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phone: (+48 32) 237 26 58

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BIONIC MODELS IN OPTIMAL DESIGN OF FLAT GRIDSHELL SURFACES

Ewelina GAWELL [1/] **Wiesław ROKICKI** [2/]
ORCID 0000-0002-8941-7472 ORCID 0000-0003-2094-3244

[1/] Faculty of Architecture at the Warsaw University of Technology (WAPW)
Department of Structural Design, Construction and Technical Infrastructure
ul. Koszykowa 55, p.216, WARSZAWA, POLAND
email: welina.gawell@pw.edu.pl
[2/] Faculty of Architecture at the Warsaw University of Technology (WAPW)
Department of Structural Design, Construction and Technical Infrastructure
ul. Koszykowa 55, p.216, WARSZAWA, POLAND
email: wieslaw.rokicki@pw.edu.pl

Abstract. Contemporary architectural explorations are also concerned with the structural developments of geometric spatial forms. More and more original objects are created or even mapped in reference to nature creations. The reasons for such undertakings are, on the one hand, the need to rationalize structural solutions, while on the other hand the creation of new forms in the context of aesthetics, functions, symbolism, etc. The dynamically developing computer programs that enable multilateral analysis of the proposed solutions in the design process, especially in the aspect of irregular shapes are a significant impulse for the introduction of bionic patterns into architecture. A significant pragmatic change of approach in the design process is the interdisciplinary cooperation of specialists from many fields. As a result, architectural objects in which innovative techniques, materials and technological solutions are tested, often differ from known modern building technologies. The use of bionic models in the search for new aesthetics in architecture requires the shaping of structural elements following the logic of Nature, which determines unconventional, but at the same time rational material solutions optimized towards minimal consumption of materials and energy required to produce them. Such perception of load-bearing structures is not new, but only a continuation of logical thinking from the past, and the development of digital tools supporting designers provides multiple optimization opportunities in synergistic architectural explorations. An important element of an article is own research on optimization of flat gridshell surfaces. The search criterion is the minimum mass and the study compiles selected classic models (regular divisions) and selected bionic models (irregular divisions).

Keywords: structural surfaces, bionic models, topological optimization

1 Introduction

Forms encountered in the natural world have always interested and inspired architects. The development of construction technologies and design tools has enabled the use of various references to the world of nature in architecture. As a consequence, we can distinguish among others architecture using elements from the world of nature for architectural expression, i.e. biomorphic architecture, curvilinear architecture inspired by "soft forms" found in nature, and bionic architecture. The transfer of simple analogies from the world of nature was already visible in historical architecture, in a plant form and animal ornaments. Nowadays, the mapping of nature can be seen in architectural objects in which the form is trivially mimicking plant forms or animal silhouettes or is a qualitatively new ornament using

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inanimate (water) and animate (vegetation) elements in shaping variable and dynamic architecture [3].

An interesting pavilion project that is characterized by an ephemeral visual expression is *Blur Pavilion* realized for the 2002 EXPO in Yverdon-les-Bains, Switzerland (Fig. 1a, b, c).

