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A DISCOURSE ON THE APPLICATION OF BIOLOGICAL PRINCIPLES IN BUILDING DESIGN

Abstract:

This paper elaborated on a variety of reasons for the use of biological principles in building context over time. A particular accent was placed on position of biological systems within the contemporary concepts of sustainability, circularity, resilience, and regeneration. Existing design barriers were identified and discussed, and the currently available ways to overcome them were outlined. Conclusively, several general steps towards a more comprehensive future application of biological principles in building design were suggested.

Keywords: biological principles, building design, contemporary concepts, challenges

ДИСКУРС О ПРИМЕНИ БИОЛОШКИХ ПРИНЦИПА У КОНТЕКСТУ ПРОЈЕКТОВАЊА ЗГРАДА

Сажетак:

У овом раду су анализирани разлози примене биолошких принципа у контексту зграда током времена. Нарочито је истражена позиција биолошких система у оквирима савремених концепата одрживости, циркуларности, отпорности и регенерације. Утврђене су и разматране актуелне пројектантске баријере, и предочени тренутно расположиви начини за њихово превазилажење. Закључно је предложено неколико општих корака ка будућој широј примени биолошких принципа у контексту пројектовања зграда.

Кључне ријечи:биолошки принципи, пројектовање зграда, савремени концепти, изазови

1. THE EVOLUTION OF BIOLOGY-DESIGN NEXUS

Humans possess the innate tendency to focus on life and lifelike processes [1]. Complex human relation with life and nature is based on biological, cultural, psychological and ethical bonds [2]. An essential need to worship nature [3] stretches back to the early examples of human creativity. Architectural artifacts of different historical periods repeatedly demonstrate the imitation of natural shapes applied to ornamental surfaces or the three-dimensional elements.

First notable examples involving biological principles in the function of achieving both the innovation and the usefulness [4] belong to the sphere of invention. Pioneering biologically inspired and deliberated design solutions emerged as a result of the research of living species' abilities and their translation to designed objects. Leonardo da Vinci, for example, examined biomechanics of flying animals, muscle forces and the functions of joints, and attempted to apply biological features in his technical inventions. Matthew Baker studied the flow-optimized form of fishes to enhance the performance of his new galleon-type ship [5:4]. The use of biological principles in various fields and in a reasoned way was largely made possible during the 19th century. At that time, natural sciences became more mature, and communicated fund of knowledge from newly emerged disciplines enlarged significantly.

In the 19th century architecture, however, the application of biological principles was rather a topic for debate than a design inspiration or a research subject. While some notable representatives of this period believed that the ultimate beauty of nature should simply continue to be imitated, others, like Eugene Emmanuel Viollet-le-Duc, argued for the architecture that does not copy the nature, but instead emulates its laws [6]. The later design approach was a stimulus for more thoughtful analogies with biological systems that aimed to derive technically usable solutions based on natural abstraction [5:4]. The works of Antonio Gaudi show that such approach also leads to a unique aesthetic result.

Particular scarcity of biology-inspired architectural design concepts in the second half of the 19th century [7] represents a consequence of the emergence of new technical knowledge and technical experimentation. During the first half of the 20th century, technological and industrial progress and the overall societal shifts were used as a base of modern design philosophy, and the ideas of past were neglected together with the relation to nature and its forms, due to "conceptual barrier erected between nature and culture" [8:47]. Nevertheless, some theoretical discourses from this time, such as those written by Honzik or Keisler [9], aimed to draw analogy between technology and nature. By the middle of the past century, alternative theories and concepts started to emerge. In Metabolism, a building was compared to an organism, and, therefore, it had to be adaptive and able to grow. In the 1950ies, Peter Collins discussed the idea of 'Biological Analogies', and Otto Schmitt coined the term 'Biomimetics', referring to the mix of biology and technology. Since its first introduction, different definitions and the contexts of use of biomimetics have been emerging. According to Dollens [10:420], for example, biomimetics represents a "design where properties, elements and systems from nature are viewed, researched and extrapolated from in order to apply natural functions and attributes to architectural structures, materials, systems, spaces and aesthetics." In the 1960ies, Frei Otto and Johann-Gerhard Helmcke together founded the 'Biology and Building' research group that promoted collaboration between architects, engineers and biologists in research and experimentation [11]. In the USSR, architect and researcher Yuri Sergeyevich Lebedev developed 'Architectural Bionics' that aimed to explore analogies „not only between natural and architectural structures and functions but also between their fundamental compositional and forming principles such as architectonics, symmetry, proportions, modularity, rhythm, expression of forms, etc." [12:103]. With that, the connections between golden ratio, Fibonacci sequence and architecture were strengthened, although proportions based on inorganic, geometric rules have been applied since ancient times. Following progress in biological science, geometry of nature and the analogy with art and architecture were explored by Zeising, G.L. Raymond, S. Colman, T.A. Cook, B. Fuller, G. Doczi, I. Ševelev, Z. Pađan, and others.

