Shaping and Application of Nature-Based Solutions in Architecture and Construction

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https://doi.org/10.29227/IM-2025-02-02-072

Submission date: *2025-07-31* | Review date: *2025-08-20*

Abstract

The contemporary urban environment is undergoing rapid transformation due to global climate challenges and the increasing demand for improved energy efficiency, reduced material consumption, and enhanced user comfort. Architecture and construction—fields deeply intertwined with resource management and environmental quality—must adopt innovative and sustainable design strategies. One of the most promising approaches is bionics (biomimetics), an interdisciplinary field that draws on principles from biological systems to inform design practices. Nature has long served as a source of architectural inspiration—from the symbolic and organic forms of Art Nouveau to contemporary projects enabled by digital technologies that allow for precise modeling of biological structures. However, modern biomimetics extends beyond aesthetics. It encompasses function, structure, and adaptive processes, integrating insights from biology, engineering, materials science, computer science, and architecture to develop nature-inspired systems that are more efficient, durable, and sustainable. Key technologies in this domain include parametric and generative design, environmental simulation, digital fabrication, and smart materials, all of which enable the creation of structures that respond dynamically to external stimuli. Additionally, the growing trend of biophilic design—often combined with biomimetics—contributes to the development of spaces that are not only energy-efficient but also promote the psychophysical well-being of users. This article aims to present the current state of knowledge regarding the application of bionic solutions in architecture and construction. Selected case studies are discussed to illustrate how biomimetic strategies have achieved high environmental, aesthetic, and functional performance. The article presents examples of rod structures based on minimal forms, as well as structures with topology inspired by nature and parametrically generated. It also explores specific architectural implementations and identifies challenges and future directions for this rapidly evolving field.

Keywords: Bionics, Biomimetics, Nature-based solutions, Sustainable architecture, Parametric design, Generative design

1. Introduction

Bionics, as the interdisciplinary science of imitating biological solutions, is gaining significant recognition in both architectural and civil engineering practice. This field, also referred to as biomimetics, draws inspiration from the principles and mechanisms observed in nature, which have been optimized over millions of years of evolution. Through processes such as natural selection and adaptation, organisms have developed solutions characterized by high efficiency in terms of structure, energy use, and environmental responsiveness. These naturally evolved strategies provide a rich source of ideas for solving complex problems in the built environment [1].

Architects and engineers increasingly recognize the potential of applying these biological principles to the design of sustainable, intelligent, and energy-efficient buildings. Unlike traditional design methods, which often rely on linear and resource-intensive approaches, biomimetic strategies emphasize optimization, adaptability, and resource minimization. For example, natural organisms utilize minimal material to achieve maximum strength, regulate their internal climate without external energy input, and maintain resilience under changing environmental conditions. Translating these principles into architectural solutions offers opportunities to reduce environmental impact while enhancing building performance [2].

Numerous researchers have highlighted the transformative potential of biomimicry in tackling pressing urban challenges such as climate change, urban heat islands, and the growing demand for buildings that provide improved comfort and well-being for occupants. The urban environment is undergoing rapid transformation, with cities facing the dual pressures of accommodating increasing populations and mitigating the effects of global warming. In this context, biomimetic approaches present a pathway towards regenerative design, where buildings do not merely minimize harm but actively contribute to environmental balance and resilience [3].

Furthermore, advancements in digital technologies have accelerated the integration of bionic principles into architectural and civil engineering practice. Tools such as parametric and generative design, computational fluid dynamics (CFD), and environmental simulation allow designers to analyze and replicate natural patterns with unprecedented precision. These technologies enable the modeling of complex biological forms, the simulation of their behavior under varying conditions, and their optimization for human-made structures. The development of smart materials, capable of responding dynamically to external stimuli, further enhances the potential of biomimetic architecture by introducing adaptive properties akin to those found in living organisms [4].

In parallel, the growing interest in biophilic design complements biomimetic approaches by emphasizing the psychological and physiological benefits of connecting people with nature in the built environment. While biomimicry often focuses on functional aspects—such as energy efficiency or structural optimization—biophilic design prioritizes human well-being, incorporating natural elements, daylight, greenery, and organic forms to create restorative spaces [5]. When combined, these two approaches have the power to redefine architectural design, leading to spaces that are not only sustainable but also supportive of human health and happiness.

