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Research paper

Parametric evaluation as a tool for evaluating shell geodesic domes. Modelling the Fuller Dome with ReSa mobile recreational facility panels.

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Abstract: Mobile structures are one of directions of shaping recreational facilities. In terms of their geometry, geodesic domes and quasi-dome systems deserve special attention. Panel shell domes were the subject of consideration, e.g. Buckminster Fuller and David Geiger, whose patent solutions are referred to in the article. Combining a system of layered self-supporting panels with the geometry of geodesic domes was one of the significant construction and material challenges as part of the ReSa research and the respective implementation project carried out at the Wroclaw University of Technology in 2021–2023 as part of a competition organized by The National Center of Research and Development. Concerning the preliminary analysis, it was necessary to determine the types of dome solutions intended for the implementation of research models. The article presents a detailed analysis of shell geodesic domes with different geometries. The differentiation resulted from the type and the rotation of the base polyhedron relative to the base plane. The main objective of the study was to rank the types of panel geodesic domes in relation to their use in the construction of mobile recreational facilities. The development of 12 virtual dome models made it possible to evaluate their parameters in five main research areas – energy efficiency, environmental impact, support reactions, ergonomics and complexity of prefabrication and assembly process. An extensive evaluation of the parameters in each field, a summary within each domain, and a global evaluation of the shells were performed. The study allowed to develop a hierarchy of panel dome types in relation to the assumed criteria and to check the possibility of using multi-aspect, parametric evaluation. In addition, a detailed study of the geometrical parameters of the shells carried out as part of the indirect tests made it possible to identify the most effective structures in this aspect. This study has proven that parametric evaluation of criteria is a good tool for evaluating shell geodesic domes. This method is developing both in the field of scientific research and in terms of the implementation of domes. It allows for flexible introduction of basic data (here: energy efficiency, environmental impact, support reactions, ergonomics and complexity of prefabrication and assembly process), determination of coefficients and the use of additional weight criteria for individual research fields in relation to the assumed goal.

Keywords: geodesic shell structure, Buckminster Fuller‘s dome, self-supporting sandwich panels

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1. Introduction

1.1. Shell dome analysis background

Optimization of material consumption and the possibility of easy self-assembly make geodesic domes popular architectural forms of recreational facilities. These are usually bar structures, where in the case of their use in a moderate climate, the key features are thermal insulation, elimination of thermal bridges, maintaining the tightness of the coating and load capacity of the structure. Currently, the most popular domes are made of a frame structure (steel or wooden) and are covered with PVC foils of varying degrees of translucency and fabric (impregnated cotton). Tent structures of this type, however, cause a greenhouse effect in the summer season (the need to cool the internal air) and significant heat losses through penetration in the winter season due to the low thermal insulation of the cover and low thermal inertia of the entire facility. In order to ensure optimal thermal conditions for the spherical tent, internal air exchange systems with the option of heating and cooling are used, as well as solid-burning stoves are installed inside the facilities. Objects of this type usually do not have a supply and exhaust ventilation system, which causes condensation of water vapor on the inner surfaces of the coating in the winter season.

The first building in the shape of a geodesic dome was designed by Walther Bauersfeld, and the idea and nomenclature of domes were developed in many aspects by Richard B. Fuller [1]. One of the flagship examples of architecture shaped in a concentric system, which is the beginning of the use of geodesic dome structures in residential design, is Dymaxion House (designed by R.B. Fuller) [2]. The main assumption of R. Fuller was to create a housing unit intended for mass production, which would also be completely autonomous in terms of energy. Initially, the unit was shaped on a hexagonal plan and then a circle to minimize the heat losses of the building. The solution to the problem of maintaining the proper insulation of external partitions, high thermal inertia, and ensuring tightness while consequently ascertaining quick

Fig. 1. Panel shell mock-up in geodesic dome (Fuller's dome) geometry completed as part of the ReSa project (Author's photo)

assembly of the facility is to create the dome in the form of a shell of prefabricated panels. The implementation of three-layer panels made of two layers of thin concrete reinforced with glass fiber (GRC) and an internal filling of the insulating material results in a change from a skeletal structure to a shell structure. As prof. W. Bober noted: "the use of thin GRC concrete slabs in the load bearing layers allows working with metal edges around the entire perimeter of the panel" [3]. The construction of a research model in the form of a dome made of panels of a size and weight that enables its road transport and a specific assembly system (as well as disassembly and reuse) became the subject of research and development works carried out under the NCBR ReSa project (Fig. 1). It is worth to repeat – especially in aesthetic comparison between lightweight Fuller dome structures and those made of GRC – dr A. Tofiluk quotation: "prefabricated architecture is everyday architecture, not particularly aesthetically sophisticated and not luxurious, but it has the potential to provide acceptable working, living [. . .] conditions to a relatively large number of users" [4].

1.2. Research assumptions of the NCBiR ReSa project

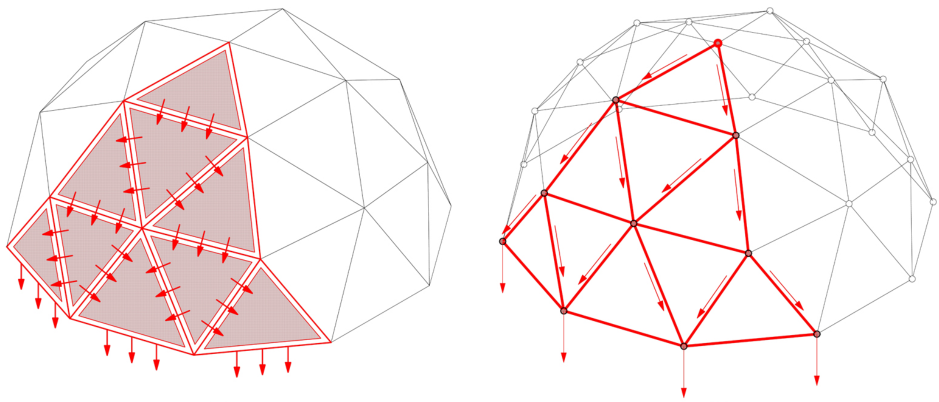
The main topic of the ReSa project, which received funding from the National Center for Research and Development in 2021–2023, was the development of an innovative structural and architectural panel system for the ReSa mobile recreational facility. The word ReSa is an acronym for the words "recreational structure" and refers directly to the temporary use of the designed mobile unit in tourist areas. The assumption of the project was to develop an original, experimental method of designing mobile units using layered panel elements covered with GRC concrete pressed plates in a geodesic dome arrangement. The innovativeness of the solution is related to the way the panels are shaped in the context of building physics and connections into new geometric forms. The development of the mobile unit was based on the key novelties of the project result: environmental protection by reducing CO_2 emissions, saving energy needed to heat the building due to losses through heat transfer through partitions, obtaining high tightness of the building n50 [1/h] and reducing the compactness parameter.

