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Bionic Approach to the Organization of Architectural Objects in the Sustainable Development Paradigm

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Abstract Global environmental, social, and economic problems have led to the need to search for new architectural ideas according to the concept of sustainable development. The bionic approach makes it possible to identify optimal solutions developed by nature over the centuries of its existence for the organization of architectural objects. The purpose of the paper is to establish the prospects of applying the bionic approach to the organization of sustainable architectural objects. The paper presents a comparative analysis of scientific papers considering methods of biomimetic design, a case study, and a survey of experts. The characteristic directions of architectural bionics have been identified and described. Based on the analysis of the conditions for creating a comfortable living environment, solutions to sustainability problems using a bionic approach in the organization of architectural objects have been proposed. The authors pay special attention to the life cycle stages using natural forms in architectural shaping, borrowing natural structures to form the structures of architectural objects, interpreting natural materials and matter of living organisms in construction, and reproducing natural processes to solve architectural and urban problems. The authors identify the main approaches of bioanalog design based on the existing morphological characteristics of wildlife (branching, spiral formation, adaptation, polymerization) and propose solutions to the problems of creating sustainable habitats in the context of architectural space. It is concluded that the use of this approach will contribute to the formation of an ecological balance between nature and architecture.

Keywords Sustainable Development, Challenges of Habitat Sustainability, Architectural Bionics, Biomimetics, Bionic Approach

1. Introduction

A socially oriented urban environment (the territory of Sustainable development covers such spheres of human activity as the economic, social, and natural spheres. Sustainable development is located at the intersection of these spheres of activity [1]. At the Symposium on Sustainable Architecture in 2011, G. V. Esaulov [2] proposed the definition of sustainable architecture as "architecture that demonstrates a consistent unity of the aesthetic positions of the author and the time and socio-economic, engineering, technological and environmental requirements based on the principles of sustainable development, the completeness of implementation, which is determined by the requirements of the rating systems for assessing the sustainability of the habitat accepted in global practice and the practice of a particular country". Based on this definition and the accepted principles of formation, one can locate biomimetics in the sustainable architecture paradigm (Figure 1).

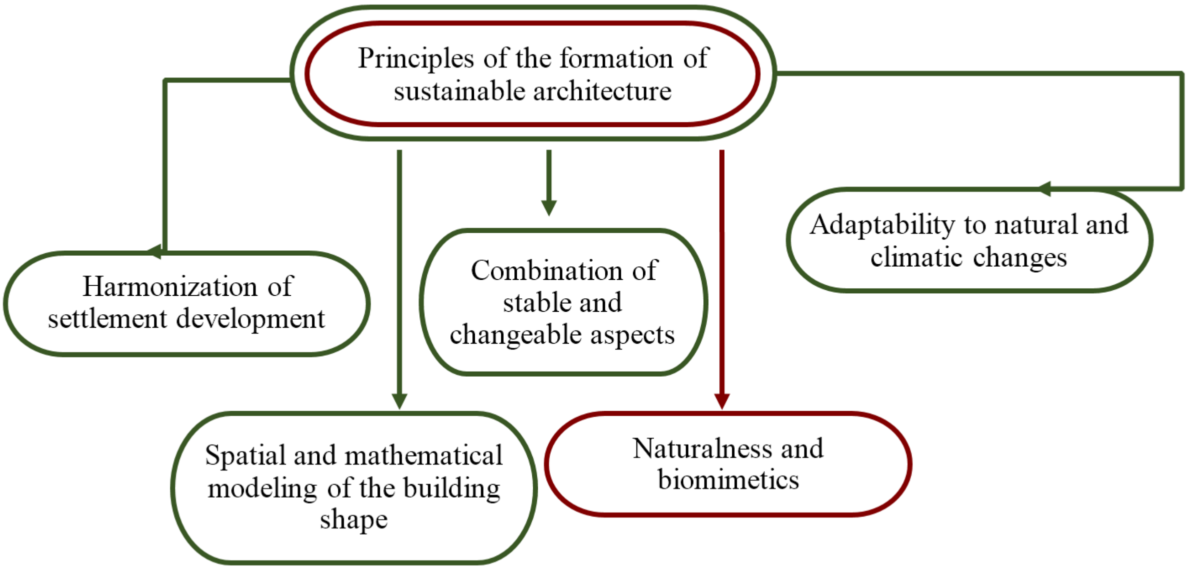


Figure 1. The place of architectural bionics in the model of sustainable architecture

		
Paveletskaya Plaza multifunctional complex (MFC) (Russia)	Lycee Jean Moulin (France)	Inter-Continental Shanghai Wonderland Hotel (China)

