THE IMPACT OF CONTEMPORARY TECHNOLOGY ON SHELL STRUCTURES: MATERIAL AND LIGHT SOLUTIONS

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ABSTRACT

With the development of technology and the materials used, shell structures have developed into more complex forms. This article is a comparison between contemporary and historical shell structures. The change is an effect of the evolution in the design process that is the result of parametric design thinking. The study aims to investigate the impact of new technologies on the architectural form of shell structures. Was there any pivot point in the history of shell structures? The secondary objective of the study is the focus on lighting in such forms and their evolution with the view of the evolution of lighting solutions applied in architecture. With the use of new technologies, shell structures can have a new form and complex detail. They may vary in scale from small objects to large-scale structures.

Keywords: *Shell structures, computer design, digital design, sustainable constructions, artificial light, daylight, curvature*

1. INTRODUCTION

Shell structures are defined as a rigid thin combination of the carrier and covering system. Hyperbolic paraboloids are surfaces that enable large span widths with small thickness, they are generated by moving in straight lines [1]. The first thin hyperbolic paraboloid concrete shells appeared in France in the 1930s and were created by Bernard Laffaille and Fernard Aimond [2]. In recent years, new technology has significantly increased the diversity in applied constructions [3]. The shell structures from the second half of the XX century were based entirely on reinforced concrete [4]. In the last 20 years, many new materials have been introduced, starting with wooden and steel construction and ending with light composite fibers and elastic textiles. The achieved design form is often a result of material selection [5-6]. The change is also visible in the achieved form. With the development of technology and the materials used, shell structures have developed into more complex forms. The change is an effect of the evolution in the design process that is the result of parametric design thinking [7-8]. In shell structures, the cover element and the carrier element are consistent. Shell structures were used to cover large areas economically and without intermediate support. However, it is also possible to design amorphous shapes in different scales. Besides this, gaps in different shapes and sizes can be made in shell structures with an increasing variety of materials used today and today's technology.

The aim of the study is to investigate the impact of new technologies on the architectural form of shell structures. New technologies are understood as both design and fabrication methods. Among the design methods, it is worth highlighting here the digitization of the design workshop, in particular BIM (Building Information Modeling) technologies or computational design. In the case of fabrication, technologies related to the automation of creation based on e.g. CNC cutting or the use of robotic tools have an increasing share.

Was there any pivot point in the history of shell structures? If there was, did digital technology have a significant impact? How did the evolution of materials and design methods change the structures and their detail? If the detail is more complex was it connected to the introduction of new materials in shell structures.

The secondary objective of the study is the focus on lighting in such forms and their evolution with the view of the evolution of lighting solutions applied in architecture. What was the character of applied light fixtures? If it has evolved what did new solution led to integration and coherent with the form artificial lighting of the form.

Increasing interest in automation in different fields of engineering has a strong impact on architecture. New design technologies such as scripting automation have a strong impact on the entire discipline. The recent research shows the strong impact of such solutions not only on the design process but also on the final esthetic and character of the design. Architects and designers are exploring new paths and methods of design with increasing interest in numerous forms of automation [9]. Moreover, the architectural education curriculum is developing towards data-based design processes [10] and parametric solutions that increase the flexibility and responsiveness of design [11].

Digital technologies and automation in the design process created the opportunity to improve the quality of detail and application of new forms and materials [12]. Contemporary architectural solutions are often the result of a complex system based on natural patterns of growth [13]. The development of design tools brings a series of new opportunities such as automated creation of floor plans [14] or even entire buildings [15] and, but has to be applied with caution and appropriately selected to meet the needs related to a specific problem. The impact of new technologies on fabrication brought new opportunities to shell structures with the application of materials. The change is visible in the whole field of architectural design [3]. Form finding process is often connected to optimization of the fabrication process that allows for cost management and reduction of manufacturing waste.

The important factor of the change in the design process is driven by the search for more sustainable solutions. The idea is to limit the carbon footprint of design and follow the agenda of three R – reduce reuse recycle [16]. The rising awareness of limited resources and climate change had an impact on all parts of design even applied lighting, to overcome issues such as light pollution[17] The search for more ecological solutions is often the reason for the introduction of emerging technologies into design practice such as block-chain [18]. The recent development of the design process has significantly influenced the way of designing, reducing the consumption of materials and reducing the carbon footprint associated with the operation of buildings.