This article analyzes domes that are popular as part of skeletal systems and can be installed in recreational facilities made of self-supporting panels. The aim of the study was to indicate the optimal type and location of the polyhedron to indicate the most effective type of dome. The test was divided into 4 parts: geometry test, structure mass test and ground reaction forces test, thermal insulation and carbon footprint test, and architectural and ergonomic tests. Chapter 2 presents the collected data and methods of obtaining and evaluating them. Chapter 3 indicates and discusses the results of research on each of the four mentioned aspects. Chapters 4 and 5 summarizes results of the study with weights and conclusions.

2. Materials, methods and study area

The research methodology was based on a comparative analysis of 5 types of domes in 12 variants. Geometric data was obtained by developing virtual 3D models of the domes. Each of the 12 models was tested in terms of its geometrical parameters and structure weight, energy efficiency and environmental impact, architectural parameters and complexity of prefabrication and assembly process. Aggregated data has been compiled in each of the sections (Chapters 2.1–2.4) and summarized in its entirety in the conclusions section. In the study, proprietary performance indicators were developed so as to clearly indicate the most effective variant of the dome made of panels. The metrics in the global summary (Chapter 4) have been converted to point values and summed to produce a hierarchical list of shells. During the evaluation, the weights of the criteria, the meaning of which was described in the discussion, were omitted.

The subject of the study were geodesic domes built of panels, which (unlike skeletal domes) work as a shell (Fig. 2a, b). The principle of the structure operation in this case is the edge transfer of loads within the shell, contrary to the linear one – to bars and nodes – as in the case of bar structures. The triangle of forces is closed within each panel of the shell and at the same time the planes of the panels are pulled together, which is not the case in the bar structure method, whereby the shell of the dome does not carry any loads.



(a) (b)

Fig. 2. The difference in the distribution of forces in the shell dome made of panels (a) and the skeletal dome (b) made of bars and nodes (Author's elaboration)

2.1. Geometrical studies

Three basic types of regular polyhedra were used in the study: regular octahedron (½), regular dodecahedron and regular icosahedron. The edges of the polyhedrons were projected onto the plane of the outer sphere with the assumption of a single division of their edges. The base polyhedra were rotated in three segments (A, B and C) to indicate differences and determine their optimal location relative to the projection. The rotation consisted in placing the edge of the polyhedron (index 1), its face (index 2) or its corner (index 3) in the upper zone. As a result, three models were obtained for a regular icosahedron geodesic dome (A1, A2 and A3), three models for a regular dodecahedron geodesic dome (B1, B2 and B3), and three models for a truncated icosahedron geodesic dome (C1, C2 and C3), respectively. The subject of the study was supplemented with two models for a geodesic dome made of a half of a regular octahedron (D1 and D2) and a part of a regular icosahedron (E1) (Fig. 3).

Minimizing the expected number of different types of panels, it was decided for the B2, B3, C1 and C2 domes to raise the projection center (here: the center of the sphere) by 1.21 m, 0.66 m, 0.59 m and 0.24 m, respectively. Raising the projection center relative to the 0.00 level allows the corners or edges of the dome to be located on the base. The obtained single-layer geodesic domes were scaled to obtain a convergent net internal area of 32.973 m^2, which corresponds to the net area of the dome made under the ReSa project and provides the opportunity to compare the results. Based on preliminary analysis of the layer arrangement and panel thickness carried out as part of the research work of the aforementioned grant project, it was determined that the analysis would concern geodesic domes built of panels with a minimum thickness of 21 cm. This corresponds to two load-bearing layers of 1.0 cm GRC[1] (inner and outer shell) and 19 cm of thermal insulation located between them. Panel thicknesses have been introduced in the virtual 3d models of domes.

2.2. Data analysis

In set A (domes A1, A2 and A3), models of panel domes were made as a result of projecting a regular icosahedron onto the plane of a sphere. 1st degree division (projection of the center of the edge of the icosahedron) was used. In the case of the A1 and A2 domes, 4 types of panels were obtained, and in the case of the A3 dome – 2 types. (Fig. 3: A1/A2/A3).

In set B (domes B1, B2 and B3), models of panel domes were made as a result of projecting a regular dodecahedron onto the plane of a sphere. 1st degree division was used (projection of the geometrical centers of the pentagonal faces of the dodecahedron). In each case, 2 types of panels were obtained. In model B1, the edge at the top of the polyhedron is visible, in model B2 its corner, and in model B3 its face (Fig. 3: B1/B2/B3).

In set C (domes C1, C2 and C3), models of panel domes were made as a result of cutting the corners of a regular icosahedron. The cut was made in 1/3 of the length of each edge so as to obtain a dome composed of pentagons and hexagons. In the case of the C1 and C3 dome, 4 types of panels were obtained, and in the case of the C2 dome – 5 types. In the C1 model, the corner is visible at the top of the polyhedron, in the C2 model its wall, and in the C3 model its edge (Fig. 3: C1/C2/C3).

In set D (domes D1 and D2), models of panel domes were made as a result of projecting half of a regular octahedron onto the plane of a sphere. The octahedron is an axially and centrally symmetrical polyhedron. Rotation of the octahedron so that an edge appears at the top multiplies the types of panels in the base. It was decided to limit the projection to two degrees of division of the corner of the octahedron in the form of a symmetrically situated pyramid with a square base (half the height of the polyhedron). The 1st degree division was used – in the case of D1, the projection of the center of the edge of the octahedron's corner, and in the case of D2, the division of the edge into 3 parts and the projection of the obtained points onto the plane of the sphere. In the case of the D1 dome, 2 types of panels were obtained, and in the case of D2 – 4 types (Fig. 3: D1/D2).

[1] GRC – glassfiber reinforced concrete.