Over the last decades of the 20th century, experiments on natural models [13] were surpassed by digitization and experimentation with the new design media [14] such as animations of morphological transformations, deformations, or movement through time [15]. Together with parametric modelling and generative techniques for design and manufacture of building products [16], including 3D printing, these tools allowed for the development of very complex design concepts like the pattern design. At the same time, the bond between design and ecology was becoming firmer, and the role of biological systems in building context was again redefined (e.g. the works of Hundertwasser). In 1997, Janine Benyus introduced the term 'biomimicry revolution' to describe new "era based not on what we can extract from nature, but on what we can learn from her" [17:2]. In the 21st century, the application of biological principles in the building context is seen as a contribution to the universally relevant frameworks: sustainability, circularity, resilience and regeneration.

2. BIOLOGICAL PRINCIPLES IN CONTEMPORARY FRAMEWORKS

In 2016, the European Commission has included nature-based solutions among focus areas for research and innovation on environment, and provided the following definition: Nature-based solutions are "solutions that are inspired and supported by nature, which are cost-effective, simultaneously provide environmental, social and economic benefits and help build resilience. Such solutions bring more, and more diverse, nature and natural features and processes into cities, landscapes and seascapes, through locally adapted, resource-efficient and systemic interventions" [18]. Nature-based solutions addressing social, economic and environmental challenges have also been promoted in the global policy contexts, by science-based organizations, the World Bank, and the United Nations [19]. So far, however, nature-based solutions at the building scale have not been particularly emphasized in policy frameworks.

In contemporary terms, the application of biological principles in building contexts can refer to a reasoned adoption of biological characteristics, an actual introduction of biological entities into a building, or both, while a simple imitation of natural forms accounts for an obsolete approach from above discussed reasons.

2.1. Sustainability and circularity

Analogies with living organisms, applied to the system of an environmentally sustainable building and possibly connected with intelligence component as well as underlying design concept, aim to support efficient use of natural resources and the reduction of negative environmental impact.

Biological principles may be applied to achieve energy efficiency of a building, i.e. to reduce energy demand (e.g. through the adoption of methods for wise energy use by living organisms) and to generate energy (e.g. by introducing solar panels based on photosynthesis). Some bio-based measures are multi-beneficial: facades with integrated algae, for example, capture carbon, produce oxygen and generate renewable energy [20]. A particular contribution of living systems to water efficiency is recognized in the domains of water harvesting and wastewater recycling (e.g. living machine installations). Similarly, living organisms can contribute to organic waste decomposition in situ. Nevertheless, the greatest progress in the application of biological principles in contemporary building context has so far been achieved in the field of materials.

The experimental and research work of Frei Otto in the field of minimal surfaces and their analogies with natural principles could today be compared with the optimal use of building materials encompassed by sustainability and circularity concepts. Next to that, there is a wide range of bioinspired building materials whose modified features ultimately result in bettered ecological quality, from improved durability (e.g. self-healing materials [21]), to enhanced interaction with surroundings (e.g. color changing surfaces, or intelligent glass that reacts to temperature or light changes), to carbon storing, e.g. [22], etc.