New technologies are not only positive but also a risk. Automation of the design process may lead to an incomprehensible approach, not only to minor design errors but also to the creation of objects that will not be properly embedded in the urban context. Digitization may also lead to an increase in the repeatability of the constructed objects, but paradoxically it also allows for much greater freedom in the scope of individual adjustment of a repeatable object. However, the greatest risk is the loss of individual design methods and traditional craftsmanship, which often constitute the nature and value of the designed object. A big challenge related to the digitization of a project workshop is the appropriate selection of methods and avoiding repetitive patterns that can reduce the quality of projects.

2. METHODS

The study was conducted in the need for new materials and methods in architectural practice. The method applied in this paper consists of several steps considering historical and contemporary shell structures, development of the design process, new materials applied for shell structures, and new light solutions (Fig. 1). The study is supported by a wide theoretical framework referred to the major direction of change in the discipline of architecture.

The first part of the study focuses on the historical shell structures, with the search for the most relevant ones and their innovation and their future impact on the development of construction and design. The study is supported by an overview of contemporary shell structures with the board view on novelty and reference to historical forms. The outcome of the overview is the selection of elements repeated in a group of representative examples. The selection of examples was preceded by the analysis and comparison of nearly 100 examples of shell structures. The aim of the selection was to find several ones that were most relevant to the development of the design process over nearly 70 years. In the same step, contemporary design methods are analyzed in reference to shell structures, lighting solutions, and newly applied materials are discussed.

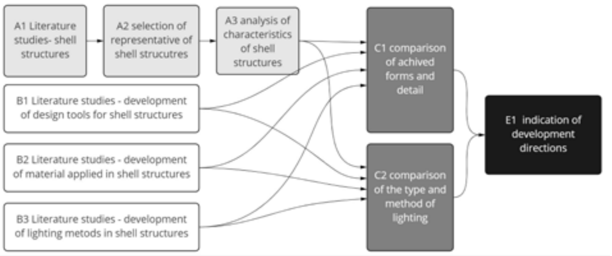

***Figure 1**: Research methods.*

The outcome of the acquired knowledge of the shell structure is the comprehensive examination of contemporary and historical shell structures with a focus on structural materials. In the same step the evolution of light solutions are discussed and their impact on shell structures. All steps are summarized by the determination of changes in shell structures and an indication of the direction of further development.

3. MATERIALS

The constant evolution of the design method has a strong impact on the final outcome. Architects and designers are searching for new methods and material solutions to create buildings and structures for a variety of reasons from higher quality, and lower cost to a smaller carbon footprint. Nevertheless, development and novelty have been a part of the profession since its very beginning. An example of such are shell structures, the forms that gave architects new means of expression and fewer limits in comparison to traditional reinforced concrete constructions.

The overview of shell structures starts with the pioneering work of Felix Candela who was inspired by the revolutionary thought of Laffaille and Aimond, designed in 1958 shell structure called the Los Manantiales Restaurant [19]. The design of the restaurant at Xochimilco in Mexico was based on a search for a new construction form that could have a large span without any additional construction pillars besides the ones that are on the perimeter of the form. The roof covering the restaurant was formed by an octagonal groined vault. As Tomás and Martí [20] argue: From these early experiences, an enormous variety of vaults with free edges were built: triangular, square, pentagonal, hexagonal, and octagonal. It is created with four intersecting hyperbolic paraboloids. Inside the building, there are eight groins marking the roof surface and affecting the outside appearance of the building [21-22-23]. The interest in hyperbolic paraboloids as Dziewrzynska [24] argues: was caused by its positive static properties, allowing the creation of shells with a large span, as well as a great possibility of various arrangements of single shells in compound ones. It is created out of reinforced concrete, steel, and glass facades that open the building toward the surroundings and let in natural lighting. The formwork system was made by straight stripers, in order to make this shell of a restaurant. When the building is viewed from above, it looks like an 8-leaf flower. As a result of this, daylight is provided from all around. In the interior, the lighting elements can be placed to illuminate equally the entire space of the restaurant. Extensions of hyperbolic paraboloids, which are all over the form, also serve as a fringe and shading element. Candela considers this structure as one of the most important shell structures that he has accomplished. It is unique and it has all of the properties that a shell should have: simple, elegant, and light [21].

