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Article

The Obverse/Reverse Pavilion: an example of form-finding with isogeometric analysis in the design of temporary, low-cost and eco-friendly structure.

Jerzy F. Łątka [1]* and Michał Święciak [2]

[1] Department of Architecture and Visual Arts, Faculty of Architecture Wroclaw University of Science and Technology, Poland; B. Prusa st. 53-55, 50-317 Wroclaw, Poland; ORCID 0000-0003-1122-0933; jerzy.latka@pwr.edu.pl
[2] Super Architektura Michał Święciak; Plac Niepodległości 2/22, 86-300 Grudziadz, Poland; www.superarchitektura.pl; SuperArchitektura@gmail.com
* Correspondence: jerzy.latka@pwr.edu.pl; Tel.: 0048 605 606 880

Abstract: Temporary pavilions play an important role as experimental fields for architects, designers and engineers, apart from providing exhibition spaces. Novel structural and formal solutions applied in pavilions also can give them unusual appearance that attracts eyesight of spectators. In this article authors explore the possibility of combination of structural novelty, visual attractiveness and low-cost by a design and construction of a temporary pavilion. For that purpose, an innovative structural system and design approach was applied, i.e. membrane structure designed in Rhino and Grasshopper environments with the use of Kiwi!3D IsoGeometric analysis tool. The designed pavilion, named Obverse/Reverse, was built in Opole, Poland, for the occasion of World Architecture Day in July 2019. Design and construction was performed by the authors in cooperation with students' organisation Humanisation of Urban Environment from the Faculty of Architecture Wroclaw University of Science and Technology. The Rresultant pavilion proved the possibility of obtaining a low-budgets but visually attractive architectural solution with the adaption of parametrical design tools and some scientific background with innovative structural systems.

Keywords: parametric design, paper in architecture, temporary architecture, pop-up structures, membrane structures, isogeometric analysis, fabrication

1. Introduction

Today more and more events such as festivals, trades, exhibitions require individual spatial design and should attract eyesight in order to draw the attention of passers-by. Often, this function is fulfilled by temporary pavilions. Although an event may last for a very limited time, small architecture structures are usually built from traditional materials and in simplified .i.e. rectilinear forms, that result from limitations of using conventional CAD tools.

The construction of temporary pavilions makes it possible to highlight technological, cultural or artistic values and advancements of a presenting person, social group or even whole nations during events, celebrations or fairs. The most famous events allowing for such displays are the World Fairs (EXPO) during which nations exhibit their cultural, scientific and technological legacy and advancements. Those expositions take place in pavilions designed especially for these occasions by architects usually selected through a competition or by honouring their current achievements. Temporary pavilions, originally intended for the facility housing the actual exhibition, had become over the years subject of those exhibitions on their own. Out of the 'temporary' pavilions built on the occasion of World Fairs, some were made using breakthrough technological solutions and they are still standing today (e.g. Portugal's Pavilion – Figure 1). Pritzker award winning architect

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Frei Otto was the author of German Pavilion during World Fair in Montreal in 1967, which disseminated the use of membrane structures. Nowadays, temporary pavilions that display cultural heritage, technological advancement or constitute artistic manifests, occur also during events of minor importance than World Fair's. Every year since 2000 the Serpentine Galleries in London invites a world famous architect to design and build a pavilion that would attract visitors just by its appearance.

Figure 1. Portugal Pavilion for Expo Lisbon '98 - architect Alvaro Siza.

Pavilions attract eyesight as something "which has not been seen before" - especially as built objects which stand and can even be touched, contrary to pictures which nowadays can be arbitrarily altered and depict unreal and impossible structures. In such sense temporary pavilions gained more impact on spectators. In order to outstand from permanent structures and other pavilions, novel and innovative geometrical and structural solutions are willingly used. Tight cooperation between architects and engineers is required in order to achieve solutions characterised by extreme properties such as volume to mass ratio or constructional section area to span.

Nowadays, while new technological solutions are introduced through pavilions (plate-stable structure Trada Pavilion [1] bending-active structures, e.g. ICD/ITKE Research Pavilion 2010 [2]), other technologies, previously reserved for highly specialized designers, become more and more available due to the rapid development of parametric design tools. Membrane structures belong to this group of technologies. Even though permanent membrane structures require specialized approach, the design and construction of temporary pavilions based on this technology is possible. Also as a technology not yet exploited in everyday surroundings, it attracts eyesight of spectators well.

In this article authors describe design investigation and development of an eco-friendly temporary pavilion with the use of parametric design software: Rhnioceros3D + Grasshopper + Kiwi!3D isogeometric analysis plug-in. The obverse/reverse pavilion was designed and built for the occasion of World Architecture Day in July 2019. The software was used at every stage of the project, starting with a conceptual idea, where hand sketches were transformed into the virtual model, form-finding, preparation of shop drawings, fabrication, and construction.

2. Interaction between public space and its users

In contemporary urban environment, the public spaces play a unique role as common areas, where interaction between their users is interwoven with the interaction between the users and the place itself. The public spaces create stimuli and in the same time they are affected and created by other stimuli.

A public space can influence its users' emotions, perception and sense of the space as well as physiological comfort. The reception of the space is influenced by sensory

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systems which can be divided into visual, auditory, basic-orientating, haptic and taste-smell systems [3]. Creations of architects and designers can influence almost all of those sensory systems (or all of them if for example a designed object attracts visitors with its scent i.e. a coffee shop), however the most influential are visual and auditory (so called 'far-space' stimuli), and haptic ones ('close-space' stimulus). The emotional factor is a result of the influence of all sensory systems together with one's own experiences, physiological and psychological comfort. Physiological comfort can be influenced by temperature, humidity, noise and other environmental conditions. Psychological comfort depends on the sense of safety/ danger, inclusion/exclusion which can be characterised by spatial order, organisation, complexity, legibility and mystery, which give the balance between relaxation and stimulation [4].

Public spaces in urban areas are infiltrated by information. The amount of information creates a chaos, which in fact becomes disinformation, where every single player of the public market tries to get the attention of a potential visitor. The dominating sensory system is a visual one, however visual perception can be amplified by the psychophysiological component and other sensory system experiences [5]. This multi-layered sensual composition creates a narration about the place and events that occur in architectural scenography.

3. Pop-up structures

In a public space design, the complementary order of space, movement and events should be considered simultaneously. The space can be treated as a stage where architectural events take place while the observer is in motion. The conditions such as user's emotions, perception, sense of the space influenced by the legible, narrative design are the key to successful design of an architectural object in public spaces. Especially when its role is to trigger someone's attention by being positively received.

The cultural development and economic development are correlative. It means that by strengthening one of them, the other will also be enhanced. Architecture has a significant impact on the cultural regeneration of the city. The realisation of a spectacular public building that draws people's attention, brings the popularity and crates a space for cultural events and thus economical boost already has its name in academia and architectural language: "wow-architecture" or "Bilbao effect" (after the great success and development of Spanish city of Bilbao thanks to the realisation of Guggenheim Museum designed by Frank Gehy in the mid. '90s). Those visionary buildings bring new qualities in neighbouring areas, re-establish local identity and break through traditional barriers.

