STRUCTURES IN NATURE AS AN INSPIRATION FOR CONTEMPORARY ARCHITECTURE AND CONSTRUCTION

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Abstract

Biomimetic design represents an interdisciplinary framework that integrates principles of evolutionary biology, structural mechanics, materials science, and computational modeling to enhance the performance of architectural and structural systems. Natural structures exhibit hierarchical organization, optimized force distribution, and material-efficient geometries developed through evolutionary adaptation. This study presents a comparative analysis of ten representative biological systems and their engineering analogues, focusing on morphology, mechanical behavior, geometric efficiency, and structural functionality.

Key biological models—including trabecular bone, plant vascular networks, hexagonal cellular structures, spider silk tensile systems, and hydrodynamically optimized aquatic forms—demonstrate universal principles of minimum material usage, high strength-to-weight ratios, and efficient load transfer. Using parametric modeling, topology optimization, and numerical simulations, these principles are systematically translated into lightweight structural configurations, adaptive façade concepts, and material-efficient construction strategies.The results confirm that biomimetic design provides a robust and transferable framework for the development of sustainable, energy-efficient, and high-performance building systems. Natural systems, shaped by evolutionary selection, offer fundamental structural strategies that can significantly improve the reliability, efficiency, and optimization of contemporary engineering structures.

Keywords: *biomimetic design, natural structural systems, hierarchical materials, topological optimization, parametric modeling, adaptive facades, energy-efficient constructions, biologically inspired geometries, fractal and lattice structures, evolutionary morphology.*

1. INTRODUCTION

Biomimicry in modern engineering is profiled as a conceptual and methodological framework in which natural systems are viewed as highly optimized "reference constructions", whose principles of organization, material distribution and geometric rationality can be directly translated into architectural and construction solutions of new generations [25-27]. In contrast to the traditional approach, in which forms and systems are primarily the product of technological constraints and experiential engineering rules, biomimetic design starts from the assumption that evolution has already "performed" an enormous number of experiments over geologically long time scales, whereby the very structural concepts that simultaneously meet the requirements of minimal material consumption, energy efficiency, and adaptive resilience have survived.

Natural structures – from the trabecular architecture of bones, through the hexagonal alveolar matrices of honeycombs, to the fractal vascular networks of plants and the tension systems of spider silk – are characterized by an extremely sophisticated multiscale organization [29-31]. At the micro level, density gradients, fiber orientation and heterogeneous phase distributions are present; at the meso level, differentiation of load-bearing zones, dissipation and stabilization; and at the macro level, clearly recognizable geometries such as logarithmic spirals, geodesic schemes, fractal hierarchies, and minimal areas [32]. Such a hierarchical structure allows for the simultaneous fulfillment of multiple, often conflicting, requirements: local adaptation to stress, global stability, wear, shock and fatigue resistance, as well as economical use of available resources.

In architecture and construction, these natural models are becoming particularly relevant in the context of several contemporary challenges: the need to reduce mass and material consumption over large ranges, improving the energy efficiency of building envelopes, developing adaptive façade and roof systems, and introducing new biocomposite and functionally gradient materials. Trabecular bone is analyzed as a physical prototype of a topologically optimized support, where the density of the material is adjusted to the stress field [35]; plant vascular networks as a natural analogue of network systems of fluid and energy distribution across multiple hierarchical levels [36]; honeycomb as a paradigmatic example of minimal material consumption at maximum rigidity [37]; spider web as an extremely efficient tension system with the ability to localize damage Hydrodynamic forms of marine organisms as a model for minimizing fluid resistance and eddy effects. The geometry of the sea urchin, with its geodesic arrangement of tiles, indicates the principles of formation of double-curved scales and lattice domes of great stability [40].

The development of digital design techniques, especially parametric modeling, generative design, topological optimization, and numerical methods (FEM, CFD), is fundamentally changing the possibilities of applying these natural principles in technical practice [41, 42]. Instead of an intuitive or purely aesthetic "reference to nature", the engineer today has tools with which structural patterns observed in biological systems can be quantified, simulated and then precisely implemented in supports, trusses, shells, façade panels and spatial networks [43]. Additive technologies (3D printing of metals, polymers and composites) further open up the possibility of realizing complex, topologically optimized forms that until recently were constructively or economically unfeasible [44].

In this context, biomimetic architecture and civil engineering are not reduced to formally "biomorphic" objects, but introduce a deeper level of analogy: functional, material, structural, and performative. Natural systems are viewed not as a decorative model, but as an operating model, in which the concepts of morphological analogy (geometry and form), structural optimization (stress and stiffness distribution), material mimicry (biocomposites, gradient materials), and functional adaptation (reaction to changing external conditions, e.g., light, wind, humidity, temperature) are clearly distinguished.

Starting from this conceptual framework, this paper analyzes ten carefully selected biomimetic pairs – natural structures and their contemporary architectural-structural interpretations – through four key dimensions: (i) morphology and geometric logic, (ii) mechanical behavior and stress distribution, (iii) material organization and composite principles, and (iv) functional and energy efficiency of systems [47]. Particular emphasis is placed on structures that have already served as a basis for concrete engineering realizations (e.g., trabecular-inspired lattice systems, honeycomb facades, mesh and membrane structures, hydrophobic sheaths, and aerodynamically optimized towers), thus providing a direct link between biological analogues and measurable engineering performance.

