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ANALOGUE AND COMPUTATIONAL FORM-FINDING TECHNIQUES IN SHELL STRUCTURES DESIGN

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Abstract
The article is dedicated to the problem of design of shell structures in terms of architectural form-finding methods from a historical and contemporary perspective. The form-finding theory and techniques formulated by Robert Hooke were put into practice by Antonio Gaudi with his designs of the churches of Colònia Güelland and Sagrada Familia. Moreover thin concrete shell structures were used in the middle of XX century and their structural forms were derived from experiments with physical models. Innovative form-finding techniques were developed by Frei Otto for the design of membrane structures.
The article presents some historic, physical models based methods used for experimental determination of form and verification of the structural systems. Nowadays, computational methods are used in static analysis with dynamic environmental load simulation, which allow predicting the behavior of designed forms and structural systems. Architects can use 3D modelling twinned with visual programming to perform conceptual analyses enabling structural optimization of the architectural form. The Exhibition Pavilion of the University of Zielona Góra concept project was presented as an example of the use of computer numerical form-finding tools in supporting architectural design in the analysis of the effectiveness of structural solutions.

Keywords: parametric design; form-finding; wooden architecture; finite element analysis

INTRODUCTION

The efficient load carrying capabilities of shell structures are reflected in their widespread use in both architectural and structural design. Innovative engineering applications and the continuous development of new structural materials lead to ever increasingly complex structural design of shells that require careful analysis. Models representing calculations, design processes and their physical implementations have been evolving for centuries. Various disciplines have developed numerical, geometric, and material aspects, but at the core is the externalization of ideas into material construction in various forms of abstraction, from representations of numerical systems to dimensionally scaled architectural artifacts.

Physical models are an effective tool for problem-solving, experimentation, and representation equally adept at realizing abstract, construction aids such as scale models and full-scale architecture.

As pointed out by B. Kolarevic: "*In a radical departure from centuries old traditions and norms of architectural design, digitally-generated forms are not designed or drawn as the conventional understanding of these terms would have it, but they are calculated by the chosen generative computational method. Instead of working on a parti, the designer constructs a generative system of formal production, controls its behavior over time, and selects forms that emerge from its operation. The emphasis shifts from the "making of form" to the "finding of form", which various digitally-based generative techniques seem to bring about intentionally*" [B. Kolarevic 2003].

1. FORM-FINDING OF SHELL STRUCTURES

The term form-finding, or 'finding form', means the process of designing, researching and finding optimal structural shapes based on the behavior of materials under the influence of gravity. The method of finding form was first used by Robert Hooke in 1675. The English scientist used a suspended model in which the components of the structure were subjected to stretching as a result of gravity. This allowed us to determine a form in which only compression occurs in the inverted form. This method is therefore the oldest and most widespread form-finding technique.

B. Kolarevic and K. Shea state: "*the form-finding techniques used in the design of tensile membrane structures (pioneered by Frei Otto) as the nearest example of performance-driven architectural form generation, in which the form of the membrane is dynamically affected by changing the forces that act on the model. (…) the form-finding techniques in structural engineering are generally limited to either pure tensile or pure compression structures*".

In the chapter entitled "What is shell?" Chris Williams describes the shell as a structure defined by a large surface, curved in three directions. Additionally, we can distinguish between shell structures and tensioned structures, such as membranes or cable meshes [C. Williams 2014]. As noted by P. Debney: "*Incredibly thin arches and shells are achievable when they are geometrically optimised, such as Robert Maillart's 1939 Cement Hall from the Zurich National Exhibition. The door openings on the bridge indicate both the scale and the thinness of this reinforced concrete shell. When the shell is constructed from a grillage or lattice, often of timber, then it is referred to as a gridshell. The nature of these structures enables very organic forms to be produced; a well-known example being the Mannheim World Garden Exhibition building*" (Fig. 1a–b).

