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The evolution of architectural morphogenesis at the beginning of XXI century in the context of scientific advances

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Abstract

Innovative spatial forms arise and develop at an intersection of science and art, engineering and architecture. Various geometric structures with different types of symmetry are studied by mathematicians, engineers and architects. Computer simulation reveals a new range of geometric shapes as well as various types of partitioning and filling of two-dimensional surface and three-dimensional space. For the engineering and architectural theory it is important to study fundamental mechanisms of form shaping and the form itself in the context of conceptual evidence of modern interdisciplinary studies. This is necessary for the further development of the creative potential of architecture and engineering.

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Keywords: engineering and architectural shaping; geometry; morphogenesis; self-organization; computer modeling; spatial partitioning; innovative architecture

The shaping potential of engineering and architectural organization of space is far from an exhaustion. Mechanisms underlying form shaping in the light of the latest trends and achievements of modern interdisciplinary science are important for the study of the theory of architecture. These scientific advances would have been impossible without the development of computer technology, which gave the opportunity to design highly complex (from a geometric point of view) construction. The new tools of scientific and practical work of a designer, and new technologies change conceptual principles of architectural space building. The tasks include the analysis of existing architectural forms, the search of algorithms and adequate models of architectural shaping as well as use of

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computer modeling in the experimental architectural design. Shaping involves a wide variety of forms, analyzed using mathematical concepts and terminology. This study is associated with such scientific fields and specializations as geoinformatics, biology, mathematics, crystallography and computer modeling. This makes it possible to attract professionals from other fields to carry out interdisciplinary researches. The revival and development of bionics and ideas of organic architecture, the use of analogs of natural structures, the promotion of new architectural ideas, the use of computer and telecommunication technologies can contribute to the development of architecture and engineering of the XXI century on a new theoretical and technological level. Such approaches involve interaction with biology, neuroscience, mathematics, physics, chemistry, cybernetics and engineering sciences.

The elaborating problem of architectural and engineering diversity as a certain similarity of biodiversity include consideration of the landscape as a part of the architectural composition, the use of alternative energy sources, reducing energy consumption, re-use of materials and the creation of facilities, designed for a long service life with the possibility of transformation and adaptation to the changing conditions. There is the concept of reverse engineering as the study of a device in order to understand and reproduce its functions. Eco-housing may use local materials, include landscape as a part of the architectural composition and involve landform geoplastics, vertical gardening, gardens on the roof and floors.

Geometry is the most important, fundamental part of the architectural shaping. Greek philosophers discovered five Platonic bodies – polyhedra with the edges formed by regular polygons. Such polyhedra: tetrahedron, hexahedron, octahedron, dodecahedron and icosahedron, with 4, 6, 8, 12 and 20 sides respectively, have a spatial symmetry. Somewhat later, Archimedean bodies (which include, in particular, a truncated icosahedron, resembling a soccer ball) and Katalanean bodies were discovered. The astronomer and mathematician J. Kepler added two rhombic polyhedra. Almost all of these regular patterns are found in nature. For example, the carbon atoms in diamond located in the corners of a tetrahedron; rock salt and pyrite form cubic crystals, calcium fluoride – octahedral crystals.

The vast majority of engineering and architectural buildings is rectangular, utilitarian and unattractive “boxes”; innovators in architecture and engineering avoid this traditional orthogonal thinking. This creates the prospects for innovative shaping of public buildings and technical installations, which can be more meaningful as art works. Perhaps the new materials created using nanotechnology, new alloys, ceremic metal, carbon composites allow to make an evolutionary step in the architectonics of buildings and constructions of different functional purposes.

General principles of shape formation on the micro, meso and macro levels in the various systems can be revealed by the comparative analysis of morphogenesis in architecture and biology, technology, crystallography [1]. The introduction of scientific achievements, including crystallographic and biological molecular data, as well as scientific conceptual metaphors, in the architecture can provide a saltatory evolution in the forming and functioning of the new architectural forms. Architectural design is a field of the practical application of mathematical concepts of spatial partitioning. During creation of large architectural forms, various polygonal and polyhedral patterns can be used for the realization of high-quality design and solutions of constructive tasks. Similar approaches have already been realized, more or less successfully, in many projects.

During the century and a half, the evolution of metal network structures was largely due to the achievements of the enthusiasts, who worked at the interface of engineering and architecture. Geometrically complex, spatial metal constructions began to appear in the middle of the XIX century, and one of the clearest manifestations was the “Crystal Palace” by D. Paxton. Somewhat later, architectural and engineering design in metal was fullfilled by G. Eiffel. In Russia, by the end of the XIX century, V.G. Shukhov was the founder of many metal constructions of the revolutionary design, striving for the synthesis of engineering and architecture and creating the first hyperboloidal towers, suspended and vaulted coverings. He had mastered design with minimal material expense. Meshy coverings and hyperboloid towers are solutions that combine the lightness, simplicity and elegance; so unusual and bold shapes of metal structures transformed engineering systems into architecture decisions. German engineer Frei Otto created and actively developed various types of hanging meshy coverings, combined with the membranes and vaulted structures. Duringr the second half of the XX century, frame-membrane constructions were developed.