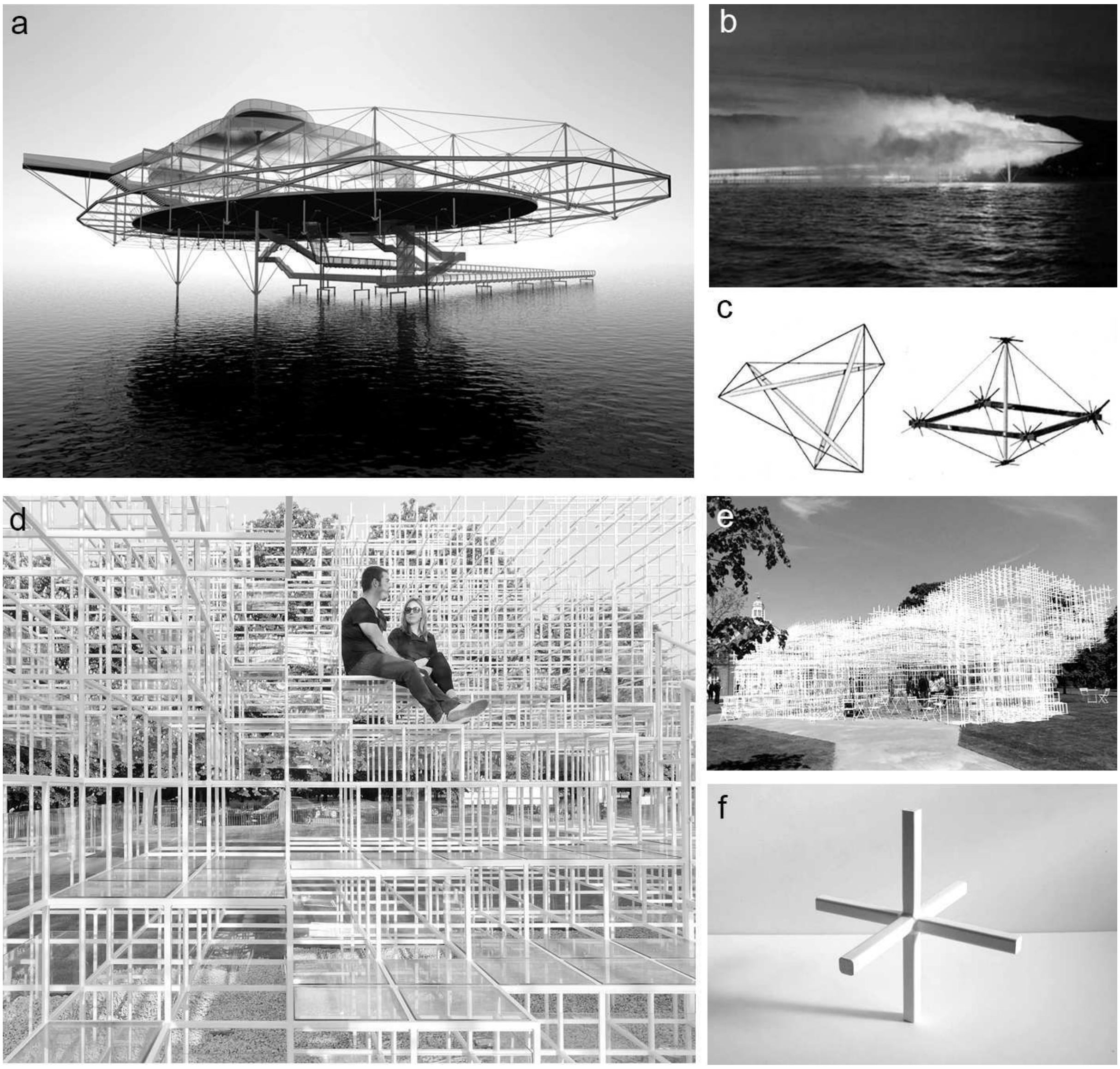


Figure 1: *Blur Pavilion* made for 2002 EXPO in Yverdon-les-Bains Switzerland, designed by Diller Scofidio + Renfro design studio; *a* - perspective view of the pavilion's structural form, *b* - view of the pavilion covered with artificial fog, *c* - tensegrity model used in the pavilion's load-bearing structure; *Serpetine Gallery Pavilion*, London 2013, designed by Sou Fujimoto: *d* - view of a fragment of the pavilion, *e* - perspective view, *f* - repeatable element of the load-bearing structure

source: a – „COROFLOT”, „GSAPP by Leo Mulvehill”, [access: 30 July 2019]
< http://www.coroflot.com/lemulvehill/GSAPP >
b – „Spatial Interactions”, „Diller Scpfidio Blur Building Switzerland”, [access: 30 July 2019]
< https://spatialinteractions.wordpress.com/2011/09/25/diller-scofidio-blur-building-switzerland/ >
c – „COROFLOT”, „GSAPP by Leo Mulvehill”, [access: 30 July 2019]
< http://www.coroflot.com/lemulvehill/GSAPP >
d, e, f – „Serpentine Galleries”, fot. Iwan Baan [access: 30 July 2019]
https://www.serpentinegalleries.org/exhibitions-events/serpentine-gallery-pavilion-2013-sou-fujimoto

The designers from the Diller Scofidio + Renfro studio assumed the use of artificial fog (which is a symbolic combination of two elements - air and water) as the basic element shaping the architecture of the object. At the same time the structural form of the pavilion which was made as a tensegrity system arouses interest. This underlined the idea of biomorphism also expressed in the desire to reduce the consumption of structural material. An element which is an important part of inspiration with bionics.