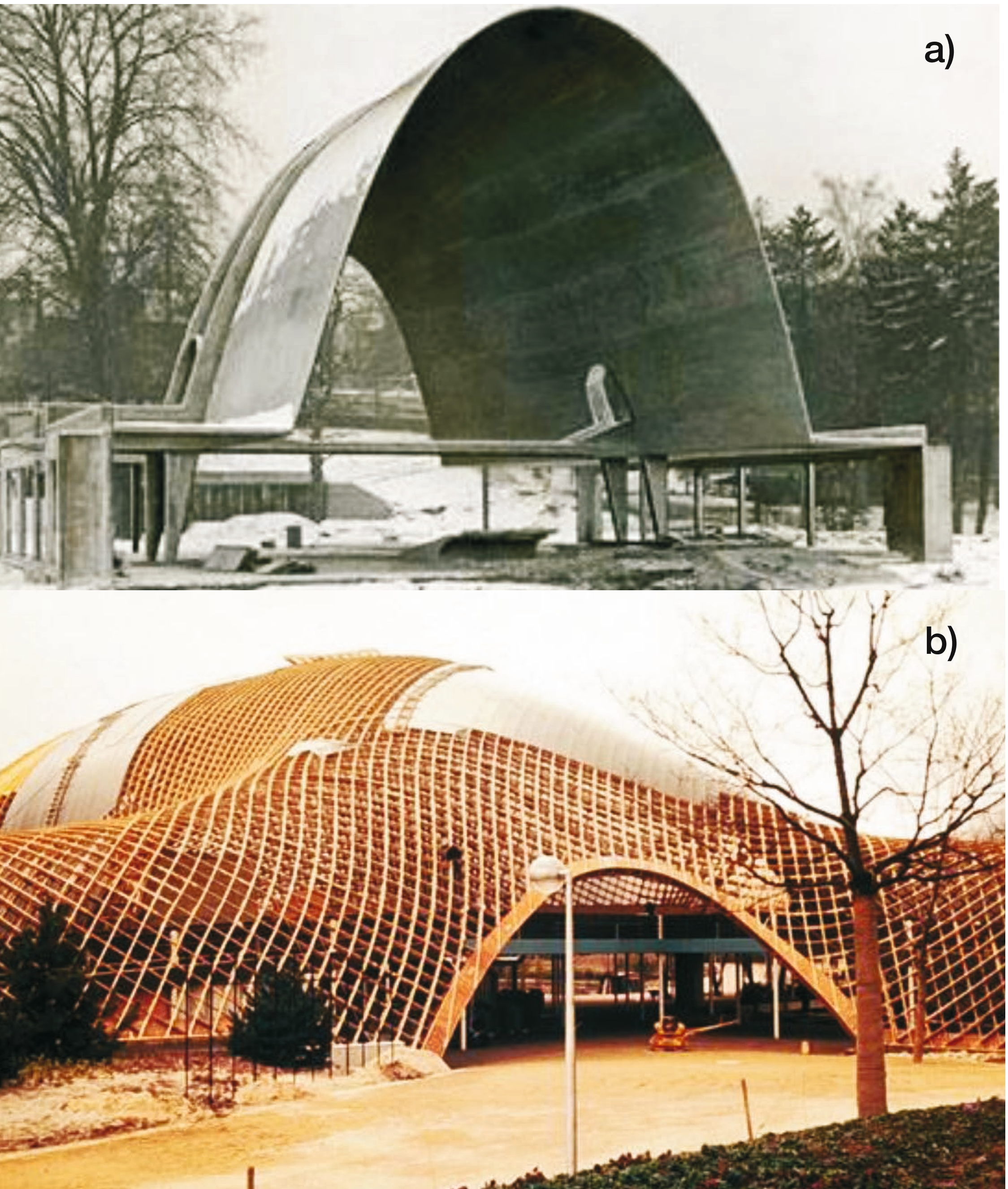


Fig. 1a–b. Shell structures, a) Robert Maillart, Cement Hall, Zurich National Exhibition, 1939, b) Frei Otto, Carlfried Mutschler, Joachim Langner, Multihalle, Mannheim, 1975; source: Debney P. (2015).

2. FORM-FINDING IN ARCHITECTURAL AND STRUCTURAL DESIGN

Until the beginning of the 20th century, form-finding was based on analog research processes. Antoni Gaudí (1852–1926) worked with physical models of the churches of Sagrada Familia and Colonia Güellin Barcelona. Gaudí was obsessed with finding the structural and material given limits, which is why he investigated every detail in scale models [M. Burry 2011].

Antoni Gaudi used suspended chain models to prefigure profiles of vaults and arches (Fig. 2a–b). The Catalan architect constructed suspended models made from chains, changing their form with weights to obtain the shape of the supports. The beauty of a form shaped in this way lies not in aesthetics, but in the way in which this form was created, referring to both the material and the structure of the form [C. Chuang, J. Clinton 2016]. Frei Otto in his experiments with soap bubbles explored the properties of matter to generate minimal surfaces. Otto was fascinated with the experimentation to understand the physical, biological and technical processes behind material organization of structures. Goldsmith writes that Frei Otto, an architect and structural engineer well known for his tensile structures, described the role of the architect in the form-finding process – "*the architect is more acting as a midwife than God the creator*" [N. Goldsmith 2016]. M. Liżewska in her article describes the design solutions developed by Antoni Gaudi on the basis of physical spatial models built by the architect, in which he focuses on the search of the optimum form in the form of the principle of "honesty of architecture". The author also presents test results concerning the catenary that prove the validity of using traditional methods of construction of physical models at the stage of preliminary design of a form consistent with the construction's action [M. Liżewska 2019].

