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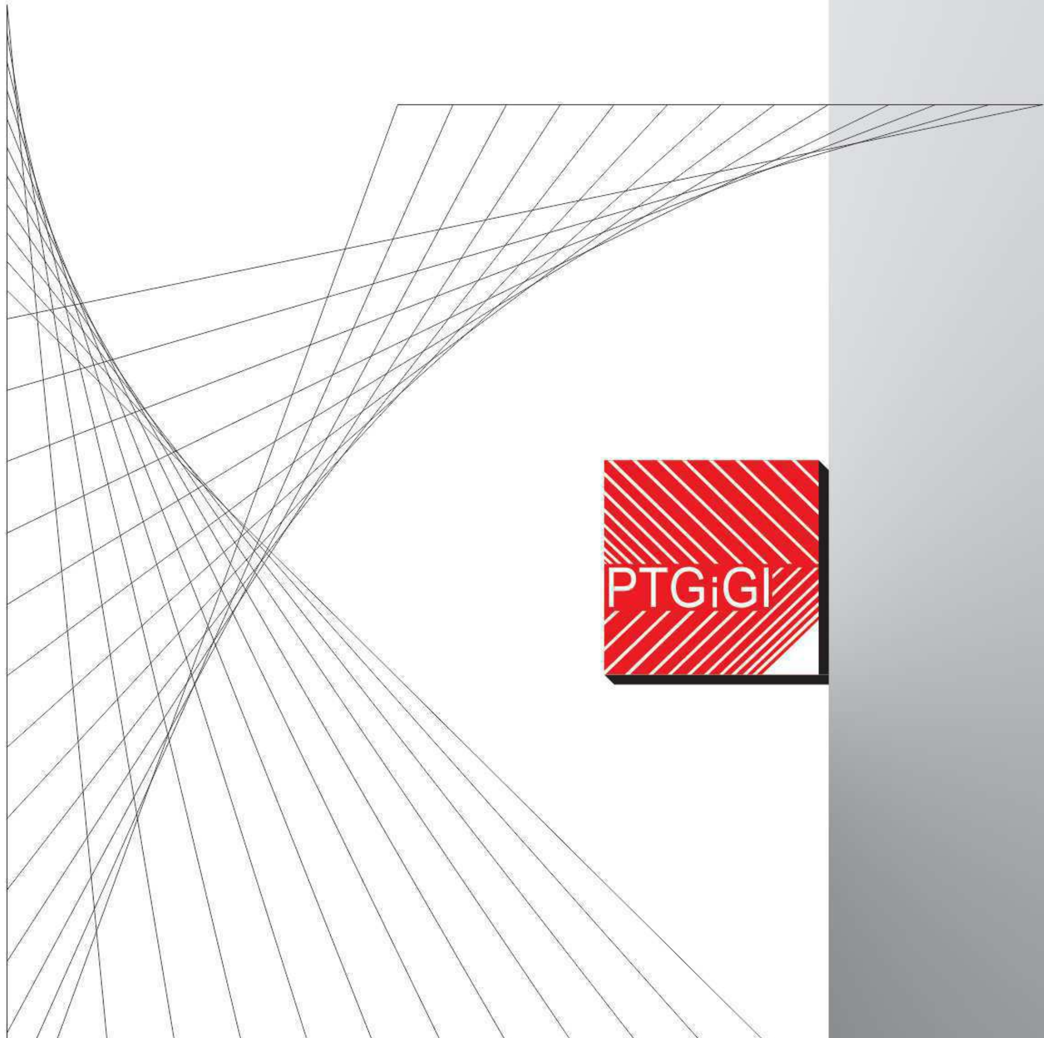

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phone: (+48 32) 237 26 58

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COMPARATIVE ANALYSIS OF BIONIC AND GEOMETRICAL STRUCTURAL FORMS

Ewelina GAWELL[1/], Anna NOWAK[2/], Wiesław ROKICKI[3/]

