Searching for Bionics Structural Forms Optimization

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Abstract. The architectural design becomes an interdisciplinary process while the architectural forms, due to their various criteria, are more and more often created as a result of conducted optimization (simulated processes - "form follow process"). Activities that mimic the processes occurring in nature seem to be of particular interest. The inspirations with observed structures in nature shaped under the influence of loads acting on them constitute an interesting aspect of the search for optimization. The material and energy consumption were minimized through the evolution of structures and their adaptation to the environment. Therefore, such processes can serve as important patterns in the pursuit of building objects, effectively adapted to the location conditions, as an urban ecosystem element in accordance with the idea of sustainable development. In modern architecture, research is conducted using mathematical models in the search for optimal forms, based on the patterns of structures observed in nature. The article presents an analysis of a number of examples of bionic architecture in terms of structure and material. In addition, own model studies of selected bionic and geometrical structural forms were presented. The aim of the analysis at hand was to conduct optimization searches for the shaped bionic rod structures, selected due to the criterion of minimum mass. Among the analyzed structures, a noticeable effectiveness of forms transferred from nature was observed, which indicates the need for further research in this area.

1.   Introduction

Architecture created in accordance with the idea of sustainable development means building objects that are better adapted to the surrounding conditions. More effective solutions in this field can be seen in the world of nature. Living organisms have developed through a long evolutionary process based on their best capabilities to adapt to the environment in which they live. Therefore, the resulting structures are characterized by obtaining a minimum of material and energy. Here, the morphological (changes in structure and form), metabolic (changes in intra-body functions) or physiological adaptation (changes in intra-vitro processes) may be of particular interest. The observations of patterns found in nature become the impetus for the possibility of transferring these systems and structures to technology. This is feasible thanks to the appropriate mathematical models that allow in a simplified way to reproduce the changes taking place. Bionics or biomimicry, concepts which are used in various ways, deal with the issues of models created by describing the structures and processes encountered in the natural world, mainly in the context of technological application. Bionics (Greek: bios, life) as "the field of knowledge from the borderline of biology and technical sciences, dealing with the technical application of the principles of living organisms or processes observed in these organisms or in their communities" can be treated interchangeably with the concept of biomimicry (from Greek bios-life

and mimesis - to imitate), that is, the imitation of the elements encountered in nature and used in technology. Initially, the concept of bionics was used, among others, by Jack E. Steele in 1958 and came from the technical term bion, meaning a unit of life and was attributed the meaning "according to the rules of life." The article adopts the meaning of the word bionics and biomimicry as identical, defines research and analysis of living organisms, processes and functional systems occurring in them, the aim of which is to create models corresponding to biological counterparts, enabling their use in technology. The design of bionic architecture is understood as shaping a structural form by using mathematical models describing the structures found in nature and using bionic systems and material technologies [1]. In the architectural design, the inspiration from nature is not a new phenomenon, as seen in the projects of Antonio Gaudi, or Santiago Calatrava. Santiago Caltrava referred to the sculptor's Auguste Rodin statement as "the harmony of living bodies results from balancing the masses in motion. As Calatrava claimed, "everything is related to mathematics and a unique dimension of time", and as a result, statics is a potential movement [2]. The seemingly biomorphic forms and their organic capabilities of structures and details have been confirmed in the studies conducted by Jane and Mark Burrych as optimized structures, which were not only guided by the aesthetic goal. Contemporary research in the scope of structural optimization possibilities based on bionic models is a new qualitative action using the development of digital tools in the pursuit of synergistic design.