However, wow-architecture created by famous architects might be a risky investment. As Lähdesmäki states, those big and large investments are not flexible to the changing demands and strategies for cultural regeneration. The other solution for architectural and cultural regeneration might be the use of temporary architectural structures for cultural, commercial or leisure use [6]. Those event-oriented architectural installation can create space or landmark for cultural activities. They also can achieve the wow-effect, although on a smaller scale and with a much smaller budget involved. Therefore the solutions that bring new and surprising quality in the existing (i.e. known) context of public spaces are temporary structures, or so called a "pop-up architecture".

To pop-up means to appear or happen, especially suddenly or unexpectedly, in architectural language pop-up means places such as shops, restaurants, exhibitions or pavilions that operate temporarily only for a short period of time, when it is likely to get a lot of customers [7].

Although the pop-ups are known since the ancient times, when temporary structures had the form of theatres, festival or public games areas, it is since the beginning of the 21st century that they received substantial attention. The popularity of pop-up structures arises from the fact that the urban fabric had been fulfilled with the permanent structures, while the temporary nature gives an opportunity for testing unconventional solutions and experimenting in a public space with limited financial and legislative issues. They are structures or spaces that are built fast and are intended for temporary use which fulfil users' functional and aesthetical needs [8].

The pop-up structures can play a role of temporary pushpin in urban aquapuncture creating new quality in existing spaces and focusing the user's attention on the sense of "being" in particular place [9]. Temporary objects can become catalysts of changes in the existing environment. The example of Shugeru Ban's project of Nomadic Museum, shows how the temporary structure made out of shipping containers and paper tubes brought the attention to abandoned Pier 5 on the Hudson River in New York.

Sometimes, however, temporary structures turn into permanent ones, becoming important urban landmarks or even city symbols, such as the Eiffel Tower, which was intended to be built just for 20 years and currently it has served as a Paris landmark for over 130 years [10].

The pop-ups can have the form of a large and prestigious structures such as those built for Expo World's fairs, they can also be precisely engineered structures designed for repeatedly and quickly assembly and disassembly such as scenography for pop-star concerts. Another version of pop-up ups are recreational machines and infrastructure of amusement park. On the other hand, they can be an artistic expression that provokes a cultural dialog, such as a dystopian amusement park created by the artist Banksy in 2015 in Weston-super-Mare in England, or realisations of temporary summer Serpentine Pavilions designed by the world's leading architects and built annually in Kensington Gardens, Hyde Park in London [11] .

Less spectacular realisations often have a function of small living apartments or public facilities which can be installed both in the urban and non-urbanized space. Temporary architecture by creating a dialogue between the existing urban form and a new, temporary object has significant influence in the urbanised areas where new permanent structures are not possible due to the legal and technical circumstances [12].

Temporary architecture is characterised by simplified structural systems and functional layout. Due to the mobility and lightweight requirements it is most often single story structures. Provisional and experimental character of those objects create an opportunity for implementation of new technologies and materials, which often are derived from different disciplines and industries.

The pop-ups in the urban layout are often stylish urban furniture with the use of innovative low ecological footprint materials. The materials that temporary objects are made of have an important role in the perception. Low-tech materials complemented by advanced technologies from other industries bring new values such as symbolism, emotions, originality and environmental concern.

The sensory (visual, haptic) attractiveness of the pop-up structures can be achieved by both materials used for construction and architectural ones. The latter can carry content and ideas that are in relation to the existing social and spatial context of a urban space.

4. International Day of Architecture in Opole – a case study for pop-up pavilions

Since 2016 the Chamber of Polish Architects branch in the city of Opole has been organising attractions and events on the occasion of the World Architecture Day, established to remember the foundation of the International Union of Architects on 1st of July . The all-day long event focuses on the promotional action of the profession of an architect and its role in a society, exhibitions, presentations, workshops and discussions. A the same time a temporary pavilion is being built every year. The pavilion is prefabricated and then assembled on site. The assembly process is a performance that draws attention and as such is planned as part of World Architecture Day. The size of the pavilion is approximately about 5 x 5 x 5m. Every year the form of the pavilion responds to certain aspects of architectural creation.

In 2016 architect Dawid Rószczka designed and built Wood and Shadow Pavilion (Figure 2). This cubic form with was made out of plywood slender elements that were slit to each other. The whole structure was mounted without the use of any screws or nails. Thanks to that it was practical and easy to assemble and disassemble the pavilion and

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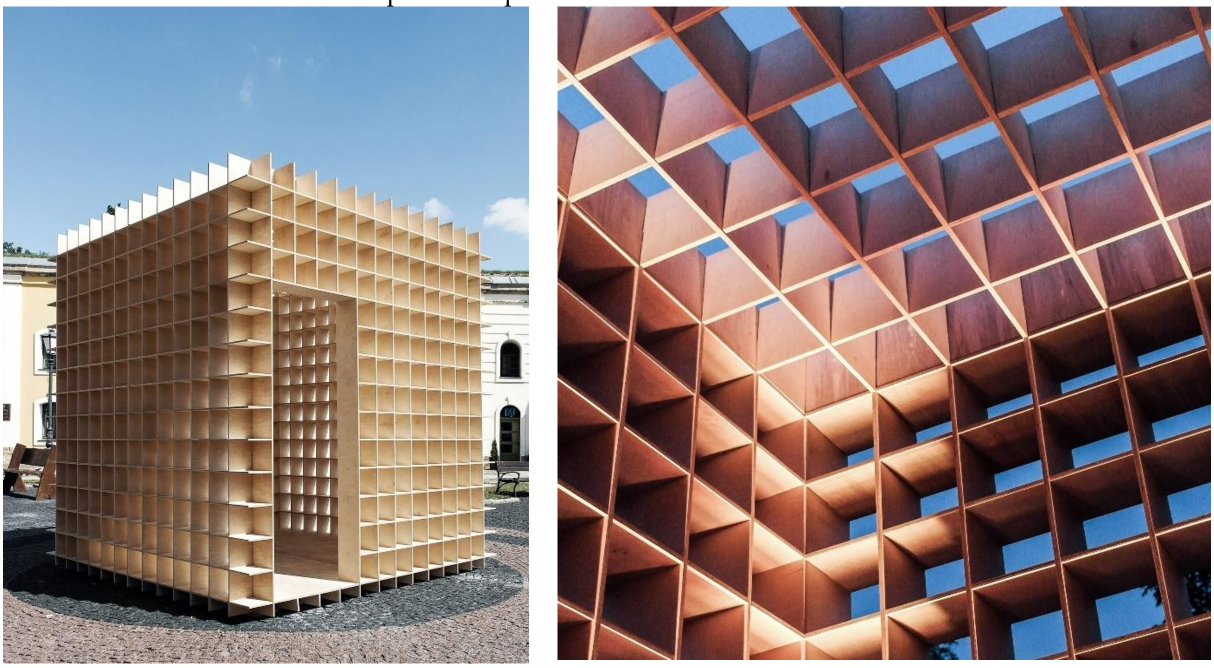
transport between the places. The voids which were created by the orthogonal divisions of the structure allowed the light to go through and visually change the object during the day as well as by means of night backlight. When viewed frontally, the pavilion seemed as a delicate, lightweight structure, however when observed at some angle the thin plywood panels created an impression of a full wall. That resembled traditional Japanese window shutters giving an oriental touch to the structure and responded to the lectures and exhibitions about Japanese architecture presented during the event. The pavilion was first built at Bastion of St. Jadwiga in the city of Nysa and then dismantled and rebuilt at the main square of Opole.