Warsaw University of Technology,
Faculty of Architecture, Department of Structural Design, Construction and Technical Infrastructure,
ul. Koszykowa 55, p. 214, 00-659 Warszawa, POLAND
[1/]e-mail: gawellewelina@gmail.com, [2/]e-mail: anna.patrycja.nowak@gmail.com, [3/]e-mail: wrokicki@poczta.fm

Abstract. In contemporary architecture is the rise of bionics as a source of inspiration in the development of unusual forms. The reason for such actions is both searching for new solutions, as well as the improvement of novelty in engineering design. There is a substantial interest in the field of bionics research in modern technology, also reflected in architecture. The attempt to render the morphology of the living organisms in the interaction of architectural and design can lead to optimal structural solutions, combining aesthetics with an expression of support and consistent static logic. At the same time, with the improvement of digital design tools it is possible to analyze technical solutions on many levels structural engineering. In modern architectural design the synergy of design solutions is an important field of activity for the people involved in the creative process. The search for efficient structural forms covered in the article is an attempt to discuss the optimization of load-bearing structures in the field of bionic morphology and geometry. The development of modern technologies enables the extension of the scope of the research, including the additional analysis dedicated to the interaction of the various fields of technology related to the evolution of architecture.

Keywords: structural optimization, bionics, solids of revolution, architecture

1 Introduction

There is an interesting trend in architecture which is characterized by the search of spatial forms analogous to living organisms. It is therefore increasingly important to analyze the conducted possibilities of describing the natural patterns of the world with mathematical models, enabling for a more accurate mapping of structures found in Nature [1]. In nature there are both asymmetric structures, characterized by one axis of symmetry (symmetry side) or structures having multiple axes of symmetry. Among such structures one could look for structurally efficient forms "adapted" to the prevailing conditions, where the shape has been optimized according to the applied loads [2].

Figure 1: Examples of symmetry found in the natural world. On the left: A butterfly characterized by an apparent symmetry side. *Source*: own; On the right: Dandelion characterized by the apparent central symmetry. *Source*: A. Nowak

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Today's digital tools used in an interdisciplinary design process are growing more important in the search for effective structures. The mapping of biological structures and the development of complex structural grids was made possible thanks to parametric design programs. The optimal forms of structural solutions may be sought through the use of programs calculating and analyzing building structures [3]. The following study attempts to seek the efficiency of grids and structural forms by comparing selected solids of revolution characterized by organic shapes as well as basic geometric solids.

The possibilities of modeling structural forms transformed in a topological way makes it easier to look for optimized shapes as an effective architectural solution, rational also in terms of a spatial design [4]. The emerging concepts in the design of modern architecture are often qualitatively new elements formed as a result of the synergy of design solutions. The comparative analysis of the morphology of forms shaped by topological transformation leads to the solution which of the classic rotary geometric solids are a structurally efficient structure while identifying the optimal classical structural grids.

2 Purpose and scope of the study

The research featured selected symmetric organic forms and some basic rotary geometric shapes. The morphology seen in the natural world has been selected based on biological structures, the shape of which can result from adapting to the prevailing conditions while being subjected to heavy loads such as the hydrostatic load. As a result, the following were chosen: the limestone structure of the regular Echinus sea urchins' skeleton of the class Echinoidea that appears in tidal areas (resistant to the strength of the waves), the skeleton of the siliceous sponge Euplectella aspergillum (Venus' flower basket) of the species Hexacitinellida found at depths of 35-5000 meters and finally a spider's web structure shaped with the influence of gravity loads (chain model).

Figure 2: Selected bionic morphology for the strength analysis.From left: Skeleton of regular sea urchin Echinus of the class Echinoidea. *Source*: A. Nowak;

Middle: The structure of a spider's web as a perfectly flexible, uniform and non-extensible chain hanging freely between two supports in a uniform gravitational field, which corresponds to the shape of the catenary. *Source*: "Zdjęcia.biz.pl-świat-poukładanych-world images," Image, cobweb, drops, 2010

[Access: 28.06.2016] <www.zdjecia_biz_pl / *Zdjęcie pajęczyna, Krople*_php>

Right: The skeleton of sponge Euplectella aspergillum species Hexacitinellida.