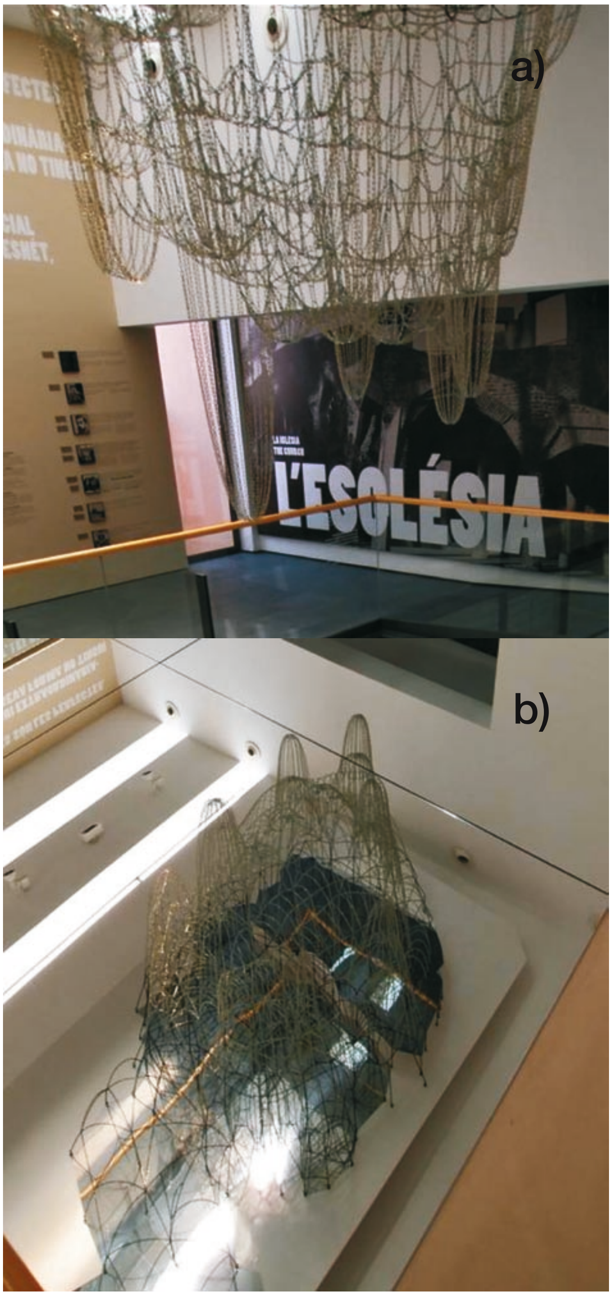


Fig. 2a–b. Antoni Gaudí, funicular model of Colònia Güell church exhibited at Colònia Güell Interpretive Centre; source: Debney P. (2015).

3. ANALOGUE FORM-FINDING TECHNIQUES IN DESIGN SHELL STRUCTURES

In the 1950s Heinz Isler (1926–2009), famous for his intuitive engineering creativity, broadly divided form-finding methods into three categories: analytical, experimental and free form modeling. Moreover, for him, double curvature shell structures were the most efficient shapes in terms of load-bearing capacity, material use and spatial values. Shell structures, he said, constitute both the structural element and the envelope of a building; these are shell structures that create static and functional units.

Heinz Isler used physical models to obtain structurally and materially effective shapes of coating surfaces formed by gravity forces. The chosen method did not answer the question: how the surface would be shaped and, along with it, how the lines of force would run. In his works, Gaudí used suspended models made of chains to determine pressure lines. He also investigated how and whether it is possible to influence their shape using the weights of a scale. Gaudí's explorations focused more on the shape of the ribs and columns than on the geometry of the surfaces. Heinz Isler's experiments were focused on searching

Fig. 3a–c. Heinz Isler, Sicli SA Factory in Geneva, 1968–1969, a) elastic rubber model small-scale epoxy resin model, b) the model used for the evaluation of structural behavior of the Sicli SA Factory in Geneva, c) Sicli SA Factory in Geneva; source: J. Chilton (2011); C.C. Chuang, J. Chilton (2016)

for the shape of the surface formed by the law of universal gravity, which would be characterized by the best efficiency of the structural design. Form-finding techniques used today include a variety of experimental strategies and tools, both analog and virtual [M.W. Weller 2010].

The shapes Isler created in the form finding process were based on physical models structurally optimized according to the principles of physics. Isler found the basic principles of his shell structures in three observations he made by accident in 1955: an inflated membrane, a hanging membrane, and frozen elastic structures. Based on these principles, he designed most of his forms using physical models. He obtained the final geometry for implementation using independently developed methods of collecting data on curvatures through scaled measurements from physical models. In other words, the logic of construction and form are in harmony, as postulated by Eduardo Torroja y Miret, describing the purpose of designing load-bearing structures as the interaction of material, structure and form [J. Chilton, C. Chuang 2017].