2. Mathematical models in the optimal formation of bionic structures

Optimization of technical structures in contemporary architecture is a complex process and includes the qualitative intervention of forms at various stages of its formation, also as a significant element in the process of its implementation. Optimization methods that currently apply in shaping spatial architectural forms can be divided as follows: the first group of tools is used to **shape surfaces** whose geometry meets the intended architect's idea, and at the same time is the optimal structural solution. A separate group consists of methods used to determine divisions on a given structure and to control the number of nodal points on its surface (**nodal subdivisions of a surface**). The third group of the optimization methods in the process of architectural and structural design is **material optimization**, which does not change the geometry of the structural form, but only minimizes the weight of a given structure. It includes both the selection of the most structurally advantageous material for a given structure, as well as the processes of acquiring new materials with better strength parameters. The emerging tendencies in architecture, based mainly on the formation of free structural forms, pose increasing requirements for material engineering. With the use of biomimicry in architecture, in parallel there is a growing need for composite materials and materials with biological structure and properties. In the development of material technologies, specialist knowledge in the field of biology, biomimetics, biochemistry and nanotechnology is increasingly used [3]. Modern trends in material optimization, such as functional surfaces, rely on introducing modifications to the material structure to improve strength parameters. Modifications include activating the device or the coating, chemical changes, changes in the morphological structure or other regulations that lead to product improvement, without changing the characteristic properties of the object. Material optimization is the rationalization of costs and improvement of engineering solutions, however, it does not affect the shaping of the spatial form. When considering the structural forms and the way they are shaped due to the rationality of engineering solutions, more reference should be made to the rules and physical and mathematical laws. Technological development, and in particular access to digital tools, meant that known geometrical assertions and canons of beauty gained a new meaning in architecture design. Following the stream of optimization of engineering solutions (minimizing the use of energy, material, energy acquisition, etc.), architects increasingly create atypical forms, the geometry of which goes beyond the Euclidean paradigms. Curvilinearity in contemporary architecture is now a common element and is also increasingly becoming the result of shape optimization. In designing free structural forms, various digital modeling techniques are used, based on directions such as, for example, mathematical surfaces (including expandable surfaces, chain models, minimal surfaces), topological transformations, or chaotic systems and algorithms. Integrating the appropriate digital tools with the philosophy of

searching for geometry that most faithfully reflects the technology of Nature, is one of the most expressive directions of development in the architecture of recent years.

The minimal areas can be of great importance due to the search for effective forms. The Plateau experiment made it possible to obtain the surface of a soap bubble, the shape of which was created as a result of the system's striving for a minimum of energy. Minimal areas were used in the design of functional forms and connections of the Australian Wildlife Health Center according to the design of Minifie Nixon. A similar effect was obtained in the case of the Minimal Surface Pavilion constructed in 2011 as part of a student project from the University of Tokyo. A drop of water, which served as inspiration for the construction of the BMW Bubble pavilion in Frankfurt by the Franken Architekten project was also part of the designers' field of interest. The project, carried out in 1999, was one of the first in which digital tools were used to optimize the surface stress of the form using parameters. A strength analysis and digital prefabrication methods were carried out for the construction of the pavilion's frame structure. The use of digital tools makes it possible to carry out analyses and simulations on the model of biological form development processes.

Homology, which is visible in biological structures with a common evolutionary origin characterized by a certain similarity is noteworthy in this context. The mapping of these changes in mathematics is homeomorphism, which is one of the basic concepts of topology. Homeomorphism consists in transforming figures without breaking them and adhering elements, but only through stretching, squeezing, bending and twisting them, which makes it possible to maintain its continuity and identity functions. This type of transformation can be found in architecture. Embryological House by Greg Lynn is a concept design example where the design process was based on the topological transformations of the "embryo" represented by the Bézier curve. As a result, during the computer simulation (the animation as called by the author) the topologically inconsistent solutions were eliminated and thus the curvilinear form was achieved (shaped due to the plan and cross-section criteria) [4]. Animation in this case, as the author writes in the Animate Form essay, is understood as a kind of development of form. The action carried out in this way allowed to present the object's body as a structure built dynamically, while trying to address the changing location conditions and functional and spatial needs. Topological transformations were also applied in the case of the temporary form of the Chanel Mobile Art Pavilion designed by Zaha Hadid Architects. The torus shaped on the basis of a gold spiral was subjected to topological transformations. The mentioned gold spiral, based on the Fibonacci sequence, which has been noticed by Alan N. Turning in the arrangement of the leaves of plants is a mathematical model associated with the golden division identified with harmony and proportion. The conceptual design of The Spiral Extenstion to the Victoria and Albert Museum in London is an example of an object, the structure of which was shaped on the basis of a gold spiral. The design of Daniel Libeskind and Cecil Balmond assumed the division of the spiral into polygons, by means of which a flat surface was bent at different angles, creating a self-supporting stiffening system without the need for intermediate supports, which had a significant impact on the space flexibility inside the designed building. The geometry of the spiral was shaped based on the preliminary results of strength analyses. It is worth noting that, in principle, the form of the object was integrally associated with the function of the museum, where the spiral was a visitor's path. Material optimization can also be carried out using materials of varying strength, strengthening only the places where it is necessary.