Another example of outstanding work of Candela is the Lomas de Cuernavaca Chapel, which was designed in 1958 and built-in 1960, using a single concrete sheet with a hyperbolic paraboloid shape with edges constrained by arches made with traditional formwork. The form of the chapel looks like a saddle and is only 4 cm thick [25-26]. Based on a sketch of a triangular raised roof, Candela reshaped the form into a thin curved structure which made the chapel unique and dramatic [27]. The form expands and rises in the seating area of the chapel which is given a feeling of infinity, it narrows and decreases in the part where the altar is located. The chapel is 30 m wide and reaches 24 m in height [28]. The windows are located on the altar side, and on the other side, the form is completely open. With this form of a hyperbolic paraboloid, daylight was used more and provided the religious structure with a different atmosphere, while offering a unique view of the landscape and mountains of the Cuernavaca Valley.

Since 1951, when Candela designed the Pavilion of Cosmic Rays, he completed several projects that involved shell structures. He experimented with different geometries and spatial solutions. One of his groundbreaking projects was San Vicente de Paul Chapel from 1959 which was designed with Enrique de la Mora and Fernando López Carmona. In the project, he created a dynamic form out of three straight-edged asymmetric hyperbolic paraboloids which were combined with two truss beams. The straight-edged forms have an average thickness of 4 cm achieved with reinforced concrete. The resulting geometries are asymmetrical because of irregular curvature [21-23-28]. The resulting form of a space has a unique character because of the dynamic lines that create the inner form of the building. The shape is opened to the daylight due to the space in between the concrete shapes that were covered with steel and colored glass. Natural lighting was provided by leaving a space between hyperbolic paraboloids, additionally, aesthetic features are provided with the colored glass used.

On the other hand at the time, many other architects and engineers experimented with the new free-form shapes that were introduced to architecture. One of them was Heinz Isler [29-30] who experimented and devoted his work to applying new forms to the discipline. One of his early projects was Wyss Garden Center from 1962, which was created in Solothurn. The Swiss engineer developed new form-finding methods by using expansion, inflation, and hanging of thin membranes. The methods applied by Isler enabled optimal forms in terms of structural behavior. Sasaki [31] defines a membrane shell as an expansion of Antoni Gaudí's inverted hanging arches to curved surfaces. He balanced perfectly the aesthetics of his shells against their structural efficiency [32-33]. When the dome is viewed from above, it looks like it was cut with four lines from the sides. These openings sides become the facade of the building and are used for lighting and entrance to the building. The structure is constructed on the ground with four points. However, because of the Switzerland climate, it needed additional insulation, as Tang [34] argues: Insulation was used as permanent shuttering in many of Isler's shells. [..] thin timber boards were placed at regular intervals across the beams or trusses. The insulation was on top of this and has a role as permanent shuttering.

The shell forms were also applied due to the need of a large span, Palazzetto dello Sport was built in Rome, for the Summer Olympic Games in 1960, by Italian architect Annibale Vitellozzi and structural engineer Pier Luigi Nervi. The spherical cap is chosen as the architectural form and there is a pressure circle in the center of the shell. This pressure circle is used for natural lighting and hanging lighting installations. The shell is 58.50 m wide and in height reaches 21 m. To create the cladding of the roof 1620 precast concrete panels were used. With the joining of these panels, radial arcs were formed in the interior of the dome, and this image resembles a sunflower. To reduce the shell thickness by rippling edge stiffening the architect decided to create a ribbed shell dome that was possible due to the use of ferro-cement as a construction material. The material is created out of concrete and rigid steel mesh. The spherical roof is raised from the ground with 36 Y-shaped columns. These Y-shaped columns collected and transferred the forces to the ground [28-33-34].

Newly adopted technologies and materials have a significant impact on the form of contemporary shell structures and their detail. The development of the design process that is the consequence of new tools and materials allowed for new architectural forms and complex detail. However, there is still a strong connection between classical shell structures and new forms that follow the same directions of design.

