Minimising the material consumption in bionic and geometric structural forms

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Abstract. Interdisciplinary design in an important process is influencing the shaping of the architecture. In contemporary architectural design, the integration of the form and load-bearing structure is becoming more and more important. The integrated design process enables verification and selection of solutions that are more advantageous in relation to the given criteria. As a result, it is also possible to search for the model solutions in an attempt to optimize the architectural-construction as an important element of the interdisciplinary design process. Synergic methods of architectural design, enabling the creation of more effective systems, are of particular significance. The combination of the architectural and structural analyses is increasingly visible, especially in the research projects, where the form of the object is created in a synergic way, taking into account other parameters such as the properties of the materials used. The search for possibilities of shaping optimal and sustainable structures led to the creation of analogies to the living organisms, as exemplified by the bionic architecture. Architects are interested in methods of surface discretization, which can influence not only the aesthetic perception of the object, but also the material efficiency of the load-bearing structure. As a result of such a design, the search for synergistic solutions that meet both aesthetic and endurance criteria is pursued. The minimization of the material consumption by means of interdisciplinary analyses is part of the sustainable architecture trend, which respects the environment and its resources. The article presents the model research, based on the analysis of the structural forms with homeomorphic assumptions, which corresponds to homologous transformations among structures of common evolutionary origin. In analytical research on the selected models, computer-aided design methods were used to minimize the material consumption.

1. Introduction
Interdisciplinary design in an important process is influencing the shaping of the architecture. In contemporary architectural design, the integration of form and load-bearing structure is becoming more and more important. The integrated design process enables verification and selection of solutions that are more advantageous in relation to the given criteria. As a result, it is also possible to search for model solutions in an attempt to optimize the architectural-construction as an important element of the interdisciplinary design process. Synergic methods of architectural design, enabling the creation of more effective systems, are of particular significance. The combination of architectural and structural analyses is increasingly visible, especially in research projects, where the form of the object is created in a synergic way, taking into account other parameters such as the properties of the
The search for possibilities of shaping optimal and sustainable structures led to the creation of analogies to living organisms, as exemplified by bionic architecture. Architects are interested in methods of surface discretization, which can influence not only the aesthetic perception of the object, but also the material efficiency of the load-bearing structure. As a result of such a design, the search for synergistic solutions that meet both aesthetic and endurance criteria is pursued. The minimization of material consumption by means of interdisciplinary analyses is part of the sustainable architecture trend, which respects the environment and its resources.

2. Assumptions applied for model research
Models of structural forms based on bionic and geometric patterns were adopted in the research. Bionic forms respond to the patterns observed in nature, which are affected by hydrostatic loads, wave impacts or gravitational loads. As a result, the structures of organisms living on the seabed, in the tidal zone and shaped taking into account gravitational loads, which are characterized by apparent multi-axial symmetry, were adopted as models. Selected biological models, i.e. the structure of spider net, egg shell (gravitational loads), Euplectella Aspergillum sponge of the species Hexactinellida (hydrostatic loads) and the structure of the skeleton of regular sea urchins Echinus of the Echinoidea class (tidal zone) were described using mathematical models with catenary curve
\[ f(x) = 2\cosh \left( \frac{x}{2} \right), \]
an elongated ellipsoid located along the longer axis, the Spline curve, an elongated ellipsoid located along the shorter axis. Organic shapes were transferred with a copy of irregular shapes with an accuracy of 1 millimetre. The skeleton of the sponge, due to the lack of access to the original, was reproduced to the digital model with the use of a photo.

For selected bionic models their geometric equivalents were selected, i.e. paraboloid \( f(x)=0.5x^2 \), elongated ellipsoid of similar proportions, Spline curve and sphere. The following pairs of structural forms I form B1 (spider web - catenary curve) and G1 (paraboloid described by the formula \( f(x)=0.5x^2 \)), II is form B2 (egg shell - elongated ellipsoid) and G2 (elongated ellipsoid of different proportions), pairs III are formed by form B3 and G3 (sponge skeleton - Spline curve) and pair IV is a form B4 (urchin skeleton transferred by elongated ellipsoid) and a form G4 (sphere) as cooperative were chosen.