As a result of computer analyses, it is possible to precisely determine places with the greatest strains and stresses. This optimization process was carried out in the design of the research pavilion implemented in 2013-2014 by the Institute for Computational Design (ICD) and the Institute of Building Structures and Structural Design (ITKE) of the University of Stuttgart. The project involved the creation of a pavilion inspired by the armor and wings of beetles. The analyses were carried out in cooperation with biologists from Bionics of Animal Constructions led by prof. Oliver Betz (biology) and Prof. James. H. Nebelsick (geosciences) Tubingen University. As a result, a design made of glass and carbon fiber was proposed.

3. Bionic design in the pursuit of optimization of load-bearing structures on the example of catenary models

The search for optimal spatial forms can be carried out using mathematical models of a homogeneous and inextensible chain hanging freely between two supports in a homogeneous gravitational field, as exemplified by the catenary curve visible in the structure of the spider curve. In the era of universal digitization, a computer program has been created that uses the logic of chain models to shape optimal structural forms and to discretize the surface.
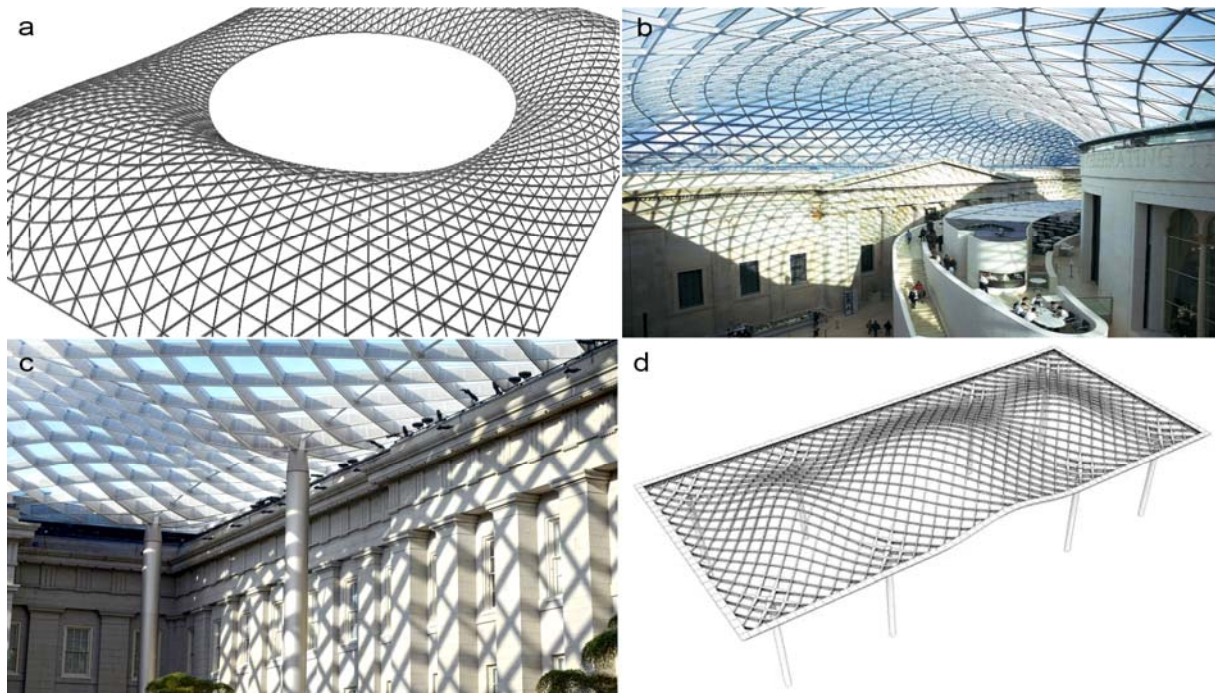
Figure 1. Steel structures shaped and discretized using the Dynamic Relaxation model; British Museum's Great Court, London, designed by Foster & Partners, 2000; a - 3D structural model [5]; b – perspective [6]; Smithsonian Institution, Washington, design by Foster & Partners in collaboration with Smith Group Inc., (2004 - 2007); c – perspective [7]; d - structural model of the roof [8];