Source: "Phys.org" Sea sponge anchors are natural models of strength, 04.06.2015,

[Access: 06.28.2016] <http://phys.org/news/2015-04-sea-sponge-anchors-natural-strength.html>

The shape of the sea urchin's shell was described with an ellipse, and the spider's web with a catenary formula $f(x) = 2\cosh(x/2)$. The sponge skeleton was drawn using a spline curve. The sphere and the rotary paraboloid described with formula $f(x) = 0,5x^2$ were chosen as the basic morphology of solids of revolution.

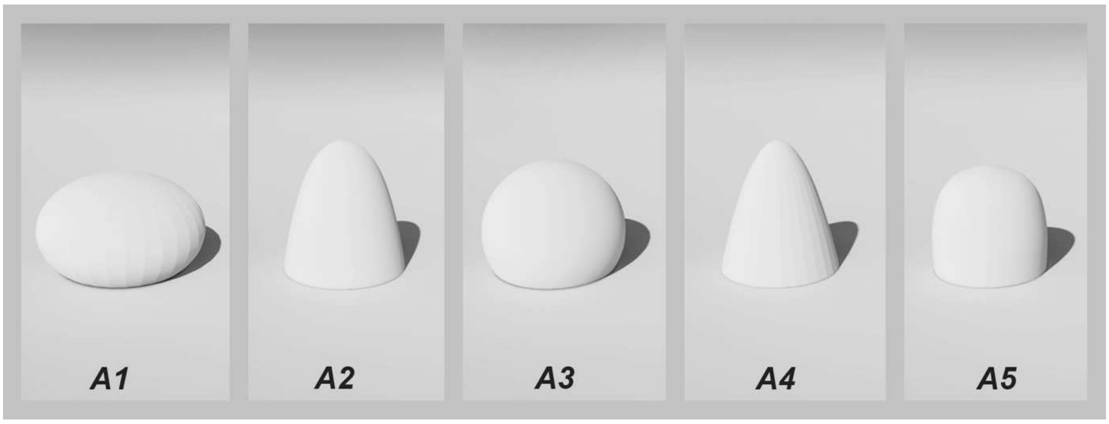

Figure 3: Researched morphologies ***A1*** – the skeleton of the sea urchin, ***A2*** – catenary, ***A3*** – sphere, ***A4*** – rotary paraboloid, ***A5*** – sponge skeleton. *Source*: A. Nowak

The subject of the study are symmetrical structural forms described on the basis of a 15m radius circle for a structural span equal to 30m. The study assumes a constant ratio of the curve length to the forming curve radius of a 2.4 base ratio, which allowed for obtaining comparable topological examples.

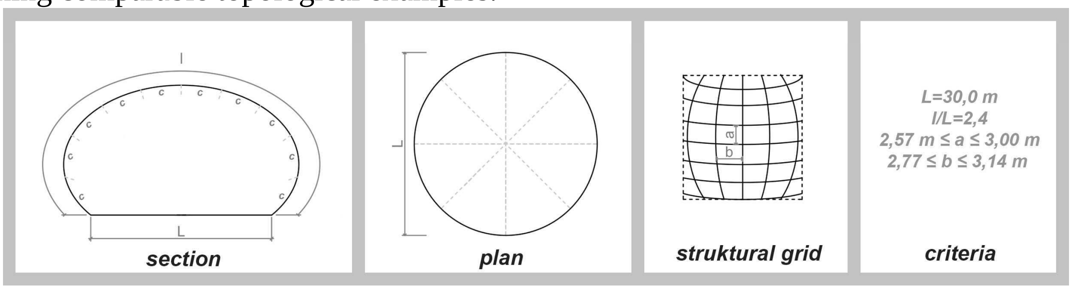

Figure 4: The assumptions in shaping the structural form. *Source*: A. Nowak

The search for morphological efficiency and structural grids was possible by changing the geometric divisions using topological transformations and identifying the impact of different types of loads on the structure. The objective of the analysis was a comparative analysis of selected bionic morphologies and basic bionic solids of revolution on the example of rod structures through optimizing superstructures due to the minimum weight.