It is common to base a new design on the principles of the classical one. An attempt like that is the KnitCandela pavilion design by Zaha Hadid Architects and ETH Zurich. It is an exhibition shell structure that pays homage to Candela. The main inspirations for the project were the Los Manantiales Restaurant and the traditional Mexican dress. The textile material was fully automatically knitted [35] at the ETH in Zurich, Switzerland, and then just carried in suitcases to Mexico. At the same time in Mexico City, the supporting structure was built. After mounting the textile material on the form, the construction was insulated to avoid leaks and then covered with concrete. This approach introduces a new kind of formwork that besides taking its basic role can have a visible role in building aesthetics. In the KnitCandela the textile material that was used as formwork for thin concrete shell had a strong impact on aesthetics. A unique colorful inner surface that stands out from other shell structures was created with the custom 3D weft-knitted textile [36-37-38]. Besides, the concept of the supporting frame falsework was to make a self-stressed system that did not require any anchorage into the site ground structure. The structure was designed as a 3 cm-thick concrete shell with 4 cm-deep stiffening ribs running in both directions [39]. The resulting plan of the building is significantly larger than the area covered by these support points, as the structure rises, its surface has increased and some of it acts as a canopy. Since the KnitCandela was made for a temporary exhibition, no lighting elements were used.

The spatial experiments and competitions work often bring new forms to the architecture. An example of such is the Trifolium pavilion was designed by Australian studio AR-MA and built for the Sherman Contemporary Art Foundation's (SCAF) annual competition that seeks to solve some of the emerging issues. To achieve the complex form more than three-thousand unique panels were put together. When making hyperbolic paraboloid shells, flat boards are used in molds, here they were used as a self-supporting final structure. The thickness of the shell gets thicker as it approaches the support where the shell sits. Shell structures have high bearing strength as well as very thin structures. Due to the chosen construction method, no mold was used. All the pieces were fabricated beforehand and then assembled on the site. In the interior shell; curved, black, mirror-polished stainless steel panels were used. Lighting is placed within the concrete paving slabs with fibre-optic cables that also create reflections on the inside. As a result, the space changes all the time. In other words, the image is infinite according to the time, the light, and the angle viewed [40].

A quite similar design method was used in the Buga Wood Pavilion, which was designed and developed in 2019 by The Institute for Computational Design and Construction (ICD) with the Institute for Building Structures and Structural Design (ITKE) at the University of Stuttgart and BUGA GmbH and Müller Blaustein Holzbauwerke (Daniel Müller, Bernd Schmidt, Oliver Fried, Reinhold Müller. The pavilion was designed using computational design and robotics technologies. The form was inspired by the plate skeleton of sea urchins and is a temporary building with a height of 30 m, built for events and concerts. Each of the 376 polygonal pieces that were created by combining six different wooden layers and joining was done by robots. Wooden parts were screwed together from pre-drilled points. They were installed at the construction site using cranes, in ten working days by a team of two craftsmen [41-42]. Bechert et al. [43] defined segmented shell structures as load-bearing structures composed of individual elements that are joined along their edges. The resulting form is created out of planar elements and is considered a polyhedral plate structure [44-45]. The shell has the function of both carrier and covering element therefore can be classified as a segmented shell structure [45-46]. The empty part of these polygonal elements provides both daylight and space for the design illumination system. In Buga Wood Pavilion, artificial lighting is provided by placing LED light elements in the wooden parts that make up the shell. In addition, the lighting elements placed in each piece illuminated the interior of the shell homogeneously.

The innovative attempt to create a shell structure with assembled multiple elements was made by Marc Fornes from THEVERYMANY. The Hyperbole was composed of flat aluminum parts which we calculated with a computer program. This shell structure consists of 582 3-millimeters thick aluminum panels and is supported by 3 different points on the ground. Compared to the concrete shell structures it is extremely thin. The solution is similar to the use of flat interwoven wood strips, such as in Shigeru Ban projects, which can increase project sustainability[46]. The technology used for the project is a development of technology from early projects of Marc Fornes such as The Labrys Frisae, as Andrew H. Dent and Leslie Sherr [47] argue: only aluminum sheet offers the stiffness, workability, accurate cutting, and permanence that this unique installation possesses. Sometimes, different patterns or color transitions can be seen in structures created by combining pieces such as puzzles. While lighter tones are used in terms of being bright in the interior, these colors may differ on the outside of the building. The color of the structure is light green and gets slightly darker upwards, on the interior near the top is blue, which is reminiscent of a sky and gives a feeling of infinity. Daylight passes through the gaps formed at the joints of these parts and holes created in each panel. Thus, different light games can be seen in the interior depending on the angle of the solar light and the locations of the gaps.