The concrete shell for Sicli SA Factory was a project carried out in Geneva (1968-1969) in cooperation between Isler and the architect Constantin Hilberer (Fig. 3a–c). The shell of the factory has seven supports, its formation is characterized by freedom of shape and departure from symmetry. The basic dimensions of the object are 35 × 9 × 30 m, with a height of approximately 8.75 m. The thickness of the SAF shell coating is only 90 mm and 50 mm of insulation. Originally, the facility consisted of a production hall with an area of 1,100 m^2, a spacious hall and an administration center [J. Chilton 2012].The geometry of the form was determined without the help of analytical functions, but rather as a result of using an analytical and experimental method based on finding the form under the influence of the law of gravity. The model made of plexiglass was made on the basis of a wooden form in accordance with the designer's concept. The test results were used to design the distribution of reinforcement in the thin concrete shell.

The diligent search for integral structural forms also characterized the work of the Italian engineer Sergio Musmeci (1927–1981). Examples include form-finding experiments with saddle supports in the Palazzo del Lavoro in Turin (1959), as well as with a curvilinear funnel-shaped roof for the church in Villaggio del Sole in Vicenza (1960) and the Basento Bridge project (1967–1976) [S. Musmeci 1971].The shapes of the engineering structures designed by Musmeci's team far exceeded the design and construction possibilities of the time. Musmeci envisaged the use of digital tools allowing the control of a greater number of parameters in order to research design solutions and use the full possibilities offered by new materials. Already in the 1970s, the Italian engineer supported himself in the static analysis of structures with the first digital engineering program ANSYS. The results of numerical methods of analyzing the deformation and strength of structures largely coincided with the results of calculations performed using analog methods. Unfortunately, his premature death in 1981 did not allow him to take full advantage of the possibilities of new technologies.

Analogue research methods used by architects allow for a greater understanding of both material and structural aspects. Working with physical scaled models requires intuition, helping to overcome the inability to perform accurate calculations. The analogue approach has clear limitations resulting from physical model scaling of complex geometries and requires a number of tests and variations.

4. COMPUTATIONAL FORM-FINDING TECHNIQUES IN DESIGN SHELL STRUCTURES

As noted by Bucalem and Bathe: "*Although analytical techniques are very important, the use of numerical methods to solve shell mathematical models of complex structures has become an essential ingredient in the design process. The finite element method has been the fundamental numerical procedure for the analysis of shells.*" [M.L. Bucalem, K.J. Bathe 1997].

The development of computer science initiated the development of computer-aided design (CAD) systems, and now the adaptation of sensor-enabled robotic systems is revolutionizing design processes and geometric representations to establish a closer link between the computational model and the material domain. Since the end of the 1960s, the rise of computer science has made it possible to develop form-finding methods in the theoretically unlimited design space offered by computers. Block and Veenendaal categorize algorithmic form-finding methods in three fundamental families [S. Adriaenssens et al. 2014]:

- Stiffness Matrix Methods, e.g. Natural Shape Finding (1974) which are based on standard elastic and geometric stiffness matrices;
- Geometric Stiffness Method, e.g. Force Density Method (1971), Thrust Network Analysis (2007);
- Dynamic Equilibrium Methods, e.g. Dynamic Relaxation (1984), Particule Spring System (2005).

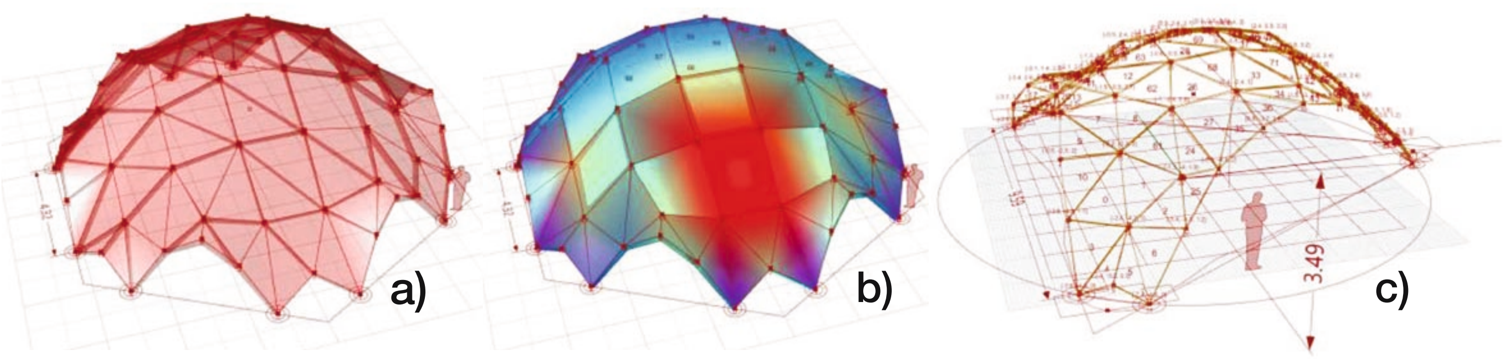


Fig. 4a–c. Computational design of the Exhibition Pavilion of the University of Zielona Góra; source: J. Juchimiuk and Author