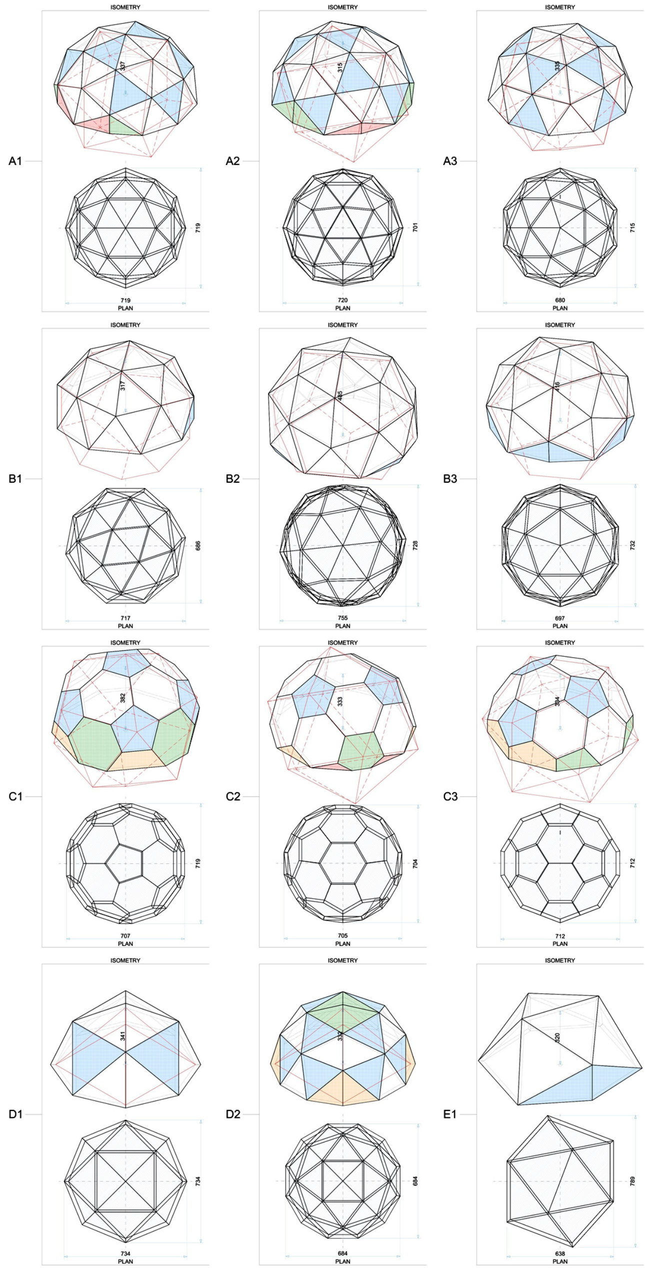


Fig. 3. Isometry of domes divided in sets according to the sphere projection differences: set A – icosahedron, set B – dodecahedron, set C – truncated icosahedron, set D – octahedron, set E dome isometry – icosahedron (Author‘s elaboration)

In set E (E1 dome), a model of a panel dome was made on the basis of a regular icosahedron, omitting the process of projection onto the plane of the sphere. The icosahedron was used in the models of groups A and C as the basic polyhedron for projection. It was decided to supplement the study with a single polyhedron model without additional sphere approximation. In the case of the E1 dome, 2 types of panels were obtained (Fig. 3: E1).

Measurements of each dome model were made by downloading data from the model and calculating the length, area and volume of individual elements. The obtained data were developed separately for each model and aggregated in the form of a summary table of measurement results.

Throughout the measurements of virtual models carried out across this study, 20 parameters were obtained for each type of dome: net area, building area, internal height, internal volume, number of panels, number of panel types, internal and external surface area, panels volume, number of partitions and partition types, partitions area, number of base surfaces and base surface area, panel thicknesses, dome center elevation, external and internal edges length as well as number of nodes. Detailed development of measurements in the field of internal and external surfaces, the number of panels and their types, volume and, among others, the number of division planes made it possible to develop and introduce indicators (outlined below) that allow to indicate the optimal geometric form for panel shell domes. The measurement results and indicators are described in Chapter 3. The collected data were analyzed and used for research in the field of geometrical parameters and weight of the structure, energy efficiency and environmental impact, as well as architectural parameters of panel geodetic coatings.

2.3. Loads assumptions and z-axis reactions

The starting point for the study of the mass of the domes and the ability to transfer their loads was the assumption of masses of materials in analogy to the materials used in the ReSa project. The mass of the material for the construction of the panels is directly proportional to the mass of the entire structure, thanks to which it is possible to evaluate 12 types of domes with the assumption of a homogeneous type of construction. It was assumed that the panels would be made of 1 cm GRC boards (two layers: internal and external) with mineral wool filling between the boards. The assumed mass of GRC is 1750 kg/m^3, and the mass of mineral wool is 100 kg/m^3. Total weight of all shell variants are presented in (Table 1).

In the calculations, in order to maintain the possibility of comparing the reactions transferred to the foundation in the assumed typology of domes, the thickness of the panels was standardized to 21 cm (1 cm GRC + 19 cm WM + 1 cm GRC). The weight of 1 m^2 of the panel in this case is 54 kg. Simulations were performed in the Robot Structural Analysis program (educational license) assuming identical loading conditions in each variant. The load case concerned only the dead weight of the panels, ignoring the influence of external forces. Determining the vertical component of the reaction at the base level (*Rz*) made it possible to compare the domes being the subject of the study and to indicate the geometry that will be characterized by the minimum possible reaction and therefore minimize problems in the foundation of the object. The sum of the reactions and the minimum and maximum reactions in the Z axis in the nodes are listed in the table (Table 2).