3 Assumptions

The static scheme of the system is a spatial rod structure generated by the rotation of the path curve forming an axis perpendicular to the base, which is supported by pivot supports and loaded in the direction of the axis with a uniform load.

Basic homeomorphic assumptions have a fixed ratio of the length of the path curve forming the solid of rotation to the base (span) equal to 2.4.

The structural forms were compared on radial grids for the selected mesh size. The side formed by the equal division of the curve forming ranged at <2.570 m; 3,000 m> and the length of the longest of the possible opposite sides formed by the equal division of the circle that serves as base of the rotary body in the range at <2,772 m; 3,141 m> (Fig. 4).

The structure was loaded with dead weight in the endurance analyses, a load of glass panels equal to 0.50 kN / m^2 and a running load of 0,40 kN / m^2 (according to EN 1991-1-1) [5]. The load combinations were adopted in accordance with PN-EN 1990: 2004 and the permissible deformations according to PN-EN 1990: 2004. The dimensioning of steel profiles was made according to PN-EN 10210-2: 2000.

Circular cross section solid steel S235 profiles were used in the analysis for each of the structures. To obtain comparable results, the base elements were limited to the circular pipes, RO type PN-EN 10210-2: 2000.

Due to the minimum weight a quantitative criterion was assumed in the analysis. In the case of different lengths of a worn out rod, the net weight of the unit was used for comparison.

4 Presentation and analysis of results

The search for optimal morphology was based on a comparison of radial grids of all kinds of maximal mesh sizes according to the division of the path curve forming the solid of revolution and the circle described on the base separating them into equal sections.

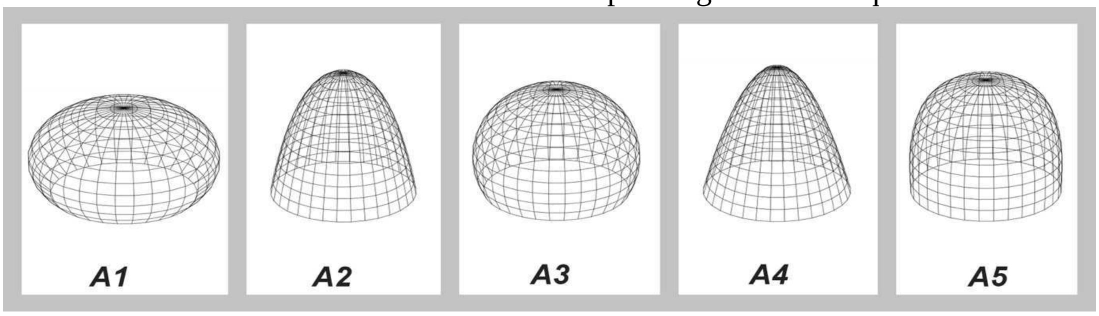

Figure 3: The structure of the radial grids. *Source*: A. Nowak

Analysis 1 aimed at comparing structural forms with the use of radial grids having 34 divisions of the base (meridians - vertical divisions) and 14 divisions of the path curve (parallels - horizontal divisions). As a result, the horizontal circles are within a 2.57 m distance and the maximum distance between the base of the meridians is 2.77 m.

Table 1: List of system parameters after optimization in Analysis 1

Example No.	Number of vertical divisions	Number of horizontal divisions	Profile [mm]	The total length of the rods [m]	Total weight [kg]	Unit weight [kg/m]
A1	34	14	127,0 × 3,2	2457,32	24008	9,77
A2	34	14	76,1 × 3,6	2145,40	13816	6,44
A3	34	14	76,1 × 3,2	2086,26	11996	5,75
A4	34	14	76,1 × 3,6	2096,10	13499	6,44
A5	34	14	101,6 × 2,0	2277,66	11183	4,91

Due to the minimum weight of the unit, the most effective structural form was the A5 form – a bionic structure formed according to the skeleton pattern of the Euplectella aspergillum sponge. The lightest rod arrangement in terms of the total weight of the structure is also A5. The heaviest structure both due to the mass per unit and the total weight is characterized by structure A1 - sea urchin. However, the longest total length of the rods was obtained in the A1 form, while the shortest in the A3 form.