(**a**) (**b**)

Figure 2. Wood and Shadow Pavilion, 2016, a) general view at the pavilion b) interior of the Wood and Shadow Pavilion, 2016 by courtesy of the Chamber of Polish Architects branch in Opole.

One year later the World Architecture Day in Opole was focused inter alia on the activisation of public spaces. Several lectures, discussion and exhibitions concerned this topic. The pavilion accompanying the event was designed by Dawid Rószczka, Kamila Wilk and Łukasz Kościuk (Figure 3). The *Architectonic Sculpture* pavilion was composed out of 14 frames with M-like forms made out of timber planks. This tunnel shaped pavilion was covered with interlining material membrane in order to diffuse the LED light illumination from below. The pavilion was located at the Plac Wolnosci (Square of Freedom) in Opole and served as a needle in the acupuncture of the urban environment. Due to its size and shape it attracted the passers attention to the other events organised within the World Architecture Day. Similarly to the year before, the pavilion was first built in Nysa and then transported to Opole.

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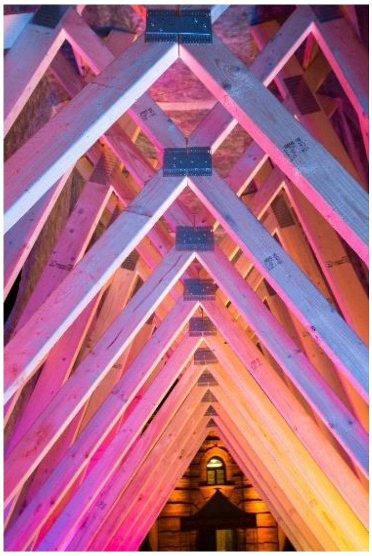
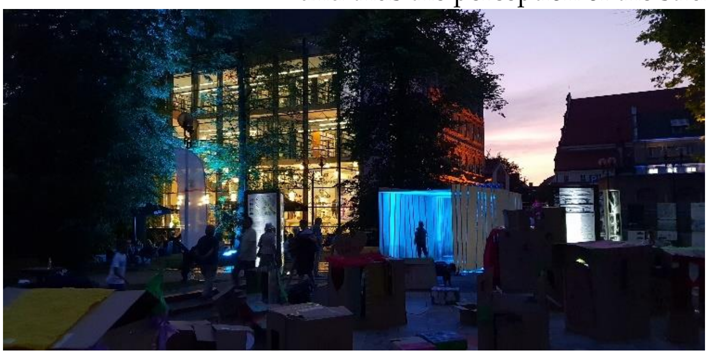
(a)



(b)

Figure 3. The Architectonic Sculpture Pavilion, 2017 a) view at the Pavilion erected in Nysa, photo by Maciej Zych Photography, b) the detail of the pavilion, photo by courtesy the Chamber of Polish Architects branch in Opole

The theme of the World Architecture Day in 2018 was "Architecture and Water". For that occasion the pavilion was designed by Wiesław Półchłopek and Marcin Zdanowicz (Figure 4). The structure had a rectangular shape. The pavilion was made out of timber frame clad with plywood plates. The plates had irregular shapes with gaps between, which brought dynamic perception assisted with day and evening light. The special feature were three waterfalls created inside of the pavilion. This feature was very appreciated specially by kids playing around and it also brought the refreshment into air during the hot summer days. Everyone who wanted to cross the pavilion had to take a special route otherwise it would get wet, giving a straightforward connection between water and architecture. In the evening the Pavilion was lit with LED lights which changed the colours and thus the perception of the structure.



(a)

(b)

Figure 4. Water Pavilion, 2018 a) the view from the at Plac Wolności b) water installation in the pavilion, by courtesy the Chamber of Polish Architects branch in Opole.

5. Obverse/Reverse Pavilion – concept, materials and design methods

In the year 2019 the theme of the World Architecture Day in Opole concerned ecology and architecture. Co-author of this article was commissioned by the Chamber of Architecture branch in Opole to design and construct together with the students from Wroclaw University of Science and Technology the temporary pavilion which would suit the topic.

The aim of the project was to create a pro-ecological, temporary structure, which as an eye-catcher in the urban public space, and would attract attention of passers-by on several levels of interpretation.

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The pavilion was planned to be exhibited for a few days at Plac Wolności (Square of Freedom) in the city centre of Opole, and later to be moved to another location – a square next to the Contemporary Art Gallery in Opole where it should bring a new value as an urban sculpture.

Creation of the project which would meet the demands of pro-ecological character of this temporary object in the urban area was a goal set by the authors during the design and development process. The form, materials and structural feasibility were the main design objectives set out at the beginning of the process. It was obvious that the pavilion, similarly to the previous ones, should have an attractive and surprising form, that would draw attention of the passers-by. Therefore other design criteria that would meet the requirements for pop-up objects in the urban environment were defined as follow:

the object should have a meaning included in its form, which should be narrative i.e. tell some story or have a symbolic code incorporated,

the pavilion should be an eye-catcher i.e. a surprising, unobvious form which stands out from the urban background and triggers someone's attention being received positively in the same time,

the pavilion should influence at least visual and haptic sensory system,

the shape of the pavilion should be unusual and should arouse the curiosity, but on the other hand it should have a soft, friendly (relaxing) but stimulating (not boring) form,

the form should create some kind of narration (coming closer, going through),

the form should be inclusive (accessible , open, accompanied with chairs),

it should have a potential to be a pushpin in the urban area with some sort of wow-effect (with respect to the small scale and limited budget of the object), especially in the later localisation next to the Contemporary Art Gallery.

As the main role of the World Architecture Day was to bring closer the profession of an architect to the wide audience, the formal goal of the design concerned its symbolism. The decision was made to create a pavilion which referred to the double-side character of architectural profession. On the one hand, an architect is an engineer, rationalist who operates in the area of legal, technical and budgetary conditions, who has to face the demands of investors and future users, and often seek compromise solutions that can solve complex and accumulated structural, legal, functional and semantic difficulties. On the other hand, an architect is an artist, creator who cross his/her own boundaries and often is not afraid to dream and think big. The personal development of an architect, even if it is not seen by the others is a constant process in a life-long career. Finally, an architect is a person with many fields of specialization and boards knowledge in the fields of art, engineering, ergonomic, economy, psychology, sociology, history [13].

