through the movements of plants, animals, and humans, reflects adaptive potentials that serve as an inspiring source for architecture. The geometric and morphological features of plants offer a rich basis for extracting interactive strategies with light, which can be employed in designing kinetic shading façades that are able to move from static to dynamic states. An example is the Council House façade in

Melbourne, whose movement was inspired by the behavior of trees. This design contributed to reducing energy consumption of up to 82% and decreased reliance on mechanical lighting and ventilation systems by 65%, demonstrating the high potential of biomimicry approaches in providing energy-efficient and sustainable technological solutions for façade design [5]. Additionally, López et al. introduced biomimetic principles for adaptive architectural envelopes based on understanding plants at both macro and micro levels to address environmental challenges. Their approach follows the dynamic mechanisms in plants that respond to external stimuli through movement [9].

The integration of nature-inspired forms and their transformative properties offers an opportunity to create new façade systems that are intelligent, interactive, and responsive to environmental conditions [5]. Furthermore, smart envelopes made from materials capable of shape transformation in response to environmental changes can facilitate movement without the need for complex computational devices. However, these systems can be integrated with building intelligence to function as both sensors and Kinetic building components, thereby enhancing the interaction between the building and its environment [10].

In addition, the adaptability of kinetic façades has been enhanced through the use of machine learning algorithms and artificial intelligence, enabling façades to learn from the environment and user interactions and to make appropriate adjustments. This adaptability allows façades to anticipate and respond to environmental conditions, thereby improving energy efficiency and meeting user needs [16]. Responsive façades can adapt to changing environmental conditions by altering their configurations or positions without compromising their structural integrity [17].

In the following sections, the study explores the role of nature in the design of several contemporary building façades and envelopes.

5.1 One Ocean – Thematic Pavilion for Expo, 2012, Yeosu, South Korea, by SOMA and Lima

The kinetic facade of the building is inspired by the movement of fish gills, featuring flexible plates that move in a wave-like sequence in response to sunlight and wind. Controlled by sensors and a centralized computational system, the plates enhance shading and ventilation. Actuators and servo motors drive their motion along a helical axis, following a programmed movement pattern. The actuator of the louvers is a screw spindle driven by a servomotor. A computer-controlled bus system allows the synchronisation of the actuators. Each louver can be addressed individually within a specific logic of movement to show different choreographies and operation modes. They reduce the distance between the two bearings and in this way induce a bending which results in a side rotation of the louver (Figure 9) [9, 10, 17, 24, 31, 35].

Figure 9. One Ocean – Thematic Pavilion for Expo [10, 24]

5.2 Arab Institute building, 1987, Paris, France, by Jean Nouvel

The IMA building's southern façade is inspired by traditional mashrabiya, featuring metallic shading elements with camera-like apertures that open and close automatically to regulate light and heat. Powered by photovoltaic cells and controlled by sensors, actuators, and computational technologies, the kinetic system responds to environmental conditions and user input, enhancing comfort through adaptive shading (Figure 10) [10, 25, 31, 33, 36, 37].

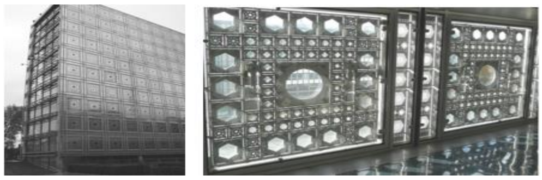

Figure 10. Arab Institute building [36]

5.3 Wind Arbor, 2011, Singapore, by Ned Kahn

The hotel lobby's glass façade is covered with 500,000 hinged elements that sway naturally with the wind, while the western façade features 260,000 flexible aluminum fins that move independently in a circular wave-like motion without control systems. This passive kinetic design enhances shading and reduces solar heat gain (Figure 11) [17, 38, 39].

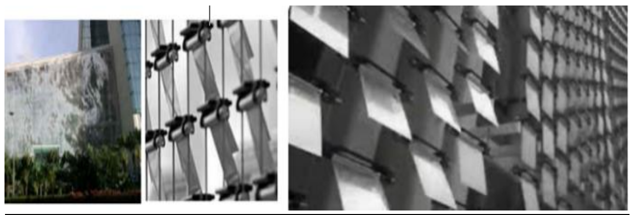

Figure 11. Wind Arbor [38, 39]

5.4 Mokyeonri Wood Culture, 2017, South Korea, by Soft Architecture Lab

The museum features an interactive façade made of hexagonal wooden panels that rotate in response to wind and light. Mounted on metal frames with spring-loaded joints, the panels adjust their angle to control daylight entry, creating a dynamic experience for visitors (Figure 12) [17, 40].