Computational design is the convergence of computational power and design techniques through a sequence of logical processes. For centuries, architects have designed relying on their experience and intuition to come up with new design solutions. The advanced technology available at our disposal has entirely changed that process. Using 3D numerical modeling as a tool in architectural design can facilitate structural form-finding and general decision making. The use of numerical models ensures access methods required to obtain a computational simulation of the structural behavior of the designed building (Fig. 4a–c).

These methods can then be classified into two categories: static problem methods (stiffness matrix methods) and dynamic problem methods (dynamic equilibrium method). F. Chéraud claims that: "*The first category includes methods that require a rigorous description of boundary conditions (geometry, topology, material, loads), the simulation is dependent on the material and on solid geometry, which is difficult to reconcile with any prospective approach. Methods such as the FEM consume a lot of computing power and are intended to evaluate a given solution. In short, it is a knowledge-based process, while the objective of the form-finding process is precisely the opposite; to produce variety.*" According to the same author: "*The second category includes methods making it much easier to perform interactive deformations and manipulate complex interactions with only a few equations and parameters. In fact, these methods are well suited to generate visually correct simulations. For example, the Dynamic Relaxation Method is based on the resolution of the balance of forces to reach the static state of a structure.*" [F. Chéraud 2020].

K. Januszkiewicz writes about natural form-creating processes as an inspiration for form-finding methods and the connections between mathematics and architecture: "*Mathematics provides operational tools for science to create mathematical models that are descriptions of simple and complex real phenomena. Such modeling is used to learn about a given process by replacing it with a simplified system that reflects only selected features of the process. The mathematical description of the model is presented here in the form of a system of algebraic or differential equations. The studied processes describe models with complex parameters, and the variables included in them are subject to changes both in time and space.*" [K. Januszkiewicz 2013b].

5. CASE STUDY – CONCEPT DESIGN OF UZ EXHIBITION PAVILION, 2022

An example of the use of parametric modeling methods in the design of wooden structures is the Exhibition Pavilion of the University of Zielona Góra (Fig. 5). The pavilion, with a span of 9.6 m and a height of 3.5 m, was designed as a shell structure. The idea behind the project and its intended implementation is a presentation of the possibilities of contemporary architecture, digital design and new technologies. The concept project of the pavilion was created in 2022 by Justyna Juchimiuk and Michał Golański from the Institute of Architecture and Urban Planning WBAIŚ UZ. Students from the Architecture in Sustainable Space Scientific Club were invited to cooperate. Design work on the pavilion project continued in 2023. The project is going to be realized at the university Campus A in Zielona Góra. The pavilion will host small exhibitions, lectures, concerts and meetings.

Structural and material solutions are being considered and analyzed with plywood as a structural material. FE analysis was carried out to assume occurrence of permissible deflection in accordance with PN-EN 1995-1-1:2010 and NA 3. The form-finding modeling of the pavilion and FE analysis were carried out according to a Grasshopper script (Fig. 6.). Design methodology:

- Definition of input parameters: size of projection, determination of the number and location of support points and types of loads,
- Form-finding (KangarooPhysics),
- FE Analysis of the structural model (Karamba3D) in terms of the use of material properties (wood) and structural and material efficiency,
- Visualization of FE analysis results (node displacements, stresses).

Form-finding techniques were used in the design of the pavilion. The doubly curved architectural form was created by using the inverted hanging model form-finding method using Kangaroo Physics. The resulting structural form primarily transfers compressive loads and limited bending loads (Fig. 7a–d).

Kangaroo Physics, which belongs to this category, is an add-on for Grasshopper/Rhino and Generative Components which embeds physical behavior directly in the 3D modeling environment and allows one to interact with it 'live' as the simulation is running. It can be used for various sorts of optimization, structural analysis and animation. Kangaroo is a Live Physics engine for interactive simulation, form-finding, optimization and constraint solving. It consists of a solver library and a set of Grasshopper components D. Piker 2013].