Table 1. Table of domes evaluation (Author's elaboration)

	Dome segment		**A**			**B**			**C**			**D**		**E**
	Dome number		A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	E1
Rowno.	Basic polyhedron		Icosahedron			Dodecahedron			Truncated icosahedron			Octahedron		Icosahedron
1	Total weight	kg	3 940.66	3 980.14	3 927.74	3 929.32	5 963.73	4 736.46	4 862.95	4 463.15	4 116.19	3 716.58	3 822.28	3 967.76

Table 2. Table of domes evaluation (Author's elaboration)

	Dome segment		**A**			**B**			**C**			**D**		**E**
	Dome number		A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	E1
Rowno.	Basic polyhedron		Icosahedron			Dodecahedron			Truncated icosahedron			Octahedron		Icosahedron
6	Z-axis reactions sum	kN	40.68	40.75	40.2	40.33	61.14	50.72	50.15	40.32	42.17	37.88	39.08	41.67
7	Min Rz	kN	0.99	–0.04	1.52	1.06	–5.54	–5.59	1.55	0.50	1.64	1.16	1.26	0.89
8	Max Rz	kN	3.48	4.73	2.24	3.16	13.32	12.97	2.90	8.52	2.28	1.97	2.35	3.00

2.4. Energy efficiency and impact on environment

2.4.1. Energy efficiency

Energy efficiency indicators of model variants were proposed, based on the study of building elements that have the greatest impact on energy consumption for heating and cooling. Due to the high similarity of the individual variants of the domes, it was decided to develop and analyze indicators intended only for heat exchange through transmission and ventilation, such as compactness, building envelope, thermal bridges and ventilation coefficients, because they are largely responsible for energy losses [5–7]. Indicators proposed:

- Compactness of Building Indicator (CoB), defined as the ratio of the area of the external partitions to the volume of the building. The compactness of the building has a large impact on heat loss in the building through transmission [8–12] and the resulting energy efficiency is more favorable compared to buildings with the same volume and partitions [13–17].
- Transmission per Area Indicator (TpA) defined as the ratio of the sum of the external surfaces of the panels, the length of all edges and the sum of all nodes to the usable area of the building. It also takes into account linear thermal bridges on the edges of the dome and point thermal bridges in nodes, the impact of which on energy losses can be significant [18–21].
- Heated Volume per Area Indicator (HVpA) defined as the ratio of the building volume to its usable area. When geodesic domes are compared with similar rectangular buildings, energy savings can be as high as 30% [15–17].

The subject of the research is to verify the degree of energy efficiency of each variant of the dome. For this purpose, simplified calculations of heat losses by transmission and ventilation will be carried out for all dome variants, and then the results and their interdependencies will be compared.

2.4.2. Impact on the environment

One of the parts of building sustainability is its impact on the environment [22]. Buildings, according to the position of the European Commission, are responsible for about 40% of the total energy consumption in the European Union and are the source of 36% of greenhouse gas emissions from the energy consumed [23]. In addition, buildings absorb about 50% of the materials extracted [24]. One of the indicators describing the impact of a building on the environment is the Global Warming Potential (GWP) [25]. It has been indicated as one of the indicators in the Level(s) building rating system developed by the European Union [26]. In addition, its calculation for all new buildings in the European Union is to be mandatory from 1 January 2026 [27].

In order to briefly verify the variants of the domes, the Mass Volume per Area Indicator (MVpA) was proposed, the value of which is the ratio of the volume of the dome cover elements (panels) to the usable area. Since the GWP is directly proportional to the amount of material used to build the dome, lower MVpA values will indicate a lower environmental impact of the building.

The subject of the study is to verify the degree of impact of individual variants on the environment by performing calculations of the built-in carbon footprint (GWP).

2.5. Architecture and functionality of interior variants

Architectural functional solutions of interiors of virtual models of geodesic domes have been analyzed in four aspects: single-space solutions, solutions with a central functional core, solutions with a perimeter arrangement of furniture and solutions with usable space separated symmetrically. Functional diagrams for particular types of domes have been added to each description: A (Icosahedron – regular icosahedron), B (Dodecahedron – regular dodecahedron), C (Truncated Icosahedron – truncated icosahedron), D (Octahedron – regular octahedron), E (Icosahedron – part of a regular icosahedron). Entrances to particular types of domes must be made individually, maintaining the minimum proportions of openings regulated by regulations. The principle of creating openings (both doors and windows) is to dismantle individual (or a group of) panels and install a transparent panel or a panel with a door leaf. It is also possible to connect the dome complex with a common entrance hall at ground level.

The single-space layout is an ideal solution to the design assumption that the hygiene and sanitary space will be separated in a separate facility. Positive aspects of single-space layout are open interior and the elimination of barriers in the form of vertical partitions, as well as the possibility of freely shaping the interior and introducing mobile partitions (Fig. 4).

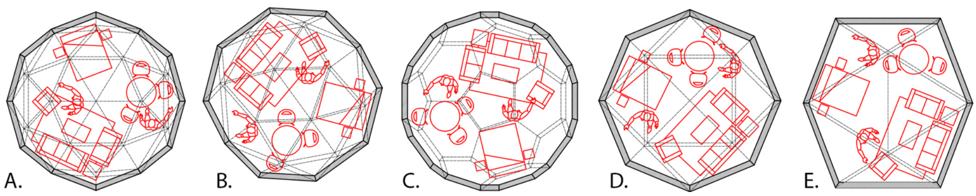


Fig. 4. Functional schematics of the single-space layout of the selected domes: set A – icosahedron, set B – dodecahedron, set C – truncated icosahedron, set D – octahedron, set E dome isometry – icosahedron (Author's elaboration)

Solutions with a central functional core is a direction of shaping the interior that allows connecting all functional zones that do not require additional sunlight and locating them in the central zone of the building. The positive aspects of the central functional core are the condensation of all elements and zones that do not require access to daylight (hygienic and sanitary zones, kitchenette zone, storage rooms). It is possible to provide glazing in the lower zone of the dome structure in the form of a panoramic opening of the interior in the 360° system (Fig. 5).

The peripheral layout is a special spatial arrangement in which the space for free arrangement of movable furniture is provided in the central, highest usable part (Fig. 6).

Functional solutions with symmetrically separated usable space of 1/2 of the area for the zone of a kitchenette and a hygiene and sanitary room provides 50% open space. The symmetrically separated usable space will be the best solution for users who require the closure of the kitchenette area and the hygiene and sanitation room. Furthermore, separate areas of the bathroom and kitchen have the largest usable area relative to other solutions (Fig. 7).