The objective of this paper is to present the current state of knowledge regarding the application of bionic strategies in architecture and construction. The article illustrates how these solutions have been successfully implemented in a range of projects, from energy-efficient buildings to adaptive facades and lightweight structural systems. By analyzing selected case studies, the paper demonstrates the

environmental, aesthetic, and functional benefits of biomimetic architecture and construction. In addition, the article presents original examples of bionic roofs created using generative design tools. Furthermore, it discusses the challenges associated with adopting such strategies and outlines potential directions for future research and innovation in this rapidly evolving field.

This study ultimately seeks to highlight the role of bionics as a transformative force in architecture—one that bridges biology, technology, and design—to create the next generation of resilient and ecologically integrated built environments.

2.Bionic Inspirations in Architectural and Civil Engineering Design

Nature has always been an invaluable source of inspiration for designers. Drawing on its solutions makes it possible to create structures and systems that are not only aesthetically pleasing but also functional and aligned with the principles of sustainable development. Contemporary design increasingly relies on biomimetics, seeking to translate mechanisms found in the natural world into the language of architecture and engineering.

One of the most iconic examples of the use of biomimetic strategies is the Eastgate Centre in Harare, Zimbabwe, designed by Mick Pearce in collaboration with engineers from Arup. This building utilizes a passive ventilation system inspired by termite mounds, which maintain a constant internal temperature despite significant fluctuations in the external climate. Applying this principle to the building design has enabled a reduction in cooling energy consumption by up to 90% compared to traditional buildings of similar function [3]. This case is regarded as a milestone in the history of sustainable biomimetic architecture.

Another groundbreaking example is Al Bahar Towers in Abu Dhabi (United Arab Emirates), where a dynamic façade inspired by the traditional Arabic mashrabiya lattice was implemented. The system consists of hundreds of movable panels that automatically adjust their position to the angle of sunlight, reducing interior overheating and minimizing the energy required for cooling. As a result, the building achieved a 50% reduction in energy consumption while maintaining high user comfort [4]. This project demonstrates a successful fusion of tradition with modern technology in the spirit of biomimicry.

An increasingly important approach is biophilic design, which complements biomimicry by focusing not only on functionality but also on user well-being. Biophilic design involves the deliberate incorporation of natural elements into architectural spaces—both directly (vegetation, water, natural light) and indirectly (organic shapes, natural materials). Research has shown that such environments positively influence human mental and physical health, improving concentration, reducing stress, and enhancing the overall sense of comfort.

A remarkable example of integrating biophilic solutions into high-rise architecture is One Central Park in Sydney, Australia. This tower, designed by Jean Nouvel, is covered with vertical gardens and green terraces that not only improve air quality but also enhance urban biodiversity. A system of heliostat mirrors installed on the tower reflects sunlight to the lower parts of the building, allowing plant growth and reducing the need for artificial lighting. These solutions increase the building's energy efficiency, support the local microclimate, and create a welcoming living environment [5].

Contemporary projects increasingly combine biomimicry and biophilia, creating spaces that are energy-efficient, environmentally friendly, and beneficial to human health. This approach departs from the traditional perception of a building as a static object, introducing the concept of architecture as a living system that reacts, adapts, and interacts with its surroundings.

The following sections of this paper will present further examples of the application of bionics in architecture and civil engineering, including nature-inspired structures, innovative bionic materials, and case studies demonstrating the effectiveness and potential of these solutions in practice.

3. Structures Inspired by Nature Created by Generative Tools

In the field of structural engineering, the observation and analysis of forms and mechanisms found in plants and animals have inspired the development of innovative designs that combine lightness, strength, and efficiency. Natural organisms have evolved structures that achieve maximum performance with minimal use of resources, a principle that architects and engineers have successfully transferred into construction practices.

