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Research paper

Topological Optimization as a Factor of Sustainability of Architectural Structures

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Abstract

It is shown that numerous destruction of buildings and structures under extreme natural impacts (tsunamis, earthquakes, floods, etc.) urgently require revision of existing approaches to their design. It is proposed to use the method of parametric (algorithmic) architecture in the design of buildings and structures operated in extreme weather conditions. It is shown that the algorithmization of the architectural space, subject to chaotic natural effects, is possible with the use of topological optimization methods. n the work used application Autodesk Revit, Grasshopper. As a natural analogue, one of the diatom algae species was selected, which have a light, strong and efficient structure. The project of a floating ecological settlement for 1,5 thousand people is presented. It is shown that with parametric design it is possible to take into account a multitude of factors affecting the construction and, thereby, to increase its resistance to natural disasters.

Keywords: *parametric architecture, ecological settlement, cataclysm, topological optimization, diatom algae, modeling.*

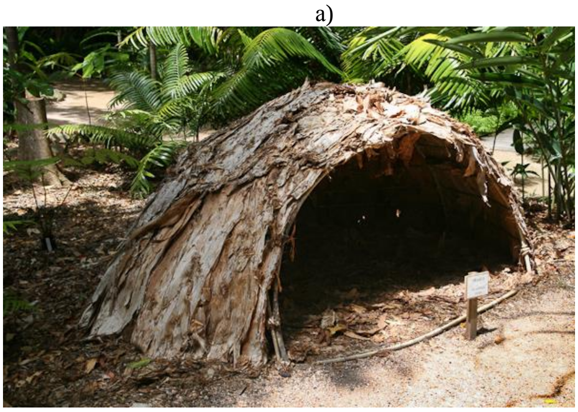
1. Introduction

In conditions of global climate change, frequent natural disasters: earthquakes, floods, volcanic eruptions, tsunamis, hurricanes, mudflows, forest fires, etc., architecture has become a "hostage" of nature, forced to develop according to its strict laws [1].
Depending on the location and characteristic natural disasters, the requirements for architectural objects are regulated. For example, in Japan, the construction of high-rise buildings is carried out only on special supports made of multi-layer structures consisting of several materials, which in combination extinguish the fluctuations of the earth's crust.
The monstrous Hurricane Katrina in the United States, which claimed the lives of 2,000 people and flooded 80% of New Orleans, made it necessary to radically revise the approaches to construction in this region to reduce the damage from possible flooding in the future [2].
The threat of future cataclysms gives rise to the orientation of the activity of architects to create projects of buildings and cities of the future that can withstand the raging elements.
Humanity already faces a number of tasks, the solution of which requires taking urgent measures to:
- Development of constructive, technological and engineering solutions that increase the resistance to external environmental influences of already constructed architectural structures;
- The design of new buffer zones for the mass resettlement of people from the affected areas;
- The construction of new ecovillages with the possibility of an autonomous existence.
The problem of saving from natural disasters in recent years is the most discussed at all levels. According to most scientists, the main trends of the rapid deterioration of global and regional environmental conditions have not changed, although hundreds of billions of dollars have been invested in nature protection activities over the past 45 years.
Based on the above data, the solution to the problem of creating new types of eco-settlements for the inhabitants of the Earth is an urgent task. The development of conceptual projects of eco-cities of the future will provide an opportunity to take operative measures to reduce the threat of deaths from natural disasters.
One of the innovative solutions in this direction is the creation of autonomous urban settlements in the form of the modern Noah's ark [3-4]. In essence, this is a mobile structure that combines all the attributes of a modern city and home: a large-scale structure with an isolated, unified system of energy, resources and life-support.
The use of natural forms in architecture (architectural biomorphology) and the principles of constructing such forms (architectural bionics) together make it possible to ensure the sustainable existence of urban settlements in conditions of extreme changes in the environment.
In recent years, computing technologies are increasingly used in the architecture, and physical and biological processes are used. The use of natural analogs and computational technologies allowed to change the existing idea of the architectural form and space and led to the emergence and development of new tools, methods and methods of architectural design. As a result, the principles of modern architectural morphology represent a symbiosis of biology and mathematics - parametric architecture.
The basis of the parametric architecture is the principle of preserving the integrity of the structure under external influences. In mathematics, the topology deals with the stability of the properties of geometric objects under deformations [5-6]. Thus, the parametric architecture is based on topological principles of preserving the integrity of the structure under any external influences.