The goal of the introductory theoretical framework is not only to affirm the inspiring value of nature, but to argue that biological systems contain clearly identifiable engineering strategies, which can be formalized, numerically modeled, and translated into sustainable, energy-efficient, and structurally rational building concepts. In this sense, nature is treated as a "large-scale experimental laboratory" and biomimicry as a bridge between evolutionary morphogenesis and contemporary architectural-engineering practice [50].

2. NATURAL STRUCTURES AS AN OPTIMIZATION MODEL

2.1. Natural Structures as a Model of Optimization: Theoretical Foundations and Biological Principles

Natural systems represent an extremely relevant model for the development of engineering structures thanks to their multiscale organization, adaptive mechanisms, and functional efficiency, resulting from long-term evolutionary processes. Understanding their internal structure, geometric structure, and functional logic makes it possible to formulate engineering models that combine minimal material consumption and high mechanical stability — a principle that modern architecture and construction seek to integrate through advanced digital and experimental methods [51].

This chapter discusses four fundamental groups of natural structures: (i) hierarchical biostructures, (ii) fractal and lattice systems, (iii) hexagonal and cellular organizations, and (iv) aerodynamic biofluidic forms, with particular emphasis on their direct engineering applicability [52].

2.1.1. Hierarchical Bio-Structures and Multi-Scalar Design

Hierarchical organization is one of the most common and evolutionarily efficient structural principles in nature. Structures such as bone, wood, and shells form complex composite systems in which material and geometric properties change through multiple levels of organization.

1. *At the nanoscale*, mineral phases (e.g., hydroxyapatite) and protein components (collagen) are arranged in crystallographically oriented matrices that determine local strength and fracture resistance.
2. *On the microscale*, lamellar and fibrous structures govern stress direction and deformation control.
3. *On the mesoscale*, the differentiation of zones of different densities allows for the formation of stiffness gradients and local adaptation to external forces.
4. *On a macro scale*, a global shape — such as the geometry of a femur or a vertical tree — is optimized according to the load

regime to which the structure is predominantly subject.

This multiscale principle has been directly applied in engineering through [54]:

1. Density gradient (FGM) materials.
2. Ultralake Sendvich structures,
3. topologically optimized carriers,
4. Variable inertia and modular lattice systems.

The application is particularly important in the design of tall buildings, slender structures, high-span bridges, and seismically resistant building systems, where hierarchical organization allows for improved weight-to-load ratios [55].

2.1.2. Fractal, dendritic and lattice structures

Fractal and lattice structures in nature represent a fundamental mechanism for optimizing transport, load distribution, and spatial organization.

1. Biological systems such as *lungs*, *circulatory networks*, *plant vessels,* and *root systems* use fractal logic to achieve maximum exchange surface area with a minimum amount of material.
2. Natural dendritic processes (e.g., the formation of river deltas or crystals) exhibit an efficient flow organization and branching that can be mathematically described by fractal principles.

In an engineering context, these models allow: [57]

1. design *of ultra-efficient lattice structures*,
2. development *of mesh façade and roof systems*,
3. optimization *of drainage and consolidation matrices* in geotechnics,
4. Analytical modeling of the redistribution of forces in minimal mass structures.

The most notable applications include the parametric design of load-bearing networks, the generative formation of structures according to mapped stress fields, as well as the additive factory realization of fractal-inspired elements.

2.1.3. Hexagonal, alveolar and cellular biostructures

Hexagonal and cellular geometries represent a universal principle of natural achievement of maximum rigidity with minimal material consumption. The most well-known examples include [59]:

1. *honeycomb bees (Apis mellifera)* – optimal hexagonal organization of cells for storage and load collection,
2. *trabecular bone* – a cellular network that locally adapts density according to strain,
3. *plant parenchymal tissues* – lightweight structures optimized for mechanical and fluid function,
4. *Coral and spongy skeletal forms* – biogenerated cellular composites with a high strength-porosity ratio.

These models have been used to develop [60]:

1. With the help of aluminum cores,
2. High Span Sandwich Panel,
3. two-layer façade systems,
4. biocomposite concrete with alveolar matrices,
5. Materials with improved thermal insulation and reduced weight.

Cellular logic has also shown significant potential in 3D printing of concrete and metal, where controlled porosity allows for mass optimization and improved thermomechanical functions [61].

2.1.4. Aerodynamic Forms and Biofluidic Optimization

Many organisms — fish, birds, insects, and marine mammals — have evolved in fluid environments that require optimal control of resistance, swirls, and stability. The body shape, surface texture, and stiffness distribution of these organisms are the result of multiple iterations of selection under turbulent and changing conditions.

For engineering, this made it possible to formulate a model for [63]:

1. design *of tall buildings in strong wind zones*,
2. development *of aerodynamic façade and roof profiles*,

3. optimization of *bridge bodies and girders with minimal resistance*,
4. Reduction of aeroelastic effects such as *flutter* and *galloping*.

Of particular importance are the so-called *"teardrop bodies"*, geometries with a minimum drag coefficient, used today in the design of bridge piers, canopies and special supports of high-performance structures [64].

2.2. Biomimetic transfer and systematization of the transfer of natural principles into engineering solutions

A biomimetic process is a methodological sequence of steps that enables the translation of natural phenomena — shaped by evolutionary, biomechanical, and biochemical processes — into usable engineering and architectural models. The key challenge of this approach is not only the identification of the relevant natural phenomenon, but its abstraction, mathematical formulation, and implementation into structural, material, and energy systems [65].

2.2.1. Stages of the biomimetic process

The methodological procedure of biomimetic transfer encompasses four interdependent phases: biological identification, theoretical abstraction, numerical modeling, and engineering implementation [66].