The rational use of material, energy etc, as well as their re-use or acquisition, is an indispensable element of inspiration from nature in contemporary architecture. Thanks to the improvement in generative modeling tools, bionic formulas are used not only in search for new artistic language, but also in optimization of engineering solutions. Inspirations from the world of nature are also visible in the design of architectural objects, referring in an abstract way to the forms encountered in nature. The design ideas that are part of biomorphic architecture are particularly evident in the designs of exhibition pavilions and culture related facilities. Bionic inspirations also increasingly refer to the shape and structure of architectural surfaces. The Sou Fujimoto’s design of the temporary *Serpetine Gallery Pavilion* in London in 2013 endeavured "to blend the form” with the landscape. The irregular light and transparent structure of the building refers to a shape of a cloud (Fig. 1 d, e, f), and the spatial gridshell structure constituting the supporting structure was modeled parametrically. In the project, one can see the synergy of architectural and structural solutions expressed in the innovative tectonic form of the pavilion on the one hand, and in modularity and lightness of the structure on the other hand. The structural form is visually perceived as an integrated spatial system (homogeneous load-bearing structure constituting a sculpture in itself).

2 Bionic models and generative modeling tools

The digitization of architect's work tools affects the way disciplines related to architecture work together. On the one hand, the trends are changing and by using algorithms it becomes possible to duplicate complex bionic patterns, but on the other hand the quality of the designed solutions is increasingly determined by optimization processes carried out in various technical and technological areas. Contemporary parametric architecture uses many bionic concepts- depending on the needs, they can include fractals, cellular automata, catenary models, minimal surfaces, aperiodic tessellation, quasi-crystals and many other [1]. When it comes to the use of bionic standards in shaping flat gridshell structures, the selection can be limited to two directions: surface discretization and topological optimization. Emerging the form by means of a bionic model results in irregular structures with complex geometry - unless this is a condition written using an algorithmic code, there may not be any repetitive elements in such a system. Such solutions could be considered inefficient, especially in the context of universally recognized construction technologies. In the search for rational structural solutions, one should take into account the available material and construction technologies because the costs of load-bearing elements are an important condition for rationalizing solutions. However, attention should be paid to the dynamic development and dissemination of modern fabrication technologies (e.g. 3D printing) - parameters such as material and energy consumption or the time it takes to build an object become increasingly important.