Figure 2. Examples of architectural structures demonstrating the interaction of architectural objects with the landscape

The main features of sustainable architecture are also highlighted, namely, environmental friendliness and the use of high technologies. A shorter definition is given stating that "Sustainable (green) architecture is environmentally oriented high-technology architecture" [3, p. 5]. These features of sustainable architecture include the following areas:

The interaction of architectural objects with the landscape implies the harmonious integration of buildings into the environment. Specialists identify the following ways buildings interact with the landscape: the introduction of an architectural structure into the body of the landscape (full implementation or implementation with the exit of part of the building outside the landscape); following the shape of the relief [4]. Besides, depending on the nature of the relief, techniques of the interaction of objects with the landscape are distinguished: a plain relief with a slight elevation difference (steppes, fields, plains) provides for the deepening of architectural objects into the body of the landscape or its hyperbolization while working with hilly mountainous terrain (mountains, hills) consists in terracing objects located along the relief [4] (Figure 2).

The use of natural materials in construction forms an eco-friendly architectural space for human life and health and minimizes its harmful impact on the environment. The active use of natural construction technologies is implemented in the integrated direction of eco-low-tech. This direction is divided into the following methods of handling materials: the use of natural materials in construction (wood, stone, clay, vegetable raw materials, adobe (superadobe), natural fibers and their composite combinations; research, processing, and reuse of natural materials in building structures [5].

Modern construction technologies that widely use natural materials include the manufacture of composite materials based on low-grade wood; the production of reed and straw slabs; the method of high-speed ultra-thin sawing of stone materials; the creation of structures based on mesh metal blocks filled with stone (gabions), etc [6].

The secondary use of natural materials is one of the ways to create new building components. Based on crushed shellfish shells, specialists reproduced a natural polymer called chitin, which is an environmentally friendly building material used to create structural systems and individual elements of a building [7, 8]. In addition, technologies have been developed to replace traditional fittings with hemp fittings, the use of balsa wood instead of classic double–glazed windows, bio-coal cladding made from forest and agricultural waste, etc. [9].

The exploitation of natural objects is materialized in the idea of using large-sized plants without interrupting their life cycle. This method is called arboarchitecture (Figure 3). As a rule, the structural basis of the bearing or enclosing system of a building is formed using various spatial schemes of fastening branches and trunks of such trees as willow and poplar.

The inclusion of natural components in the structure of buildings is based on various approaches to landscaping the surfaces of architectural objects. In architecture, several such approaches are observed, namely, landscaping of the cover, landscaping of the vertical and horizontal surfaces of the object, and the use of plants in the formation of its interior [10] (Figure 4).

Landscaping of the cover, or green roof, depending on the type of care, is divided into an extensive cover that requires minimal care and is characterized by herbaceous flat-growing drought-resistant plants and an intensive cover that imposes special requirements for care, as well as constituting a multi-layered carpet with flowers, shrubs, and trees. Landscaping of vertical and horizontal surfaces of a building can be represented by continuous vertical landscaping, landscaping by a group of plants, Patrick Blank's vertical garden technology, and container landscaping [11]. In vertical continuous gardening and landscaping with a group of plants, climbing plants and vines are used, fixed with the help of racks and staking on a vertical surface, whereas in container gardening modules are used where plants are planted. The concept of Patrick Blank's vertical gardens is to form a metal frame with two layers of polyamide felt attached to it, which serves as a substrate for the roots of the plant. The inclusion of plants in the interior space is ensured by horizontal and vertical landscaping of internal surfaces [12]. Herbaceous, flowering, and shrubby plants are used as green spaces. This approach is reflected in such types of design as ecodesign and phyto-design.

The introduction of renewable energy systems into architectural objects is a booming direction of the development of modern architecture. Currently, there are many different energy-efficient and environmentally friendly technologies [13].

The concept of an energy-efficient building is based on the creation of increased comfort through automatic control of the internal microclimate and autonomous energy supply [14]. Autonomous energy supply systems use renewable natural resources, including wind, solar, tidal, hydro, and geothermal energy, as well as energy derived from biomass. When these systems generate more energy than necessary, the building becomes active. The idea of a passive building is to use renewable natural resources and reduce energy consumption from traditional sources (no more than 15 kV/m^2 of total area) with the help of high-quality insulation of enclosing structures and heat recovery of exhaust air and sewage.