Table 2: Summary of the distribution of structural grid system parameters in Analysis 1

Example No.	The number of vertical/ horizontal divisions	Area of mesh near base [m^2]	The length of the vertical division rods [m]	The length of the horizontal division rods [m]	The ratio of the vertical and horizontal division lengths	Length of the sides of the mesh near base (vertical, horizontal) [m]
A1	34/14	7,12	1224	1233,32	0,99	2,57 ; 2,77
A2	34/14	7,12	1224	920,4	1,32	2,57 ; 2,77
A3	34/14	7,12	1224	862,26	1,42	2,57 ; 2,77
A4	34/14	7,12	1224	872,1	1,40	2,57 ; 2,77
A5	34/14	7,12	1224	1053,66	1,16	2,57 ; 2,77

Analysis 2 aimed at comparing structural forms with the use of radial grids having 32 divisions of the base (meridians - vertical divisions) and 13 divisions of the path curve (parallels - horizontal divisions). As a result, the horizontal circles are within a 2.77 m distance and the maximum distance between the base of the meridians is 2.95 m.

Table 3: List of parameters in systems Analysis 2 after optimization

Example No.	Number of vertical divisions	Number of horizontal divisions	Profile [mm]	The total length of the rods [m]	Total weight [kg]	Unit weight [kg/m]
A1	32	13	$101,6 \times 5,0$	2299,52	27364	14,9
A2	32	13	$88,9 \times 3,2$	2011,52	13598	6,76
A3	32	13	$76,1 \times 3,2$	1952,96	11230	5,75
A4	32	13	$101,6 \times 3,2$	1959,04	15222	7,77
A5	32	13	$114,3 \times 2,0$	2131,84	11810	5,54

Due to the minimum weight of the unit, the most effective structural form was the A5 form - a bionic structure formed according to the skeleton pattern of the Euplectella aspergillum sponge. Next structures in terms of efficiency are the form A3 - sphere, then form A2 – catenary. The lightest system in terms of the total weight of the structure was A3 - sphere, while the heaviest structural form, both because of the total weight and the mass per unit was the bionic structure A1 – the sea urchin. The shortest total length of the rods was used in structure A3, and the biggest in the A1 structure.

Table 4: Summary of the distribution of structural grid system parameters in Analysis 2

Example No.	The number of vertical/ horizontal divisions	Area of mesh near base [m^2]	The length of the vertical division rods [m]	The length of the horizontal division rods [m]	The ratio of the vertical and horizontal division lengths	Length of the sides of the mesh near base (vertical, horizontal) [m]
A1	32/13	8,17	1152	1147,52	1,00	2,77 ; 2,95
A2	32/13	8,17	1152	859,52	1,34	2,77 ; 2,95
A3	32/13	8,17	1152	800,96	1,44	2,77 ; 2,95
A4	32/13	8,17	1152	807,04	1,43	2,77 ; 2,95
A5	32/13	8,17	1152	979,84	1,18	2,77 ; 2,95

Analysis 3 aimed at comparing the structural forms with the use of radial grids having 30 divisions on the base and 12 divisions of the path curve. As a result, the horizontal circles are within 3.00 m distance and the maximum distance between the base of the meridians is 3.14 m.