Dynamic Relaxation is on such computer program tool, which is a numerical method of computational modeling, the aim of which is to find geometry where all forces are in equilibrium (Figure 14a). This method, based on Newton's 2nd law, allows for an optimal structure - a grid - and also to find the right number of nodal points (constructional points). For example, with the use of Dynamic Relaxation, complex divisions and refractions of the glass surface of the British Museum's Great Court roof dome have been generated, a project designed by architects from the Foster & Partners office. The glass roof of the Smithsonian Institution building (2004 - 2007) is another similar example of the Dynamic Relaxation method in architectural design. The design of the central courtyard roofing was the main element of the reconstruction. As a result, one of the largest spaces of this type in Washington was created, concentrating new galleries and integration venues of the local community. The roofing project was developed by the Foster & Partners architectural office in cooperation with Smith Group Inc.
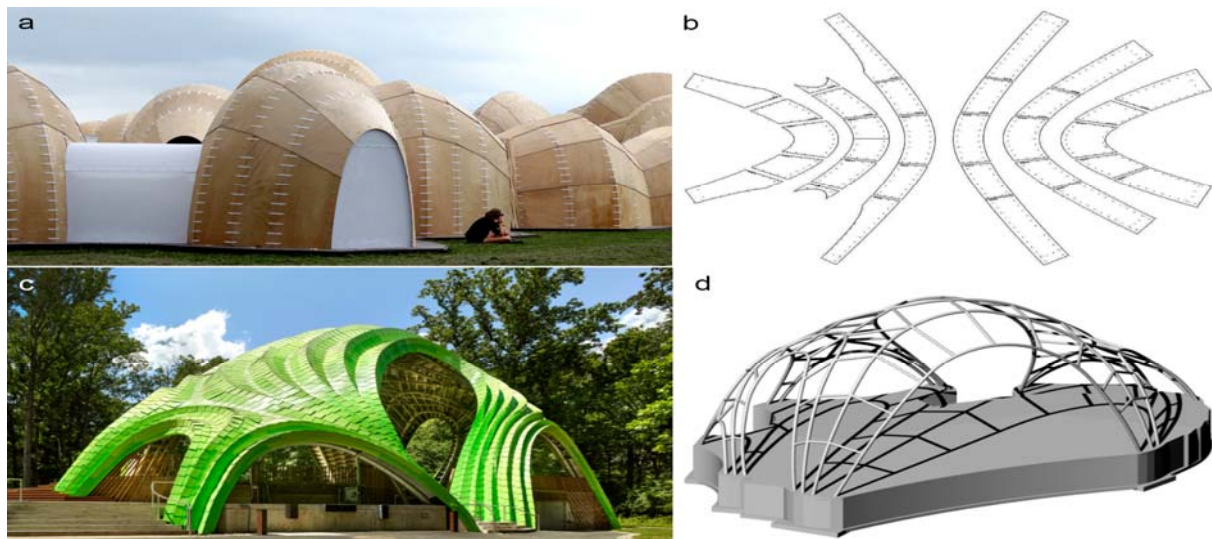
Figure 2. Velvet State Pavilion, Roskilde, designed by SHJWORKS Architectural, 2013; a – perspective [9]; b - a flat element, from which the pavilion structure was shaped; The roofing of the Chrysalis, Maryland, Colombia, design of the Living Design Lab in cooperation with Arup, 2016-2017 ; c – perspective [10]; d - steel structure model [11];