Figure 12. Mokyeonri Wood Culture [40]

5.5 Council House 2, 2020, Melbourne, Australia, by Kajal Unahariya

Inspired by trees, this adaptive façade uses vertically moving wooden slats to reduce energy use by up to 82% and cut reliance on artificial lighting and ventilation by 65%. Controlled by sensors and mechanical actuators, the slats adjust automatically to the sun's path, closing quickly in summer to reduce heat and glare and opening slowly in winter to improve comfort (Figure 13) [6, 17, 41, 42].

Figure 13. Council House 2 [42]

5.6 The Syddansk Universitet, 2014, Denmark, by Henning Larsen

This responsive façade features 1,600 triangular metallic units that act as movable shutters, adjusting to temperature and light changes to maintain indoor comfort. Equipped with sensors and mechanical actuators that control the opening and closing of the panels, the system transitions between open, partial, and closed states based on real-time environmental data processed by a computational system for optimal shading (Figure 14) [14, 31, 43, 44].

Figure 14. The Syddansk Universitet [31, 43]

5.7 RMIT Design Hub, 2012, Melbourne, Australia, by Sean Godsell architects

Inspired by human skin, the building's exterior features over 16,000 circular glass cells connected to rotating rods powered by electric motors. Controlled by environmental sensors, the system includes automated shading, photovoltaic cells, evaporative cooling, and fresh air intakes. It adapts to humidity and temperature changes, improving indoor air quality and reducing energy use (Figure 15) [14, 45, 46].

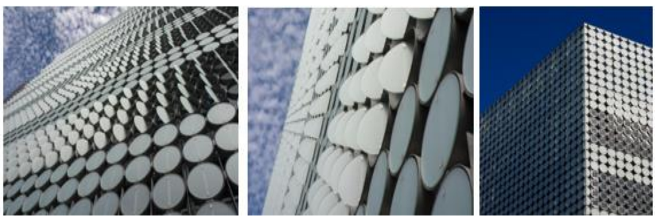

Figure 15. RMIT design hub [46]

5.8 Windswept installation, 2012, San Francisco, California, U.S., by Charles Sowers Studios

The southern façade of the Windswept Museum uses a passive system with 25 metal panels and 612 aluminum wind indicators that move freely with the wind. Without motors or sensors, the indicators form dynamic patterns that visualize wind flow, blending aesthetics with environmental responsiveness (Figure 16) [17, 47].

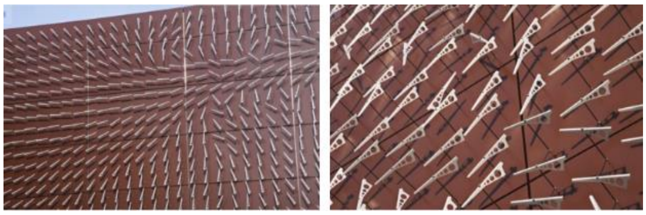

Figure 16. Windswept installation [47]

5.9 HelioTrace Façade System, 2013, New York, U.S., by Hoberman Associates and SOM office

The HelioTrace Façade combines kinetic shading, structural elements, and internal mechanics to reduce energy use and enhance comfort. It features programmable external devices that track the sun's path and adjust within 5 seconds. With three degrees of freedom, the system enables complex forms and is powered by electromechanical motors and sensors. The Strata system controls light and heat flow in real time based on environmental conditions (Figure 17) [14, 48, 49].

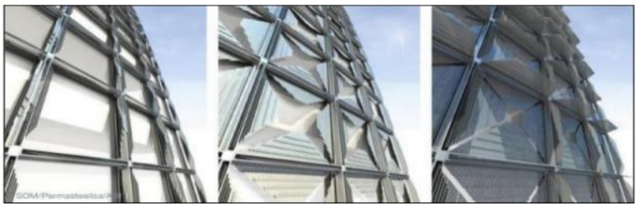

Figure 17. HelioTrace Façade System [48]

5.10 Cost Action TU1403, 2015, Tehran, Iran, case study by Sadegh et al. [50]

This modular kinetic façade, inspired by the four-petaled lotus flower, was developed for an office building in Tehran to optimize daylight, comfort, and energy use. Petals bend from a central axis, forming diamond shapes when open and diagonal patterns when closed. The system aims to minimize mechanical components and structural load while allowing independent control of each unit (Figure 18) [50].