This tension between the rational and romantic side of the profession of an architect was represented by the form of the pavilion. From the inside, the pavilion received the form of an archetypical house, with straight lines and a double pitched roof. However on the outside, this form grows into an unpredicted, soft shape, which expands outwards from the regular i.e. rational lines into curved i.e. creative peaks. The mind and spirit of an architect grows out of the box as his way of thinking should. Those obverse and reverse sides of architectural practice was underlined by the colours. It is commonly known that architects wear black [14], therefore this colour was used to cover the walls roof and floor of the house-shaped interior, to enhance this stereotype. While the blob-like part was white as a symbol of freedom of architect's mind that can grow unabashedly. Perversely, the superficial perception of the architect was directed inward, while the part that symbolizes his internal development and creativity was directed outwardly, referring to the direct connection of the architect's creation with the surrounding world.

The final form of the Obverse/Reverse Pavilion was developed in several steps shown in Figure 5. First, the traditional shape of a house that formed the interior of the pavilion was skewed. As the both ends were bigger than the middle, the pavilion got an open, inviting form. Next, the longitudinal shape was broken in the middle to reduce the tunnel-like impression and increase the visibility of the pavilion from many directions. The substructure of the pavilion was divided into 5 frames, which formed the inner house-like

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shape. This form was covered with a membrane – an outer skin, which by being parametrically designed achieved an organic, soft shape. The membrane was positioned and stretched on the tubes that were fixed to the frames.

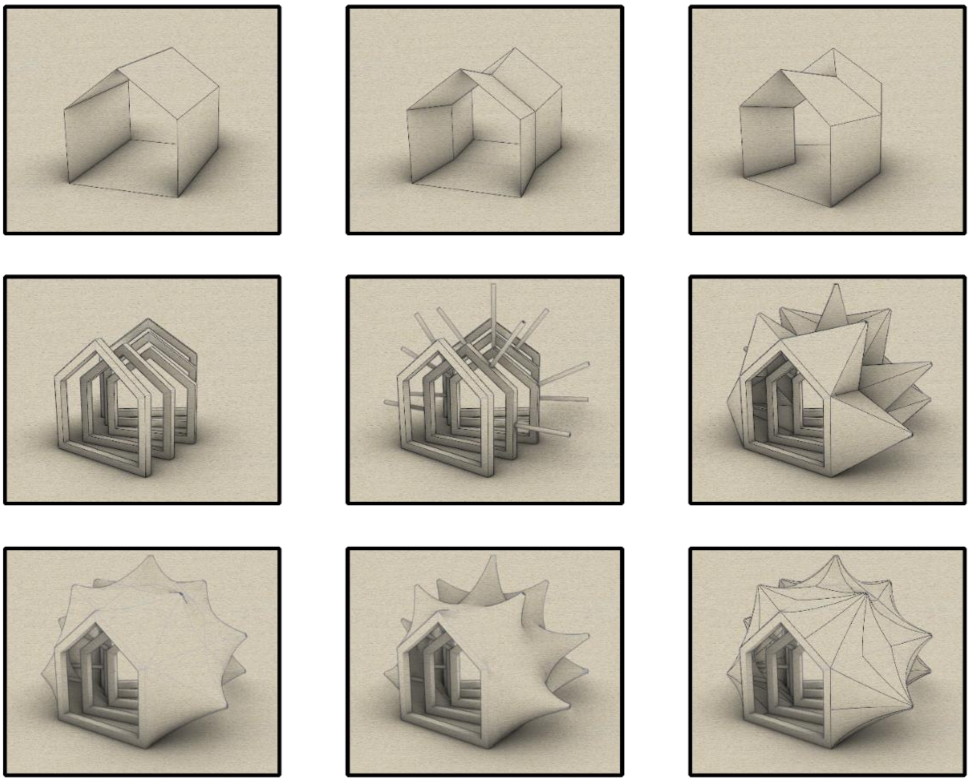

Figure 5. Development of the Obverse/Reverse Pavilion.

As the World Architecture Day in Opole in 2019 referred to the ecology and architecture, it was decided that the main structure of the pavilion would be made to the possible extent with paper- based products.

3.1. Paper in architecture

Paper is a material of natural origin. Its main component is a cellulose fibre, which is the most common natural polymer on the globe and its resources are considered to be inexhaustible [15]. The first attempts of the use of paper in architecture reaches ancient China and Japan, while the European attempts started in the second half of the nineteenth century [16]. The contemporary era of paper architecture began in the mid-1980 when Japanese architect Shigeru Ban for the first time used paper tubes as a structural element in an architectural object [17]. Since that time, there has been a large body of research conducted at several universities such as TU Delft, ETH Zurich, Wroclaw University of Science and Technology or TU Darmstadt. Additional knowledge was gained by the occasion of execution of buildings with paper-based structural elements [18-20].

There are several mass-produced paper-based products which are employed as structural elements of buildings. Paper tubes and full cardboard L- and U-shapes can serve as rod elements, while honeycomb cardboard panels and corrugated cardboard as planar elements. However, paper-based products are often incorporated with other materials for strengthening, protection or improvement of properties of paper-based building elements [21].

Paper is fragile for contact with water. In the case of getting wet, the bonds between cellulose fibres get loose and finally paper transforms into pulp again. This feature allows for recycling the paper elements up to six times, however each time some new fibres are added to the batch to strengthen the recycled material [22]. There are several methods to protect paper elements against water and moisture. They can be coated, painted with various varnishes, covered with foils or other water-tight materials or left natural but placed in such a way so as to minimize their contact with the external environment.

3.2. Computational design of the external skin

The duality of the pavilion also covers relations between architecture and engineering on two particular levels. The first one is revealed as a pure idea of a building, a traditional section shape with walls and roof slopes, clearly marked and cut in space, whereas the second, the engineering level, has no explicit shape that was preconceived by the architect. It is expressed on the external side of the pavilion. Its shape is vaguely specified by the interior conditions – the core idea. External skin of the pavilion is a tensile membrane. Both levels together create an idea dressed up in a structural skin.

External membrane of the pavilion was designed, form-found and prepared for fabrication with the use of Rhinoceros 3D and Kiwi!3D Isogeometric Analysis plugin [23]. Despite Rhino3D was not originally devised as a membrane designing tool, its versatility and add-on resources allow for solving increasingly demanding engineering tasks.

A standard method for describing doubly curved surfaces in Rhino 3D, such as membranes, a mathematical concept of Non-Uniform Rational B-Splines (NURBS) surfaces is used, whereas in the field of computer aided engineering discrete descriptions of forms (meshes) are used that can be used for a finite element analysis. Especially in the context of digital form-finding a continuously curved form cannot be reliably obtained from previously discretized (meshed) simulation model. The discretization itself can also be a source of form-finding and calculation errors. It should also be emphasized at this point that Kangaroo3d, shipped with Rhino 3D, is not a finite element method analysis tool, but an interactive physical and constraint solver.