Shadow play and perforation became a permanent part of contemporary shell structures design. Markus Schietsch Architekten in the Kaeng Krachan Elephant Park at Zoo Zurich, have used perforation for the daylighting system. The object is designed for up to ten elephants and has an area of 8,440 square meters [48]. People can closely watch elephants from the glazed pool. Elephants can travel freely between indoors and outdoors. Due to the undulating form of the roof, the height of the edges of the roof is different from the ground. In parallel with this, since the glass ratios change on the facades, the amount and angle of daylight also changes. There is a reinforced-concrete tension ring at the low point of the roof, which prevents the shell from splaying. The wavy wooden roof was formed from 550 uniquely shaped, cross-laminated spruce panels. The roof has 271 openings providing natural light that sums up to 30 percent of the entire shell, and at the same time, the weight of the shell is reduced [49-50-51]. Natural light coming from the roof is highly important for inhabitants and necessary for elephant vegetation. The necessity is emphasized by Maulana [52]: The conditions are even if the elephants are not free, trying to create a home for elephants to feel in their natural environment.

4. RESULTS

Nowadays shell structures are based on the heritage of pioneering achievements of technology from the mid-twentieth century. Los Manantiales Restaurant, Chapel of Vincent, Lomas de Cuernavaca Chapel, KnitCandela, Hyperbole, Trifolium are based on a geometric form of a hyperbolic paraboloid. Wyss Garden Center, Palazzetto dello Sport, Buga Wood Pavilion, and Kaeng Krachan Elephant Park are created in the form of a dome(Figure 2). The differences between objects are visible in materials used for the construction and approach towards the usage of daylight. Even though the general idea and the shape are similar there are a lot of significant differences in the achieved form and process of construction. New material applied in shell structures allowed the creation of even thinner and lighter construction with more openings (Figure 5).

New technologies such as parametric design, scripting, or automation allow for more precise construction and material selection freedom. With the change in architectural design that incorporates more often the process of fabrication that change is visible in the material selection that spread from wood through steel and aluminum event to textile (Figure 3). Early shell structures were made almost entirely out of the cast-in-place reinforced concrete while contemporary objects use cutting-edge technology such as double-curvature self-supporting form created with planar aluminum plates, through textile-material formwork, wooden panels to robotically cut Corian heat-bent panels. The change is a result of the 1990s digital technologies revolution [3-53] that has significantly changed the process of design [50] and had a huge impact on the resulting forms. As noticed by Šimkovič et al: *The digital approach to architecture - algorithmic, parametric, emergent modelling processes - have the ability to process complex influences and reflect them in the formal and/or programmatic structure of architecture and design [54].*