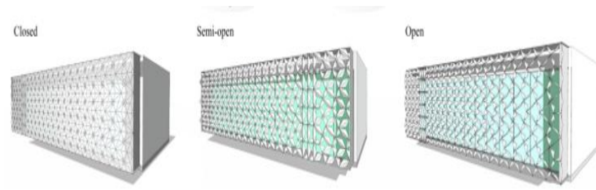

Figure 18. Cost Action TU1403 [50]

5.11 Q1, Thyssenkrupp Quarter, 2010, Essen, Germany, by Chaix & Morel et Associés and JSWD architekten

The façade features 3,150 feather-like stainless steel panels that open and close based on user input and sensor data. Each panel has an electric motor that adjusts according to the sun's movement, regulating light and preventing unwanted solar heat gain (Figure 19) [17, 51].

Figure 19. Q1, Thyssenkrupp Quarter [51]

5.12 Media-ICT 2011 in Barcelona (Spain) by Enrique Ruiz Geli, Barcelona (Spain)

The façade features inflatable ETFE cushions, supported by a steel mesh, which adjust in response to sunlight. These cushions inflate and deflate without the need for mechanical actuators. This smart pneumatic system acts as a dynamic sunshade, opening in winter for solar gain and closing in summer for shading. The cushions reposition in just three minutes, enhancing indoor climatic comfort and reducing energy consumption (Figure 20) [39, 48, 52].

Figure 20. Media-ICT [39, 52]

5.13 Kiefer Technic Showroom, 2010, Gleichenberg, Austria, by Ernst Giselbrecht + partner

The building's envelope features perforated aluminum panels that fold, slide, and rotate around a central axis. These panels adapt to climate conditions, improving the internal environment. The system is operated by electric motors that are electronically controlled, with sensors monitoring environmental changes. The system is programmed to display different configurations and patterns (Figure 21) [17, 25, 37, 53].

Figure 21. Kiefer Technic Showroom [25, 37]

5.14 Al Bahr Towers, Abu Dhabim 2012 in the United Arab Emirates by Aedas

The tower façades feature an automated shading system composed of umbrella-like glass units that open and close with a central folding motion, mimicking the blooming of mangrove flowers in response to sunlight. The system operates with computer-controlled technology, where PTFE panels adjust according to the sun's path to block direct sunlight and regulate shading. Sensors control the movement based on climatic conditions (Figure 22) [10, 11, 49].

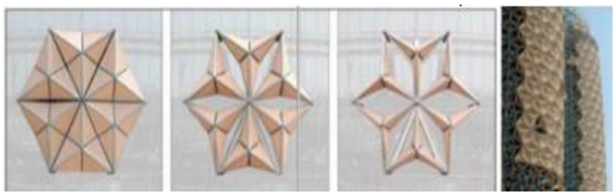

Figure 22. Al Bahr Towers [11, 49]

5.15 Wave-Wall, 2007, Ligo Visitor Center, U.S., by Shawn Lani, Charles Sowers, and Peter Richards

The massive kinetic façade features 35-foot pendulums activated directly by the wind, creating fluid, wave-like motions. Magnets connect each pendulum to its neighboring one [54] , producing a dynamic display that reflects light, resonance, and gravity (Figure 23) [17, 54].

Figure 23. Wave-Wall [54]

5.16 Children's Museum of Pittsburgh, 2004, Pennsylvania, U.S., by Koning Eizenberg architecture

The artwork features thousands of white plastic squares forming a wind-activated façade that evokes a digitized cloud. The elements are set within an aluminum frame, creating a light, bright effect (Figure 24) [17, 55].

Figure 24. Children's Museum of Pittsburgh [17, 55]

5.17 Moving goalposts, 2022, California, U.S., by Ned Kahn

The designer incorporated 4,000 aluminum rods mounted on garage openings, with each rod swaying freely in the wind. A balancing weight on each rod ensures it automatically returns to its vertical position after each gust (Figure 25) [56].

Figure 25. Moving goalposts [56]

5.18 The building's skin: New kinetic façade, 2018, Spain, by Amusement Logic team

The façade features vertical sculptural panels made from organically cut boards that move on independent axes, adjusting based on natural light. The panels open at dusk to let in light and close during the day to reduce solar heat. A computer-controlled system manages their movement, creating changing shadows and offering dynamic visual effects. At night, the rotating panels reveal the rear façade, adding a striking light contrast (Figure 26) [57].