The subject of the research is symmetrical, rod structural forms, formed by the rotation of a curve forming around an axis perpendicular to the base with the application of topological transformations. In order to enable comparison of forms of different shapes, a homeomorphic parameter was introduced, corresponding to homologous transformations observed among structures of common evolutionary origin. The homeomorphic parameter was adopted as a ratio of the length of the curve forming the base equal to 2.4, on the basis of proportions observed in the frame of the sea urchin. Structural forms are rotating solids with a span of 30 meters based on articulated supports. The structural grid was formed by the use of two different algorithms enabling the creation of a radial grid with 34 divisions of the base and 14 divisions of the curve forming into equal segments and angular divisions. The structures are made of S235 steel from RO 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 catalogue. 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/m² and the service load equal to 0.40 kN/m². 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 analyses 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];
The assumed structural forms with the markings are presented below (figure 1).

![Figure 1. The assumed structural forms](image)

### 3. Model studies of selected structural forms

The studies were carried out for two selected algorithms of radial grid shaping, taking into account structures shaped from one type of rod or with the division of them into groups of rods according to geometric and structural criteria. Each structure was divided into 28 groups of rods, taking into account the effort of rods and tensile and compressive stresses resulting from the geometry of the adopted forms. An algorithm optimizing the bars with regard to minimum weight was used. As a result, a different number of profiles matched to the particular structures was obtained, falling within the range of 10-19 profile groups. The comparison of profile groups for particular grids is presented in Table 1.

| Type of grid division | B1 | B2 | B3 | B4 | G1 | G2 | G3 | G4 |
|-----------------------|----|----|----|----|----|----|----|----|
| 34/14                 | 18 | 17 | 18 | 16 | 16 | 17 | 16 | 15 |
| 34/14 α               | 13 | 12 | 10 | 19 | 13 | 12 | 11 | 13 |

#### 3.1. Material optimization analysis of bionic and geometric structural forms on the example of a radial grid with equal divisions of the forming curve

The analysis concerns the comparison of the effectiveness of structural forms with the same divisions of the structural grid 34/14 with the same cross-section of the bar for the whole structure and with the division into groups of bars. The analysis was carried out in order to determine the effect of changes in member cross-sections depending on the effort and stresses on the material efficiency of individual structures. The results for particular structural forms were compared due to Mc, Mj and Mp parameters.

The relation between the influence of the division into groups of rods and the efficiency of individual forms due to the Mc parameter, which describes the total mass of structures, is presented in the diagram below (figure 2).
Figure 2. Influence of the application of division into groups of rods on $M_c$ parameter for particular structural forms with divisions 34/14

As a result of material optimization, the $M_c$ value decrease from 32% to 46% was observed. The highest percentage decrease of $M_c$ parameter was observed for B4 structure. The lowest percentage optimization by division into groups of rods was obtained for B2 form.

The relation between the influence of the division into groups of rods and the efficiency of individual forms due to the $M_j$ parameter, which describes the mass per unit length of structures, is presented in the following diagram (figure 3).

Figure 3. Influence of the implementation of the division into groups of rods on the parameter $M_j$ for individual structural forms with divisions 34/14

As a result of optimization, the value of the parameter $M_j$ decreased from 32% to 46%. The highest percentage decrease of $M_j$ parameter was observed for B4 structure. The lowest percentage optimization by division into groups of members was obtained for B2 form.

The relation between the influence of the division into groups of rods and the efficiency of individual forms due to the $M_p$ parameter, describing the mass of structures per unit area of an envelope, is presented in the following diagram (figure 4).
Figure 4. Influence of the implementation of the division into groups of rods on the parameter \( M_p \) for particular structural forms with divisions 34/14

Similarly as for other parameters, as a result of optimization, the value of the \( M_p \) parameter decreased from 32% to 46%. The highest percentage decrease of \( M_p \) parameter was observed for B4 structure. The lowest percentage optimization by division into groups of members was obtained for B2 form.

3.2. Material optimization analysis of bionic and geometric structural forms on the example of a radial grid with equal angular divisions.

The analysis concerns the comparison of the effectiveness of structural forms with the same divisions of the structural grid 34/14 \( \alpha \) with the same cross-section of the bar for the whole structure and with the division into groups of bars. The analysis was carried out in order to determine the effect of changes in member cross-sections depending on the effort and stresses on the material efficiency of individual structures. The structural forms were compared with respect to particular parameters \( M_c \), \( M_j \) and \( M_p \). The relation between the influence of the division into groups of members and the efficiency of individual forms due to the \( M_c \) parameter, describing the total mass of structures, is presented in the diagram below (figure 5).