Table 5: List of parameters in systems Analysis 3 after optimization

Example No.	Number of vertical divisions	Number of horizontal divisions	Profile [mm]	The total length of the rods [m]	Total weight [kg]	Unit weight [kg/m]
A1	30	12	127,4 × 4,0	2227,2	26949	12,1
A2	30	12	88,9 × 3,2	1875,3	12677	6,76
A3	30	12	88,9 × 3,2	1820,4	14581	8,01
A4	30	12	88,9 × 3,2	1714,5	11590	6,76
A5	30	12	88,9 × 3,2	1987,5	13435	6,76

Due to the minimum weight of the unit, the most effective structural bionic forms were the A5 – sponge; the A2 - catenary and the geometrical form A4 - the paraboloid. The shortest and lightest system in terms of total weight was the A4 structure - the paraboloid of revolution, the heaviest and longest structure of them all was the form A1 - sea urchin.

Table 6: Summary of the distribution of structural grid system parameters in Analysis 3

Example No.	The number of vertical/ horizontal divisions	Area of mesh near base [m^2]	The length of the vertical division rods [m]	The length of the horizontal division rods [m]	The ratio of the vertical and horizontal division lengths	Length of the sides of the mesh near base (vertical, horizontal) [m]
A1	30/12	9,42	1080	1147,2	0,94	3,00 ; 3,14
A2	30/12	9,42	1080	795,3	1,36	3,00 ; 3,14
A3	30/12	9,42	1080	740,4	1,46	3,00 ; 3,14
A4	30/12	9,42	1080	634,5	1,70	3,00 ; 3,14
A5	30/12	9,42	1080	907,5	1,19	3,00 ; 3,14

The above results of the analyses have been collected and presented in Table 7 and 8, and ranked according to the minimal mass per unit and the minimal total weight criteria.

Table 7: Comparison of all analyzed examples according to the minimal unit weight criterion

Example No.	Number of vertical divisions	Number of horizontal divisions	Profile [mm]	The total length of the rods [m]	Total weight [kg]	Unit weight [kg/m]
A5	34	14	101,6 × 2,0	2277,66	11183	4,91
A5	32	13	114,3 × 2,0	2131,84	11810	5,54
A3	34	14	76,1 × 3,2	2086,26	11996	5,75
A3	32	13	76,1 × 3,2	1952,96	11230	5,75
A2	34	14	76,1 × 3,6	2145,40	13816	6,44
A4	34	14	76,1 × 3,6	2096,10	13499	6,44
A2	32	13	88,9 × 3,2	2011,52	13598	6,76
A2	30	12	88,9 × 3,2	1875,30	12677	6,76
A4	30	12	88,9 × 3,2	1714,50	11590	6,76
A5	30	12	88,9 × 3,2	1987,50	13435	6,76
A4	32	13	101,6 × 3,2	1959,04	15222	7,77
A3	30	12	88,9 × 3,2	1820,40	14581	8,01
A1	34	14	127,0 × 3,2	2457,32	24008	9,77
A1	30	12	127,4 × 4,0	2227,20	26949	12,1
A1	32	13	101,6 × 5,0	2299,52	27364	14,9

The results of analysis indicate the efficiency in terms of mass per unit of most bionic structural forms (A2, A5) compared to the corresponding geometric examples. The differences are visible only in the case of sphere based forms (basic geometric) and the ellipsoid (bionic), where the A3 form exhibits the greatest efficiency. The lightest system in terms of weight per unit structures is A5 - the sponge skeleton.

The efficiency in design in terms of weight for the analyzed morphology was determined on the basis of the average weight for a given form parameter.

Table 8: Comparison of all analyzed examples according to the minimal mass per unit criterion for a given morphology ranked in order of structural design efficiency

Example No.	Number of vertical divisions	Number of horizontal divisions	Profile [mm]	The total length of the rods [m]	Total weight [kg]	Unit weight [kg/m]	The average unit weight [kg/m]
A5 	34	14	101,6 × 2,0	2277,66	11183	4,91	5,74
	32	13	114,3 × 2,0	2131,84	11810	5,54	
	30	12	88,9 × 3,2	1987,50	13435	6,76	
A3 	34	14	76,1 × 3,2	2086,26	11996	5,75	6,50
	32	13	76,1 × 3,2	1952,96	11230	5,75	
	30	12	88,9 × 3,2	1820,40	14581	8,01	
A2 	34	14	76,1 × 3,6	2145,40	13816	6,44	6,65
	32	13	88,9 × 3,2	2011,52	13598	6,76	
	30	12	88,9 × 3,2	1875,30	12677	6,76	
A4 	34	14	76,1 × 3,6	2096,10	13499	6,44	6,99
	30	12	88,9 × 3,2	1714,50	11590	6,76	
	32	13	101,6 × 3,2	1959,04	15222	7,77	
A1 	34	14	127,0 × 3,2	2457,32	24008	9,77	12,26
	30	12	127,4 × 4,0	2227,20	26949	12,10	
	32	13	101,6 × 5,0	2299,52	27364	14,90	