State of the art membrane designing tools based on discretized models are highly specialized and usually offer abilities to analyse and include in designed structures such factors as intrinsic, anisotropic material properties and imperfections, complying prestressing forces and elastic deformations of fabric [24]. These factors should be taken into account for permanent buildings that during their lifetime will be subject to varying forces such as wind loads, thermal deformations and material fatigue in order to prevent membranes from wrinkling, tearing or flapping. Taking those factors into consideration also require the usage of advanced, multi-layered membrane fabrics capable of withstanding atmospheric influence without deterioration of their structural properties [25]. Although very lightweight, thin and efficient, membrane structures pose a challenge on both designing and production steps.

Although some factors related with material behaviour were omitted during our design process due to a simplified approach, Kiwi!3d allowed us for completion of a whole digital design process, from concept to production drawings, within single CAD environment and without losing the quality of the model, i.e. remeshing of NURBS surfaces. Such a simplified approach is still valid for temporary objects that are geometrically correct and eye-catching. Designing and construction of such temporary structures is nowadays within reach of designers thanks to the increasing accessibility of computer aided engineering tools like Kiwi!3D.

3.2.1. On form-finding

Form-finding strategies have been developed ever since they were first used in a big scale to intentionally devise an optimal from a structural point of view. An examples of well recorded and documented cases of early form finding techniques used in architecture and engineering are the catenary model of Sagrada Familia by Antoni Gaudi and Ponte Musmeci (Musmeci Bridge) in Potenza by Sergio Musmeci [26]. Physical form-finding methods, although powerful and allowing to optimise structure's forms while gaining greater spans, heights, etc., are limited by the natural behaviour of materials used for simulations (e.g. strings, rubber bands, springs, soap films). Nowadays the awareness of feasibility of unconventional structures grows. So called free-formed structures, released from the limitation of orthogonal forms, opened a wide range of studies focused on answering the questions in what scope these structures can be prefabricated and simplified. For example, doubly curved glazed grid shells are composed of parts that are not individually curved (rods, glass panels) [27] and membrane structures are composed of patches that are flat in their original configuration so that as a resource they can be manufactured in rolls of long, developable bands..

So called fabrication aware design, a term introduced to emphasize the responsibility of designing un-orthogonal structural and architectural systems [28]. Apart from answering what shape would be optimal for a particular system of supports and edges of a membrane, it is also important to include fabrication factors into the process of form-finding. In the case of membrane structures that is the anisotropy of materials (fabrics tend to deform more in directions diagonal to their fibres), initial raw material dimensions, different properties of material along seams, etc. Those and other purely geometrical factors are abstract when form-finding membrane structure with the use of soap films. However, digital simulation tools allow us to take some of such abstract factors into considerations [29].

The profound understanding of membrane structures is owed to Pritzker Prize laureate Frei Otto, an architect who has been studying these structures morphologically [30]. His first structures (from 1955) were form-found with the use of physical methods like soap-films and stockings. Otto's membrane structures got chance of gaining worldwide attention on the occasion of EXPO world fair in Montreal 1967. German Pavilion covered with tensile canopies promised technological advancements in terms of lightweights, versatility and durability. In 1969 Frei Otto was invited to cooperation with a design studio who won the competition for Olympiastadion in Munich. The winning project was inspired by Otto's membrane structures. Now tensile structure had to permanently cover about 88,000 square meters. Although the former approach of iterative form-finding and building physical model in a trial and error manner was sufficient for previous buildings, for the purpose of Olympiastadion canopies CAD modelling was also introduced for designing.

In order to design a shape for membrane Otto was using elastic stockings or soap films spread across the preconceived edge borders. The second method was more accurate despite limited to small scales. Tensile forces in stockings are disrupted by forces caused by elastic deformations, whereas in soap films such disrupting forces are eliminated (despite gravitational forces). Studying soap films allows for finding forms (hence form-finding) of thin membranes which are solely under tensile forces. When in equilibrium tensile forces are tangent to the surface of a film. At each point of a membrane two pairs of tension force vectors can be derived, which cancel each other as shown in Figure 6.

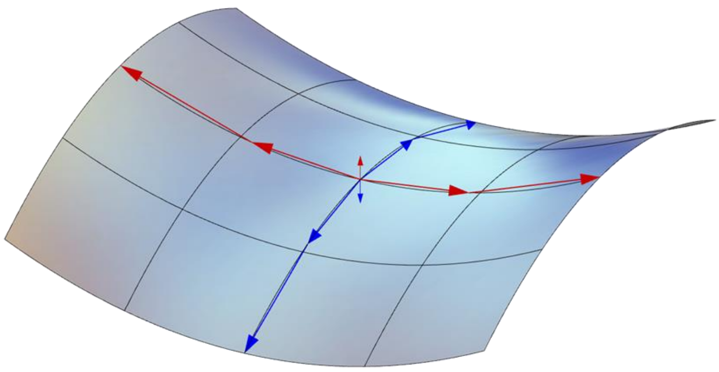

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Figure 6. Anticlastic surface representing a section of a membrane. Forces acting on a point on that surface in two directions shown as vectors. Tangential forces (represented as discretized vector chains) and resultant forces, perpendicular to the base surface.

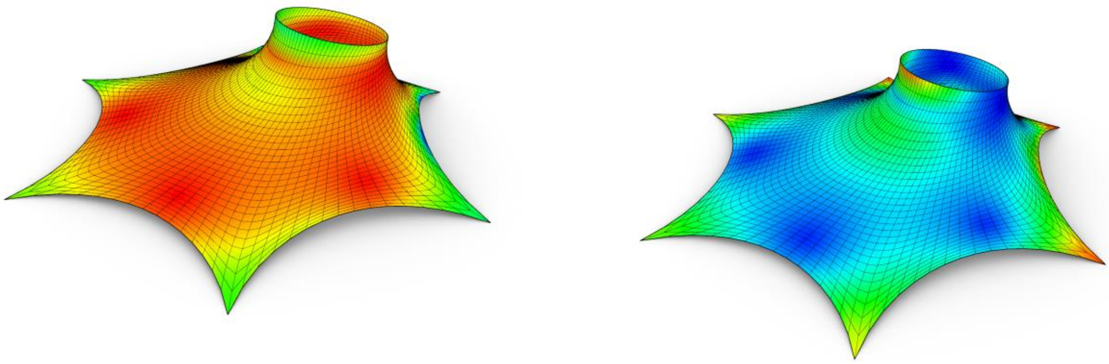
Two opposite vectors are slightly not collinear due to the curvature of surface and their resultant vector is perpendicular to the membrane at a selected point – this force tries to move membrane perpendicularly. However, this perpendicular force is cancelled by an opposite force, resultant from two opposite vectors of tangent forces, that act in perpendicular direction. Hence, if no other forces act on a membrane (e.g. pressure as in pneumatic membrane structures), in order to obtain equilibrium, the curvature of two perpendicular to each other directions have to be opposite, i.e. the surface has to be anticlastic, with negative Gaussian curvature sign.