2. Topological architecture and ecology. Ergonomic aspects

At the initial stage of its development, humanity built its existence on a close union with nature. The first human dwellings more resembled natural formations than artificial structures (Fig. 1).

a)



b)

Fig. 1: The first human dwellings: a) Neolithic dwelling Skara Bray; b) Aboriginal Bush Shelter;

With the advent of artificial building materials, human dwellings increasingly lost their natural features, acquiring a clear man-made look.

The further development of mankind is connected with the merciless attitude to nature: barbaric extraction of natural resources, massive deforestation, destruction of a huge number of animal species, etc. And with the transition to the stage of mass production - the pollution of the atmosphere, lithosphere and hydrosphere of the Earth.

All this was the reason for the development of the most global crisis - the environmental one. The relationship of humanity to nature as a source of raw materials and led to the emergence and catastrophic development of this crisis.

One of the main and most complex global environmental problems of the 21st century is the change in the global planetary climate. One of the main causes of global warming is an ever-increasing intensification of man's anthropogenic activity, which has a significant effect on the chemical composition of the atmosphere of our planet in the direction of increasing the content of greenhouse gases in it.

According to EM-DAT data (the global base of natural and man-made disasters, which contains basic data on more than 18 thousand accidents around the world from 1900 to the present [1]), the last twenty years have been characterized by a general rapid growth in the dynamics of cataclysms.

Today, it is impossible to underestimate all the factors and scale of the influence of various space and geological processes on the global change in the earth's climate. A careful analysis of the growth in the number of natural disasters, extreme weather events around the world, as well as statistical indicators of space and geophysical parameters over recent years has shown an alarming tendency to significantly increase in a short period of time.

During the period 2006-2015, the main cause of deaths from natural disasters in all regions of Africa, Central, and South America, as well as in Central, South and West Asia were flooded. Storms have led to the largest number of deaths in North America, the Caribbean, Southeast Asia, Melanesia, and Micronesia. Extremely low and high temperatures became the most deadly disasters in Eastern, Northern, and Western Europe, as well as in Australia and New Zealand, while earthquakes caused the greatest deaths in East Asia, Southern Europe, and Polynesia. In 2016, the regional lethal effects of floods are somewhat different. All African and Asian regions of the UN and Western Europe were flooded, resulting in the death of many people. Storms have led to the most fatalities in North and Central America, the Caribbean, Australia, New Zealand, and Melanesia. Earthquakes caused the greatest mortality in South America and in Southern Europe. Finally, in Eastern Europe, extreme temperatures continued to kill most people

On the other hand, in all its manifestations global warming is also a deeply local issue. It is in this context that urban centers of different sizes, especially cities, play an important role in climate change. The main sources of greenhouse gases are urban economic and industrial enterprises, infrastructure. In cities, the population, economic activity, and techno genic environments are concentrated. This significantly increases the likelihood of catastrophic consequences from floods, heat waves and other climatic and weather hazards that are expected to deteriorate. Many of the city centers are in the most insecure areas (for example, on the coast), which makes them more vulnerable to possible events related to climate change. But in addition to the obvious risks and vulnerabilities that climate change will bring to urban areas, these same city centers will play a key role in mitigating impacts and adapting to natural disasters. Urban centers are centers of development, sources of innovation and scientific and technical solutions to reduce gas emissions, heat and energy and adaptation to the effects of climate change.

One of the innovative solutions in this direction is the creation of autonomous urban settlements [3-4]. In fact - a mobile structure that combines all the attributes of a modern city and home: a large-scale construction with an isolated unified system of energy, resource and life support.

The main purpose of modern architecture is to form an ecological civilization in the form of urban aggregations - autonomous cities.

Of course, the transition to a new architecture should be carried out gradually. Due to the fact that a large area of the Earth's surface is occupied by water, and the number of people is rapidly increasing, a person will actively explore water space. According to the calculations of scientists, by 2060 the population of the Earth will reach 17 billion, and in the future the situation will only get worse, so that by the middle of the XXII century we will have a population of about 40 billion people. Under these conditions, the distribution of the space occupied by the world's oceans will play an important role [7]. Naturally, in this case, systems of underwater transport communications will be actively developed, artificial islands and underwater cities will be created.

3. Main part

Bioecopolis is a compact small-scale settlement that fully provides itself with electricity, heat, utilizes its waste and conducts efficient economic activities using biotechnology. The basic system-forming principle of the formation of such a settlement is energy self-sufficiency, which, according to current scientific views, is possible due to integration into a biological (more precisely, biotechnological) circuit.