Biological identification **-** At this stage, analytical observation of the natural structure is performed, including its morphological structure, mechanical behavior, adaptive mechanisms, and multiscale organization. Reference models include trabecular bone tissue, streamlined fish forms, spider tensile webs, coral skeletons, and hexagonal honeycomb structures.

Abstraction is the stage in which principles that have engineering validity are extracted from a natural system: mass optimization, stress distribution according to the force field, gradient organization of materials, fractal branching logic, or geometry of minimal surfaces.

Mathematical and numerical modeling **-** Bio-principles are then formalized through various numerical models:

1. *FEM models*, especially in the analysis of stress transfer in trabecular bone and shells;
2. *CFD models*, in the analysis of the aerodynamic forms of birds, fish, marine mammals, and fluid flows around high-altitude objects;
3. *topological optimization*, which simulates the evolutionary processes of bone growth, distributing the material in proportion to local stresses;
4. *generative and stochastic algorithms*, which simulate the natural processes of branching, growth and adaptive morphogenesis.

This phase involves moving from a digital model to a real-world structural system, using advanced materials, parametric design, additive manufacturing, and system integration. Biomimetic patterns have been implemented in shell roofs, membrane structures, adaptive facades, mesh trusses, and energy-integrated cladding.

2.2.2. Bio-inspired materials

The development of bio-inspired materials today occupies a key place in construction and architectural science. These materials are not simple copies of natural substances, but rather engineered synthesized structures based on principles that occur in bones, plant tissues, insect chitinous shells, or protein fibers [67].

Composites with a gradient of stiffness and porosity **-** A martial analogue of trabecular bone tissue. The gradient allows for efficient stress dissipation and high load capacity with low weight.

Superhydrophobic Lotus Leaf-Inspired Nano-Coatings **-** Micro and nano-structural duality of the surface allows for extreme hydrophobicity and self-cleaning. This principle is applied in façade cladding and protective coatings.

Spider silk is one of the most resistant natural materials, with a specific tensile strength greater than steel. This structure is the basis for the development of high-resistance polymer fibers.

***Lignin and cellulose-inspired biopolymers* -** Modified cellulose structures are used to develop flexible, lightweight and biodegradable composites.

***Reactive and stimulus-responsive materials* -** Inspired by the hygroscopic movements of plants, these materials change shape or rigidity when exposed to moisture, heat, or light.

Each material is described through fundamental mechanical parameters (E, G, ν, σu, σy) and areas of application.

2.3. Application of biomimetic principles in contemporary architecture and construction

2.3.1. Structural systems

Biomimetic models increasingly determine the development of new constructions [68]:

1. *The tension structures*, based on interacting tension and compression components, are directly inspired by the tension webs of spiders.
2. *Arched, shell and dome systems* take optimization principles from sea urchin shells, corals and skeletons.
3. *Pneumatic and membrane structures* are based on the logic of minimum surface areas and uniform stress distribution, observed in biological membranes.
4. *Fractal lattices* replicate the dendritic branching logics of trees to achieve minimum mass and maximum range.
5. *Variable cross-section columns*, taken from the biomechanics of trees and bamboo, enable an optimized distribution of materials according to the stress field.

2.3.2. Energy Systems

Natural systems of energy distribution, storage and exchange have served as the basis for the development of high-efficiency building technologies [69]:

1. *Ventilation systems inspired by termite hills*, which maintain a stable microclimate through convection flows.
2. *Cold wraps inspired by the skin of an elephant*, whose multi-scale wrinkles and surface topology reduce thermal radiation.
3. *Solar systems inspired by heliotropism*, which follow the sun's path to maximize energy.
4. *Acoustic structures inspired by snail houses*, which optimize the absorption and propagation of sound.

2.4. Geometric systems

Biomimetic design also influences the development of new geometric paradigms [70]:

1. *Parametric design* allows the simulation of natural forms and their structural features.
2. *Generative algorithms*, imitate the processes of growth, fractal distribution and morphogenesis.
3. *Fractal architecture* uses multi-level geometries to create systems of exceptional spatial efficiency and visual complexity.

The biomimetic approach brings clear structural, energy and functional advantages: reduced weight of structures, increased energy efficiency, reduced operating costs, better aerodynamic and seismic response, and increased durability and adaptive resistance.

However, there are also significant limitations:

1. Lack of standardized design procedures and standards.
2. The complexity of multiscalar modeling of biological materials.
3. the need for interdisciplinary teams (architecture-biology-engineering),

4. The high cost of digital fabrication and biocomposite materials at an early stage of application.

The discussion shows that biomimetic design is in a phase of intensive development and that it represents one of the most promising directions of future engineering progress.

3. CONTEMPORARY BUILDINGS INSPIRED BY STRUCTURES IN NATURE

Contemporary architecture is marked by a growing tendency to view nature not only as an aesthetic benchmark, but as *a structural, energetic and biological model*. Numerous buildings around the world demonstrate how natural principles are successfully transformed into spectacular, technologically advanced buildings. The most important global examples that represent the highest reach of biomimetic architecture are systematized below.

3.1. Sea sponge *Euplectella aspergillum* → 30 St Mary Axe, The Gherkin (London)

*(**Architect:** Norman Foster, 2004)*

The biogenic skeleton of the deep-sea sponge *Euplectella aspergillum* (Venus' Flower Basket) represents one of the most sophisticated natural examples of hierarchical structural organization (Figure 1, right). Its architecture is based on a multilayered diagonal network of silicate spicules, arranged in regular rhomboid and hexagonal cells. This *diagrid structure* provides exceptional resistance to combined loads, high torsional stability, and minimal material consumption, making it one of the most widely studied natural models of structural efficiency [71-73].