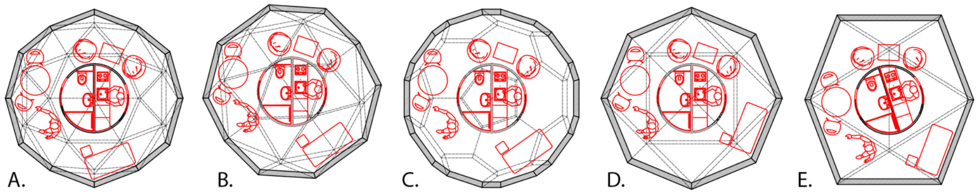


Fig. 5. Functional schematics of the central functional core of the selected domes: set A – icosahedron, set B – dodecahedron, set C – truncated icosahedron, set D – octahedron, set E dome isometry – icosahedron (Author's elaboration)

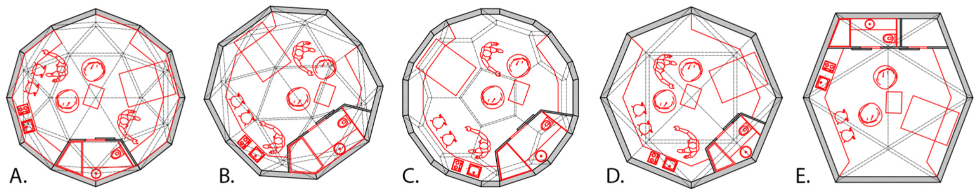


Fig. 6. Functional schematics of the peripheral layout of the selected domes: set A – icosahedron, set B – dodecahedron, set C – truncated icosahedron, set D – octahedron, set E dome isometry – icosahedron (Author's elaboration)

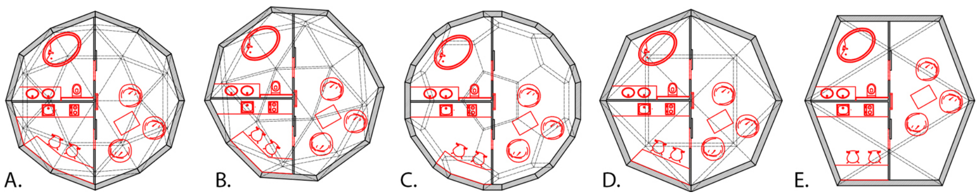


Fig. 7. Functional schematics of the symmetrically separated usable space of the selected domes: set A – icosahedron, set B – dodecahedron, set C – truncated icosahedron, set D – octahedron, set E dome isometry – icosahedron (Author's elaboration)

3. Research results

3.1. The loads assumption and z-axis reactions

Evaluation of the panel geodetic shells for the Z-axis reaction at the base level in comparison with the global weight of the shells confirmed the proportionality of the sum of the reactions in relation to the global weight of the shells. The smallest sum of reactions corresponding to the best variant of the coating was marked for the D1 dome and (consecutively) D2 and A3. Domes A1, A2, B1, and C2 had similar results at 40 kN rounded to full values (Table 3 row No. 2). The highest reaction value in the joint at the base level (i.e. 13.32 kN) was recorded for the B2 dome, and the lowest (i.e. –0.04 kN) for the A2 dome. Importantly, the difference between the smallest and largest recorded reaction does not correspond to the evaluation of the sum of reactions. The largest difference was noted for the B2 dome, and the smallest for the C3 dome.

Table 3. Table of Z-axis dome reactions (Author's elaboration)

Dome segment			**A**			**B**			**C**			**D**		**E**
Dome number			A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	E1
Rowno.	Basic polyhedron		Icosahedron			Dodecahedron			Truncated icosahedron			Octahedron		Icosahedron
1	Total weight	kg	3 940.66	3 980.14	3 927.74	3 929.32	5 963.73	4 736.46	4 862.95	4 463.15	4 116.19	3 716.58	3 822.28	3 967.76
2	Z-axis reactions	kN	40.68	40.75	40.2	40.33	61.14	50.72	50.15	40.32	42.17	37.88	39.08	41.67
3	Min R_Z	kN	0.99	–0.04	1.52	1.06	–5.54	–5.59	1.55	0.50	1.64	1.16	1.26	0.89
4	Max R_Z	kN	3.48	4.73	2.24	3.16	13.32	12.97	2.90	8.52	2.28	1.97	2.35	3.00
5	Max R_Z – min R_Z	kN	2.49	4.77	0.72	2.10	18.86	18.56	1.35	8.02	0.64	0.81	1.09	2,11

3.2. Sustainability

3.2.1. Energy efficiency

As a result of analyzes of the geometry of individual dome variants, the values of individual indicators were determined. The results them are included in (Table 4).

Table 4. CoB values for different variants of the dome (Author‘s elaboration)

Indicator	Dome type											
	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	E1
CoB (Compactness of Building)	1.073	1.076	1.084	1.091	1.010	1.044	1.067	1.093	1.088	1.199	1.113	1.140
TpA (Transmission per Area)	7.378	7.543	7.043	6.666	9.483	8.073	6.853	6.576	6.131	5.130	6.752	4.937
HvpA (Heated Volume per Area)	2.125	2.130	2.085	2.078	3.403	2.646	2.641	2.191	2.179	1.776	1.974	2.056
Discrepancy [%]	6.2	6.5	7.3	8.0	0.0	3.3	5.6	8.2	7.7	18.7	10.2	12.8

The results show that the best value of the CoB index equal to 1.01 is characteristic for variant B2 (a regular dodecahedron with a corner at the highest point of the dome), the most favorable value of the TpA index equal to 4.937 is characterized by variant E1 (regular icosahedron) and the most favorable value of the HVpA index equal to 1.776 characterizes variant D1 (half of a regular octahedron).

In order to verify the degree of adjustment of the indicators to the calculated heat losses through transmission and ventilation, the values of these losses were calculated. The calculations took into account transmission through external panels, heat losses through linear thermal bridges at the edges, heat losses through point thermal bridges, heat losses resulting from heating the air inside the domes. The calculations were made in THERM 7.8 [28] and the assumed calculation parameters are: average annual outdoor air temperature te = +8°C (value for Wroclaw [29]), indoor air temperature t_i = +20°C (calculated value for residential buildings [29]), exhaust air stream $V_e = 1/3V$ m^3 (calculated value for residential buildings [30]), no heat recovery assumed. The calculated values of the heat transfer coefficient for a panel consisting of GRC concrete (thermal conductivity = 1.2 W/(m·K)) and insulation (thermal conductivity = 0.032 W/(m·K)) range from 0.167 to 0.173 W/(m^2·K), the calculated values of the linear heat transfer coefficient ψe for the edges amounted to 0.33 W/(m·K) the calculated values of the point heat transfer coefficient ψn for the nodes were 0.091 W/K.