The idea of the development of urban life (policies) on a strictly scientific basis, on reasonable principles, was developed in the era of Antiquity, for example, in the writings of Xenophanes. The design of such settlements on the basis of a scientific approach was undertaken by the ancient Greeks in organizing their colonies. Today, for example, the transition from urban projects to the creation of eco-settlements seek to substantiate both economic and environmental considerations [8].

In this regard, it should be noted that in many works of philosophers, writers and poets, the City (Civilization) and Nature are thought of as antagonists: The city is the bearer of the dead, the mechanical principle in contrast to the living, joyful Nature [9].

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The development of additive technologies finds an increasing application in the use of libraries of biological patterns for the creation of objects, the so-called "living" architecture [10]. Their construction will be carried out from biosynthetic materials with the help of bacterial printers and swarms of mechanical assembly devices. A building constructed of such materials will be able to adapt to changes in external conditions and effectively counter emerging extreme situations. Thus, it becomes possible to solve the problem of resource dependence by integrating ecosystems into the existing environment.

The formation of a nature-integrated architecture with the inclusion of natural elements will ensure ecological, aesthetic and functional harmonization of the dwelling with the environment.

The use of natural forms in architecture (architectural morphology) and the principles of constructing such forms (architectural bionics) together provide an opportunity to ensure the sustainable existence of urban settlements under conditions of extreme changes in the environment [11-12].

The main extra genic natural situations can be caused by several reasons:

1. Periodically occurring natural cataclysms associated with the geological activity of the Earth (volcanic eruptions, earthquakes, tsunamis, landslides, etc.);
2. The rapid warming of the climate, the rise in the level of the world's oceans and, as a result, the flooding of vast areas of the globe;
3. Asteroid-comet threat.

And, if the latter situation is force majeure and unpredictable consequences, then the first two situations can be predictable, and, consequently, there is the possibility of organizing protective measures. First of all, it concerns buildings and constructions.

The strategic tasks of the architecture in the context of extreme situations are:

1. Development of constructive, technological and engineering solutions for increasing the resistance to external influences of already constructed architectural structures.
2. Designing urban settlements of a new generation capable of withstanding various impacts of the natural elements, designing climate shelters, autonomous shelters, arched buildings, modular construction with the possibility of relocation, etc.
3. Development of marine urban planning, the design of artificial land, artificial islands, archipelagos, etc. instead of the lost and flooded areas of natural land.

Earthquakes, tsunamis, floods, hurricanes and other natural disasters in the context of global climate change are becoming increasingly intense, which forces architects and builders to fundamentally rebuild the principles of design and construction of buildings and entire cities. Increasing requirements for seismic stability of buildings, systems of an autonomous power supply and life-sustaining are being developed, mobile homes are becoming increasingly important. Thus, traditional approaches to architecture are replaced by the principles of adaptive architecture, which requires non-traditional approaches to innovative knowledge about the composition and dynamic interaction between buildings and environmental conditions. These approaches are based on the behavior and integration of living systems in the environment. Prototype living building system can adapt to various functional needs, location, time of day and other contextual conditions.

In recent years, computing technologies have been increasingly used in architecture, physical and biological processes are used. The use of natural analogs and computational technologies allowed to change the existing concept of architectural form and space and entailed the emergence and development of new tools, methods, and methods of architectural design. As a result, the principles of modern architectural morphology represent a symbiosis of biology and mathematics - a parametric (digitized from English digital) architecture. If the architectural forms of the past could be considered as a finite structure, then now it must be considered through the development of form - morphogenesis.

Today, architects use forms, functions, behavior or whole ecosystems of living organisms as a source of project creativity and sustainability. They create an artificial environment based on advanced digital technologies based on lessons learned from nature.

The behavior of living organisms and the principles of their functioning under extreme conditions are quite complex. For their description, it is necessary to involve a complex physical-mathematical apparatus. As a result, modern architecture, based on physical and mathematical models of natural objects, goes to a new direction - parametric (digital, digital) architecture.

Adaptive architecture, thus, is a symbiosis of architectural bionics and parametric architecture, adapting its shape, color or function to the objectives of the greatest compliance with the requirements of operation [13].