Figure 5. Influence of the implementation of the division into groups of rods on the \( M_c \) parameter for particular structural forms with divisions 34/14 \( \alpha \)

As a result of material optimization, the \( M_c \) value decreased from 25% to 48%. The highest percentage decrease of \( M_c \) parameter was observed for B4 structure. The lowest percentage optimization by division into groups of rods was obtained for B3, B2, G3 forms.
The relation between the influence of the division into groups of rods and the efficiency of individual forms due to the $M_j$ parameter, which describes the mass per unit length of structures, is presented in the following diagram (figure 6).

**Figure 6.** Influence of the implementation of the division into groups of rods on the parameter $M_j$ for individual structural forms with divisions 34/14.

As a result of optimization, the value of the parameter $M_j$ decreased from 25% to 48%. The highest percentage decrease of $M_j$ parameter was observed for B4 structure. The lowest percentage optimization by division into groups of members was obtained for forms B2, B3 and G3.

The relation between the influence of the division into groups of rods and the efficiency of individual forms due to the $M_p$ parameter, describing the mass of structures per unit area of an envelope, is presented in the diagram below (figure 7).

**Figure 7.** Influence of the implementation of the division into groups of rods on the parameter $M_p$ for particular structural forms with divisions 34/14.

Similarly to other parameters, as a result of optimization, the value of the $M_p$ parameter decreased from 25% to 48%. The highest percentage decrease of $M_p$ parameter was observed for B4 structure. The lowest percentage optimization by division into groups of members was obtained for forms B2, B3, G3.

3.3. Comparative analysis of the effectiveness of selected structural grids of bionic and geometric structural forms

The analysis concerns the comparison of the efficiency of structured grids with two algorithms of shaping, i.e. with the division of the forming curve into equal segments and equal to the radius division. The results of analyses for structures with the same cross-section of the bar for the whole
structure and with division into groups of bars were assumed in the study. The analysis was carried out in order to determine the effect of changes in member cross-sections depending on the effort and stresses on the material efficiency of individual structural grids, taking into account the variable shape of the structural forms studied.

The relation between the influence of the change of structural grid divisions with the same cross-section of members on the efficiency of individual forms due to the $M_c$ parameter, describing the total mass of structures, is presented in the diagram below (figure 8).

**Figure 8.** Influence of the change in the division of structural grids with the same cross-section of rods on the $M_c$ parameter for particular structural forms

For most of the forms, the radial grid 34/14 $\alpha$ with equal angular divisions turned out to be more advantageous. The exception is the B4 form, for which a lower total mass was obtained for the radial grid 34/14 with equal divisions of the forming curve. The most positive results were obtained for geometric form G1 and the worst for form B4.

The relation between the influences of the change of structural grid divisions by groups of rods on the efficiency of individual forms due to the $M_c$ parameter, describing the total mass of structures, is presented in the diagram below (figure 9).

**Figure 9.** Influence of the change in the division of structural grids into groups of rods on the $M_c$ parameter for particular structural forms

After the material optimization, based on the division into groups of rods, different results were obtained due to the $M_c$ parameter. As a result, the 34/14 grid with equal divisions of the forming curve for all analysed structures turned out to be the most advantageous structural grid due to the $M_c$.
The parameter. The lowest value of $M_c$ parameter was observed for geometric form G1 and the highest for form B4. The $M_c$ parameter depends on the length of the structural grid, which does not allow for a clear determination of the effectiveness of the adopted structural forms. It is necessary to determine the effect of the relation between the length of the structural grid and the total weight of the structure and define the parameter $M_j$, describing the unit weight of the structure, which enables comparison of structural grids of different lengths.

The relation between the influence of the change of structural grid divisions with the same cross-section of rods on the effectiveness of individual forms due to the $M_j$ parameter, describing mass per unit length of structural grid, is presented in the following diagram (figure 10).

| Structural forms | Bionic forms radial grid 34/14 with the same rods | Geometric forms radial grid 34/14 with the same rods |
|------------------|---------------------------------------------------|--------------------------------------------------|
| B1               | ![Graph](image1.png)                              | ![Graph](image2.png)                              |
| B2               | ![Graph](image1.png)                              | ![Graph](image2.png)                              |
| B3               | ![Graph](image1.png)                              | ![Graph](image2.png)                              |
| B4               | ![Graph](image1.png)                              | ![Graph](image2.png)                              |
| G1               | ![Graph](image1.png)                              | ![Graph](image2.png)                              |
| G2               | ![Graph](image1.png)                              | ![Graph](image2.png)                              |
| G3               | ![Graph](image1.png)                              | ![Graph](image2.png)                              |
| G4               | ![Graph](image1.png)                              | ![Graph](image2.png)                              |

**Figure 10.** Influence of the change in the division of structural grids with the same cross-section of rods on the parameter $M_j$ for particular structural forms

More effective results due to the $M_j$ parameter were observed for the radial grid with equal angular divisions for most structures. As in the case of the $M_c$ parameter, the exception is the B4 form. The best equal result were obtained for forms B1, G1, B3, B2, G3 and G2, while the worst result were obtained for form B4.