One of the pioneers in this approach was Frei Otto, whose groundbreaking work in the 1960s and 1970s revolutionized architectural thinking. His use of biological tension structures, such as those seen in the membrane roof of the German Pavilion at Expo 67 in Montreal, demonstrated that strong and durable constructions can be achieved with extremely low material consumption. By studying natural tensioned surfaces—like soap films or biological membranes—Otto developed lightweight roofing systems that became a symbol of sustainable architectural innovation [6]. His legacy continues to influence contemporary designers exploring tensile and minimal surface structures.

Today, advanced computational tools allow for the accurate modeling and simulation of complex natural geometries. The use of parametric and generative design enables architects to experiment with thousands of iterations to find the most efficient structural solutions. An outstanding example of this approach is the ICD/ITKE Research Pavilion at the University of Stuttgart. Inspired by the exoskeleton of sea urchins and beetles, this experimental structure utilizes composite fibers arranged in patterns that mimic biological reinforcement strategies. The result is an ultra-lightweight yet highly durable system, showcasing how digital fabrication combined with biomimetic principles can push the boundaries of architectural engineering [7].

Visual design using modern digital tools such as Rhinoceros 3D/Grasshopper or Revit/Dynamo offers significant potential for bionic form design [8]. In this case, each form/structure is defined parametrically using a block-based script composed of components logically connected via cables that enable information flow between components. In this way, the form/structure is described by a set of parameters that can be modified depending on the initial assumptions, and the results of the modifications are displayed in real time. Furthermore, using this type of software, it is possible to optimize structures or their topologies using genetic algorithms. Genetic optimization mimics the principles of natural selection to evolve optimal solutions over time. Furthermore, genetic algorithms allow for the creation of steel rod structures that feature complex and highly efficient configurations, often impossible to design through conventional methods. By simulating evolutionary processes, designers can eliminate unnecessary elements while enhancing load-bearing capacity and stability. Such optimized structures frequently employ minimal surface geometries, resulting in forms that are not only structurally superior but also aesthetically compelling [9].

Minimal surfaces—such as those seen in soap films or spider webs—offer exceptional structural properties: they distribute stresses evenly and minimize material usage. When translated into architectural design, these geometries lead to buildings that are both visually dynamic and resource-efficient. The exploration of minimal surface-inspired structures has given rise to lightweight steel gridshells, curvilinear space frames, and innovative roof systems that combine artistic expression with engineering logic [10].

Moreover, non-bionic forms and patterns can be incorporated into bionic design when they exhibit geometric characteristics typical of biologically inspired structures — such as minimal surfaces like the Enneper surface, helicoid, or catenoid and Voronoi diagrams, which appear naturally in many biological structures.

The integration of biological inspiration, computational power, and new materials opens a new chapter in architectural construction. Structures inspired by nature no longer merely imitate organic shapes—they embody the same principles of efficiency, adaptability, and optimization that govern living organisms. This approach not only enhances the performance of buildings but also aligns with global goals of sustainability and resource conservation. In the next section, attention will be given to how bionic thinking influences the development of innovative materials, further expanding the possibilities of contemporary architecture and civil engineering.

4. Bionic Materials and Their Applications

Biomimicry in architecture is not limited to imitating natural forms; it also extends deeply into material innovation, opening new possibilities for sustainable and adaptive construction. Inspired by biological processes and properties, bionic materials are designed to improve performance, increase durability, and reduce environmental impact.

One of the most well-known examples is the development of self-cleaning surfaces, inspired by the lotus leaf effect. Lotus leaves have microscopic structures that repel water and prevent dirt particles from adhering. This natural phenomenon, known as superhydrophobicity, has been successfully replicated in coatings applied to building façades, glass panels, and solar panels. These surfaces enable rainwater to wash away dust and contaminants, minimizing the need for chemical cleaning agents and reducing maintenance costs [11]. Beyond improving cleanliness, such coatings also enhance the efficiency of solar panels by ensuring that dust accumulation does not interfere with energy generation.

Another significant advancement in biomimetic materials is the use of smart materials that respond dynamically to environmental stimuli. These materials, often referred to as 4D materials, go beyond static properties—they change their shape, stiffness, or permeability in reaction to factors such as humidity, temperature, or light. This behavior mimics natural movements, like the opening and closing of leaves or pine cones, allowing buildings to adapt passively to changing conditions. Applications include adaptive shading systems, ventilation components, and responsive façades, all of which contribute to improved energy efficiency and user comfort [12].