The Velvet State pavilion project implemented in Roskilde as part of the Roskilde Festival 2013 uses the arched structure formation in which the optimal stress system occurs. The project by the SHJWORKS Architectural studio is a structure composed of a sequence of catenary curves, from which several forms made of bent plywood boards connected with polycarbonate elements were created. A similar application of the catenary curve is visible in the case of the Chrysalis scene roof project in Maryland, Colombia. The curvilinear structure designed by Living Design Lab in cooperation with Arup was formed as a result of analysis of catenary discs as steel structural surfaces.
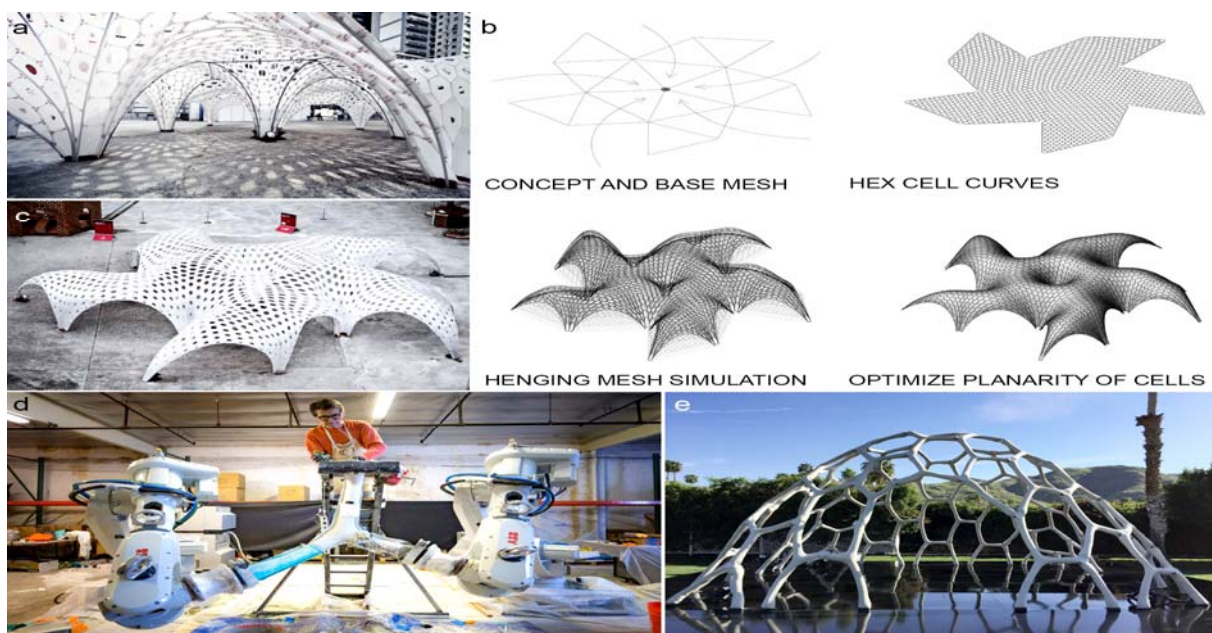
Figure 3. Shellstar Pavilion, Wan Chai, Hong Kong, designed by Matsys, 2012; a - perspective view of the interior of the pavilion [12]; b - a diagram showing the stages of shaping the form; c - perspective; Mars Pavilion, designed by Form Found Design; d - Robot during the production of structural elements [13]; e - perspective

The asymmetric form proposed by the architects was a major technological challenge not only due to curvilinearity, but also due to limited costs and the use of local construction techniques and materials. Considering the results of load analyses and simulations (BMT Fluid Mechanics of London conducted specialized aerodynamic analysis), engineers decided to use a steel frame (main steel frame) reinforced with a system of secondary steel elements. The rod structure was covered with a sheet arranged in a characteristic pattern of scales - bent in order to delineate the form and give the coating additional stiffness. The Shellstar Pavilion, the design of which was developed by the Matsys studio, was also made based on the catenary. The aim of the project was to minimize material consumption, during which both the form, the discretization of the surface and the possibilities of prefabrication were optimized. The form of the pavilion was shaped as a result of the digital process of optimal modeling ("form finding") based on the classical catenary technique model, developed, among others, by Antonio Gaudi and Otto Frei. Using the Grasshopper and Kangaroo programs, the designers created an algorithm responsible for self-organization of the structural form - the form itself is "organized" into a catenary model, where the nodes stay in balance and the cross-sections of structural elements have minimal geometry. An individual Python script was used to create building elements (made of Coroplast material) which allowed to generate flat divisions and prepare for the production. The designers' assumption was to divide the surface in such a way as to enable the curved form to be formed from flat elements, which greatly simplified and lowered the implementation costs. The Mars Pavilion project designed by Form Found Design is an equally interesting example. The design assumed the shape of the pavilion in such a way as to maximize compressive stresses in the structure using a catenary, due to the properties of the material used - concrete. The organic bar structure of the pavilion was created as a result of the work of robots whose arms manipulate the sleeves of the fabric creating an adjustable formwork, to which the concrete is then poured. Additionally, in order to increase the strength of the concrete, a steel fiber was introduced instead of rebar. The use of an innovative construction method has enabled the implementation of a complex structure in a very short period, where there are no repetitive elements [14-18].