The annual heat loss results show large differences depending on the dome variant (Table 5). Heat losses through penetration through the panels depend on the surface of the dome and are close to each other. Heat losses through thermal bridges on the edges depend on the total length of the edges in the dome and are the highest for variants B2 and the lowest for variant E1. Heat losses through thermal bridges in nodes depend on the number of nodes and differ significantly from each other. Heat losses through ventilation depend on the volume of the dome, are similar and are not dominant.

The sum of heat losses is the lowest for variant E1 and the highest for variant B2. The difference between them is 100.00%. Other variants indicate higher heat losses from the best from 2.75% to 68.68%.

Table 5. Values of total energy losses for different variants of the dome (Author‘s elaboration)

Energy losses		**Unit**	**Dome type**											
			A1	**A2**	**A3**	**B1**	**B2**	**B3**	**C1**	**C2**	**C3**	**D1**	**D2**	**E1**
1	Transmission through panels	kWh/y	1358	1365	1365	1346	1358	2060	1655	1661	1412	1397	1236	1306
2	Transmission through edges	kWh/y	4947	5124	4714	4333	6078	5317	3322	3350	3007	3088	4487	2712
3	Transmission through nodes	kWh/y	277	287	249	230	268	249	383	421	383	124	239	96
4	Ventilation	kWh/y	818	820	802	800	1310	1019	1017	844	839	684	760	791
5	Total	kWh/y	7401	7596	7112	6720	9715	8239	6382	6027	5626	5132	6792	5002
6	Discrepancy [%]	%	50.89	55.03	44.77	36.46	100.00	68.68	29.28	21.74	13.24	2.75	37.97	0.00

3.2.2. Environmental impact

As a result of analyzes of the geometry of individual variants of the domes, the values of the MVpA index were determined. The results are included in (Table 6).

Table 6. MVpA values for different dome variants (Author‘s elaboration)

Indicator	**Dome type**											
	A1	**A2**	**A3**	**B1**	**B2**	**B3**	**C1**	**C2**	**C3**	**D1**	**D2**	**E1**
MvpA (Mass Volume per Area)	0.44	0.45	0.45	0.45	0.67	0.52	0.54	0.56	0.47	0.43	0.44	0.44
Discrepancy [%]	2.86	5.05	3.77	3.32	54.16	21.09	25.88	30.47	8.59	0.00	1.46	0.82

The results show that the most favorable MVpA value of 0.43 is characteristic for variant D1. Variant B2 (a regular dodecahedron with a corner at the highest point of the dome) has the least favorable value of 54.16, worse by 54.16%.

In addition, in order to assess the degree of compliance of the indicator with the calculated impact of a given variant on the environment, GWP calculations were made for individual variants. In the calculations for phases A1–A3, the values of environmental impact indicators for the following materials were taken into account: GRC concrete with a GWP value of 1576.4 $kgCO_2eq/m^3$ [31–33], PIR foam with a GWP value of 278.55 $kgCO_2eq/m^3$ [33], steel sheets with a GWP of 30.680 $kgCO_2eq/m^3$ [33]. The calculated values of the GWP indicator indicate the most favorable variants D1 the value of 5490 $kgCO_2eq$ (Table 7).

Table 7. Results of calculations of GWP indicator for different variants of the dome (Author's elaboration)

Indicator	**Dome type**											
	A1	**A2**	**A3**	**B1**	**B2**	**B3**	**C1**	**C2**	**C3**	**D1**	**D2**	**E1**
GWP (Global Warming Potential)	7 119	7 236	6 892	6 629	9 797	8 144	6 786	6 140	5 838	5 490	6 621	5 566
Discrepancy [%]	37.82	40.52	32.54	26.45	100.00	61.61	30.09	15.09	8.06	0.00	26.25	1.76

3.3. Architecture

Architectural evaluation data are indicated in (Table 8). Moreover, for all layouts and types of geodesic domes, parameters related to the analysis of usable area and net area were analyzed:

– net area according to ISO 9836:2017
– usable area according to ISO 9836:2017

Additionally, the parameter obtained was the ratio of net area to usable area.

Table 8. Parametric analysis of four functional types of interior (Author's elaboration)

		Icosahedron			**Dodecahedron**			**Truncated icosahedron**			**Octahedron**		**Icosa-hedron**
Indicator	–	A			B			C			D		E
Surface analysis		A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	E1
1. Single-space area													
ratio of usable area to net area		0.28	0.31	0.27	0.29	1.00	0.81	0.73	0.46	0.29	0.00	0.23	0.22

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Table 8 – *Continued from previous page*

		Dome type											
		Icosahedron			**Dodecahedron**			**Truncated icosahedron**			**Octahedron**		**Icosa-hedron**
Indicator	–	A			B			C			D		E
2. Central functional core													
net area according to ISO 9836:2017	m^2	32.96	32.96	32.96	32.97	32.96	32.96	32.96	32.96	32.96	32.96	32.96	32.96
usable area in accordance with ISO 9836:2017	m^2	20.53	21.1	20.44	20.75	32.28	29.19	22.87	23.55	20.73	16.01	19.71	19.51
including the usable area of the hygienic and sanitary zone		5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.48	5.48
ratio of usable area to net area		0.28	0.31	0.27	0.29	1.00	0.81	0.42	0.46	0.29	0.00	0.23	0.22
3. Peripheral layout													
net area according to ISO 9836:2017	m^2	32.96	32.96	32.96	32.97	32.96	32.96	32.96	32.96	32.96	32.96	32.96	32.96
usable area in accordance with ISO 9836:2017	m^2	20.84	21.41	20.75	21.06	32.59	29.50	28.18	23.86	21.04	16.32	20.02	19.82
including the usable area of the hygienic and sanitary zone		1.79	1.79	1.79	1.79	1.79	1.79	1.79	1.79	1.79	1.79	1.79	1.79
ratio of usable area to net area		0.28	0.31	0.27	0.29	1.00	0.81	0.73	0.46	0.29	0.00	0.23	0.22

Continued on next page

Table 8 – *Continued from previous page*

		Dome type											
		Icosahedron			**Dodecahedron**			**Truncated icosahedron**			**Octahedron**		**Icosa-hedron**
Indicator	–	A			B			C			D		E
4. Symetrically separated usable space													
net area according to ISO 9836:2017	m^2	32.96	32.96	32.96	32.97	32.96	32.96	32.96	32.96	32.96	32.96	32.96	32.96
usable area in accordance with ISO 9836:2017	m^2	20.57	21.14	20.48	20.79	32.32	29.23	27.91	23.59	20.77	16.05	19.75	19.55
including the usable area of the hygienic and sanitary zone		5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2	5.2
ratio of usable area to net area		0.28	0.31	0.27	0.29	1.00	0.81	0.73	0.46	0.29	0.00	0.23	0.22

In terms of the analysis of the usable interior area, the largest area is shown by the dodecahedron in the B2 version in a single space layout. The usable area of 32.79 m^2 is very close to the net area of 32.96 m^2. On the contrary, the smallest usable area is shown by the D1 octahedron in the arrangement with a central functional core (16.01 m^2).