Equally transformative is the development of self-healing concrete, which contains bacteria or encapsulated healing agents capable of autonomously repairing cracks. This material mirrors natural regenerative processes found in living organisms, where damage triggers self-repair mechanisms. When cracks form in the concrete, the bacteria activate and precipitate calcium carbonate, sealing the fissures and restoring structural integrity. This innovation significantly extends the lifespan of concrete structures, reduces the need for costly repairs, and minimizes the environmental footprint associated with frequent renovations [13].

Other promising bionic materials include phase-change materials (PCMs), which store and release heat in a manner similar to natural systems like animal fat layers; bioinspired composites that replicate the hierarchical structure of bone or shells, offering both lightness and strength; and biodegradable construction materials, designed to break down naturally at the end of their lifecycle. These developments highlight the potential of nature as a guide for creating materials that are not only high-performing but also environmentally responsible.

The integration of these advanced materials into architectural practice enhances the sustainability, adaptability, and resilience of buildings. By combining material innovation with biomimetic design principles, architects can develop structures that behave more like living organisms—capable of self-maintenance, adaptation, and interaction with their environment. The next section will examine how these materials and structural innovations intersect with broader trends, presenting the challenges and perspectives for the future development of bionic design and construction.

5. Case Studies

The following case studies demonstrate the diverse application of biomimetic principles in contemporary architecture, illustrating how inspiration drawn from nature leads to solutions that are not only visually striking but also functionally and environmentally superior.

5.1 Eastgate Centre, Harare, Zimbabwe (1996)

Designed by Mick Pearce in collaboration with Arup engineers, the Eastgate Centre is one of the most celebrated examples of biomimicry in architecture. The building employs a passive cooling system modeled on the ventilation mechanisms of termite mounds. Termites regulate internal temperatures of their nests despite extreme external variations, and this principle was applied to the building's design, enabling natural air circulation and temperature stability. As a result, energy use for air conditioning was reduced by up to 90% compared to similar conventional buildings [3].

5.2 Guggenheim Museum, Bilbao, Spain (1997)

The Guggenheim Museum, designed by Frank O. Gehry, embodies organic forms inspired by marine life, resembling the shapes of fish and sea creatures. The use of advanced digital modeling tools allowed the creation of its iconic flowing titanium-clad structure, which harmonizes with its riverside location. Although primarily aesthetic, the museum's form demonstrates how biomimetic inspiration can redefine architectural expression while integrating with its natural surroundings [4].

5.3 Al Bahar Towers, Abu Dhabi, UAE (2012)

Designed by Aedas Architects, the Al Bahar Towers feature a kinetic façade inspired by the traditional mashrabiya lattice. Thousands of triangular shading elements open and close in response to sunlight, reducing solar gain and minimizing the energy needed for cooling by approximately 50%. The façade also enhances interior comfort and exemplifies the fusion of cultural heritage with modern biomimetic engineering [5].

5.4 The Gherkin, London, UK (2004)

Designed by Norman Foster, this high-rise office building was inspired by the structure of sea sponges and certain marine organisms. Its aerodynamic shape minimizes wind loads while the central atria facilitate natural ventilation, reducing reliance on mechanical systems. The Gherkin stands as an early example of sustainable skyscraper design that incorporates nature's logic into urban architecture [10].

5.5 ICD/ITKE Research Pavilion, Stuttgart, Germany (2012–2015)

This experimental project by the University of Stuttgart demonstrates the potential of biomimetic design combined with digital fabrication. Inspired by the exoskeleton of sea urchins and insect shells, the pavilion uses fiber-reinforced composites arranged in

patterns derived from biological reinforcement strategies. The resulting structure is ultra-lightweight yet strong, proving that bioinspired construction methods can reduce material consumption while maintaining high structural performance [7,9].