Green movements that were emerging from the 1970ies shed a new light on materials of plant and animal origin, and raised awareness about their ecological advantages, including: abundance, renewability, low embodied energy and CO_2, low ecotoxicity and toxicity, provision of good indoor air quality, biodegradability, recyclability, etc. In the 21st century, the application of bio-based solutions became an integral part of sustainability and circularity schemes, and the matter of biological origin an optimal raw material. Particularly interesting nowadays are the materials made of agricultural waste, such as wheat straw, hemp shiv, flax shiv, or corn pith, and active bio-based materials with integrated living organisms – the 'living materials' – such as bricks, concrete and textiles with living bacteria. State-of-the-art research focuses on optimization of performance of bio-based materials (e.g. increased resistance to molds, and fire, or improved durability), reduction of negative ecological impact of composite materials representing a mix of natural and artificial ingredients (e.g. bio-plastics), and the development of bio-based insulation materials that contribute to both material and energy efficiency.

In addition to material features alone, functional circularity schemes emphasize their bonds within building components and systems, altogether known as design-for-disassembly approach. It is being foreseen that the analogies supporting circularity and sustainability concepts could in future be extended from individual organisms to ecosystems, their cycles of matter and energy transfer [22], [23].

2.2. Climate resilience

One of the basic functions of a building is to protect its users from variable external conditions such as climate. Examples from different historical periods point at the multitude of measures applied for this purpose as well as the shifting character of barrier separating indoor from outdoor space. These variations – ranging from isolation and independence to responsiveness and adjustment – are well observable in the 20th-century building design. The designers who took later approach were in particular interested in exploring the potential for dynamic response to climate patterns, and biological principles were often used as role models. In 1964, Andrija Mutnjaković developed the Homobil – a vision of the house behaving as an organism-machine thanks to its flowerlike form that opens and closes depending on external circumstances [24]. Kinetic buildings based on biological principles were designed by the Archigram group, the Japanese Metabolists, Buckminster Fuller, Yona Friedman and, more recently, Santiago Calatrava.

The key role in building adaptation has been assigned to the envelope, for which reason it is often referred to as 'adaptive skin'. By changing functions, properties and behavior over time, adaptive building skins are aimed at improving the overall sustainability-related building performance [25]. In spite of increasing number of examples, however, the use of biological principles in design and construction of adaptive building envelopes should be developed further. Possible directions include diversification of applied biological characteristics, accomplishment of multifunctionality [25], development of systemic solutions [26] and, in that regard, development of building skins that perform well under the impact of climate change manifestations.

Climate change is experienced, scientifically proven and widely recognized phenomenon. In addition to mitigation covered by the concept of sustainability, there is an urgent need to find ways to develop resilience to climate change-related manifestations in the built environment. "The pursuit of resilience adds another dimension to design projects, gives additional challenges to architects, and redefines the complexity of the design process and methodology, by requiring transdisciplinary and a systemic approach, as well as the inclusion of various correlating agents that determine the future behavior of a building subjected to climate change" [27:45]. The application of principles of the living world in the context of building resilience is yet to be studied. At the root of current scarcity of building design theories and examples lies the so far modest body of work dealing with the effects of climate change on living organisms and their responses to gradual (long-term) changes and sudden surprises.

According to some authors, the notion of climate resilience in the built environment extends beyond the boundaries of individual buildings. In such a conceptual approach, a building is not only an independent object, but also part of an ecosystem in which diversity and redundancy are present, which results in a greater ability for adaptation [22:177] [23:7]. Therefore, application of biological principles in building resilience refers not only to the characteristics of built objects, but as well to their users, e.g. [28].

2.3. Regeneration

In 1993, Wilson pointed to the obligation of psychologists and other scholars to consider biophilia in more urgent terms, as the natural environment is disappearing. "What, they should ask, will happen to the human psyche when such a defining part of the human evolutionary experience is diminished or erased?" [29:35] It appears that sustainability and circularity measures taken until now can only slow down negative processes in natural capital. From the other hand, advanced regeneration schemes aim to shift the course of negative phenomena by creating net positive effects for the environment.