When analyzing the adopted spatial arrangements of the interior in terms of aesthetics, ergonomics and usability, it appears necessary to adopt non-technical parameters. The expectations of the target user are also an important in terms of choice, as each of the following adopted spatial alternatives may turn out to be the target solution.

3.4. Complexity of the prefabrication and assembly process

In the case of the above For the ReSa project, the time and complexity of the prefabrication and assembly process were decisive. It was assumed that the degree of complexity of the structure measured by the number of different panels while obtaining the largest possible internal volume will be of decisive importance. The number of different types of panels affects the prefabrication time and the degree of complexity during assembly. In order to assess the complexity of the prefabrication process, the Panel Types per Volume (PTpV) indicator was adopted for the analysis, i.e. the number of partitions in relation to the number of partition types.

3.5. Variant evaluation

In order to make a comprehensive comparative assessment of all variants in relation to each other in all categories, it was proposed to calculate and assign each variant in each category its value calculated in the awarded scores. The most favorable variant (with the most favorable numerical value) in a given category received score 1, the least favorable variant received score 0, and the intermediate variants received values in accordance with the Formula (3.1):

$$P_{c,n} = \frac{(V_{c,n} - V_{c,\min})}{(V_{c,\max} - V_{c,\min})} \tag{3.1}$$

where:

P_{cn} – score value for a given variant (n) in a given category (c),
V_{cn} – numerical value for a given variant (n) in a given category (c),
$V_{c,min}$ – the lowest numerical value in a given category (c),
$V_{c,max}$ – highest numerical value in a given category (c).

Four significant assessment categories were identified (c). These are Energy Efficiency (c_1), Environmental Impact (c_2), Reactions (c_3), Use of Space (c_4) and Complexity of the prefabrication and assembly process (c_5). As a result of calculations in every categories was shown in (Table 9).

Table 9. Results and scores for each category (Author's elaboration)

Category	Unit	A1	A2	A3	B1	B2	B3	C1	C2	C3	D1	D2	E1
Energy Efficiency (results from 3.3.1)	Scores	0.49	0.45	0.55	0.64	0.00	0.31	0.71	0.78	0.87	0.97	0.62	1.00
Environmental Impact (results from 3.3.2)	Scores	0.62	0.59	0.67	0.74	0.00	0.38	0.70	0.85	0.92	1.00	0.74	0.98
Reaction discrepancy (results from 3.2)	Scores	0.90	0.77	1.00	0.92	0.00	0.02	0.96	0.59	1.00	0.99	0.98	0.92
Average Surface loss (results from 3.4)	Scores	0.28	0.31	0.27	0.29	1.00	0.81	0.65	0.46	0.29	0.00	0.23	0.22
Discrepancy (results from 3.5)	Scores	0.24	0.24	0.24	0.78	0.78	1.00	0.90	0.45	0.00	0.26	0.68	0.45

As a result of calculations of energy losses (c_1) for each variant, the highest score was awarded to variant E1 (1 point) and the lowest to variant B2 (0 points), for the environmental impact (c_2) the highest score was awarded to variant D1 (score 1) and the lowest to B2 (score 0), for the uniformity of distribution of vertical components of reactions on supports in each of the variants (c_3) the highest score was awarded to variant C3 (score 1) and the lowest to variant B2 (score 0), for the calculations of the percentage loss of usable area in relation to the net area (c_4) the highest score was awarded to variant B2 (1 point) and the lowest to variant D1 (0 points) and for the complexity of the prefabrication and assembly process (c_5) the highest score was given to variant B2 (rating 1), and the lowest to variant C2 (rating 0).

4. Summary results and discussion

In order to assess all variants together, the scores obtained in each category were added together. The summary score is shown in (Table 10).

Table 10. Total scores for all variants (Author‘s elaboration)

	A1	**A2**	**A3**	**B1**	**B2**	**B3**	**C1**	**C2**	**C3**	**D1**	**D2**	**E1**
Sum:	2.52	2.37	3.28	3.36	2.00	2.42	3.47	2.69	3.34	3.65	3.01	3.89

Taking into account the sum of points from each category, the results for each variant were obtained. The highest value was given to variant E1 (3.89 points), which was caused by the high number of points in category C1, C2 and C3. The achievement of the best result was not influenced by the worse result in the c4 category. It is worth noting that the second and fourth best variants C3 and D1 were influenced by very good results in the categories C1, C2 and C3. This leads to the conclusion of a large discrepancy between the categories C1 (Energy Efficiency), C2 (Environmental Impact) and C3 (Reaction) in relation to C4 (Use of Space). This is also confirmed by the results for the two variants with the low number of points B2 and B3, which achieved the highest values in category C4 and in category C5. This points us to concluding that the criterion of the use of space and complexity of the prefabrication and assembly process, being a criterion of a qualitative nature, resulting from the subjective normalization of space assessment and potential difficulties in prefabrication and assmebly process, does not correlate with the criteria of a quantitative nature, such as energy losses, environmental impact or structural properties of the material.

In the study being the subject of this article, the assessment of five aspects of the shell geodesic domes that were considered under the ReSa project was initially determined: Energy Efficiency (3.5.1), Environmental Impact (3.5.2), Reactions (3.5.3), Use of Space (3.5.4) and Comlexity of the prefabrication and assembly process (3.5.5). It is worth noting, however, that the set of research fields that are used to determine partial parameters and indicators is an open set and can be extended by further aspects related to, among others, with local availability of materials (transport, price) or life cycle assessment of dome components (LCA). The new assessment categories will have an obvious impact on the global evaluation results of shell domes. What is equally important – the criteria may have weights that will allow for a subjective increase in the importance of some of them (e.g. for the prefabrication process), and decrease in the importance of other criteria (e.g. due to small differences in the usable area of the considered variants). This situation took place, for example, in the case of the aforementioned ReSa grant project, where the aspect of reducing the number of different panels to facilitate and accelerate the prefabrication process was of the most important and the research models were developed on the basis of B3 and A3 domes.