4. Own model research in search for optimal structures formed on the basis of bionic patterns

Based on the study analyses of examples of the implementation of bionic projections in architecture, model studies were carried out in order to search for the effectiveness of selected rod structures.

Assumptions made

Symmetrical bar-shaped structural forms are subject of the research, created by the rotation of a curve which forms around an axis perpendicular to the base using topological transformations. Two models were selected for the study: a bionic and geometric one with similar proportions and properties. The aim was to determine the impact of bionic patterns on structural optimization. The result was a rotational body shaped based on the shape of the catenary curve described by the formula $f(x) = 2\cosh\left(\frac{x}{2}\right)$ and a similarly shaped rotating paraboloid described by the formula $f(x)=0.5 \ x^2$. In order to compare forms with different shapes, a homeomorphic parameter was introduced, corresponding to the homologous transformations observed among structures of common evolutionary origin. This parameter was assumed as the ratio of the length of the forming curve to the base (span) equal to 2.4. A fixed structure span of 30 meters was assumed. Modularity of the structure was also assumed, allowing for an easy assembly of the repetitive elements - rods. As a result, the possibility of shaping the structural grid to the radial mesh with the divisions of the forming curve and the base to equal sections was limited. For technical reasons, an acceptable range of rod lengths at the base (support zone) from 2.57 m to 3.14 m was chosen. As a consequence, three radial meshes were selected; with 30 divisions of the forming curve and 12 base divisions, 32 divisions of the forming curve and 13 base divisions, and 34 divisions of the forming curve and 14 divisions of the base. The structures were based on 12, 13 and 14 joint supports, depending on the adopted structural grid. The same cross-section was adopted for all structures made of S235 steel with circular RO type cross-section. The analyses were performed in the Robot Structural Analysis program using the optimization module, due to the minimum mass profiles available in the RPLN7 catalog. Loads were adopted in

accordance with PN-EN 1991-1: 2004. The structures were loaded with own weight, the weight of glass panels equal to 0.50 kN/m^2 and the service load equal to 0.40 kN/m^2. The load combinations were made in accordance with PN-EN 1990: 2004. The maximum deflection value was determined to be L/250 according to PN-EN 1990:2004. Static and strength analyzes were performed according to PN-EN 1993-1:2006/NA: 2010/A1:2014. As a comparative criterion, three quantitative parameters were adopted:

- parameter M_c - defining the total mass of the structure [kg];
- parameter M_j - defining the mass per length unit of the structural grid [kg / m];
- parameter M_p - defining the mass per area unit of roofing [kg / m2];

Detailed geometrical parameters of the adopted structural forms are presented in the table below.

Table 1. Geometric parameters of the adopted structural forms. Source: A. Nowak

Form	Solid width [m]	Solid height [m]	Solid span [m]	Forming curve length [m]	Base field [m^2]	Covered area [m^2]	Volume [m^3]
Paraoloid	30,00	31,53	30,00	36,20	706,84	2108,76	11021,05
Catenary	30,00	30,60	30,00	36,11	706,84	2239,96	12305,55