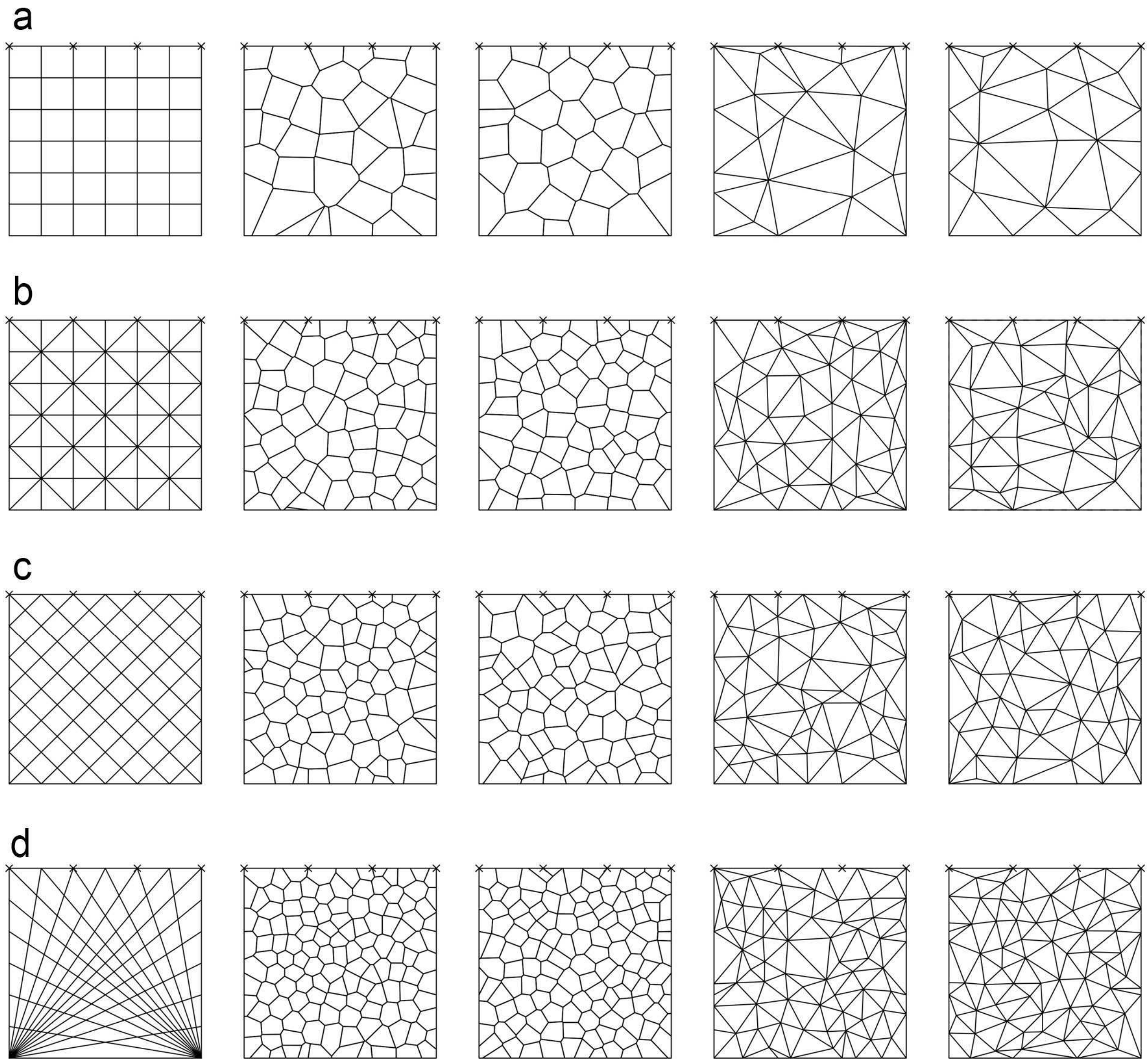


Figure 2: Sample geometric solutions generated using bionic models assuming a constant number of fields; *a* – solutions for 36 fields; from the left: orthogonal divisions, two variants of the Voronoi diagram, two variants of Delaunay triangulation; *b* - solutions for 72 fields; from left: intersecting divisions, two variants of the Voronoi diagram, two variants of Delaunay triangulation; *c* - solutions for 84 fields; from the left: diagonal divisions, two variants of the Voronoi diagram, two variants of Delaunay triangulation; *d* - solutions for 130 fields; from the left: radial divisions, two variants of the Voronoi diagram, two variants of Delaunay triangulation (*source:* a, b, c, d – copyright materials)

2.1 Surface discretization

Discretization is the most intuitive operation in the search for optimal flat surface structural solutions. Making the gridshell divisions necessary for implementation purposes also creates a visual effect that has a significant impact on the architecture. During the concept stage, a compromise between architecture and structure should be sought, determining the most important parameters for obtaining optimal solutions.

Today, there are many digital modeling tools that use bionic formulas to discretize surfaces. The most interesting are: Delaunay triangulation and Voronoi Diagrams. Both of these methods are based on one model that occurs in nature, among others, in structural divisions of living organisms: dragonfly’s wings, giraffe’s spots, turtle’s shell, etc. These formulas have been described in simplified form by the Voronoi Diagram whose delineated graph is Delaunay triangulation. Triangular divisions seem to be more effective due to structural logic, but often in the world of nature more complex forms dominate and their efficiency may be surprising for engineers. This is one of the reasons why modern parametric architecture implies different bionic patterns when looking for multi-variant solutions for output data and analyzing the results in terms of the indicated optimization criteria.