Parametric architecture, taking as a basis the shape and structure of the organisms of the animal and vegetable worlds, allows creating active "living" architectural projects, the state of which is determined by the laws of motion of the earth's surface layers, cosmic postulates about the variability and nonlinearity of the universe and mathematical formulas. The basic principle of the parametric architecture is based on the fact that even a slight change in the properties of the structural elements of the building leads to a change in the general state of the building, fixed by means of a computer model. This approach allows you to take into account almost any environmental impact and to provide possible ways to prevent the destruction of the building at the design stage. Topological optimization of the project is carried out by transforming the geometric shape of an architectural object by means of dynamic effects: extrusions, twists, deformations, bends and other volumetric transformations without gaps in the virtual computer simulation environment [14].

The fundamental principles of the parametric architecture reject the use in the design of simple geometric primitives, the simple repetition of elements and the comparison of unrelated elements or systems. Preference is given to parametrically compliant forms of elements that form an architectural object that can gradually change depending on external influences and interact systematically.

In fact, the parametric architecture is a way of physical mathematical modelling of the architectural form on the basis of its representation in the form of mathematical dependencies in the corresponding computer programs. In a parametric way, not one form is described, but a certain set, a bush of forms that can be obtained by the geometric representation of a single mathematical dependence. Changing any of the parameters present in mathematical expressions affects the overall geometry of the form. This type of simulation is well combined with pre-project analysis data, also expressed in digital form. The process of working with complex surfaces, their transformation in order to achieve optimal values of technical and economic indicators of the project, is facilitated [15]. Formation of the architecture of the adapted dwelling takes place on principles that allow ensuring its sustainable development at the design stage (differentiation, resource reservation, variability, controlled autonomy, interactive design and design continuity).

4. Implementation of topological optimization on the example of a floating eco-settlement project

Design, calculations and construction of a biomorphic structure is a rather complicated process and cannot be applied to mass construction. The "spontaneity" of the forms of the surrounding landscape or natural creatures requires the use of mathematical methods for modeling surfaces, which led to the formation of a new direction - parametric architecture.

The developed eco-settlement project is a 3-component structure consisting of an exoskeleton skeleton, which is the main part of the construct, an additional envelope and layout, which is based on the cellular structure of Alga micro and macromolecules of diatoms (Fig. 2).

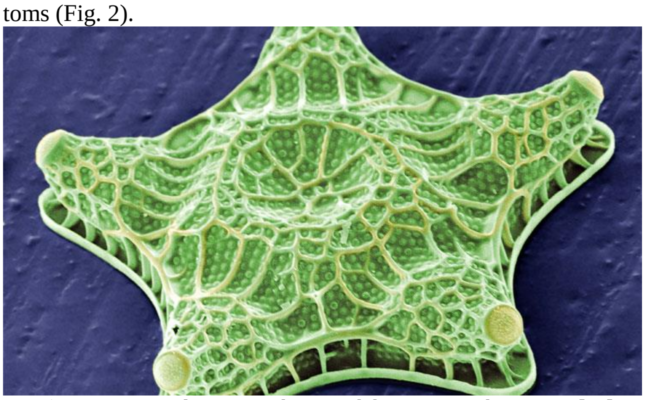


Fig. 2: Diatom Alga, SEM Photograph by Steve Gschmeissner [16]

The variety of forms of diatoms provides an extensive platform for the implementation of a biomorphic approach to architecture.

The formation of living organisms is characterized by plasticity and combinatorial character, a wide variety of regular geometric shapes: circles, ovals, rhombuses, cubes, triangles, squares, various kinds of polygons, and an infinite number of extremely complex and surprisingly beautiful, light, strong and efficient structures created as a result of a combination these elements. The formation of such structures is a consequence of the complex, centuries-old evolution of the development of living organisms.

The use of bionic shaping when creating the architectural environment of future eco-settlements also helps to improve its harmonization with the environment.

The parametric design method is based on the creation of environmental algorithms using variable parameters. In the future, the use of these algorithms allows you to solve many problems that are either not solvable or very time consuming when using traditional design.

Parametric modeling allows you to create complex curved surfaces using mathematical algorithms and sets of specified parameters. Changing the number of parameters, their ratio leads to a change in the configuration of the model. Thus, by changing, for example, the magnitude of the loads on the structure, it is possible to find the optimal shape of the object that can counteract the applied loads [17].

The use of topological optimization in the design process led to the decision to take the structure and shape of diatoms as a basis (Fig. 3).