The relation between the influences of the change of structural grid divisions by groups of rods on the efficiency of individual forms due to the $M_j$ parameter, describing mass per unit length of structural grid, is presented in the following diagram (figure 11).
Figure 11. Influence of the change in the division of structural grids into groups of rods on the parameter \( M_j \) for particular structural forms

For most of the structures, the structural grid with equal divisions of the forming curve turned out to be more advantageous. The exceptions are G3 and G4 structures, for which the lower value of the \( M_j \) parameter was observed for a radial grid with equal angular divisions. Due to different rods profiles selected as a result of optimization within one structure, no identical results were obtained as in the case of a grid with the same rods cross-section.

The parameter \( M_j \) as a ratio of total mass and the total length of the members characterizes the efficiency of a given grid for individual structural forms, not the shape. In order to further, but approximate analysis of the effectiveness of individual forms, it is possible to input the \( M_p \) parameter, which represents the relation between the structure mass and the surface of the envelope. The relation between the influences of the change of structural grid divisions with the same cross-section of bars on the effectiveness of individual forms due to the \( M_p \) parameter, describing the mass per unit area of an envelope, is presented in the diagram below (figure 12).

Figure 12. Influence of the change in the division of structural grids with the same cross-section of rods on the \( M_p \) parameter for particular structural forms

The most effective result due to the \( M_p \) parameter was obtained for the majority of structures with a radial grid of equal angular divisions. Similarly as in other cases, the exception is forma B4. The lowest value of \( M_p \) parameter was obtained for structure B3, the highest for form B4.
The relation between the influences of the change of structural grid divisions by groups of rods on the effectiveness of individual forms due to the $M_p$ parameter describing the mass per unit area of an envelope is presented in the diagram below (figure 13).

![Figure 13](image)

**Figure 13.** Influence of the change in the division of structural grids into groups of rods on the $M_p$ parameter for particular structural forms

The most advantageous was the radial grid 34/14 with equal divisions of the forming curve. In the case of B4 structure, the same result was obtained for both types of grid division. The lowest value of $M_p$ parameter was obtained for B3 and G2 forms, while the highest value for B4 structure.

The $M_p$ parameter approximates the evaluation of the effectiveness of structural forms, because the relations between the proportions of individual forms and their mass are visible.

### 4. Conclusions

The results of the analyses emphasize the need for interdisciplinary analyses in the scope of searching for the effectiveness of structural forms in accordance with the idea of sustainable development. These analyses should be carried out with the participation of an engineer and an architect in order to combine aesthetic and structural criteria. As a result of the analyses, the observed variable efficiency depending on the adopted essential and assembly criteria, i.e. the same bar for the whole structure or the division into groups of bars. More favourable results were obtained for grids, in which bar cross-sections were selected depending on their stresses and position in the structure. [2] As a result, more complex structures were also obtained in the construction process, requiring the individual design of the connections in nodes in particular zones.

In the case of material optimization based on the division of the members into the groups depending on the stresses and stresses, a percentage decrease of values was obtained for all analysed parameters. Depending on the assumed structural form, the different effects of the material optimization were obtained. The most advantageous percentage effect of the adopted optimization solutions among all analysed structures was obtained for the B4 bionic form. In the case of geometric forms, the greatest impact of the adopted optimization method was obtained for the G4 form. In the case of geometric forms, similar results were obtained for the percentage decrease of $M_c$, $M_j$ and $M_p$ parameters for particular structures.

The method applied assumed a significant decrease in mass and the further optimization can be carried out when searching for rods of the variable cross-section along the length of the rod on the pattern of structures observed in the nature. [3]
References

[1] A. Nowak, “Shaping bionic structural surfaces in the architecture of contemporary elevations”, PhD thesis at the Faculty of Architecture, Warsaw University of Technology, 2017.

[2] A. Nowak, “Morphology in Modern Architecture - Model Research in Structural Forms”, Dean's Grant for young scientists and participants of PhD studies at the Faculty of Architecture of the Warsaw University of Technology, 2017.

[3] A. Nowak, “Model analyses of selected structural forms”, work done as part of the statutory activity of the Faculty of Architecture of the Warsaw University of Technology, 2018.