For example, the above list indicates randomly generated bionic solutions for typical flat structural systems that are used in construction: orthogonal, intersecting, diagonal, and radial divisions (Fig. 2 a, b, c, d). Several unchanging parameters have been assumed here, such as fixed points on the top chord (marked 'x') and an unchanging number of fields. Modeling bionic solutions allows the generation of multi-variant solutions, but at the same time requires a series of analyzes in terms of rationality of the technical solutions.

2.2 Topological optimization

The use of algorithms allows architects to model structures by mapping the structure and behavior of living organisms, which leads to logical structural solutions. One of the methods of searching for a spatial forms is topology optimization which uses evolutionary algorithms in minimizing material consumption. The minimum mass criterion is more and more often accepted as the primary purpose of such explorations, i.a. due to modern fabrication methods where the executive process is managed by self-steering machines (3D printing, casting elements, CNC cutters, etc.). The idea of *form follows forces* assumes that the construction material is located only in places where it finds real application - by adapting the structural system to the given boundary conditions and loads in order to increase efficiency and maximize system performance. As a result, one can achieve a makeable, yet freely shaped form in a given design space.

An illustration of structural solutions shaping aiming at topological optimization is the following analysis performed in the ANSYS program. For a flat surface of 9.0x9.0 m, located in the X and Z axes, two supports were assumed and the linear load on the upper edge was applied. Along with the degrees of material reduction (Fig. 3, a, b, c), the structural shape changed. However, in all the analyzed variants, the solution proposed by the algorithm resembled a bridge structure, which is visible in the resulting force distribution. It is worth noting that in the case of topological optimization, the indication of the right solution is related to the magnitude of the forces occurring in the gridshell system, but also to the strength of the structural material and the used construction technology.

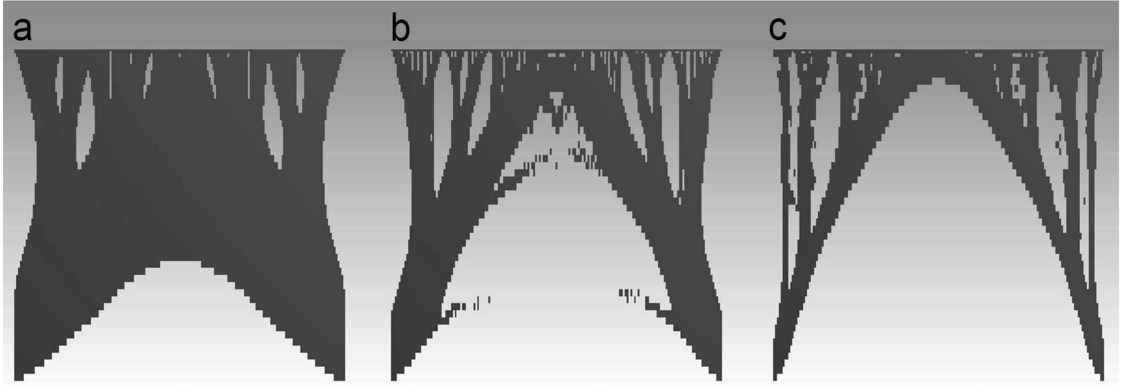


Figure 3:Analysis made by topological optimization method; *a* - structural solution assuming 50% reduction of material, *b* - structural solution assuming 70% reduction of material, *c* - structural solution assuming 85% reduction of material (*source*: a, b, c – copyright materials)

3 Own research

Due to the variety of possibilities in shaping architectural forms, it was decided to analyze a selected bionic model – the Delaunay triangulation which is now increasingly used in the discretization of the structural surfaces. The search for optimal and unconventional design solutions plays an important part in such designs. The study focuses on the analysis of geometric methods that determine structural efficiency, aesthetics and design freedom.