Due to the minimal weight in each of the selected morphologies, the design efficiency was achieved in the densest of divisions i.e. 34 by 14, therefore assuming a maximum mesh of 2.57 to 2.77 meters. Among the selected morphologies, the lightest structure in mass per unit was obtained in the A5 bionic form, replicating the shape of the skeleton foam. Another structure exhibiting a high efficiency due to the minimum weight per unit was the basic geometrical A3 form, or the sphere. A similar result was obtained when analyzing the bionic structure of the A2, formed on the basis of the catenary curve, which exhibits greater efficiency than the corresponding basic geometric shape of the A4 paraboloid of rotation.

Due to the minimal mass per unit, the structural forms were also compared as shown in Table 9.

Table 9: Comparison of all analyzed examples according to the minimal unit weight criterion

Example No.	Number of vertical divisions	Number of horizontal divisions	Profile [mm]	The total length of the rods [m]	Total weight [kg]	Unit weight [kg/m]
A5	34	14	101,6 × 2,0	2277,66	11183	4,91
A3	32	13	76,1 × 3,2	1952,96	11230	5,75
A4	30	12	88,9 × 3,2	1714,50	11590	6,76
A5	32	13	114,3 × 2,0	2131,84	11810	5,54
A3	34	14	76,1 × 3,2	2086,26	11996	5,75
A2	30	12	88,9 × 3,2	1875,30	12677	6,76
A5	30	12	88,9 × 3,2	1987,50	13435	6,76
A4	34	14	76,1 × 3,6	2096,10	13499	6,44
A2	32	13	88,9 × 3,2	2011,52	13598	6,76
A2	34	14	76,1 × 3,6	2145,40	13816	6,44
A3	30	12	88,9 × 3,2	1820,40	14581	8,01
A4	32	13	101,6 × 3,2	1959,04	15222	7,77
A1	34	14	127,0 × 3,2	2457,32	24008	9,77
A1	30	12	127,4 × 4,0	2227,20	26949	12,1
A1	32	13	101,6 × 5,0	2299,52	27364	14,9

The analysis results are slightly different from those in Table 7, showing the list of all the analyzed structural forms according to the criterion of minimum mass per unit. A5 was the lightest structure due to the 34 grid breakdown segments around the base and 14 divisions on the path curve, as described in Table 7. The next structure is the A3 form – the sphere, with 32 by 13 breakdown segments; whereas the A4 structure – the paraboloid of revolution with 30 by 12 breakdown segments. The differences in the various combinations result from the total length of the bar structures. Therefore, the mass per unit seems a more objective parameter for comparing the shape data.

The design efficiency in terms of each of the analyzed morphological weights was also analyzed against the average total weight parameter for a given form, as shown in Table 10.

Table 10: Comparison of all analyzed examples according to the minimal mass per unit criterion for the morphological data, ranked in order of structural design efficiency