Figure 26. The building's skin [57]

5.19 The Wind Veil, 2000, United States of America, by Ned Kahn

This dynamic façade, inspired by nature, features 80,000 pivoting aluminum panels that move with the wind, creating a wave-like effect. The motion mimics fields of grass, generating shifting light patterns and improving internal ventilation (Figure 27) [25, 58].

Figure 27. The Wind Veil [25]

5.20 The flare system, 2008, Germany, by WHITE

The flare kinetic façade is an interactive system that responds to climate and lighting. It consists of tilting metal slats controlled by pneumatic cylinders, offering shading or sunlight reflection. Managed by a computer system, it adapts to the building's environment using data from internal and external sensors (Figure 28) [18, 22, 14, 59].

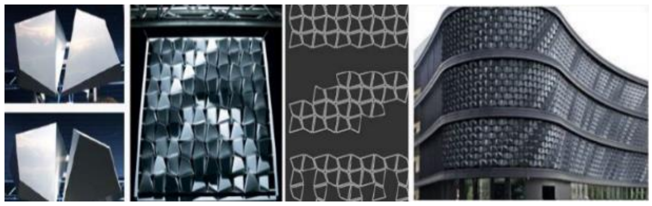

Figure 28. The flare system [59]

Based on the descriptive analysis of case studies with dynamic facades and envelopes, design strategies inspired by nature can be identified in their designs, as shown in Table 3.

Table 3. Design strategies inspired by nature in generating kinetic facades

Case Studies	The Style of Movement in the Facades							The Role of Nature in the Design of Kinetic Buildings							
								As a Reference to the Shape		As a Reference for the Movement		As a Tool for Controlling Building Performance			
													Indirect control		
	Rotation	Expansion or deployment and folding	Wave motion	Oscillatory (Vibrational)	Inflation and deflation	Tiltable or swayable	Openness and closure	Literal imitation of a shape for a reference	Abstraction of the reference shape	Imitation of the reference movement	Reaction to the reference movement	Direct control	Computational algorithm	Sensors	actuators
One Ocean – Thematic Pavilion for Expo Yeosu, in South Korea			•						•				•	•	•
Arab World Institute in Paris, France-							•						•	•	
Wind Arbor, Singapore				•							•	•			
Mokyeonri Wood Culture in South Korea	•				•	•						•			
Council House 2 façade in Melbournekajal, Unahariya	•						•						•	•	•
The Syddansk Universitet in Denmark							•						•	•	•
RMIT Design Hub opens in Melbourne	•						•		•			•	•	•	•
Windswept installation in San Francisco, California, USA	•										•	•			
HelioTrace Façade System in New York, USA		•									•		•	•	•
"Cost Action TU1403" in Iran	•						•		•					•	•
Q1, Thyssenkrupp Quarter in Essen, Germany							•		•			•			

Media-ICT in Barcelona						●					●	●			
Kiefer Technic Showroom in Gleichenberg, Austria		●											●	●	●
Al Bahr Towers, Abu Dhabi in United Arab Emirates							●	●		●	●		●	●	●
Wave-Wall in the U.S.			●					●		●	●	●			
Children's Museum Of Pittsburgh in Pennsylvania			●	●						●	●				
Moving goalposts in California				●		●					●	●			
The building’s skin: New kinetic façade in Spain	●								●				●	●	●
The Wind Veil in the United States of America		●						●			●	●			
The flare system in Germany						●							●	●	●

6. RESULTS

Kinetic architecture seeks to transform building forms in response to user needs and environmental conditions by employing biomimetic strategies inspired by nature at three levels: the first and second levels draw from natural forms and movements, while the third level reflects interactions within entire ecosystems. By mimicking natural processes and enhancing responsiveness to climatic variations, such approaches contribute to the optimization of building performance.

This study presents the findings of a descriptive analysis of kinetic architectural designs focused on the comparison between roofs and façades, as summarized in Table 4.

Table 4. Percentage of the use of nature-inspired design strategies in generating dynamic facades and roofs within the study samples

Type of Designs	The Style of Movement in Facades and Movable Ceilings							The Role of Nature in the Design of Kinetic Buildings							
								As a Reference to the Shape		As a Reference for the Movement		As a Tool for Controlling Building Performance			
													Indirect control		
	Rotation	Expansion or deployment and folding	Wave motion	Oscillatory (Vibrational)	Inflation and deflation	Tiltable or swayable	Openness and closure	Literal imitation of a shape as a reference	Abstraction of the reference shape	Imitation of the reference movement	Reaction to the reference movement	Direct control	Computational algorithm	Sensors	actuators
Percentage in kinetic roof designs	37.5%	50%					62.5%	25%	75%	75%			87.5%	62.5%	87.5%
Percentage in kinetic facade designs	30%	15%	15%	15%	10%	15%	35%	15%	25%	15%	45 %	45%	50%	55%	50%