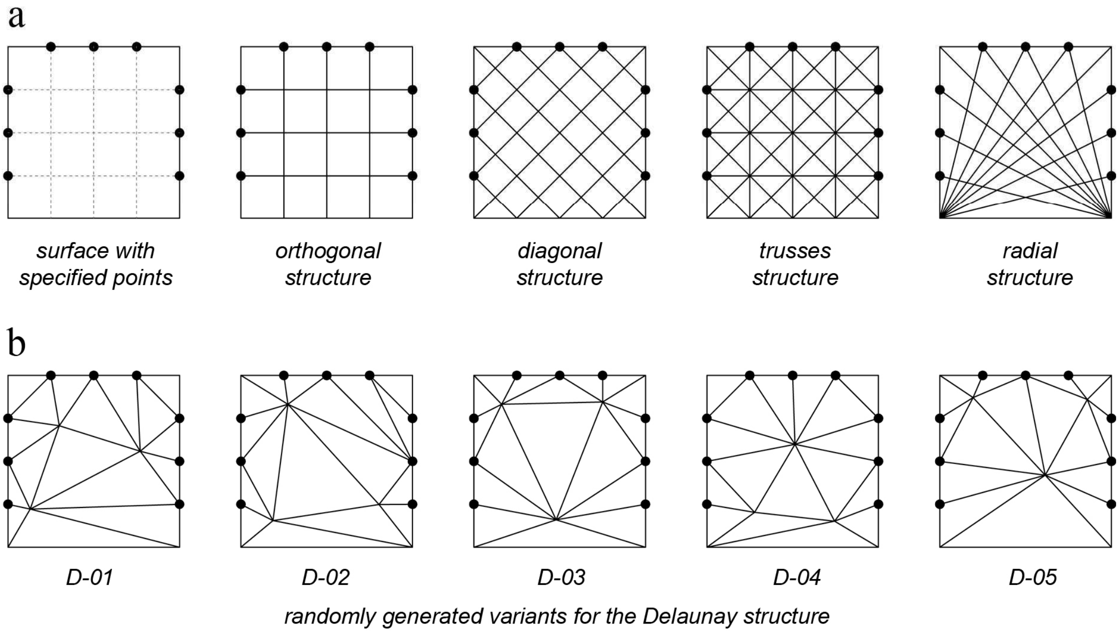
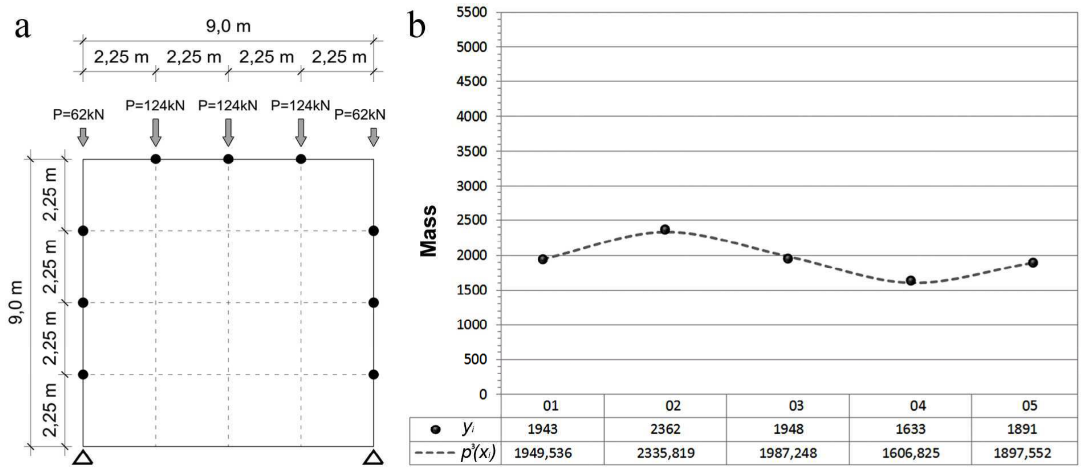


Figure 4: Examples of plane divisions with designated points; a – typical, regular structures, b – Delunay triangulations within an indicated boundry conditions generated using an algorithm (*source*: a, b – copyright materials)

In the era of parametric modeling tools, the creation of Delaunay grid structural systems is most often the process of generating multi-variant solutions for the indicated boundary parameters [3]. Choosing one system becomes difficult when the task, among others, requires a designer to rationalize technical solutions. The following design (Fig. 4) presents examples of plane divisions with 9 points (marked with black dots). For the indicated boundary conditions, it is possible to determine instances of regular typical structures, such as orthogonal, diagonal, latticed or radial (Fig. 4a). With the adoption of identical parameters, however, many different cases can be generated for the Delaunay structure (Fig. 4b).