The architectural-structural design of **30 St Mary Axe** (The Gherkin) directly builds on these bio-principles. The structure of the object is based on a steel-glass diagrid that geometrically reproduces the logic of stress distribution and sheath stabilization inherent in the *skeleton of Euplectelle* (Figure 1, left). The aerodynamic tapered profile reduces the intensity of vortex and lateral wind loads, while the diagonal mesh geometry allows for a significant reduction in torsional moments compared to conventional orthogonal frames [74-75].

Figure 1: *Sea sponge Euplectella aspergillum → The Gherkin (London)*

Biomimetic transfer in Gherkin includes the following key principles:

1. *structural hierarchy* and distribution of stiffness analogous to a multilayer network of sponges,
2. *diagonal grille*, which provides uniform voltage distribution and increased torsional resistance,
3. *aerodynamic form* that reduces vortex-shedding,
4. *increased energy efficiency* – hybrid ventilation system, inspired by passive fluid flow around the sponge skeleton, reduces the need for mechanical ventilation by up to 40%,
5. *constructive weight optimization* – application of a minimum amount of material while achieving maximum load capacity.

Due to the striking similarity of geometric and mechanical principles, the case *of Euplectella aspergillum* – Gherkin represents one of the most cited examples of biomimetic engineering analogy in the modern scientific literature, including studies from MIT, Harvard and the Max Planck Institute [71, 72, 75].

3.2. Beijing National Stadium (Bird’s Nest), Peking – Inspired by birds' nests

*(**Architect**: Herzog and de Meuron, 2008)*

The biomimetic analogy between **the Beijing National Stadium** ("Bird's Nest") and *the natural bird's nest* is based on the transfer of the principle *of an irregular* but *mechanically optimized lattice network* (Figure 2). The stadium structure is built of a massive steel diagrid whose elements are arranged seemingly "chaotically", but in reality represent a topologically optimized system designed for combined gravitational, wind and seismic loads [77, 79].

Figure 2: *Bird's Nest – Beijing National Stadium „Bird’s Nest“ An example of biomimetic inspiration in contemporary architecture.*

The natural nest, composed of bent twigs of different lengths and stiffnesses, achieves stability through *local compaction at the places of greatest stress*, thus forming a multi-layered structure with a favorable mass-strength ratio [78]. The same principle was applied in the stage: *local reinforcement zones* were formed by increasing the density of steel elements at critical points, resulting in a monolithic spatial shell with high resistance to seismic excitations characteristic of the Beijing region [80].
Diagonal and interlocking steel profiles take on *horizontal and vertical forces*, while the global stadium geometry provides a *balanced ratio of rigidity and flexibility* – a feature inherent in biological lattice structures [76]. Although visually irregular, the mesh is the result *of FEM analysis and topological optimization*, ensuring a minimum amount of material with maximum structural efficiency.
This example clearly demonstrates that *natural irregular structures* are not the result of chance, but of an evolutionary optimum. It is this *principle of optimized irregularity* that is the essence of biomimetic transfer in the construction of Bird's Nest Stadium.

3.3. Sydney Opera House - seashells

*(**Architect**: Jørn Utzon, 1956)*

The left side of Figure 3 shows **the Sydney Opera House**, whose thin-walled concrete shells are formed from a series of spherical segments that morphologically and mechanically correspond to natural shells. The natural shells of mollusks, shown on the right side of Figure 3, possess radial ribs, double curvature, and lamellar microstructure, resulting in an optimal membrane stress distribution and a high load-to-weight ratio [82]. This biological principle is transferred to the construction of the wash through curved shells that minimize bending and allow for efficient load transfer in the plane of the surface [83].

Figure 3: *Sydney Opera House - seashells*

The layered structure of the shell, based on calcium carbonate-rich microlamellae, is analogous to the ceramic tiles that line the surface of the Opera House, creating a pearlescent reflection and optical homogeneity that is typical of biogenic mineral systems [84]. The modular organization of the shell – the repetition of segments around a central geometric axis – was reflected in Utzon's system of identical spherical slices, which allowed for standardization, structural rationalization, and the retention of a clear maritime character of the object [85]. The Sydney Opera House is one of the most accurate examples of biomorphic architecture, in which the natural logic of thin-walled protective structures is directly transposed into a large-scale engineering system [86].

3.4. Milwaukee Art Museum – Inspired by the wings of birds

*(**Architect:** Santiago Calatrava, 2001)*

On the left side of Figure 4 is the **Quadracci Pavilion** (Milwaukee Art Museum), one of Santiago Calatrava's most famous works, whose distinctive morphology is based on the dynamic interpretation of wings in flight. The movable brise-soleil, composed of over 70 lamellar elements, opens and closes depending on light and climatic conditions, producing the visual and structural effect of a "mechanical organism" that responds to external stimuli, which the authors rank among the pioneering applications of kinetic biomimetics in architecture [87, 91].

On the right, a great white heron is shown in the flight phase — with clearly defined primary and secondary feathers, radial curvature and aerodynamic profile. The morphological correspondence between the arrangement of the lamellae on the museum and the arrangement of the feathers on the wing of the bird indicates an extremely precise application of the principles of morphogenetic and biomechanical inspiration in the building structure [88].