5. Conclusions

The evaluation of 12 initial, shell geodesic domes developed in the four basic research fields listed above showed the highest evaluation score for the E1 (icosahedron) dome, followed by C3 and C1 (truncated icosahedron). In terms of geometry, the highest evaluation score was awarded to the domes E1 (icosahedron), B1 (dodecahedron) and D2 (octahedron). In terms of construction, the highest scores were awarded to the C3 (truncated icosahedron), A3 (icosahedron) and D1 (octahedron) domes. In terms of environmental impact and thermal insulation, the highest marks were awarded to the D1 (octahedron), E1 (icosahedron) and D2 (octahedron) domes. In terms of architectural parameters, the highest marks were awarded to the B2 (octahedron), B3 (icosahedron) and B1 (octahedron) domes. In terms of complexity of the prefabrication and assembly process category, the highest marks were awarded to the B2 (dodecahedron), B3 (dodecahedron) and B1 (dodecahedron) domes.

Tabular list of domes with the highest parameters in the partial (separate) evaluation in (Table 11) indicates that the most common variants of geometry are de facto domes with a low degree of edge division in terms of sphere approximation, i.e. E1, D1 and D2 domes. These variants received high global evaluation values, and the E1 variant – icosahedron without projection onto the surface of the sphere received the highest evaluation score. It is worth noting that a factor strongly influencing the overall assessment of shell domes is the evaluation of the reaction to the ground, which is clearly increased when the projection center of the polyhedron is raised above the level of 0.00.

Table 11. List of domes with the highest partial (col. 1–4) and total (col. 5) evaluation parameter (Author's elaboration)

	Energy efficiency	**Environmental impact**	**Construction reactions**	**Architecture and ergonomics**	**Complexity**	**Summary results**
1	E1	D1	C3 / A3	B2	B2	E1
2	D1	E1	D1	B3	B3	C3
3	C3	C3	D2	C1	B1	C1

This study proved that parametric criteria evaluation is a good tool for evaluating shell geodesic domes. This method is developing both in the field of scientific research and in the field of dome making. It allows for flexible input of basic data (here: energy efficiency, environmental impact, support reactions, ergonomics and complexity of the prefabrication and assembly process), determination of coefficients and the use of additional weight criteria for individual research areas in relation to the assumed goal. In the case of the ReSa project, it was crucial to achieve a high score in the criterion related to ergonomics (due to the fact that the project is implemented at the Faculty of Architecture) and the complexity of the prefabrication and assembly process (due to the guidelines of the building contractor). By omitting the projection of the polyhedron onto the plane of the sphere or a low degree of division of its edges, it is possible to obtain the best variant of the panel geodesic coating in terms of its geometry, mass of the structure and reaction to the ground, as well as environmental, architectural and complexity parameters. However, this does not change the fact that the selection of appropriate indicators for evaluation allows for evaluation under any criterion or their group.

When modeling geodetic panel shells, the initial prototype BIM system for the optimization of integrated construction processes [34] was used. It should be noted that modeling the geometry of a geodesic dome made of composite (here: three-layer) panels goes beyond the basic scope of available BIM tools. To enable scaling of the size of the selected object, it is necessary to use parametric tools.

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Ewaluacja parametryczna jako narzędzie do oceny powłok geodezyjnych. Modelowanie panelowej, powłokowej, rekreacyjnej kopuły Fullera w grancie ReSa

Słowa kluczowe: powłoka geodezyjna, kopuła Fullera, samonośne panele kompozytowe

Streszczenie:

Struktury mobilne stanowią jeden z kierunków kształtowania obiektów rekreacyjnych na świecie. Pod względem geometrycznym na szczególną uwagę zasługują kopuły geodezyjne i układy quasi-kopułowe. Panelowe kopuły powłokowe były przedmiotem rozważań m.in. Buckminstera Fullera i Davida

Geigera, których rozwiązania patentowe przywołano w artykule. Połączenie systemu warstwowych paneli samonośnych z geometrią kopuł geodezyjnych stanowiło jedno z istotnych wyzwań konstrukcyjno-materiałowych w ramach projektu badawczo-wdrożeniowego ReSa realizowanego na Politechnice Wrocławskiej w latach 2021–2023 w ramach konkursu organizowanego przez Narodowe Centrum Badań i Rozwoju. W ramach analiz wstępnych niezbędne było określenie typów rozwiązań kopułowych przeznaczonych do realizacji modeli badawczych. W artykule przedstawiono szczegółową analizę powł okowych kopuł geodezyjnych o zróżnicowanej geometrii. Różnicowanie wynikało z zastosowanego typu oraz obrotu wielościanu bazowego względem płaszczyzny podstawy. Zasadniczym celem badania było hierarchiczne ujęcie typów panelowych kopuł geodezyjnych względem ich zastosowania do budowy mobilnych obiektów rekreacyjnych. Opracowanie 12 wirtualnych modeli kopuł pozwoliło dokonać ewaluacji ich parametrów w 4 zasadniczych polach badania – efektywności energetycznej, wpływu na środowisko, reakcji podporowych oraz ergonomii. Dokonano szerokiej oceny parametrów w każdym z pól, podsumowania w ramach każdej dziedziny oraz globalnej ewaluacji powłok. Badanie pozwoliło na opracowanie hierarchii typów kopuł panelowych względem założonych kryteriów oraz na sprawdzenie możliwości zastosowania wieloaspektowej, parametrycznej ewaluacji. Dodatkowo – szczegółowe opracowanie parametrów geometrycznych powłok przeprowadzone w ramach badań pośrednich pozwoliło na wskazanie najefektywniejszych struktur w tym aspekcie. Podsumowanie badania pozostawia pole do propagacji kolejnych badań w zakresie zastosowania tego narzędzia w aspekcie doboru i oceny kryteriów ewaluacji oraz uzupełnienia oceny względem ich wag.

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