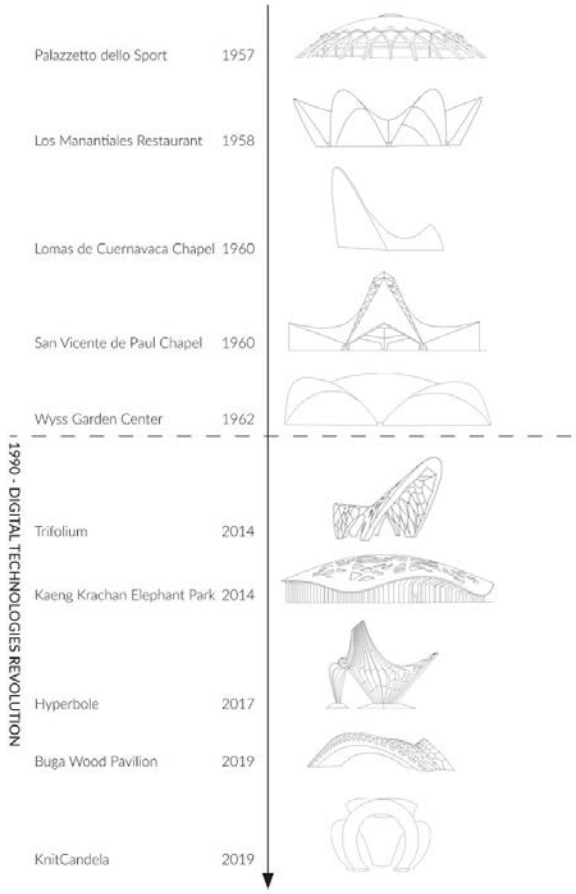

***Figure 2**: Shell structures development.*

New materials introduced into shell structures changed many parameters of the analyzed objects. The main change is obtaining a different architectural character and expression through the introduction of wood and steel. The above changes also contributed to changes in the field of construction and allowed for a new approach to the design of shell structures, e.g. in the context of the use of color and the possibility of integrating artificial lighting in the structure itself. What's more, the new materials have made the objects thinner and thus achieve completely different proportions. An important element of the study and change is the possibility of reducing the carbon footprint of the designed structures in relation to objects traditionally made of reinforced concrete.

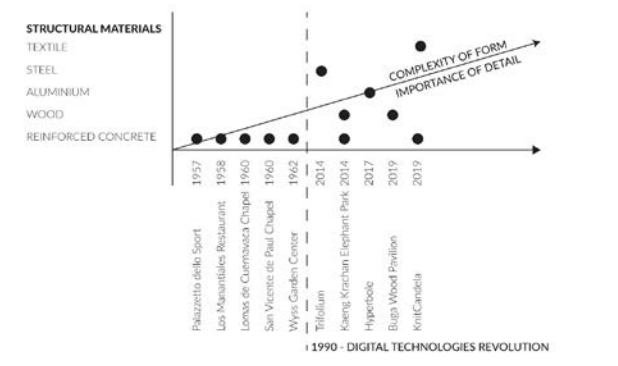

***Figure 3**: Structural materials in shell structures.*

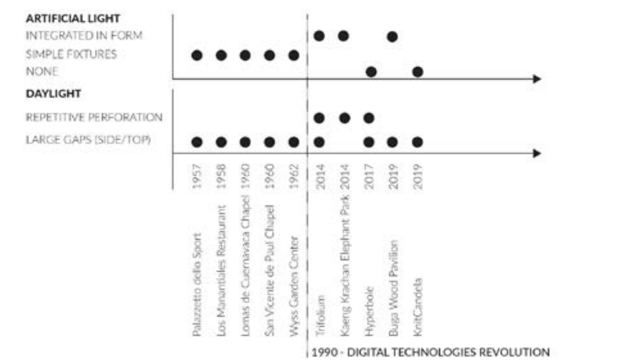

***Figure 4**: Light solutions in shell structures.*

The scope of analysis related to lighting is very wide. Light can be analyzed in terms of daylight - atmospheric light, as well as artificial light and its integration into the form of a building. Each of the above can be considered on the basis of its parameters, color, or strength, but also the climate that gives the object or, for example, the way in which it changes the architectural expression of the object. The conducted analyzes, however, focus on the basic aspects related directly to the form of the object, i.e. the type of artificial lighting used and the method of using daylight. The changes that have taken place in the design methods and materials used have had a significant impact on both of the above aspects.

Moreover, the way of lighting the interior has changed due to recently introduced materials in shell structures. In the early projects, the light was let in through the glazing located between the individual forms, today architects are eager to use the holes in the construction material itself, which gives more freedom in the form-finding process and enables even interior lighting with daylight (Figure 4). However, there were expectations from this such as Candela's Textile Factory from 1954 or Isler's Coop Warehouse from 1960, where lightning was created with regular perforation [54]. However, such a solution was a minority back at the time. Direct access to daylight is beneficial for health and should be considered one of the most important factors in the design process [55]. The development of the lighting system also contributes to energy savings [56]. In some recent examples such as the Buga Wood Pavilion or the Kaeng Krachan Elephant Park, artificial illumination systems became fully integrated into the form, so that the illumination naturally highlights the designed form of the object.