Globe of Science And Innovation (Switzerland)	Elqui Domos Astronomical Hotel (Chile)	Macaloui House (Russia)

Figure 3. Examples of architectural structures using natural materials in construction

Garden Quarters Residential Complex (RC) (Russia)	Nanyang Technological University (Singapore)	Giant Interactive Headquarters (China)

Figure 4. Examples of architectural structures with the inclusion of natural components in the structure of buildings

The active house (Russia)	Saint-Gobain Academy (Russia)	Helicon Building (UK)

Figure 5. Examples of architectural structures with the introduction of renewable energy systems into architectural objects

2. Literature Review

The principles of naturalness and biomimetics are an integral part of the scientific paradigm of sustainable architecture [15]. The term biomimetics is also currently used to define architectural bionics (from the Greek "bios" (life) and "mimesis" (imitation)). Today, the terms "bionics" and "biomimetics" are synonymous and are actively used to determine the actual form of architectural activity.

The need to search for new architectural and planning, structural, spatial, engineering, and economic solutions according to the principles of sustainable architecture determines the formation of new approaches to design [16]. Therefore, the principles of architectural bionics are interesting, as they consist in mastering the process of deep understanding of natural forms and processes, and their application in architectural design [17, 18]. The founder of Russian architectural bionics Yu. S. Lebedev [19, p. 56] thinks that one of the advantages of science is "the possibility of searching for new functionally justified architectural forms, distinguished by beauty and harmony, and the creation of new rational structures with the simultaneous use of amazing properties of the building material of wildlife, and the discovery of ways to implement the unity of design and creation of architectural means using the energy of the sun, wind, and cosmic rays". He also considers the most important result of the application of architectural bionics to be "the creation of conditions for the preservation of wildlife and the formation of its harmonious unity with architecture", which meets the main objectives of the concept of sustainable architecture [19, p. 78].

The problems of sustainable development of architecture were described by such theorists as G. V. Esaulov and Yu. A. Tabunshchikov [2, 3, 13, 15]. The bionic approach is widely represented in the works of Russian architects, including Yu. S. Lebedev, A.D. Gridyushko, and E. V. Denisenko [19-22]. Foreign research on biomimetics (biomimicry) was conducted by N. Oxman, H. Bensoussan, T. Atsushi, the University of Stuttgart, and P. Gruber [7, 23-25]. Organic and green architecture, as well as ecological construction, has been described in the works of A. N. Bliznyuk, E. A. Vashkovskaya, P. N. Sankov, T. Ya. Vavilova, E. M. Mantsurova, A.G. Zima, S. V. Ilvitskaya, O. L. Bantserova, and A. R. Kasimova [4, 5, 10, 11].

It can be argued that with the help of a bionic approach in architecture, it is possible to solve a wide range of problems of its sustainable development based on wildlife.

The analysis of scientific studies considering architectural design with the involvement of the natural component has shown that there are several characteristic directions in the application of the bionic approach. They include:

- the use of natural forms in architectural shaping;
- the borrowing of natural structures to form the structures of architectural objects;
- interpretation of natural materials and materials of living organisms in construction;
- reproduction of natural processes for architectural and urban planning solutions.

Thus, the purpose of this study is to evaluate the bionic approach to the organization of architectural objects and identify trends in its application within the framework of sustainable development.

3. Materials and Methods

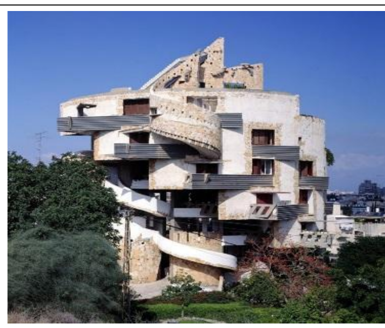
According to the purpose of this work, we carried out a qualitative study, which included document analysis, case study, and expert survey.

The study was conducted in three stages at the Moscow State University of Civil Engineering (National Research University) in 2021.

In the first stage, scientific papers which demonstrated the concept of a bionic approach to the organization of architectural objects were selected and analyzed. When reviewing the works, various morphological characteristics of natural objects were studied and analyzed, and characteristic directions of architectural bionics were generalized and identified. Based on the identified needs of sustainable architecture, solutions to the problems of creating a sustainable habitat through a bionic approach were proposed.

In the second stage of the work, we conducted a case study. Four fields in the application of the bionic approach and examples of architectural structures related to them were selected for analysis (Table 1).