Analysis results

The relationships between individual structural forms depending on the adopted structural grid divisions in terms of the M_c parameter are shown in the following graph.
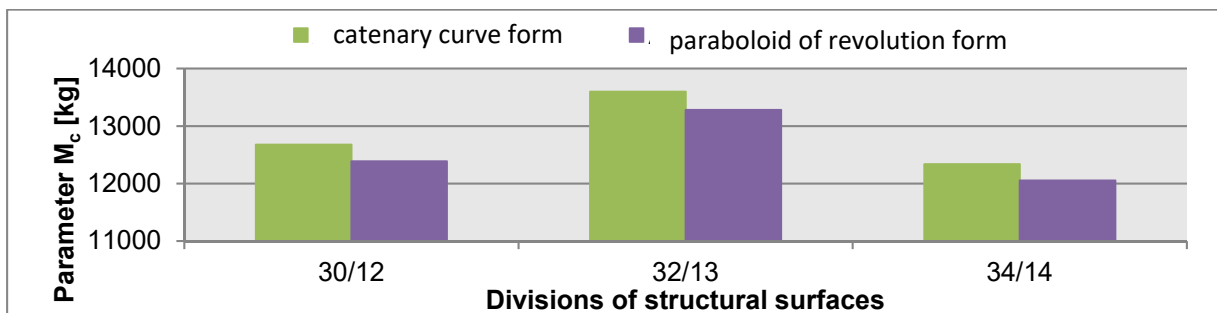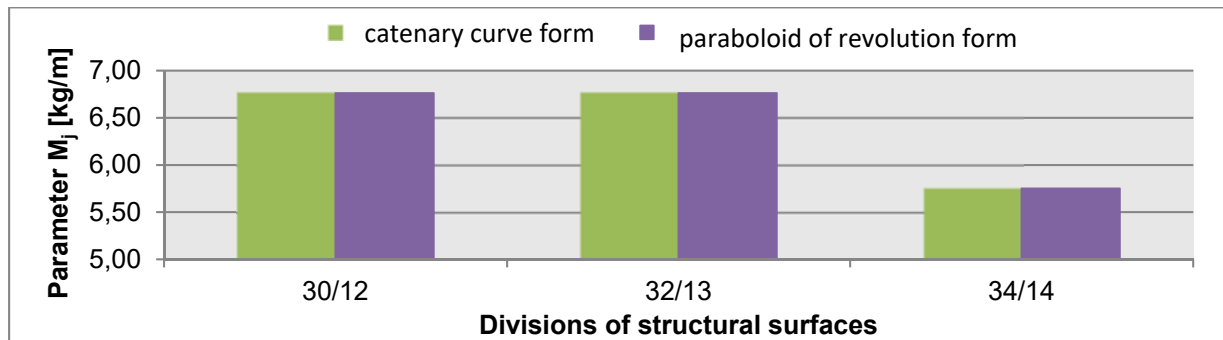

Figure 4. Comparison of efficiency in terms of the Mc parameter of the bionic structural form shaped on the basis of the curve and geometric curve described by means of a rotational paraboloid with a change in the radial mesh division density.

Among the analyzed forms, the structure formed on the basis of rotational paraboloid has a smaller total mass in comparison to the catenary curve form. Different results were obtained depending on the adopted density of the structural meshes. The smallest value of the M_c parameter was obtained for the most densely structured grid with divisions of 34/14; for both analyzed forms, the M_c parameter depends on the length of the structural grid, which does not allow to clearly determine the effectiveness of the adopted structural forms. It is important to determine the influence of the relationship between the length of the structural grid and the total mass of the structure and enter the parameter M_j, describing the mass of the structure, thus making it possible to compare structural grids of different lengths.

The relationships between individual structural forms depending on the adopted structural grid divisions in terms of the M_j parameter are presented in the following graph.

Figure 5. Comparison of efficiency in terms of the parameter Mj of the bionic structural form shaped on the basis of the curve and geometric curve described by means of a rotational paraboloid with a change in the radial mesh division density

The bionic and geometrical forms exhibit the same unit mass for individual radial grids. The weight reduction is visible for both forms in the case of a radial mesh with 34 base divisions and 14 divisions of the forming curve with the smallest field of the mesh at the base. In the case of 30/12 and 32/13 divisions, for both forms, the same results were obtained regardless of the change in the density of the structural grid. Due to the Mj parameter for structural forms, the results depend on the optimization adopted with the use of the profile algorithm selected from the available profiles database. As a result, the same rod was selected for most structures despite the possible difference in stresses. Considering the ratio of the total weight and the total length of the bars, the Mj parameter is characterized by the efficiency of the given grid for individual structural forms, not by the shape. In order to further analyze, however approximately, the effectiveness of individual forms, the Mp parameter was introduced, which maps the dependence of the structure's mass on the surface of the roofing. The introduction of the homeomorphic dependence enables a more objective comparison of rotational forms with two fixed geometric quantities, i.e. the constant length of the forming curve and the radius of the base on the basis of the aforementioned parameter. The relationships between individual structural forms depending on the adopted structural grid divisions in terms of the Mp parameter are presented in the graph below.
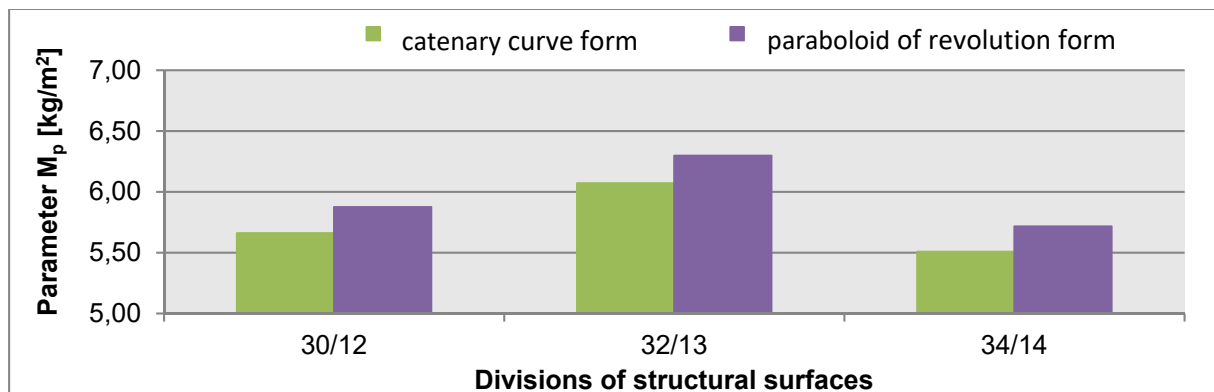
Figure 6. Comparison of efficiency in terms of the Mp parameter of the bionic structural form shaped on the basis of the chain and geometric curve described by means of a rotational paraboloid with a change in the radial mesh division density