Fig. 5. Exhibition Pavilion of the University of Zielona Góra, 2022–2023; source: J. Juchimiuk and Author

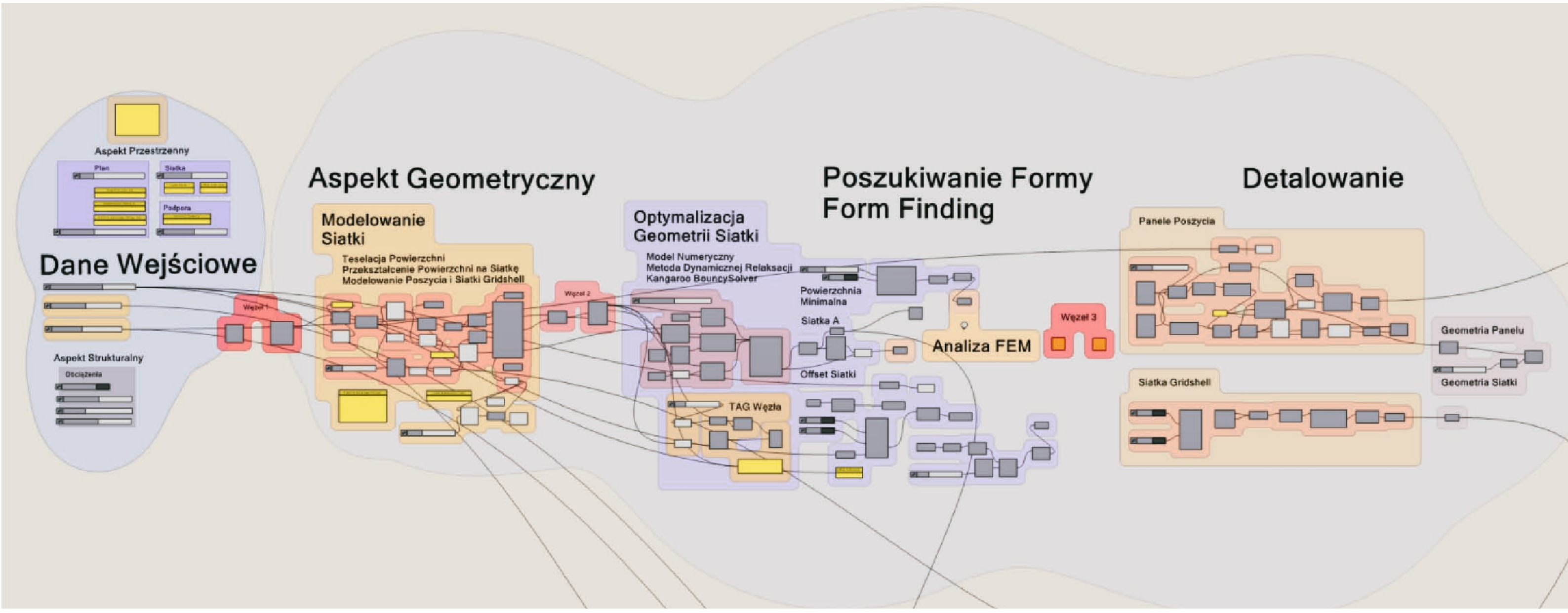
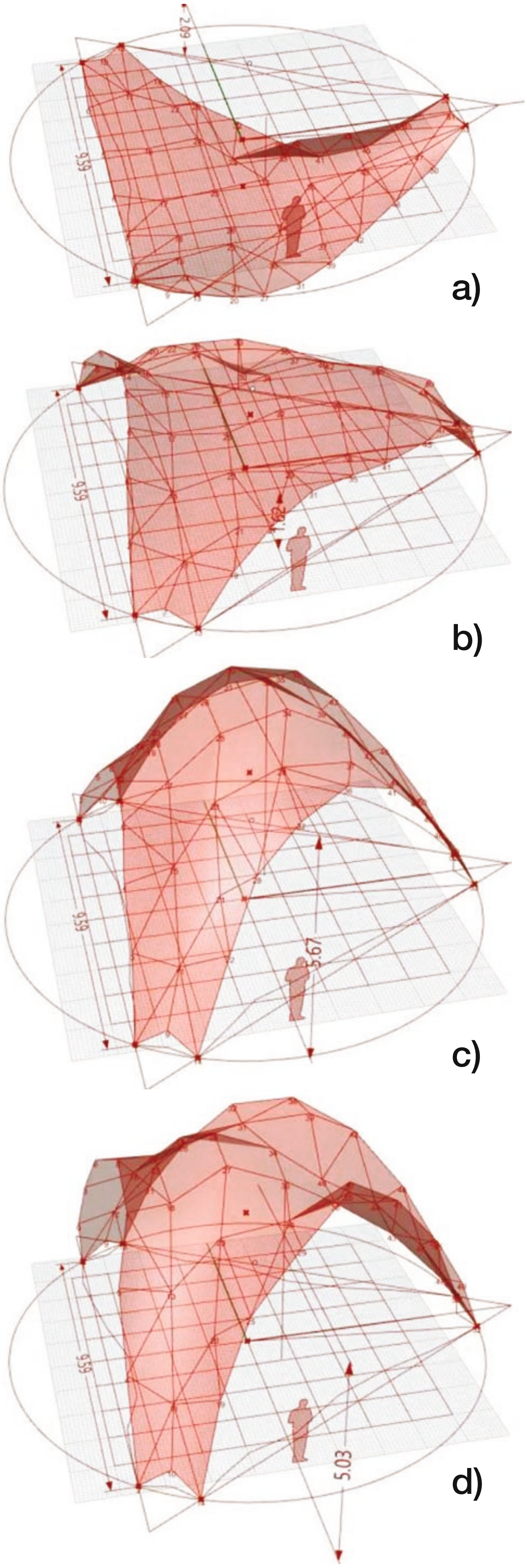