Table 1. Features of the bionic approach in the design of architectural structures

<table>
<tr><td colspan="3">Field 1. The use of natural forms in architectural shaping</td></tr>
<tr><td>
The Conch Shell House (Mexico)</td><td>
Heydar Aliyev Center (Azerbaijan)</td><td>
Harbin Opera House (China)</td></tr>
<tr><td colspan="3">Field 2. Borrowing natural structures to form the structures of architectural objects</td></tr>
<tr><td>
Moscow Planetarium (Russia)</td><td>
L'Oceanografic Restaurant (Spain)</td><td>
German Pavilion (Canada)</td></tr>
<tr><td colspan="3">Field 3. Interpretation of natural materials and materials of living organisms in construction</td></tr>
<tr><td>
GLA University Hostel (India)
Cellular concrete as a building material</td><td>
Magical Science and Technology Park (Spain)
Fiberglass as a building material</td><td>
Arboskin Pavilion (Germany)
Biodegradable plastic as a building material</td></tr>
<tr><td colspan="3">Field 4. Reproduction of natural processes for architectural and urban planning solutions</td></tr>
<tr><td>
Solaris (Singapore)</td><td>
Spiral House (Israel)</td><td>
Heinz-Galinski School (Germany)</td></tr>
</table>

In the third stage, an expert survey was conducted. In total, 25 participants of the study were selected: ten were teachers of the Department of Architecture, eight were the representatives of state institutions for construction, and seven were employees of enterprises involved in the design and construction of architectural structures. The selection of experts took place according to the following criteria: the interviewed expert had authored or co-authored at least three papers on this topic published in journals included in the Scopus or Web of Science citation databases or had at least 5 years of work experience. By e-mail, electronic messages were sent to the experts with a request to evaluate existing approaches to biomimetic design based on existing morphological characteristics and suggest solutions to problems for creating a sustainable habitat.

The e-mail contained 12 examples of buildings in four fields (Table 1) that were designed using a bionic approach, as well as a list of the following questions, which the experts were asked to answer in an expanded form:

1) Based on the presented examples, what do you think are the main morphological characteristics in applying the bionic design approach?
2) What are the most obvious challenges in creating a sustainable environment that you can highlight?
3) What solutions do you see when applying a bionic approach to the design of architectural structures?

All participants of the study were warned about the study objectives and that the organizers of the study were going to publish its results in a generalized form.

4. Results and Discussion

Currently, architectural bionics is not limited to a superficial imitation of the form but considers processes that are optimal ways of developing living systems. The mechanisms of reaction to the environment, sensory organs of living organisms, and methods of obtaining, processing, transporting, and storing nutrients, both animals and plants, are studied, which allows us to borrow from nature the principles of morphogenesis and interaction with the environment. All stages of the life cycle of biological systems are considered and all processes occurring in the biological structure of interest are studied.

The use of natural forms in architectural shaping involves direct borrowing or interpretation of the forms of the surrounding world. A.D. Gridyushko in his scientific work identifies a biomimetic approach based on the natural form, which considers such laws of form construction as zoomorphism, anthropomorphism + natural geometry, the golden section, human scale, and symmetry [20, 21, 26].

As a result of the study, it is proposed to identify such morphological characteristics of natural systems as spiral formation and branching. The fundamental bionic principle of creating a harmonious structure is spiral formation, which is widely used to create dynamic volumes that allow extended forms to be assembled into compact structures using various types of spiral curves (logarithmic spiral, hyperbolic spiral, parabolic spiral, Archimedes spiral, helix, cone-shaped spiral, and the Cornu spiral). Spiral forms have been used in architecture since ancient times, starting from the Tower of Babel to the twisted domes of St. Basil's Cathedral and the Evolution Tower by architect F. Nikandrov in Moscow. One of the important principles of natural systems is branching, which is characteristic of both molecular structures and plant organisms. An example of branching transport communications is the planning organization of the central historical part of large cities.

Borrowing natural structures to form the structures of architectural objects implies the study of patterns and modes of action of biological structures in wildlife. A biomimetic approach based on natural structures is considered, including nutshells, eggshells, turtle shells, animal shells, wings, plant petals, etc. [21, 27]. The principles of constructing these biological structures are implemented in building shells, mesh and ribbed structural systems, cable-stayed, rod and cable-stayed, pneumatic structures, membranes, and tent covers.

Interpretation of natural materials and materials of living organisms in construction consists in studying the properties of biomaterials and their derivatives, such as tissues of animal organisms, stems, and leaves of plants, spider webs, pumpkin tendrils, etc. Such a biomimetic approach involves the study of similar biological structures and the creation of new traditional materials using them, such as cellular materials and fibers, and composite and adaptive materials (nanomaterials) [21, 28]. These materials include cellular concrete, sponge iron, carbon fiber, fiberglass, and geogrid.