To carry out own research, the aim of which was to optimize the gridshell structures, due to the minimum material consumption criterion, systems with different divisions of the plane were used. A flat structural system was adopted, for which the external contour (9.0x9.0 m) was also determined along with the diagram of supports and loads (Fig. 5a). The buckling lengths of the elements of the tested load-bearing structures for simplification were assumed as for truss beams. The system was supported on two pinned supports. The following constant and live loads were introduced: dead weight of the structure, the reactions from the floors were treated as a load constituting a separate variant as part of the combination of loads with a factor of 1.5, as for the live load, the load from the horizontal structure was applied to the nodes of the top chord, and the combination of loads was adopted according to PN-EN 1990. The assumption for each analyzed system was the selection of the cross-section that would be the most effective in terms of using its load capacity. S235 steel square profiles were adopted for the analysis. The same cross-section was used for all beams of each tested structure. In order to obtain comparable results, the elements were limited to square tubular cross-sections of the RK type (square pipes) according to PN-EN 10210-2: 2000.



Graph of the approximating polynomial $p^3(x_i)$ and the value y_i (mass) for the respective Delaunay structures

Figure 5: Assumptions and results of own analytical tests on planar grid structures; a – the adopted static scheme; b – **p³(xi)** approximating polynominal chart and **yi** (mass) values for individual flat Delaunay structures (source: a, b – copyright materials)

The first group of tested systems was typical structures (Fig. 4a) resulting from various geometric concepts. The average total weight for this group of tested variants was 2246,25 kg and the minimum cross-sections obtained were square pipes with external dimensions from 70mm to 200mm. Comparing the results, a clear similarity was observed between the orthogonal and diagonal structure as well as the trusses and radial structure. The diagonal structure with a total mass of 2888 kg is an alternative solution to the orthogonal structure with an efficiency of up to 11,55%. The next two variants have a significantly lower total weight. Trusses variant obtained a mass of 1683 kg, which gives an optimization of 48,46%. However, the greatest efficiency was achieved in the radial variant, which weighs 1149 kg and allows a reduction of material by 64,81% compared to the orthogonal variant. In addition, it was noted that the smaller total length of elements, the larger cross-sections had to be used. At the same time, contrary to what one might suppose, the greater total length of elements, the lower total weight. So the effectiveness of solutions is not indicated by the number of bars and their total length - the most important condition is rational shaping, following the system of forces acting on the structure.

The second group was composed of topological Delaunay systems (the genus: a constant number of nodes and fields) which were randomly generated in the Grasshopper plugin for Rhinoceros. Unlike in previous variants, Delaunay structures had a similar cross-section, whose external dimensions ranged from 100mm to 140 mm. The average total weight is lower and amounts to 1955,4 kg. For bionic variants, total length of elements was also not decisive. The heaviest bionic variant - D02 reached a mass of 2362 kg, which gives an optimization of 27,66%. However, in the lightest variant - D04, a mass of 1633 kg was obtained, which allows a reduction of almost 50% of the construction material to the orthogonal variant. The analyzed bionic variants result from one geometric concept, which makes them look similar. However, their heterogeneous structure makes it impossible to intuitively indicate the optimal solution (following e.g. the logic of the power system).

Despite the changing geometry of the divisions within the Delaunay structure, the characteristics of the influence of topological transformations on the mass of individual systems was a curve in a variable flow (Tab. 2 and Fig. 5b). This means that regardless of the topological transformations in a given structure (and to some extent also changes in the metric) we can approximately describe the effectiveness of such systems. In addition, for the given parameters, the ability to generate an infinite number of multi-variant solutions is an undoubtable advantage of digital surface division methods in search of architectural and structural efficiency.