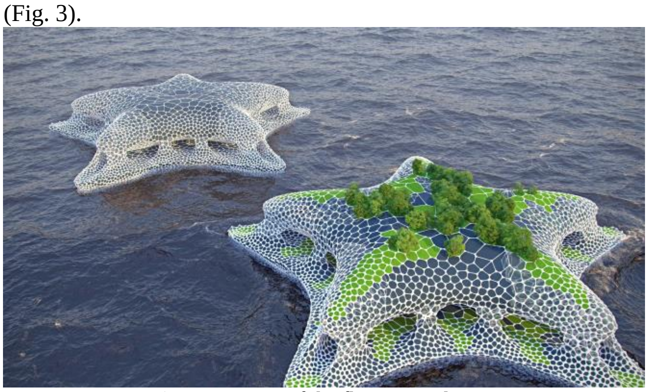
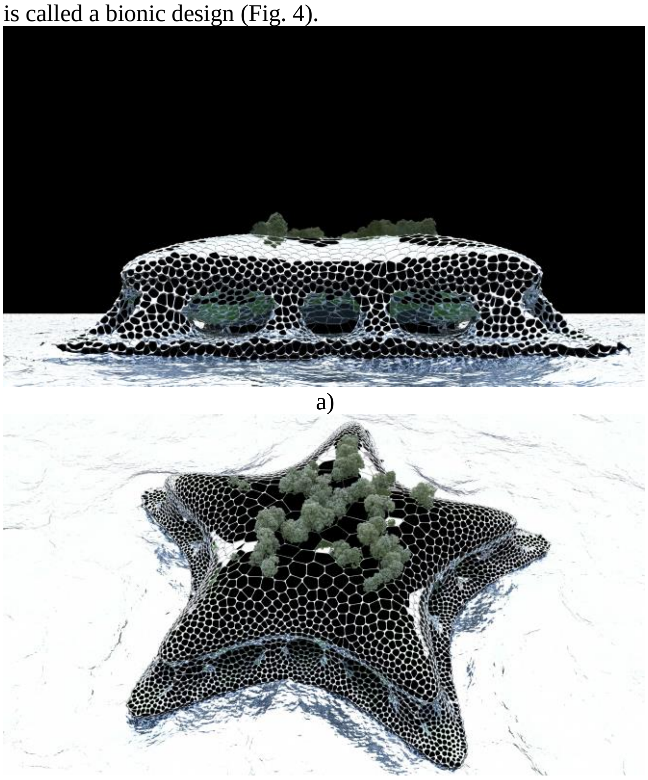


Fig. 3: Exterior of the floating settlement

The design was carried out in Autodesk Revit and Grasshopper for Rhinoceros 3D. The object was formed by prototyping in the Rhinoceros 3D environment. Then the pattern interactions were determined and the corresponding changes were made to the shape of the architectural object.

The main objective of topological optimization is to obtain a structure that is in a state of pure compression. Such a design, in contrast to conventional building structures, not only withstands topological optimization, which usually leads to structures that look like natural structures smooth, without stress concentration, what is called a bionic design (Fig. 4).



a)

b)

Fig. 4: Structural frame structures: a) side view; b) top view

The result was a lightweight, durable construction that can withstand possible external influences from the environment. Externally, the ecovillage resembles a natural formation - an island, but at the same time it is a kind of "living" organism, which fully satisfies its needs for life support.

The construction is completely autonomous and non-volatile. Energy is provided through the use of wave energy and solar panels. Water supply is provided by desalination plants. Recycling systems of water disposal make the construction environmentally friendly. The settlement is designed for 1,500 people, most of whom will be busy with research, for which special research laboratories, living quarters and recreation areas are provided (Fig. 5.)

Fig. 5: Recreation area interiors

Thus, to adapt the architectural space to changes in the external environment, an integrated approach is needed, including socio-demographic, three-dimensional, architectural-planning, typological, and technological aspects of dwelling formation.

5. Conclusions

On the basis of the analysis of the state of nature and climate of the planet, scientific research, the prerequisites for creating ecovillages of a new type with autonomous life support and the tendencies of their formation are considered.

The strategy of an innovative approach to the formation of urban settlements in the context of extragenic natural situations is considered, which is based on the use of bionic shaping and parametric modelling both at the design stage and at the management and development stage.

The ecological aspects of the formation of the concept of the future architecture in the conditions of cataclysm, which are based on the creation of waste-free production, the use of alternative sources of energy and heat, the use of shaping the objects of bionic architecture based on parametric modelling, are studied.

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