The reproduction of natural processes for architectural and urban planning solutions is based on understanding the laws of natural activity. For example, in one biomimetic approach such processes as stability, self-organization, variability, evolution, and fractal geometry are distinguished [21]. The application of the branching principle serves as a solution to the problems of territory development through staging [29]. The study of the vital activity of the moldy Physarum polycephalum fungus in terms of the routes it builds to the food locations and comparing them with the Tokyo transport network has made it possible to find out that the network built in this way is the most efficient and optimal [23]. Another approach involves studying the properties of living systems, including mimicry, metabolism, adaptation, autoregulation, discreteness, growth, reproduction, and heredity [22]. The interpretation of these properties in architecture gives objects such characteristics of living systems as the dissolution of forms and materials of architecture in the natural environment, cyclic interaction of objects with the external environment, their transformational capabilities, etc.

In addition to global natural processes, bionic technologies are being created, with the help of which models and principles of life and the functioning of natural objects are transferred to architecture [30]. Thus, based on the construction technology used by a living spider, a special mechanism was created that repeated its movements at the time of creating a spider web [24]. The pavilion built in this way is distinguished by a lightweight shell and the ability to adapt to various types of structures.

Based on the results of the analysis of experts' answers in the process of studying the directions of architectural bionics, the main approaches of biomimetic design based on the existing morphological characteristics of wildlife, such as spiral formation, branching, polymerization, adaptation of natural structures and organisms, were identified and solutions for creating a sustainable habitat were proposed (Table 2).

Table 2. Application of a bionic approach taking into account the morphological characteristics of natural systems to solve the problems of creating a sustainable habitat

No.	Natural morphological characteristics	Tasks for creating a sustainable living environment		Solutions to the relevant problems based on the bionic approach
1	Branching (similar biological structure: Greek juniper)		Optimization of urban transport infrastructure	The use of the *natural* branching *process* in urban planning in the design of moving flows of pedestrians, motor vehicles, and trolleybuses
			The insolation of the residential area	Creation of space-planning solutions of architectural complexes according to various *similar biological systems of leaf arrangement on plant stems*: the regular, opposite, whorl, and mosaic ones
2	Spiral formation Similar biological structures: seashells, horns of Dall's sheep		Provision of the building with natural light	Formation of the spatial planning organization of the object based on the *principle of cone-shaped plant growth*
			The rationality of the architectural form of the building	Formation of extended architectural forms into compact structures *(horns of mountain sheep, grapevine runners)*
			The dynamism of the architectural form of the building	Creating an architectural image based on a biological structure of seashells *(Terebra guttata, Hemifusus carinifer, Fusinus salisburyi, and Tibia indica)*
3	Adaptation Similar biological structures: Pokrovsky sunflower, chicken egg, the Luna moth		Air-thermal comfort of the building	Using *the principles of temperature adaptation of plants and thermoregulation of animals* to create optimal microclimate parameters
			Illumination comfort of the building	Using the *principle of light adaptation of plants such as sunflowers or mimosa* to create optimal illumination parameters
			Acoustic comfort of the internal space of the building	Creation of sound-absorbing materials based on the *structure of the moth wings*
			Reduction of heat loss in the building	Formation of a three-dimensional solution of an object using the principle of compactness of *natural forms based on an egg or a poppyhead*
			Protection from ionizing and electromagnetic radiation	Designing the shielding surfaces of the volume of buildings using the biomimetic principle of the *reflective structure of the film based on egg white*
4	Polymerization Similar biological structure: honeycomb		Regularity of settlement development	Polymerization of typical architectural forms based on the *principle of the uniform type of honeycomb structure*

	infrastructure and environmental quality
	the architecture of the object and the quality of its internal environment
	engineering systems of the facility and their energy efficiency

The highlighted solutions to sustainability problems based on the bionic approach are also correlated with the principles of environmental planning described by K. Daniels [25]. These principles have been developed for buildings, open spaces, and engineering systems of life support and waste disposal.

Thus, the application of the natural principles of the structure and functioning of living organisms in design and construction opens up effective directions for improving and creating sustainable architecture.

5. Conclusions

The application of the bionic approach to the organization of objects in the design and construction will contribute to the sustainable development of architecture and will make it possible in the future to achieve an ecological balance of nature and the artificial environment with the help of morphogenesis and the use of high technologies. Therefore, it is important to study the principles of natural processes, such as branching, and spiral formation, as well as the properties of living systems, such as metabolism, adaptation in response to changes in external influences, growth and development of the organism, and heredity. The identified solutions to sustainability problems based on the bionic approach will help in creating a sustainable habitat.

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