The results highlight differences between these two components in terms of movement types and the extent to which nature influences their form, movement, or performance control. Roof designs demonstrate three primary types of movement: opening and closing, rotation, and deployment/folding. In four out of eight roof cases, two movement types are combined, whereas the remaining cases utilize a single movement type. In contrast, seven distinct movement types are identified in façade designs, with rotation and opening/closing being the most prevalent. Notably, 13 out of 20 façade designs incorporate only one type of movement.

The findings also highlight that the influence of nature as a formal reference is taken into account in all roof cases, but only in eight of the twenty facade designs. In roof designs, the natural forms are abstracted in six out of eight cases, while the abstraction is applied in only five of the twenty facade designs. Considering nature as a source of inspiration for movement, its influence is observed as an imitation of the reference movement in six out of eight cases of roof designs. Whereas the effects of nature on movement were considered in nine out of twenty facade design cases. In six facade cases, the movement represents only a direct response to a natural reference, while the remaining three cases combine both mimicry of natural movement with interactive behavior. It is worth noting that facades that respond to wind movements are often designed with an emphasis on enhancing aesthetic expression.

The role of nature as an environmental control mechanism is clearly evident in both roof and facade designs. Specifically, seven out of eight roof cases and nineteen out of twenty facade cases incorporate nature-inspired strategies for adapting to environmental conditions. Kinetic roofs rely primarily on active control systems to adapt to environmental changes, while kinetic facades employ either active or passive control mechanisms.

Active systems include computing technologies, sensors, and actuators that optimize the response of dynamic elements to real-time environmental data. These technologies support sustainability goals by reducing energy consumption and improving natural ventilation and daylighting. Designs that mimic natural movement through advanced technologies, such as hydraulic actuators and environmental sensors, play a critical role in reducing a building's environmental footprint.

7. CONCLUSIONS

Nature-based architectural designs integrate aesthetics and functionality, enabling buildings to respond to environmental conditions through kinetic components. Kinetic architecture, inspired by natural principles, represents a promising approach to achieving environmental sustainability, operational efficiency, and enhancing architectural appearance. Nature is no longer just a source of formal inspiration; it has become a reference for functional and interactive performance. The imitation of biological movements and environmental patterns provides buildings with dynamic adaptability to climatic and environmental changes.

Kinetic roofs and facades are the clearest example of this transformation, evolving from decorative features to vital tools for regulating temperature, lighting, and ventilation. A comparative analysis of kinetic roof and façade designs reveals that nature-inspired shaping mechanisms are more effective in roof designs than in façades. The natural form in both surfaces and kinetic interfaces is likely to be abstracted to represent a referential symbol rather than an icon. In addition, nature's influence as a reference for the movement is more dominant in roof designs than in facades. The movement of roof designs is the imitation of the reference motion, while the movement of façade designs is a reaction to the reference motion.

In both facades and roofs, nature plays a key role as an environmental control mechanism, primarily through active systems only in cases of roof designs, and active or passive systems in cases of facade designs. Active design strategies employ computational algorithms, sensors, and actuators to respond to external environmental conditions. The integration of digital technologies with ecosystem-inspired design principles offers significant potential for expanding the horizons of architectural innovation.

Advances in computational design and simulation technologies are enabling the development of transformable architectural forms that imitate the adaptive behaviors of living organisms. Thus, biomimetic kinetic architecture paves the way for the development of living buildings as structures that seamlessly combine aesthetic value with environmental responsiveness. This approach represents a forward-looking model for intelligent and sustainable architecture, where people, buildings, and nature develop an interconnected and dynamically adaptable system.

Future trends in kinetic designs mostly seek the integration of artificial intelligence systems and smart sensors. They represent a fundamental step toward constructing responsive buildings that enhance user comfort and reduce energy consumption. For example, applying computational algorithms such as machine learning with smart sensors enables kinetic building to learn from the environment and user interactions, allowing the anticipation of environmental conditions and the response accordingly to improve energy efficiency and user comfort. They provide control systems with input data to activate building motion in responding to various environmental changes, such as outdoor weather, without direct human intervention. However, these systems need to manage and analyze large amounts of environmental data and user interaction records in real time to be able to achieve precise dynamic responses.

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