The shape formed on the basis of a catenary curve shows a smaller size of the M_p parameter in relation to its counterpart shaped as a rotary paraboloid. The most favorable result was obtained for the densest radial mesh with 34/14 divisions. The M_p parameter approximates the effectiveness of structural forms, because of the relations between the individual form proportions of and their mass.

Table 2. Comparative grid of structure parameters formed on the basis of a catenary curve and a rotating paraboloid, ranked according to the M_p parameter

Form	Divisions of structural surface	Profiles [mm]	Total rod length [m]	M_c Parameter [kg]	M_j Parameter [kg/m]	M_p Parameter [kg/m²]
Catenary	**34/14**	76.1 x 3.2	2145.40	12336.05	5.75	5.51
Catenary	**30/12**	88.9 x 3.2	1875.3	12677.03	6.76	5.66
Paraboloid	**34/14**	76.1 x 3.2	2096.10	12052.58	5.75	5.72
Paraboloid	**30/12**	88.9 x 3.2	1832.4	12387.02	6.76	5.87
Catenary	**32/13**	88.9 x 3.2	2010.24	13598.22	6.76	6.07
Paraboloid	**32/13**	88.9 x 3.2	1964.48	13279.88	6.76	6.30

Analysis conclusion

Structures based on a catenary curve may exhibit efficiency with respect to their geometric counterpart, however this depends to a large extent on the assumptions regarding grid formation. The effectiveness of the forms is influenced by the different rod total length caused by variable geometric parameters in the area of the roofing surface and the volume of individual solids. In reference to the homology of general assumptions, the M_p parameter makes it possible to compare structural forms and different cover areas and approximates the results due to the mass efficiency of structures.

5.   Conclusions

The algorithmization of modeling programs, the aim of which is to search for bionic bar structures, is a new, creative tool for shaping architecture. Nowadays, progressive digitalization reaches all stages of the building's construction as well as its subsequent maintenance, the goal of which, among others, is the rationalization of technical solutions. When it comes to shaping structural forms, the stage of creating an architectural concept is particularly interesting, which in the era of universal digitalization loses its mysteriousness in favor of multidisciplinary analyses conducted in various aspects, including minimizing the consumption of energy, material, etc. Interestingly, often enough, a changing design process can be clearly identified – this includes initial engineering optimization, which affects more and more technical areas. A team of engineers supporting the creative shaping of architecture appears more often by the side of a modern architect. Such a solution is conditioned on the one hand by the development and availability of digital tools, on the other hand, by the need to shape more sophisticated solutions, often inspired by bionics. To a lesser extent, the optimization of structural solutions seems to be surprising at the stage of construction or executive design - nevertheless, the digitization of the manufacturing processes of building elements provides many difficulties. Shaping complex, often asymmetrical, structural forms forces the development of material and construction technologies and inspires to create innovative solutions in this field (e.g. 3D printing, casting structural nodes, etc.). The development of fields in the field of analyzing technical solutions is indispensable with the simultaneous development of architectural shaping tools. In conclusion, it should be noted that structural optimization is not a secondary activity aimed at improving technical parameters, but rather it is a process accompanying the main activities of designers in the search for the new and "emerging" architecture.

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