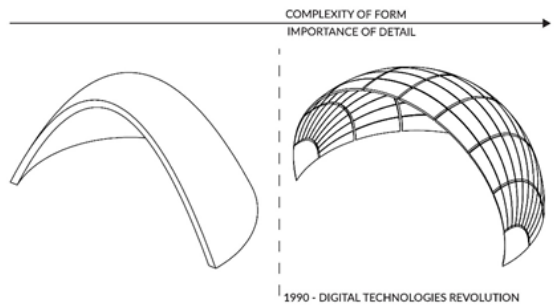

***Figure 5:** Change in shell structures – increased complexity of form and importance of detail.*

5. DISCUSSION

Shell structures are one of the most efficient and material-saving solutions for large-span objects. This ongoing change is also affected but new materials such as wood and bamboo [57]. The material solution can also decrease the carbon footprint of the designed building. The scope of materials used in the design process should be extended with the analysis of alternative material solutions and the importance of design decisions within the context of sustainable design should be emphasized. It is also relevant to notice the detail of form and its impact on the final quality of the achieved architectural form (Figure 5). This does not mean that the creators following the traditional workshop did not pay attention to the details of the project, but that the possibilities of refining and analyzing them were smaller. Moreover, the multitude of materials currently used in shell structures means that we are often dealing with very unusual solutions related to their joining. A perfect example of this is the proprietary fabrication method used by THEVERYMANY, based on the parallel joining of thin aluminum panels of various colors with rivets. It can change the interior exposure to the daylight and allow for better suited to the form and highlighting its characteristic features. Moreover, the size of structures and distances between construction elements has increased. Today, it is possible to design free-form, functional, effective shell structures by using shell geometries whose curvature is determined by the architect.

Moreover, it can also impact access to daylight and provide opportunities for designing integrated lighting systems that have a lesser impact on the natural environment [58]. The proper selection of lighting system can also emphasize the final architectural form and make its spatial components visible[59]. It can also increase comfort and living qualities inside the building [60]. The use of light in built environments has comfort, behavioral, economic, and environmental consequences [61]. The correct design illumination can have an impact on economic factors such as the need to replace plants or the quality of life for humans[62]. Reinforced concrete shells with large spans often lack daylight, for this reason, it is important to have additional gaps for lighting, however, created in a way to limit the effect on the static of the shell structure [63]. In order to allow light to reach the required amount proportionally, lighting can also be provided from the top by designing galleries, skylights, or pressure rings in the domes. Also, if there are gaps in the side parts due to the form of the structure, these can provide natural lighting. Sometimes the shell structure may consist of a combination of several minor shell structures. Gaps that are left between these shells may provide natural lighting and ventilation. Elevating the dome from the ground with columns changes the angle of incidence of sun rays, as a result, the amount and intensity of daylight are increased [64].

The differences related to the achieved form, the type of material used, and the method of illumination of the object with daylight and artificial light were analyzed. However, it should be noted that due to the introduction of a number of changes in both the design and construction process, other features have changed, such as structural behavior, solutions that allow for obtaining appropriate stiffness, ways of relieving the structure or methods of providing insulation in terms of obtaining required humidity and temperature. The above may be a good starting point for further considerations.

6. CONCLUSIONS

The architectural design process through the years has developed and incorporated many new aspects such as digital fabrication, parametric design, scripting, and even automation. The development has been supported by the rising awareness of environmental challenges. All that has a major impact on created forms, used materials, types of lighting, and architectural detail. Due to the pioneering character of shell structures, the change we can observe is even more visible than in other architectural objects.

Nowadays, different materials are being used for creating shell structures. Constructions are based on traditional reinforced concrete created on wooden formwork or on emerging new solutions such as textile supporting structures. Moreover, steel, textile, and wood have been used for creating shell structures. These materials can be used separately or in a combination. For example, wooden parts can be joined with fiber or yarn. New materials and technologies led to different more precise detail-oriented designs and new possibilities for illuminating with daylight and artificial light systems. With the use of new technologies, shell structures can lead to many different forms. They may vary in scale from small objects to large-scale structures. These merged processes can involve advanced robotics to reduce tolerance and create structures more precisely. Moreover, with the rising cost of human labor, robots can soon become a permanent solution for more complex constructions.

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