Figure 4: *Milwaukee Art Museum – Inspired by the wings of birds*

The construction of the pavilion functions as an analogous aeroform: lamellar "wings" are arranged in a series of elements that behave like artificial feathers, and their curvature optimizes airflow, reduces local eddies, and allows for more favorable aerodynamic conditions — a principle that is well known in zoological aeromechanics [90, 91]. The wing movement mechanism is the technological equivalent of avian kinesiology: the cable system functions as biomechanical "tendons", while the massive central pillar takes on the role of the bird's sternum, ensuring stability and efficient voltage distribution under varying wind loads.

This pavilion can thus be interpreted as an extremely successful translation of *natural flight into an architectural and engineering system*, where the principle of adaptivity — crucial for the aerodynamics of birds — is transformed into a mechanical-kinetic façade with a real function of regulating light, heat and ventilation [89]. The form of the building thus remains a "frozen moment of flight", but fully functional, operational and structured through an engineering-rational biomimetic approach.

3.5. The Eden Project, Kornvol – Inspired by alveoli and honeycomb

*(**Architect**: Nicholas Grimshaw, 2001)*

On the left side of Figure 5 is the **Eden Project** in Cornwall, a complex of modular biospheres whose architectural logic is based on the geometry of geodesic spheres and alveolar panels made of ETFE membranes. The domes are formed by a three-dimensional steel lattice filled with hexagonal and pentagonal cells, creating a lightweight but mechanically extremely stable shell. The slightly reflective surface and spherical morphology allow for harmonious integration into the landscape, making the complex a paradigmatic example of biomimetic and ecological architecture [92].

On the right side of the image is a macro-representation of a honeycomb, the stability of which is based on hexagonal morphology – the most efficient geometry to achieve maximum volume with minimal material consumption [93]. The honeycomb functions as a thin-walled, repetitive structure that evenly distributes stresses and allows for a high load capacity despite its low weight; it is this geometric logic that underlies the domes of the Eden Project.

Figure 5: *The Eden Project, Kornvol – Inspired by alveoli and honeycomb*

In biomimetic terms, the architectural structure of the complex represents a direct interpretation of the natural optimization present in the honeycomb: hexagonal modules reduce the use of materials, increase the load-bearing capacity and form a high-energy efficiency shell. ETFE panels, weighing only 1% of the weight of glass, provide high thermal stability, diffused lighting and minimal energy consumption for air conditioning [94]. The panels act as "inserted membranes" within a rigid steel mesh, reproducing the relationship between wax and geometry in a natural honeycomb.

The structural analogy is reflected in the interaction of local membranes and the global carrier: while the steel lattice achieves primary spatial stability, ETFE cells function as secondary, adaptive elements that contribute to energy and structural efficiency – a principle identical to the way bees build honeycombs with minimal wax, relying primarily on topology [95, 96]. Thanks to the extremely low mass of the modules, the Eden Project domes achieve a range of up to 100 m, which was previously not possible with traditional materials.

The Eden Project thus becomes one of the clearest examples of the application of natural geometric intelligence in architecture: its morphology directly reflects the evolutionarily optimized honeycomb system, whereby the principles of minimum mass, maximum rigidity and energy efficiency are transferred to a modern engineering context.

3.6. The Lotus Temple, Nju Delhi – Inspired by the Lotus Flower

*(**Architect**: Fariborz Sahba, 1986)*

The left composition of Figure 6 shows **the Lotus Temple** in New Delhi, a monumental sacral edifice whose architectural articulation is based on the interpretation of the lotus flower as a geometric, symbolic and morphological source of form. The building is formed of 27 bent-flat, marble and concrete elements arranged in three concentric rings, which creates the impression of a spatial "opening" of the building towards the zenith. The visual purity of surfaces, emphasized radial symmetry and controlled curve transitions generate an extremely harmonious composition that is often cited in the literature as a paradigm of contemporary biomimetic sacral architecture [100, 101]. The reflective pools around the temple amplify the visual effect of floating, evoking the natural ambience in which the lotus grows.

The right-hand composition of Figure 6 shows a fully open lotus flower (Nelumbo nucifera), whose geometry is characterized by radially distributed petals, clearly defined central symmetry, and smooth three-dimensional transitions. The lotus is biologically specific for its highly hydrophobic epidermal structure — the so-called "lotus effect" — which allows for self-cleaning surface behavior and minimal particle retention [98]. This natural mechanism makes the lotus one of the most studied models in biomimetic design.

Figure 6: *The Lotus Temple, Nju Delhi – Inspired by the Lotus Flower*

The Lotus Temple represents an extremely consistent transposition of natural morphology into an architectural construct. The three concentric rings of "petals" almost directly reflect the organization of the flower, with each architectural "petal" functioning as a self-contained curved plate that optimizes stress distribution, contributes to spatial rigidity, and improves the seismic resistance of the building [102]. In this sense, the morphology of the flower is not only used as a visual motif but as a structural logic.

The material concept also carries a clear biomimetic analogy: white marble possesses the ability to reflect and disperse sunlight in a way that visually resembles the diffuse optical characteristics of a lotus petal. Experimental studies indicate that polished marble surfaces exhibit reduced dust and water retention, thus creating the partial equivalent of the lotus effect in an architectural context [99].