This principle is naturally obtained by soap films, which at each of its points is moved towards prevalent perpendicular force. This happens until a film takes a form for which both opposing perpendicular forces at each point of that form cancel each other out, i.e. it will reach equilibrium. Tensile forces are transferred onto edges, which are static or onto pretensioned cables. Extrinsically form-finding is explained paraphrasing.

Patrik Schumacher [31]:

Form finding is a physical setup where form self-organizes and it is not drawn by hand or invented or preconceived. It emerges in a physical process.

The greater the curvature, the greater the perpendicular forces are. If individual curvatures along specific directions are not equal, the forces are balanced with tensile stresses, hence tensile forces are usually greater along directions with lesser curvatures and have to be compensated by prestressing (differences of forces regarding directions are shown in Figure 7). This can be done by material reduction along specific direction (the force is obtained from elastic deformation of a membrane) and by adding tensioners along specific edges.



(**a**) (**b**)

Figure 7. Analysis of tensile forces in form-found membrane regarding the (a) latitudal and (b) longitudal directions.

Both stocking and soap-film based form-finding methods are burdened with built-in errors (elastic deformation forces and scale limits), which also overlap with the digitalization issue. Although very useful for educational reasons, geometrical forms of soap-bubbles and membranes are not obvious for everyone - digital form-finding allows us to overcome an obstacle of digitalization instantaneously.

3.2.2. Form-finding of the outer skin of the Obverse / Reverse Pavilion

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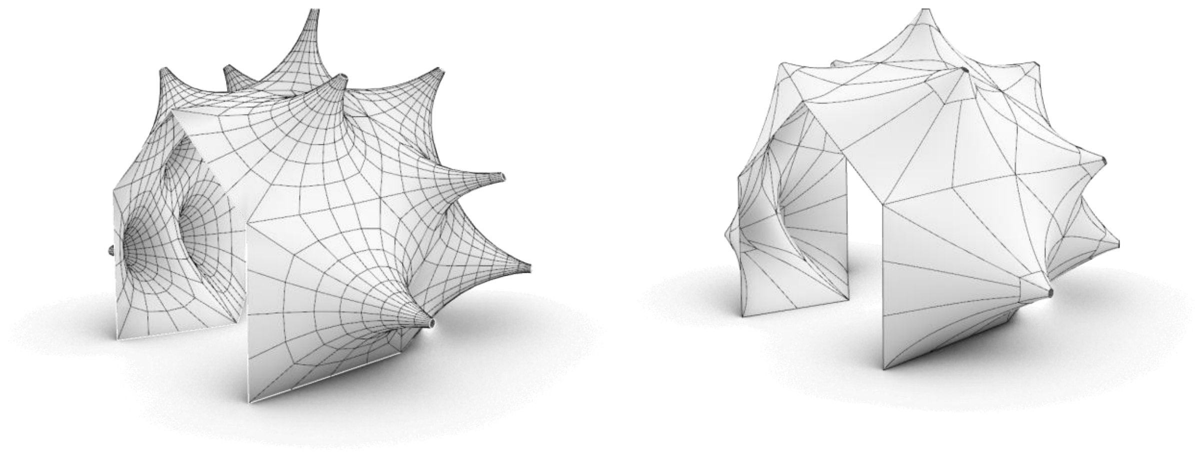
For our case we used two approaches using Kangaroo 3D addon for Rhino3D (mesh based, interactive physics/constraint) and Kiwi3D Iso-Geometric Analysis tool in Grasshopper environment. The results are shown in Figure 8.



(**a**) (**b**)

Figure 8. Comparison of two models: (**a**) minimising edge lenghts of mesh, (**b**) isogeometric analisys of NURBS surfaces.

In Kangaroo 3D a form is obtained according to a setup of geometrical goals. In the case of membranes an edge lengths goal is usually used, which constraints a Kangaroo solver to find such a setup of vertices (of a mesh) that makes the smallest (for the sake of membranes) value of all distances between connected vertices. Target length of edge length can be set to 0 or any other factor or initial length, e.g. 0,5 or 1,5 or any other positive real number. However, lengths between corresponding vertices do not correspond with tensile forces that would appear in a soap film. This approach is burdened with the built-in problem, i.e. the final state highly depends of the initial shape and discretization (the topology of analysis mesh).

Meshing (discretization), by means of finite analysis methods used for form-finding of membrane structures, should not be confused with meshes used for physical/geometrical constraint solvers. In the first case (FEM) each pair of adjacent facets of a mesh (for R2 surfaces) is described by simple functions regarding their interaction and assuming their states. The detailed comparison between Kangaroo 3D with Natural Force Density methods is in [32].

Isogeometric Analysis that we performed with the use of Kiwi!3D, the form-finding process allows us to bypass the discretization step. Shifts of analysed patches of membrane under the imbalanced perpendicular counteracting forces are introduced to a NURBS model by means of its control point transformations. The deeper theoretical explanation is contained in [23].

As seen in the comparison (Figure 8), the differences between approaches are clearly visible.

3.2.2. Creating developable patches

Although it may look like that a full scale membrane gained its shape due to elastic deformations of originally flat material sheets, in fact its shape is primarily achieved due to assembly of material patches that are developable and only secondly due to elastic deformations.

Any form of doubly curved surface (such as an anticlastic surface of membrane) cannot be obtained from a sheet of material that is originally flat, due to the holonomy, i.e. the fact that closed shapes around measured patches of surfaces have smaller (for synclastic) or greater (for anticlastic) internal angle sums that they would have had if drawn on flat surfaces – see Figure 9.

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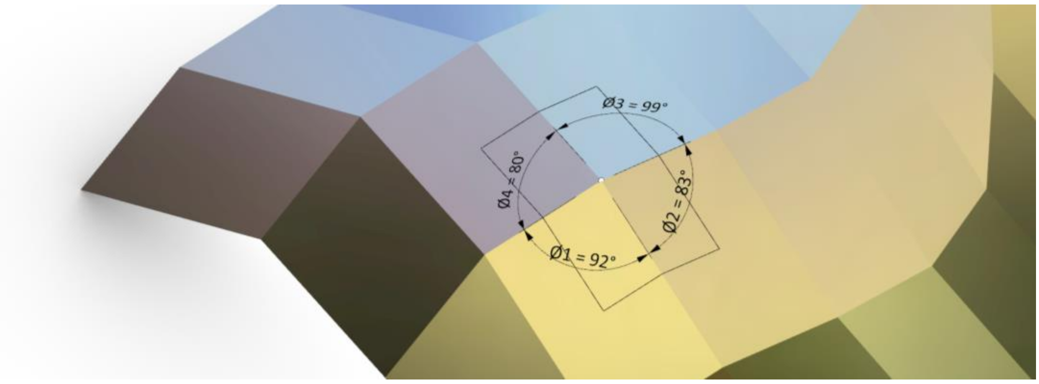

Figure 9. The total angle around a vertex is not a full angle in synclastic, and is more than full angle in anticlastic surfaces.