5.6 Eden Project, Cornwall, UK (2001)

Designed by Nicholas Grimshaw, the Eden Project consists of giant geodesic domes inspired by the microscopic structure of plant cells. The domes are clad with ETFE (ethylene tetrafluoroethylene), a lightweight and highly transparent material that allows optimal light transmission while drastically reducing weight compared to glass. This project demonstrates how biomimetic thinking can lead to environmentally integrated architecture that supports large-scale botanical ecosystems [12].

5.7 Beijing National Stadium "Bird's Nest", China (2008)

Designed by Herzog & de Meuron, the stadium's lattice structure draws inspiration from the random yet stable arrangement of twigs in a bird's nest. The intertwining steel beams provide both structural support and aesthetic identity. This design combines natural randomness with engineering precision, resulting in a landmark of biomimetic architecture that merges function with symbolism [13].

5.8 One Central Park, Sydney, Australia (2014)

One Central Park, designed by Jean Nouvel with Patrick Blanc, integrates vertical gardens inspired by natural ecosystems. The building features a system of heliostat mirrors that direct sunlight to lower gardens, supporting plant growth and reducing the need for artificial lighting. The greenery improves air quality, enhances biodiversity, and provides thermal insulation, embodying the synergy of biophilic and biomimetic design principles [5].

5.9 One Ocean Pavilion, Expo 2012, Yeosu, South Korea

Designed by SOMA Architects, the One Ocean Pavilion incorporates a kinetic façade inspired by the movements of marine organisms. Its membrane elements open and close in response to environmental conditions, regulating light and natural ventilation inside the building. This adaptive mechanism reduces energy consumption while providing an engaging, dynamic appearance. The pavilion exemplifies how biomimetic principles can be combined with advanced digital fabrication and control technologies to create responsive architectural envelopes [14].

These case studies illustrate how biomimicry is applied across different scales—from experimental pavilions to urban high-rises—addressing diverse design goals such as energy efficiency, structural optimization, environmental integration, and user well-being. They confirm that nature, as a master designer, continues to inspire innovative solutions that bridge technology, sustainability, and aesthetics. Table 1 summarizes the most important projects based on biological inspirations, showing their functions, the technologies used and the environmental benefits resulting from their implementation.

Tab. 1. Case Studies of Biomimetic Architectural Solutions

Project	**Location / Year**	**Biological Inspiration**	**Applied Technology**	**Functional / Environmental Effect**
Eastgate Centre	Harare, Zimbabwe / 1996	Termite mounds	Passive ventilation system	~90% reduction in cooling energy consumption [3]
Guggenheim Museum	Bilbao, Spain / 1997	Marine organisms (fish, aquatic forms)	Digital modeling for organic titanium structure	Iconic form harmonizing with natural surroundings [4]
Al Bahar Towers	Abu Dhabi, UAE / 2012	Mashrabiya (lattice structures)	Computer-controlled kinetic façade	~50% reduction in solar gain and cooling energy [5]
The Gherkin	London, UK / 2004	Sea sponge structure	Aerodynamic form, natural ventilation via central atria	Reduced wind loads and mechanical ventilation needs [10]
ICD/ITKE Research Pavilion	Stuttgart, Germany / 2012–2015	Sea urchin exoskeleton, insect shells	Digital fabrication, fiber-reinforced composites	Ultra-light, strong, material-efficient structure [7,9]
Eden Project	Cornwall, UK / 2001	Plant cell structures	Geodesic domes with ETFE cladding	Lightweight, energy-efficient domes supporting ecosystems [11]
Beijing National Stadium "Bird's Nest"	Beijing, China / 2008	Bird nest arrangement	Interwoven steel beams	High structural stability with symbolic design [12]
One Central Park	Sydney, Australia / 2014	Natural ecosystems, vertical greenery	Vertical gardens, heliostat mirrors	Improved air quality, thermal insulation, biodiversity [5]
One Ocean Pavilion	Yeosu, South Korea / 2012	Movements of marine organisms	Kinetic membrane façade, adaptive elements	Automatic shading and ventilation, energy savings [15]

6. Challenges and Perspectives

Although bionic solutions offer enormous potential, their implementation is still accompanied by a range of technological, economic, and regulatory challenges. The complexity of translating biological principles into architectural and civil engineering practice often requires advanced tools, specialized materials, and innovative construction methods, which can significantly increase project costs in the early stages. Furthermore, building codes and regulations in many countries are not yet adapted to accommodate unconventional designs or novel materials, creating additional barriers to the widespread adoption of biomimetic solutions [15].