In a broader theoretical framework, the Lotus Temple can be understood as one of the most consistent examples of the application of biomimetic principles to the formative logic of an architectural object. It simultaneously replicates natural geometry (radial symmetry), material logic (hydrophobic effects and light reflection), functional configuration (opening space to the outside), and the symbolic semantics of the lotus — a universal sign of purity, unity, and spiritual elevation in numerous cultures [97]. In this way, architecture, construction and natural-biological morphology merge into an integrated system, which places Lotus Temple among the key reference examples of biomimetic architecture on a global scale.

3.7. Metropol Parasol, Sevilja – Inspired by the Mushroom Network *(fungal mycelium)*

*(**Architect**: Jürgen Mayer, 2011)*

The image on the left of Figure 7 includes the **Metropol Parasol structure** in Seville, known as the largest contemporary wooden urban canopy in the world, whose geometry derives from the complex interpolation of crossed slats that generate a three-dimensional, continuous lattice surface. The visual metaphor of this system – "Las Setas" – is not arbitrary, but directly refers to biological prototypes in the form of mushrooms, where massive "stems" turn into broadly curved canopy panels, creating the effect of organically developed crowns. The woody superstructure formed in this way shares characteristics with natural porous matrices, especially those occurring in fungal mycelial networks, which is recognized in the literature as one of the most efficient natural models of load distribution and adaptive growth [106, 109]. The right side of Figure 7 shows the micromorphology of the mycelium — networks of hyphae that achieve complex fractal organization. Hyphae branch into multiple hierarchical levels, allowing the system to be simultaneously lightweight, porous, and extremely resistant to spatial and mechanical perturbations. Micellial networks apply the principle of force distribution over a series of flexible connections, which is a paradigmatic example of natural optimization of structural efficiency, and which, according to modern research, is one of the key bioinspiration models for the development of highly adaptive structures [102].

Figure 7: *Metropol Parasol, Sevilja – Inspired by the Mushroom Network (fungal mycelium)*

The biological model — the mycelium — thus becomes the generator of the design logic of the Metropol Parasol. Congruences can be classified through five fundamental domains.

The first is geometric patterns. The mycelium exhibits fractal branching patterns and dense lattice organization, while the Metropol Parasol forms a three-dimensional matrix of crossed lamellae whose continuous flow functions as a macroscopic analogy of microscopic hyphal hierarchies. Such geometric correspondence confirms that the architectural concept arises from the logic of the distribution of materials by natural matrices [108].

The second is structural logic. The mycelium transmits loads over a network of interconnected strands, rather than through massive centralized supports. Metropol Parasol uses a similar principle — the laminated truss redistributes loads, allowing for minimal use of materials with maximum load-bearing capacity. Such a "distributed" load-bearing system, by analogy with biological networks, increases the robustness of the structure to load changes and external influences [103].

The third domain relates to morphology. The mycelium system and the above-ground fruiting part of the fungus — the stem and cap — realize the geometry of a vertical-horizontal organization, where the vertical element serves as a support, while the horizontal surface expands to protect the space below. Metropol Parasol constructs the same logic: the massive "stems" at the base turn into wide, curved canopies that create a continuous urban shelter.

The fourth is a material analogy. Mycelium is known for its ratio of low mass and high resistance. Metropol Parasol uses laminated timber (LVL), a material that possesses an extremely high strength-to-weight ratio, as well as the ability to achieve mechanical properties analogous to biological networks in a cross-sipe system [105].

The fifth domain is functional transposition. In natural mushroom systems, the cap regulates the microclimate underneath, provides shade, retains moisture, and moderates temperature extremes. The Metropol Parasol performs the same function in an urban context — it reduces the temperature of the space under the structure, creates an urban microclimate zone, and functions as the macro-equivalent of a biological "climate shield" [104].

Such a multi-layered correspondence between natural and architectural structure confirms that the Metropol Parasol represents one of the purest examples of bioinspired architecture of the 21st century, where natural models are used not only as a symbolic reference, but as integrated constructive, geometric and functional principles, in accordance with contemporary theories of biomimetic design.

3.8. ArtScience Museum, Singapur – Inspired by flowers and bio-lamellar structures *(**Architect**: Moshe Safdie, 2011)*

The ArtScience Museum in Singapore (Moshe Safdie, 2011) is one of the most developed examples of architectural biomimetics in the field of geometric and structural transposition of natural lamellar systems. The architectural composition is based on the motif of the lotus flower, whose geometric and functional characteristics have been widely documented in biomimetic literature (e.g., self-cleaning effect, radial symmetry, hydrophobic geometry) (Figure 8). The object is dominated by a system of ten large, ribbed "petals" that form a radial spatial structure, organized around a central core. This concept corresponds to the bio-lamellar morphologies present in flower petals and leaves, where lamellar panels conduct loads towards the stabilization zone at the root of the structure [112].