Table 1: Comparison of results for typical, regular structures

Type of structure	Number of nodes	Profile /type, dimensions/ [mm]	Total length of elements [m]	Total weight [kg]
orthogonal	25	RK 200x200x6	90,00	3265
diagonal	41	RK 140x140x5	137,76	2888
trusses	41	RK 100x100x4	141,04	1683
radial	56	RK 70x70x3	184,24	1149

Table 2: Comparison of results for randomly generated Delaunay structures

Variant of Delaunay structure	Number of nodes	Profile /type, dimensions/ [mm]	Total length of elements [m]	Total weight [kg]
D01	16	RK 120x120x5	109,00	1943
D02	16	RK 140x140x5	112,66	2362
D03	16	RK 120x120x5	109,29	1948
D04	16	RK 100x100x5	111,22	1633
D05	16	RK 120x120x5	106,10	1891

4 Conclusion

Shape optimization in the construction of a load-bearing structures becomes an indispensable element of the architectural design process where nature is an important source of inspiration and imitation. Regardless of the design method, the creative but logical design of structures plays an important role in the optimal formation of gridshell structures, which results from a more thorough understanding of the principles of building mechanics. Parameterization becomes an important process in rationalizing engineering solutions using bionic models as it also allows to preserve the creative character of design. Determining the input data, optimization criteria and ordering the instructions of the algorithm are key elements of modern design. Generative modeling tools, and in particular form finding programs increasingly require close cooperation between the architect and the civil engineer at the stage of determining the input data - which has a very significant impact on the effectiveness of the proposed implementation solutions. The sublime interdependence of art and technology determines the quality and aesthetic of architecture, and the conscious creative exploration is an important and significant implementation aspect of the created concepts.

New trends and directions in architecture arise as a result of the digitization of architect's work tools. Innovative visions of architectural solutions provide a strong impulse for the development of technical and construction fields. The modernized digital technologies provide more and more innovative tools (digital CNC production of building components, 3D printing, etc.), hence the development of structural and mechanical design techniques should accompany these changes.

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MODELE BIONICZNE W OPTYMALNYM KSZTAŁTOWANIU PŁASKICH STRUKTUR PRĘTOWYCH

Współczesne poszukiwania w architekturze opierają się na strukturalnym budowaniu geometrycznych form przestrzennych. Coraz więcej oryginalnych obiektów powstaje w nawiązaniu, a nawet odwzorowywaniu tworów spotykanych w naturze. Powody takich działań to z jednej strony potrzeba racjonalizowania rozwiązań strukturalnych, natomiast z drugiej strony kreowania nowych form w kontekście estetyki, funkcji, symboliki, itp. Istotny impuls wprowadzania wzorów bionicznych do architektury stanowią rozwijające się dynamicznie programy komputerowe, które umożliwiają wielostronne analizowanie proponowanych rozwiązań, szczególnie w aspekcie nieregularnych kształtów. Znaczącym, pragmatycznym działaniem jest też zmiana podejścia w procesie projektowania w ukierunkowaniu na interdyscyplinarną współpracę specjalistów z wielu dziedzin. W rezultacie obiekty architektoniczne, w których testowane są nowatorskie rozwiązania techniczno-materiałowe i technologiczne, często różnią się od znanych współczesnych technologii budowania. Wykorzystanie modeli bionicznych w poszukiwaniu nowej estetyki w architekturze wymaga kształtowania elementów konstrukcyjnych zgodnie z logiką Natury, która determinuje niekonwencjonalne, ale jednocześnie racjonalne rozwiązania materiałowe zoptymalizowane z uwagi na minimalne zużycie tworzyw i energii do ich wytworzenia. Takie postrzeganie struktur nośnych nie jest nowym podejściem, a jedynie kontynuacją logicznego myślenia z przeszłości, a rozwój cyfrowych narzędzi wspomagających projektowanie oferuje zwielokrotnione możliwości optymalizacyjne w synergicznych poszukiwaniach architektonicznych. Istotnym elementem artykułu są badania własne dotyczące optymalizacji płaskich struktur prętowych. Kryterium poszukiwań jest minimalna masa, a w badaniu zestawiono wybrane modele klasyczne(o regularnych podziałach) oraz wybrane modele bioniczne (o podziałach nieregularnych).