A major factor in the success of these approaches is the need for interdisciplinary collaboration. Unlike traditional construction methods, bionic architecture demands close cooperation between architects, structural engineers, biologists, material scientists, and computer specialists. Such collaboration allows the team to correctly interpret biological mechanisms and effectively apply them to the design and construction process. Without this integration, there is a risk that biomimicry will remain a superficial trend limited to aesthetic imitations, rather than a transformative force in the built environment.

Another critical challenge is the scalability of biomimetic solutions. While many examples—such as experimental pavilions or research prototypes—demonstrate impressive performance, scaling these concepts up to large-scale urban applications often requires significant adjustments and cost optimizations. The transition from innovative prototype to practical, affordable solution remains one of the key hurdles for the field.

At the same time, emerging technologies offer promising opportunities to overcome these barriers. The integration of artificial intelligence (AI), machine learning, and big data analytics into the design process enables the simulation, optimization, and refinement of biomimetic solutions at an unprecedented scale. These tools allow architects to analyze vast datasets on climate, environmental conditions, and user behavior, enabling the creation of buildings that actively respond to their surroundings [16]. Additionally, digital fabrication methods, including robotic construction and 3D printing, provide the means to realize complex geometries inspired by nature with greater precision and efficiency.

Looking to the future, the combination of biomimetic and biophilic strategies is expected to play an increasingly important role in shaping urban environments that are both ecologically responsible and beneficial to human well-being. Cities of the future may integrate living systems—such as vertical forests, adaptive water management inspired by natural ecosystems, and dynamic facades that behave like biological membranes—creating environments that are not only sustainable but regenerative.

Furthermore, as society becomes more aware of the urgency of addressing climate change and resource scarcity, the demand for innovative, nature-inspired solutions is likely to grow. With continued research, technological development, and policy support, bionic architecture has the potential to evolve from experimental projects into a mainstream paradigm for designing the cities of tomorrow.

7. Conclusion

Bionics represents a transformative paradigm in architectural and civil engineering design, offering solutions that move beyond traditional sustainability approaches. By learning from nature's time-tested strategies, architects and engineers can develop structures that are not only resource-efficient but also adaptive, resilient, and responsive to changing environmental conditions. The incorporation of biological principles into the design process leads to buildings that harmonize with their surroundings, minimize energy consumption, and improve user comfort.

As urban areas continue to face increasing pressures from climate change, population growth, and resource scarcity, the demand for innovative solutions that balance human needs with ecological responsibility will intensify. Biomimetic strategies, drawing from the logic of natural systems, offer pathways toward reducing the environmental footprint of the built environment. At the same time, biophilic design enhances the psychophysical well-being of users, creating spaces that not only perform efficiently but also nurture human connection with nature.

The future of bionic architecture lies in the integration of advanced technologies. Developments in smart materials, self-healing composites, and 4D materials will allow buildings to adapt dynamically to their surroundings, much like living organisms. Similarly, artificial intelligence (AI), machine learning, and big data will enable the simulation and optimization of complex design processes, facilitating the creation of high-performing, climate-responsive structures.

However, achieving this vision requires addressing challenges related to costs, regulatory frameworks, and interdisciplinary collaboration. Close cooperation between biologists, architects, engineers, and material scientists will be essential to unlock the full potential of biomimetic solutions.

In conclusion, bionics has the potential to redefine the way we design and build cities. By combining nature's wisdom with technological innovation, future architecture can evolve into a regenerative system—one that not only minimizes harm but actively contributes to the health of the environment and society. As research continues to expand and new solutions emerge, nature-inspired architecture is expected to become a cornerstone of sustainable urban development in the decades to come [16].

Acknowledgments

"Financed by the Minister of Science and Higher Education Republic of Poland within the program "Regional Excellence Initiative"

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