Like resilience, regenerative design demands an outreaching, systemic approach where buildings represent nodes instead of independent objects, and human systems are indivisible from ecosystems [30]. The role of humans in regenerative framework is active, as the ultimate goal is to bring their needs into a long-lasting synergy with the requirements for natural integrity. Therefore, humans, at the current point of development, need to recognize (again) their positioning within the living systems and to understand the complex patterns of dynamics [31] in which they are embedded. "Bringing humans back to their biological nature ultimately opens a new debate on the relationship to contemporary technologies. In addition, between design that regenerates the environment by involving humans and their activities, and the perspective that looks for ways to intensify positive effects of nature on humans, a new integral framework needs to be defined. The introduction of biological entities into design is believed to represent a significant agent in the integration process". [32:268]

Hence, the application of biological principles in regenerative building design extends to the point of actual introduction of the living matter, not only during the use and maintenance (e.g. living walls or green roofs), but as well in other life cycle phases (e.g. by embedding seeds and stimulants of growth into biodegradable materials). Nature-based regenerative design concurrently contributes to sustainability – by reversing environmental impact trends, circularity – by stimulating biological cycles, and resilience – by developing ability of a system to adapt and thus overcome experienced stress.

3. CHALLENGES AND CURRENT RESPONSES

In spite of recent progress, the implementation of biological principles in building design is still under development [33]. This state is due to several interconnected key issues that concern building professionals, among them the lack of profound knowledge from the field of biological science and related disciplines, as well as the lack of classifications and characterizations based on which the design solutions could be worked out.

Exceptional complexity of living systems and their possible analogies, variety of baselines from which analogy definitions can be derived, present flexible use of umbrella terms, and, consequently, overlaps in their meaning, jointly impede the accuracy of potential typologies.

Simple systematizations of application of biological principles in the building context can be made according to:

- Type of living organisms;
- Characteristics of individual living organisms or whole ecosystems, e.g. regarding contents, structures, forms, functions, or processes;
- Analogy scope: from mono-characteristics to systemic solutions;
- Analogy type: reasoned transfer of biological characteristics or actual introduction of living organisms into the building context;
- Analogy hierarchy: materials, components, or structures; and other.

Biological studies of living organisms are encompassed by several interrelated biological branches: external morphology or eidonomy that studies external appearance of living beings; anatomy (internal morphology); and physiology. Anatomic studies are divided on microscopic anatomic research of structural units small enough to be seen only with a microscope, and macro-anatomic studies of those body structures (forms) that are large enough to be examined without the help of magnifying devices [34]. Physiology, on the other hand, is the study of functions in living organisms and their constituent parts – tissues and cells. These functions include: metabolism, transport, information transfer, and regulation [35]. Therefore, studies of forms and functions can be carried out at different scales of living organisms. These scales, nevertheless, do not always correspond to building-related scales and the relationship between parts and the whole, for which reason a scale-related parallel between natural entities and man-made artifacts cannot be drawn in all cases.

A building can feature one function (e.g. a kinetic response to external stimuli), one form, or a range of interrelationships, forms and functions that are typical of a single biological species (e.g. the tree). Deliberated transposition of a single biological characteristics into building context accounts for the most commonly applied design strategy throughout the history. The examples range from Egyptian hypostyle halls, to Gothic buildings with shells, to the dome of Brunelleschi's Santa Maria del Fiore cathedral, to Sir Joseph Paxton's glasshouses, to the Eiffel Tower, to the works of renowned 20th- and 21st-century designers: Frei Otto, Felix Candela, Jorn Utzon, Oscar Niemeyer, Eero Saarinen, Luigi Nervi, Santiago Calatrava, Frank Lloyd Wright, and others.

Biological characteristics can be applied at different building scales (e.g. material self-repairing – at micro level, movement of façade parts – at mezzo level, or kinetic action encompassing whole building structure – on macro scale). Furthermore, actual introduction of living organisms can be done at the scale of building materials (e.g. concrete with added bacteria), components (e.g. cladding with integrated algae), or structures (e.g. living plant structures). Processes of cohabitation of different species in a common space and potential for their application in building context are yet to be explored.