Example No.	Number of vertical divisions	Number of horizontal divisions	Profile [mm]	The total length of the rods [m]	Total weight [kg]	Unit weight [kg/m]	The average total weight [kg/m]
A5 	34	14	101,6 × 2,0	2277,66	11183	4,91	12142,67
	32	13	114,3 × 2,0	2131,84	11810	5,54	
	30	12	88,9 × 3,2	1987,50	13435	6,76	
A3 	32	13	76,1 × 3,2	1952,96	11230	5,75	12602,33
	34	14	76,1× 3,2	2086,26	11996	5,75	
	30	12	88,9 × 3,2	1820,40	14581	8,01	
A2 	30	12	88,9 × 3,2	1875,30	12677	6,76	13363,67
	32	13	88,9 × 3,2	2011,52	13598	6,76	
	34	14	76,1 × 3,6	2145,40	13816	6,44	
A4 	30	12	88,9 × 3,2	1714,50	11590	6,76	13437,00
	34	14	76,1 × 3,6	2096,10	13499	6,44	
	32	13	101,6 × 3,2	1959,04	15222	7,77	
A1 	34	14	127,0 × 3,2	2457,32	24008	9,77	26107,00
	30	12	127,4 × 4,0	2227,20	26949	12,10	
	32	13	101,6 × 5,0	2299,52	27364	14,90	

The results listed in both Table 8 and Table 10 illustrate the comparable effectiveness in construction performance of the researched morphologies. In both cases, the most effective form was the skeleton of a sponge, then sphere, catenary, paraboloid of revolution and the structure of sea urchin.

5 Summary and conclusions

The comparative analysis of the morphology of forms shaped according to the topological transformations enabled the unambiguous determination that the classic revolving geometric solids and the bionics represent structurally efficient designs in the selected radial grids. The most effective structural mapping form among the analyzed examples was the A5 structure – the sponge skeleton. However, the results for optimal bionic forms cannot be transferred to all structures of organic origin.

The most effective analyzed structural radial mesh with the minimal mass per unit was a mesh with 34 vertical divisions (on the circumference of the body base) and 14 horizontal divisions (on the path curve). Due to the minimal total weight among the analyzed examples, the results are not the same for all examined structural forms. Due to the minimal total weight, forms A5 (sponge skeleton) and A1 (skeleton of sea urchin) show effectiveness in construction with the radial divisions 34 by 14, while in the morphology of the A3 (sphere), A2 (catenary) and A4 (paraboloid of revolution) the efficiency is visible in the case of 30 vertical divisions by 12 horizontal radial grids. In addition, the change in grid density affects the efficiency of the structural design in terms of minimum mass. The most efficient structures in terms of the minimum mass per unit, however, were neither the shortest, nor the longest structures.

The skeleton of the sponge always turned out to be the lightest structure in terms of the minimal mass per unit and the total weight regardless of the used structural mesh. Among the bionic forms, the catenary based form proved also noteworthy as it showed greater efficiency than the rotational paraboloid. The analysis of results in the search for a structural bionic efficiency forms in inconclusive, hence the need for further research and exploration in the field of network optimization, including bionics. The introduction of climatic loads in order to fully optimize the verification of structural forms in the natural world is a necessary move.

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ANALIZA PORÓWNAWCZA GEOMETRYCZNYCH I BIONICZNYCH FORM STRUKTURALNYCH

We współczesnej architekturze widoczny jest wzrost znaczenia bioniki jako źródła inspiracji w kształtowaniu nietypowych form strukturalnych. Powodem takich działań jest zarówno poszukiwanie nowych rozwiązań plastycznych, jak również doskonalenie rozwiązań inżynierskich. Próba odwzorowania morfologii organizmów żywych we współdziałaniu architektoniczno-konstrukcyjnym może prowadzić do optymalnych rozwiązań strukturalnych, łączących estetykę z ekspresją techniczną i konsekwentną logiką statyczną. Jednocześnie dzięki doskonaleniu cyfrowych narzędzi projektowych możliwa jest analiza rozwiązań technicznych na wielu płaszczyznach inżynierii budowlanej. Poszukiwania efektywności from strukturalnych omówione w artykule stanowią dyskusję nad optymalizacją struktur nośnych w zakresie morfologii bionicznych i geometrycznych. Rozwój współczesnych technologii umożliwia poszerzenie zakresu badawczego, w tym o dodatkowe analizy poświęcone współdziałaniu poszczególnych dziedzin techniki związanych z kształtowaniem architektury.