Fig. 6. Exhibition Pavilion of the University of Zielona Góra, 2022–2023 – Grasshopper script for form-finding; source: Author

Kangaroo Physics developed by Daniel Pikeris the most popular tool within the large community of designers using Rhinoceros for integrating physical behaviors through fast simulations within the modeling process. Piker described Kangaroo as a physics engine directly embedded in the parametric modeling environment of Rhinoceros-Grasshopper allowing interactive exploration of geometrical shapes through simulated behaviors based on material properties and applied forces. Kangaroo Physics, a physical simulation engine, is dedicated for users with moderate computation skills. It provides a simplified interface for an advanced simulation tool. Thanks to the visual scripting interface provided by Grasshopper, the user has access to a fixed set of physical 'goals' and unitless variables, without having to work with more complex aspects of the Kangaroo physical model. This setup induces a disconnection between the user and the physical model with its variables. It is a Particle Spring System (PSS) relying on the Dynamic Relaxation method and offering a wide design space. A physics engine is a collection of algorithms that enable a computer to simulate some aspects of the behavior of real-world objects [D. Piker 2013].



FE Analysis of the structural model was carried out in Karamba3D in terms of the use of material properties (wood) and structural and material efficiency (Fig. 8a–e). Karamba3D is an interactive, parametric add-in for Rhino/Grasshopper that expands its capabilities in Finite Element analysis. According to C. Preisinger: "*Karamba3D is embedded in the parametric environment of Grasshopper which is a plug-in for the 3d modeling tool Rhinoceros. The initial computational core of Karamba3D has been developed by Clemens Preisinger during the research project 'Algorithmic Generation of complex Spaceframes' at the University of Applied Arts Vienna. Upon completion of the research project, the initial code basis was further developed in continued cooperation with Bollinger+Grohmann. The first release came in 2010 as an interactive structural design plug-in for the visual scripting environment of Grasshopper for Rhinoceros. Since then, Karamba3D has spread around the world through practice, research and academia*" [C. Preisinger 2013].

Karamba3D provides accurate analysis of shell structures, spatial trusses and frames. It calculates and visualizes displacements based on loads, materials (primarily Young modulus and shear modulus), cross sections and supports, which must be considered in both ULS and SLS analysis. In structural design, ULS (ultimate limit state) refers to the maximum loads or forces that a structure can withstand without collapsing or experiencing any irreversible damage. To calculate the ULS, engineers designing the construction system use a combination of analytical and numerical methods. The ULS is an important concept in structural engineering as it ensures that design structures are safe and can withstand extreme loads and environmental conditions. The SLS (serviceability limit state) is defined as the state of design beyond which a structural system loses operationally its serviceability for the actual service load that the structure is subjected to.

Architects can use Karamba3D in the early concept phase to perform quick, interactive analyses of different design options for shell structures. However, advanced FEA tools such as Robot, SAP2000, GSA would be required to perform the final code checks during the later design phases. Despite limitations, Karamba3D is a convenient Finite Element Analysis (FEA) tool, which allows for accurate prediction of the behavior of the structure under various loads. The designers can also consider the effects of various environmental factors, such as solar radiation, wind, humidity, earthquakes, and temperature changes, which can affect the behavior of the building and its structure.

Fig. 7a–d. Exhibition Pavilion of the University of Zielona Góra, 2022–2023 – Kangaroo Physics form-finding; source: J. Juchimiuk, Author