Supplementing these considerations with specificities of organisms regarding conditions in the environment in which they live, it is being confirmed that the development of analogies between biological systems and buildings should be treated as case-specific. For that reason, the possibilities for application of biological principles within the building context can only be used with sufficient knowledge and understanding.

Even the very nature of sustainability, resilience, circularity and regeneration frameworks still stretches beyond the boundaries of designer's core knowledge. Although these concepts are understandable in general, the measures to reach their encompassed values must be precise. Therefore, the application of biological principles in contemporary building context requests “a transfer of knowledge from biology and ecology into architectural design in a way that transcends poorly understood and applied analogies or metaphors” [22:172]. The lack of knowledge hinders the development of ideas, solutions and products that are novel and useful [4:349] and generates doubt as to what is the initial question: “What do the biological systems do?” or “What is to be achieved by design?”

In recently published researches, the two possible starting lines were described as: solution-based vs. problem-based; bottom-up vs. top-down; or ‘Biology to Design’ vs. ‘Design to Biology’ approaches [36], [37], [38], [39]. Regardless of the type and the definition, these approaches reflect an effort to bridge knowledge gap and establish effective design methodology and process that will allow for more successful integration of biological principles into a building context. Other compatible/complementary design-related responses to the above-mentioned challenges currently include:

- Dividing building system into parts that can be treated independently in terms of application of biological principles, and developed within separate design domains;
- Application of previously developed biologically inspired building products, mainly materials;
- Development of design guides, e.g. the Biomimicry Toolbox [40], and resource bases such as the Ask Nature [41];
- Introduction of biology-related themes into education, and development of cross-disciplinary educational contents and methodologies, e.g. [32], [39], [42], [43];
- Development of innovative building assessment systems such as the Living Building Challenge [44];
- Development of inclusive theoretical frameworks, e.g. [45], [46]; and
- Establishment of cross-disciplinary design and research teams.

4. DIRECTIONS

Lack of classifications, differing interpretations of key terms, insufficient knowledge from biological science, and scarce evidence concerning sustainability-, circularity-, resilience-, and regeneration-related advantages aggravate the designer’s perception of possibilities for the application of biological principles in building design. Although researches published during the last two decades bear witness to growing interest and progress in the use of biological principles, their integration into building context is yet to be achieved, and systemic solutions yet to be developed and applied.

To further support the application of biological principles in building design, it is necessary to create solid theoretical base by systematizing the body of published works, and to identify scientific knowledge gaps as a basis for future contributing studies. Likewise, there is a need to develop evidence-based databases that could confirm the concrete benefits of applied biology-related measures in building context. When the benefits of biological principles application are justified by sufficient number of realized cases, pre- and post-build assessment systems can be developed, and their criteria and indicators established.

Having on mind the level of specialization involving biology and building science, there is a need to promote the development of cross-disciplinary research units, to enhance experimental work, and to connect these labs both with education and practice. To that end, another raising challenge is the acceptance [47] of currently unconventional solutions by a range of actors, from policy makers, to manufacturers, to investors, to contractors, to end-users of the built space.

In terms of education alone, the introduction of innovative courses and specializing programs could represent an effective response to existing lack of knowledge. However, an extent to which biology-related themes should penetrate into formal designers’ education can be determined only when comprehensive theoretical and evidence bases are established. The content of these bases could assist in shaping the competencies of future building professionals, reveal the depth of necessary knowledge, and inform if educational concepts should opt for architects and engineers with deep knowledge from biology or those equipped with skills for advanced collaboration with biologists, not only in terms of finding an optimal design solution, but as well an optimal methodology to arrive to that solution.

Finally, a designer capable of introducing the biological principles into building context must also consider many other meanings of the buildings. There are aspects of architecture that depend but cannot be explained by natural laws [48], and sole relying on biological principles may bring a radical shift to design ideas, creativity [49] and aesthetics [50].

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