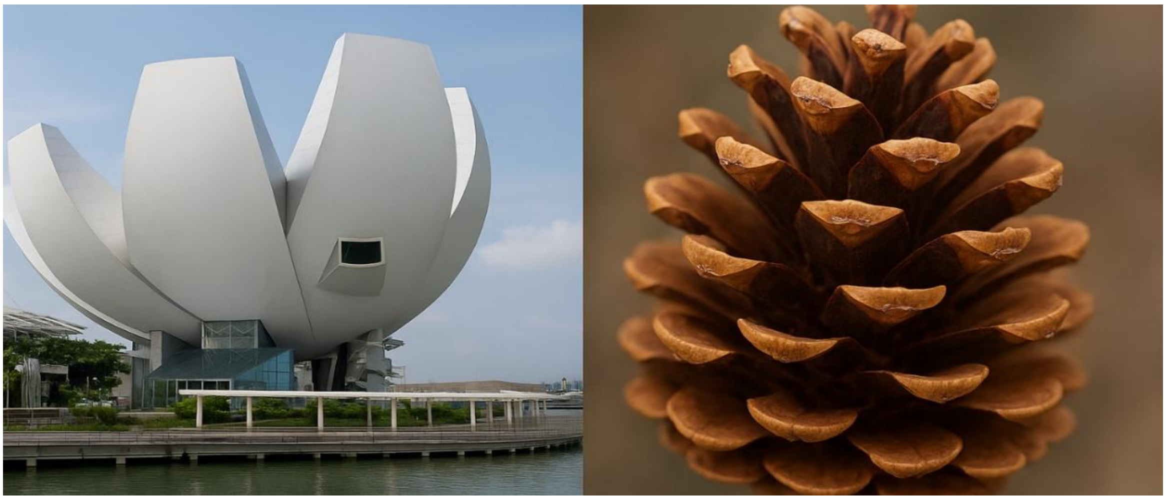

Figure 8: *ArtScience Museum, Singapur – Inspired by flowers and bio-lamellar structures*

The flowers, especially the lotus (Nelumbo nucifera), are characterized by clearly defined radial symmetry, curved lamellar elements, and integrated water guidance systems to the central part of the flower. Such structures have a high degree of geometric optimization and adaptation to environmental loads, making them a suitable model for architectural interpretations. Safdie's architecture takes these principles directly and transforms them into a complex spatial shell.

Each of the ten architectural petals is shaped as a separate lamellar volume, constructed using ribbed, curved panels. These solutions reflect the way in which biological lamellae transmit voltages [113]:

1. *The distribution of the load* takes place through curved surfaces towards the central nucleus, similar to biology where forces from the petal are transmitted to its base;
2. *continuous curvature* allows for increased rigidity with a minimum amount of material;
3. *Lamellar rib systems* mimic the living tissue structure of petals that possess an internal network of fibers for stability.

This approach fits into contemporary models of biomimetic optimization of structures, where biological patterns are used as algorithmic starting points for form-finding [112].

The object uses biomimetic principles not only in form, but also in function — a key criterion in contemporary SCI works on biomimetics.

The petals function as curved shells that transfer gravitational and external loads to a central concrete pillar. This logic is analogous to the way in which biological lamellae transfer mechanical stresses to their root [110].

Perforations are integrated in each "petal" that direct diffused daylight, imitating the filtration of light through flower structures. This reduces the need for artificial lighting and creates a dynamic light microclimate inside the museum.

The geometry of the arched petals allows rainwater to be gravitationally guided to a central point, from where the water is stored and filtered. This system is an architectural analogy of natural hydrophobic surfaces and capillary dynamics of flower petals [111].

The ArtScience Museum is a paradigmatic example of biomorphic architecture, where natural patterns are used not only as an aesthetic motif, but as a transdisciplinary generator of form, construction and sustainable performance. In combination with parameterized modeling, the object achieves a sophisticated synthesis of natural logic and modern technological infrastructure, thus becoming incorporated into the current course of SCI research on biomimetic architecture.

3.9. Heydar Aliyev Center (Baku, Azerbaijan) and biological membrane/cell structure

*(**Architect**: Zaha Haid, 2013)*

The architectural form shown on the left side of Figure 9 — **the Heydar Aliyev Center** in Baku — is a paradigmatic example of the application of biomorphic, continuous geometry based on the digital reinterpretation of biological membrane systems. The building, designed by Zaha Hadid, is based on a unique spatial logic in which the roof and façade cladding merge into a single continuous surface membrane with no clear boundary between functional elements. Such geometric continuity, which is aesthetically manifested through fluid transitions, smooth curvatures and the absence of right edges, is directly related to the principles of morphological optimization recognized in natural membrane tissues [115, 118, 122].

A microscopic representation of the biological membrane (right side of Figure 9) reveals a highly organized but nonlinear systematics: elliptical porous structures, variable lamella thicknesses, continuous pleated zones, and a topology adapted to the efficient distribution of mechanical stresses. These adaptive principles — controlled curvature, tension flow distribution, and multi-layered organization — are key patterns that contemporary architecture increasingly transposes into constructive systems of a high degree of performativity [117, 119, 123].

Figure 9: *Heydar Aliyev Center (Baku, Azerbaijan) and biological membrane/cell structure*

Biological membranes function as continuous sheaths whose curvature is not the result of formal aesthetics but rather optimization for stress distribution and minimization of strain energy. At the Heydar Aliyev Center, this principle is taken up through parametric models that allow the formation of a smooth three-dimensional "epidermis" of an object. The elimination of sharp transitions and the application of large continuous surfaces allow for the redistribution of loads through geometry — analogous to the way diaphragms carry stresses through tension flows [120].

In natural membranes, surface dynamics form ridges, depressions, and folded zones that occur in response to mechanical loads or pressure changes. A similar topological logic is recognizable in the architectural form of the center: the folds on the mantle act as "enlarged biological folds", while the overall form suggests a stretchy, elastic continuous material, like epithelial structures that change shape under the action of forces [118, 124].

Biological membranes carry loads through evenly distributed tension, relying on shape instead of material mass. The construction of the Heydar Aliyev Center realizes a similar principle: the supporting function is taken over by a system of curved shell surfaces that redirect forces through a network of voltage lines. In this way, the building functions as the architectural equivalent of a thin-walled biological membrane optimized by evolutionary processes [115, 121].