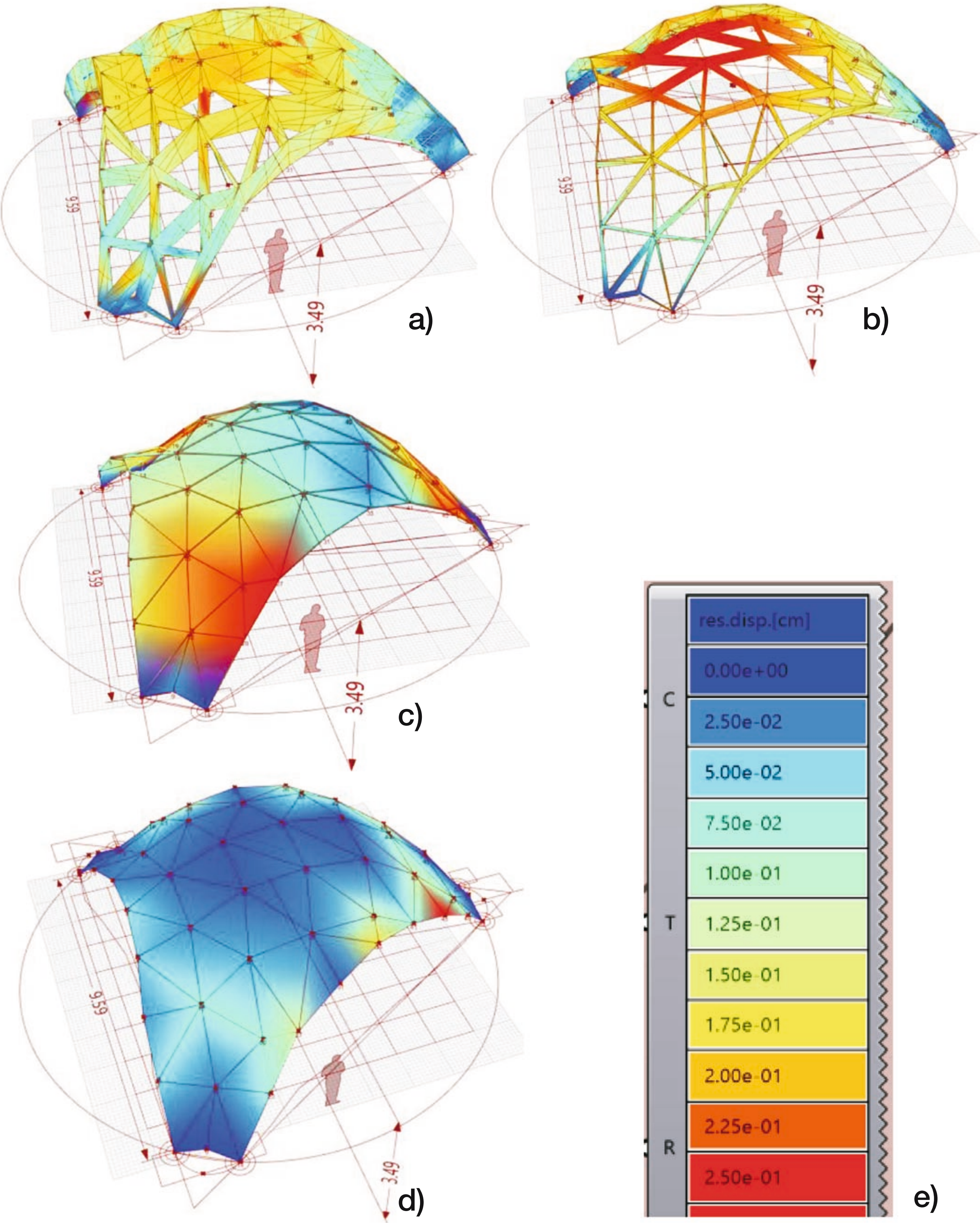


Fig. 8a–e. Exhibition Pavilion of the University of Zielona Góra, 2022–2023 – Karamba3D FE analysis (max. nodal displacement), a–b) gridshell structures, c) Segmented shell (structural panels), d) Segmented shell (flat panels), e) color scale (0–2.5 mm); source: Author

CONCLUSIONS

In architecture, defining form is an important stage of the design process in which the material obtains its spatial configuration consistent with the structural, functional and aesthetic intention. This process is iterative, in which constant changes allow obtaining the appropriate form for a specific design problem. Architectural and construction aspects are inextricably linked in design. In particular, this applies to shell structures carrying mainly compressive loads, as well as purely tension structures such as architectural membranes. Because their shape is subject to physical laws, the physical model plays a significant role in design because it represents the most comprehensive method of acquiring knowledge. It is a medium through which, at a first approximation, allows the initial idea to be materialized and translated into a feasible structure. The physical model helps both in the process of searching for a form and in the procedure of validating a conceptual idea [J. Chilton 2010].

The digitization of computational processes has meant that many complex, often non-linear phenomena of reality can now be described by mathematical models. Computer graphics have become helpful in illustrating the course of modeled processes. Currently, there is some exchange of ideas and techniques between architecture and disciplines such as biology, physics, chemistry and mathematics to imitate recognized processes occurring dynamically in nature. Architects' attention is increasingly focused mainly on natural form-finding processes for structural optimization and adaptation and on their instrumentalization through mathematical models and computational techniques, as well as their simulations and digital visualizations.

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