Euclidean geometry is implemented on surfaces with a constant zero Gaussian curvature (flat surfaces), Lobachevsky geometry – with constant negative curvature, and Riemann geometry is realized on surfaces of constant positive Gaussian curvature. Already in the late 1970s B. Mandelbrot (1924-2010) created fractal geometry, and his book “The Fractal Geometry of Nature” [2] demonstrates the importance of the mathematically formulated structural transformation as the basis of fractal morphogenesis.

In many projects during the early 2000s, there was a gradual shift away from the regular and symmetrical partitioning and filling of surface and space to the irregular, biomorphic tiling, according to the algorithm of Voronoi-Dirichlet [3]. Chaotic or pseudochaotic cell arrangement formed a natural pattern similar to the structure of living cells. This principle in architecture animates a facade, creating a continuously changing appearance of the building viewed from different angles.

R.B. Fuller, american engineer, inventor and philosopher, received a patent for the design of a hemisphere or spheroid (geodesic dome) formed from trianglular network, which can be used as a covering of large structures [4]. He postulated the principle of “minimax” – relatively small material expense in combination with high structural stability – as “substitution of material by information”. A fundamental way of self-organization, named “tensegrity”, was also formulated – this term is made up of two truncated words: tension and integrity. Stable state and resistance of geodesic dome are provided by tensegrity effect, an elastic balance of the system. In Russia, M.S. Tupolev made similar constructions. Surface tiling is based on the Platonic polyhedra, as a rule, icosahedron, dodecahedron, or their combination. The emergence of a few pentagons in the hexagonal network on a sphere is inevitable consequence of the topological organization of our world. According to Euler's theorem, only five regular (Platonic solids) polyhedra with the regular graph are possible on the sphere, and it is one of a purely topological constraints. In all other cases, there is the inevitable heterogeneity of discrete topological field tiling the surface of a sphere [5]. The occurrence of inhomogeneity of the discrete field pattern on a sphere is a consequence of the topological construction of our 3-dimensional physical space; it is follows from Euler's theorem.

In 1985, a group of researchers (H.W. Kroto, J.R. Heath, S.C. O'Brien, R.F. Curl and R.E. Smalley) found a new form of carbon (existing, as we know, also in the crystalline form of graphite and diamond), with molecules formed from the carbon atoms as closed surface in the form of a sphere or spheroid [6]. At first, authors could not understand the molecular structure of the new form of carbon. Later, after studying Fuller´ works they named the new compound “fullerene”, although this form goes back to Archimedes. Fullerenes and geodesic domes are homologous structures, similar in properties and geometric construction. Fullerenes are promising materials for a variety of new technologies. In 1996, these authors have received the Nobel Prize in chemistry.

In addition to standard geodetic layouts of Fuller´ type, new variants began to appear, including rotational symmetry. These variants are based on the so-called “snub-nosed” figures with canted vertices and shifted or twisted symmetry. In the animal world, during early embryogenesis of some animals, there is a displacement of cells in the upper hemisphere of an embryo relative to the lower hemisphere in a clockwise direction (dexiotropic shift) or vice versa (leotropic shift).

New shapes with rotational symmetry were discovered by S. Schein and J. Gaye (University of California, Los Angeles) during studies of the protein, called clathrin. This protein is involved in the intracellular transportation, forming a small vesicles. Schein displayed the mathematical explanation for clathrin vesicle formation. In the course of this work, the scientist found and used works of mathematician Michael Goldberg (1902-1990). In 1937, Goldberg described a number of new forms, which have been named in his honor – Goldberg´ polyhedra [7]. Recently, Schein and Gaye argued that a new, fourth class of Goldberg´ polyhedra is discovered [8]. In addition, they believe that this discovery indicates the probable existence of an infinite number of such classes. This is partly true, because there are many different options of partitions, and many of them have not yet been constructed and investigated.

In October 2010, A.K. Geim and K.S. Novoselov, working at the University of Manchester, was awarded the Nobel Prize in physics as the discoverers of new form of carbon, named graphene. Graphene can be represented as a single graphite plane separated from the three-dimensional crystal, a single layer of carbon atoms, just one atom thick [9]. The crystal layer of graphene is a two-dimensional hexagonal lattice of carbon atoms. Similar structures on the scale of architectural constructions are perspective both as engineering and art works.

Quasicrystals firstly were observed by Daniel Shechtman in his experiments, held in 1982 using electron diffraction with the rapidly cooled alloy Al6Mn [10]. In 2011, after a long period of non-recognition, Shechtman was awarded the Nobel Prize in Chemistry. Quasicrystals are characterized by pentameric symmetry, “prohibited” in the canonical crystallography, but common in the world of plants and animals. Similar structures have been used in the ornamental decor, but now it is possible to use them in the formation of spatial compositions.