This means that the material is in deficit (anticlastic) or in excess (synclastic). To a certain extent, these differences can be compensated by elastic deformations of flat material pieces caused by prestressing, however in a global scale, these differences are compensated by assembly of flat patches. Those flat patches can be curved directionally when connected together gaining the form of developable surfaces.

One of the main goals of designing membrane structures is finding or devising the shapes of those patches. In our case factors related with material anisotropic structure, its imperfections (for the big-scale membrane structures a structure is assembled from patches fabricated from material produced in a single production batch in order to avoid any differences), small elastic deformations within single patches and prestressing along with lesser curvatures was omitted in order to simplify the process and obtain a result which is sufficient for a temporary pavilion structure. The fabric, after assembling individual patches, was connected to the base structure without the use of tensioners to simplify the design. The resultant form of membranes was similar to the digital model obtained in a form-finding process, however some acceptable imperfections were observed such as wrinkling resulting from uneven stresses along opposite directions or excess of material.

An IGA analysis takes as an input flat, single or doubly curved NURBS surfaces and plots a result composed of such surfaces. Such 3D model of pavilion's external skin was then further processed in order to devise individual shapes of material patches. Initially the surface of membrane was divided into parts corresponding with each rod pushing it outwards. Such parts were close to the forms of cones with polygonal bases and additional longitude curvatures. Then each 'cone' was further divided around its axis along longitude directions creating triangle-like constricting patches, with concave edges. The divisions were made by the use of geodesic curves, i.e. curves that trace shortest paths between two points on curved surfaces. Pairs of those division geodesic curves were then used for definition of ruled, developable surfaces capable of unrolling on a flat surface and using their outlines as fabrication patterns. By this simplification an excess of material between geodesics that protrudes over simplified developable surfaces was flattened. The greater the distance between geodesics, the greater the simplification error is, therefore the decision about the amount of divisions around each cone was a compromise between precision and fabrication complexity.

The greater the deficit of surface between adjacent patches, the greater the distance between opposite concave edges (Figure 10). When all patches were oriented on a flat surface, one more step was made in which some of the adjacent pairs of 'triangle like' patches from different 'cones' were re-joined together, if the concavity of the opposite edges indicated negligible surface deficit, hence allowing to reduce seams.

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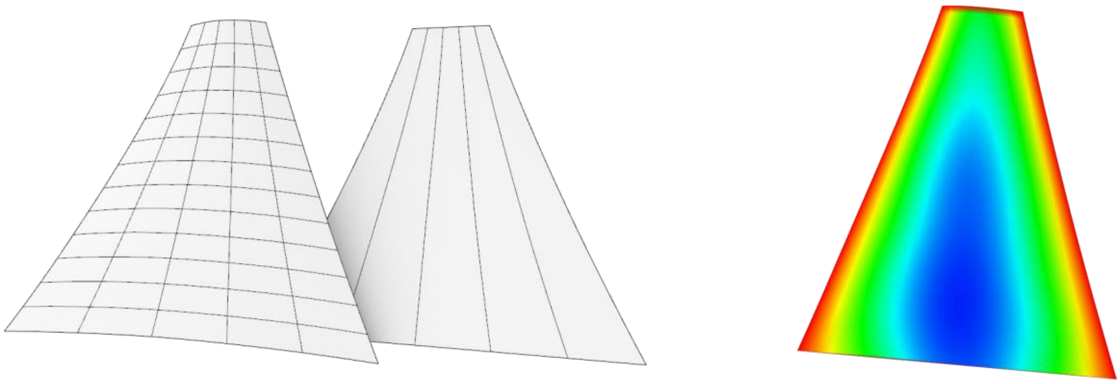
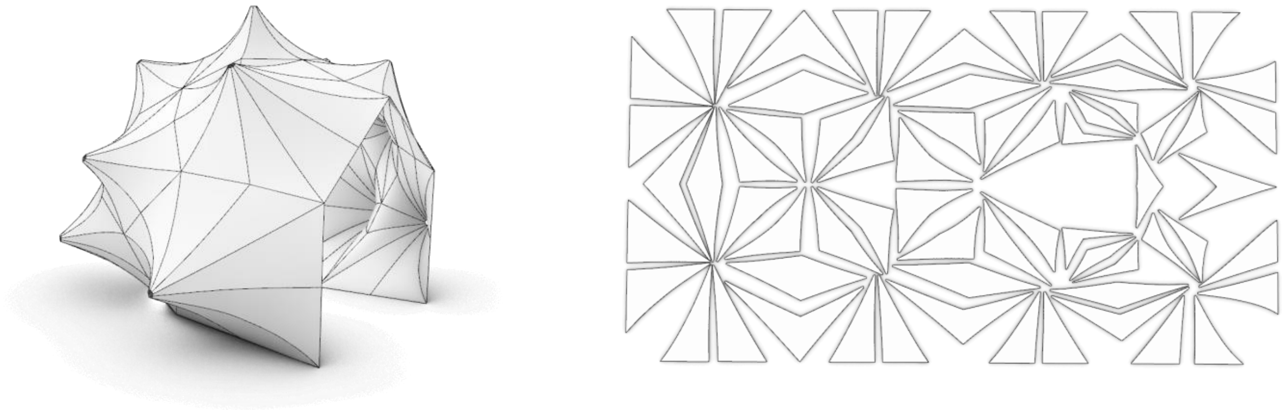


(a) (b)

Figure 10. (**a**) Comparison between original doubly curved patch and its simplified, ruled version. Curves indicate curvature directions, (**b**) coloured map indicating distance between doubly curved and developable surface - redmeaning no distance, blue 25 mm between surfaces.

The final 3D model of the pavilion and patterning is shown in Figure 11.



(a) (b)

Figure 11. (**a**) 3D model with simplified, ruled patches, (**b**) patches in flat configuration, prepared for fabrication.

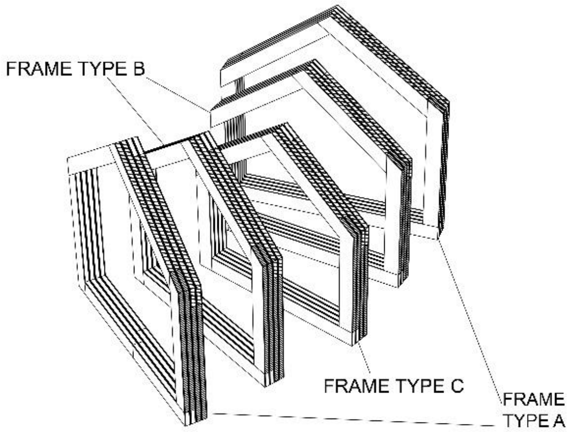
4. Results – building the pavilion

The Obverse/Reverse Pavilion was prefabricated at the ProtoLAB Laboratory at Wroclaw University of Science and Technology in cooperation with the students of architecture.