The macrostructural panels on the façade are organized in such a way as to reproduce the visual porosity and inhomogeneous texture typical of membrane microstructures. The interaction of light with curved surfaces produces effects reminiscent of the optical behavior of biological tissues — the surface appears to "breathe" depending on the intensity of the illumination. This object functions as an architectural interpretation of a living organism, where the building envelope becomes analogous to the skin that unifies and defines the interior and exterior space [122, 125].

The Heydar Aliyev Center can therefore be defined not only as an aestheticized imitation of nature, but as a performative system that operationalizes the principles of biological organization — continuity, elasticity, adaptive geometry, and the membrane logic of voltage distribution. This makes the building one of the most significant examples of the 21st century in which architecture demonstrates the ability to reconstruct natural processes and formal-structural principles in a high-tech, materially advanced context.

3.10. Al Bahr Towers, Abu Dhabi - pine cone *(**Architect**: Abdulmajid Karanouh, 2009)*

Figure 10 shows two complementary morphological patterns that demonstrate how contemporary architecture uses bioinspired principles to redefine the energetic, geometric and adaptive characteristics of façade systems. The visual parallel between the façade of the **Al Bahr Towers** system and the structural organization of the pine cone clearly confirms that modern engineering approaches increasingly rely on morphogenetic models from nature rather than just formal aesthetic analogy, a tendency widely affirmed by contemporary literature [128, 133].

On the left side, two cylindrical towers about 145 m high are shown, the entire envelope of which is enveloped by a dynamic system of geometric panels based on a modular diamond-rhombic matrix. These units, arranged according to an algorithmically generated pattern, open and close in real time depending on the intensity of solar radiation, thus achieving highly efficient solar gain regulation. Adaptive panel mechanics are based on mechatronic actuators that allow for modulation of transparency and shading, analogous to the way in which plant hygromorphic systems passively alter the geometry of tissues due to fluctuations in humidity [131, 134]. Visually and structurally, this behavior represents an architectural translation of an evolutionarily optimized natural mechanism.

The right side of the image shows a pine cone, the structure of which is one of the most famous natural examples of geometric organization in Fibonacci spiral sequences. The arrangement of the scales, formed through a diagonal and helical grid, is optimized for a combination of strength, minimal mass, and the ability to open and close adaptively as a result of hygromorphic changes in plant fibers [129]. These spiral patterns, supported by fundamental mathematical rules, simultaneously regulate mechanical stresses and stiffness distribution, making them particularly relevant for transfer to architectural façade systems.

Figure 10: *Al Bahr Towers - pine cone*

Bioinspired correlation between the Al Bahr Towers façade system (left) and the spiral-diagonal structure of the pine cone (right). Architectural mesh geometry and adaptive panels reinterpret Fibonacci-based arrangements and hygromorphic mechanisms of natural cones, demonstrating the application of biomimetics in energy optimization and structural logic of façade systems (Figure 10).

Compared to the pine cone, the façade of the Al Bahr Towers reinterprets the same logic of the spiral-diagonal grid, creating a porous-non-porous envelope whose permeability to solar radiation changes through the movement of more than 2,000 adaptive panels. This approach allows for a reduction in solar gain of up to 50%, which directly affects the reduction of energy consumption for air conditioning, confirming that biomimetic geometry can also have a high energy effect [126, 127].

The structural correlation between natural and architectural systems is manifested in their shared network topology, where the helical-diagonal distribution of elements allows for an optimal combination of rigidity, elasticity, and adaptability. In nature, this geometry allows the cone to control the opening of the shells depending on humidity, while in architecture it provides stability to the façade structure under changing wind loads and dynamic solar conditions. Thus, the Al Bahr Towers represent one of the most relevant examples of architectural biomimetics in high-performance façade systems of the 21st century, in which the natural model is not only an aesthetic but primarily a functional, structural, and energetic prototype [130, 132].

CONCLUSION

Nature is the most complex system optimized through millions of years of evolution and therefore an inexhaustible source of inspiration for contemporary architecture and construction. The analysis of natural structures, principles of formation and behavior under load enables the development of advanced structures, efficient materials and sustainable energy systems. The integration of biomimetic principles into engineering practice represents the future of design and construction — a future that combines science, technology, and biological wisdom.
An analysis of ten representative examples of biomimetic architecture clearly shows that natural structures are not just aesthetic inspiration, but extremely sophisticated models of structural efficiency, resilience, intelligence, and optimization. Each natural system analyzed — from microscopic fibers to macroscopic biological organisms — possesses clearly recognizable optimization principles: hierarchical organization, topological rationality, minimal material consumption, optimal voltage distribution, adaptive functions, and integrated sensor networks.
Architectural and building structures inspired by nature demonstrate significant advantages:

1. reduced material consumption
2. Greater energy efficiency
3. Greater resistance to wind, snow and seismic
4. Increased spans and free geometry
5. Possibility of adaptive and reactive facades
6. Integration of intelligent sensors modeled on biological systems

Biomimicry has already proven itself as a key direction of progress, and its role will only grow with the development of digital tools (FEM, CFD, topological optimization, robotic fiber winding, parametric design).
We conclude that the future of architecture and construction lies in:

1. integration of evolutionary principles into design,
2. the development of new biocomposites,
3. energy-intelligent façades,
4. minimum mass structures,
5. A digital factory based on nature.

The common denominator is the *optimization of mass, energy, form, and performance* according to a logic that nature has developed over millions of years.

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