The formation of many complex natural structures is based on the minimal energy consumption due to triple nodal points and reducing contact surfaces with the appearance of topologically stable structures. Patterns of connections and contact surfaces are the same for our three-dimensional world – in biology, crystallography and architecture. Bubbles and crystal aggregates can serve examples and simulation tool for minimal contacting surfaces. The tight packing of the solids is one of the classical problems of mathematics. A sufficiently strong pressure turns closely packed deformable balls into polyhedra. Different options in dense packing of tetrahedra, icosahedra, dodecahedra and octahedra are possible, however, 100% filling of three-dimensional space without shape distorting of these polyhedra are not realizable. In particular, tightly adjacent to each other tetrahedra can not fill all the space. In 1993, D. Weaire and R. Phelan offered a partition with a smaller area than that of the partition previously proposed by Kelvin. It includes two kinds of figures – polyhedra with 12 and 14 faces [11].

The morphology of the new architecture is formed by external factors, combined with the internal logic of spatial organization. In fact, a new morphotectonic typology of buildings, based on mathematical principles, often pseudobiomorphic, is emerged. Architects sometimes deliberately use quoting of natural forms or its fragments. Engineers and architects create dynamic, “flowing” shapes, geomorphic and landform structures. The technology of laser scanning of complex shapes gives the opportunity to create a “point cloud” describing the geometry of the object. Parametric generation methods allow you to manage such a geometry, structuring and adjusting it according to certain mathematical rules, one of which is the algorithm of Voronoi-Dirichlet. New urban formation can be generated parametrically, optimizing the crossing of people flows and the interaction of various structures. Increase of building volumes may be based on the principles, comparable to the growth of coral reefs or crystal aggregates, with the dynamic changes in local and global formation and partial fusion of structures.

By the end of the XX century, at the intersection of computer and biological research [12], a new interdisciplinary science was created by Christopher Langton and other members of the Los Alamos National Laboratory. Langton named the new science “artificial life”. According to Langton, artificial life includes modeling of life in silico, i.e. in computer, biological and chemical experiments and purely theoretical studies. It is study of artificial systems that exhibit behavioral characteristics of natural living systems. Objects of research are processes at the molecular, cellular, neural, social and evolutionary levels. The ultimate goal for the new science – to understand the logical form of living systems [13].

Mathematical modeling and development of artificial life and artificial intelligence brings more innovations in everyday life, as well as in architecture. Artificial life in its development are increasingly interacting with areas of technical aesthetics and design. Information technology has become a powerful tool, giving great impetus to economic and social development of mankind, the emergence of new and expansion of existing areas of science. The technological transformation and their speed are often revolutionary. Many of the ideas and future capabilities of the research trends raise new questions; modern attempts to response are sometimes debatable and controversial. What will be the further development of the information society and architecture?

Real and massive introduction into the daily life of technologies, which until recently seemed futuristic ideas, becomes a global trend. Many innovative ideas for architecture and design associated with the theory of self-organization are currently implemented at the level of pilot projects and exploratory technical solutions. At the same time, periodically there are new ideas emerging, possibly, as a mirage dictated by the challenges of the new technological possibilities. The use of information technology, robotics achievements, the principles of natural self-organization and the synthesis of these approaches – an effective way to build complex systems, determined by the intrinsic properties of their components.

The three-dimensional printing technology is used in all developed countries, allowing to change the mode of the production of various articles for different purposes. In particular, these technologies are promising to create homes for the refugees and displaced persons, in the areas of emergency and extreme conditions. Scientific research in the field of artificial intelligence and artificial neural networks allows to development intellectual and interactive architecture creating “smart homes”. It gives additional opportunities to create a more comfortable environment, functioning and interacting with people on a fundamentally different technological level. The beginning of XXI century was marked by the active development of a global information field and integrated socio-economic area. Distribution and relative cheapening of control means and improvement of information networks make it possible to organize a non-stop monitoring of technical objects in order to ensure their safety. Architecture and design are already under massive influence of such concepts.

So, the fundamental geometric patterns are common in living and inanimate nature as well as in man-made world, particularly, in architecture, from the micro to the macro level. Geometry is an essential component of engineering and architectural shaping. Natural and anthropogenic morphogenesis occurs in the physical space of our world with its inevitable physical, geometrical and topological constraints. In modern engineering and architecture carried out very pronounced processes of globalization and internationalization, and a convergence manifested in the architectural shaping. During integration and convergence of scientific achievements, innovative forms often occur in engineering and architecture. Interdisciplinary approach and comparative analysis of morphogenesis in architecture, engineering, biology and crystallography allow us to find the general principles of shape formation at different levels and in different systems. There is an opportunity to reveal the universality of optimal (in respect of structural stability / material expense and filling the space) constructions produced by engineers and architects, and self-organizing in nature.

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