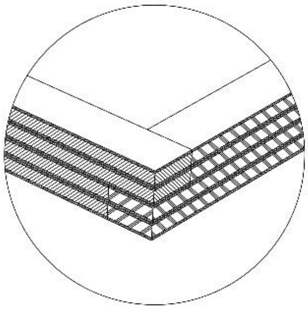
The main structure of the pavilion consisted of 5 frames (Figure 12). There were two pairs of larger frames type A and type B, and one middle frame type C. The sizes of the frames varied from 290cm x 300cm to 243cm x 252cm.

Each of the frames was composed of four layers of 5 cm thick cardboard honeycomb panels strengthened by lamination with four layers of timber-based 10 mm OSB (oriented strand board). Such sandwich element had a thickness of 24 cm and was 20 cm wide. It was composed in 83% by volume out of paper, however it kept expected structural stiffness.

For the transportation purposes the frames were prefabricated in halves. The ends of the halves were overlapping and were fixed to each other at the building site with screws. The frames were connected to each other by means of 18mm OSB floor plates, thirty two 4x4 cm wooden battens in pavilion's longitudinal direction, and eight 15 x 1 cm planks fixed diagonally to the battens to stiffen the structure against lateral forces.



(a)



(b)

(c)

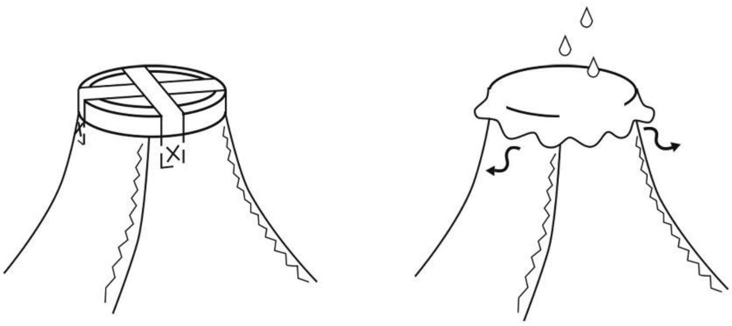
Figure 12. (**a**) Substructure frames, (**b**) connection between frame halves, (**c**) sandwich frame composition.

The membrane due to the budget constraints, technical parameters and expected life span of the structure, was made out of kodura: a polyester textile additionally impregnated with PVC layer. The planar patches presented in Fig. x were cut from the roll with 1,5 m width and 80 m length. Each of the patches was cut with an extra 1,5 cm margin for the sewing.

The membrane was sewed with the use of folded seems. First two pieces of material were sewed with normal stich, next the material was folded in a zig-zag and sewed with cross stich. Such solution minimalize the rupture caused by tensile forces by transferring the forces from stich to the material strength.

The biggest forces of the membrane were concentrated at the peaks. To ensure the freedom of movement, solid fixation, protection from the rain and possibility of wet air evaporation the cross belts were sewed on the peaks, and covered with textile caps that allowed convective movement of the air (see Figure 13).

The finished pavilion was 485 cm long, 550 cm wide, and 420 cm high, and it cost was below 1000 € (excluding transportation and production).



(a)

(b)

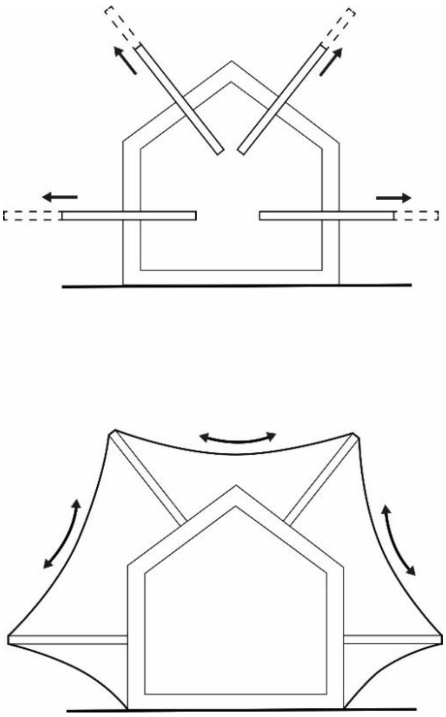
Figure 13. (**a**) Ends of the outer membrane peaks, (**b**) Outer membrane peaks.

4.1. Assembly

After pre-fabrication the pavilion was transported to the site i.e. Plac Wolności (Square of Freedom) in Opole. First the sandwich cardboard-timber frame halves were assembled together. Subsequently, the frames were connected with floor panels and horizontal beams and diagonal planks (Figure 14). The frames were covered from the outside with self-adhesive PVC foil to prevent material moisture. After completion of the main structure the outer skin membrane was placed on top of the pavilion.

Figure 14. The substructure assembly process.

Next, eleven paper tubes with the length of 250 cm, inner diameter of 10 cm and 1 cm thickness of the wall were inserted into the holes in cardboard-timber frames and were pushed outwards in order to stretch and position the outer membrane (Figure 15). The tubes were fixed to the frames with bolts and the parts that protrude from the inner side of the frames were cut (Figure 16 (**a**)). The membrane was fixed to the bottom and both ends of the pavilion with nails, and additionally covered with 4mm plywood along the front and back entrance (Figure 16 (**b**)). Finally the light installation and inner carboard walls were fixed. The inner walls were made of corrugated cardboard plates with black self-adhesive PVC foil form the both sides.

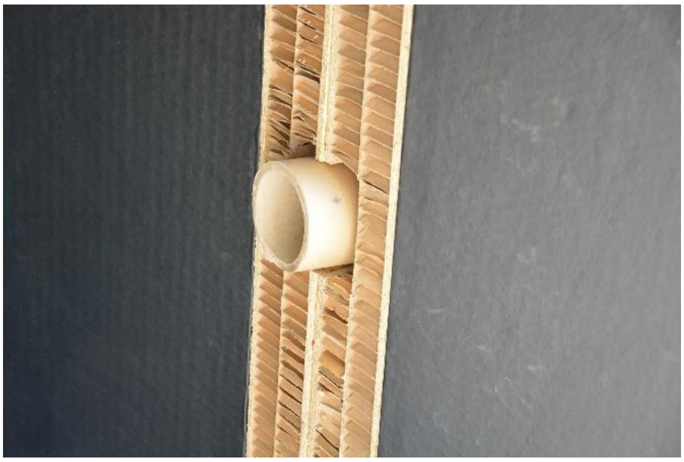


(a)

(b)

Figure 15. Stretching the outer skin membrane (**a**) The diagram of stretching the membrane with paper tubes, (**b)** Paper rod that stretches the membrane.

(a)

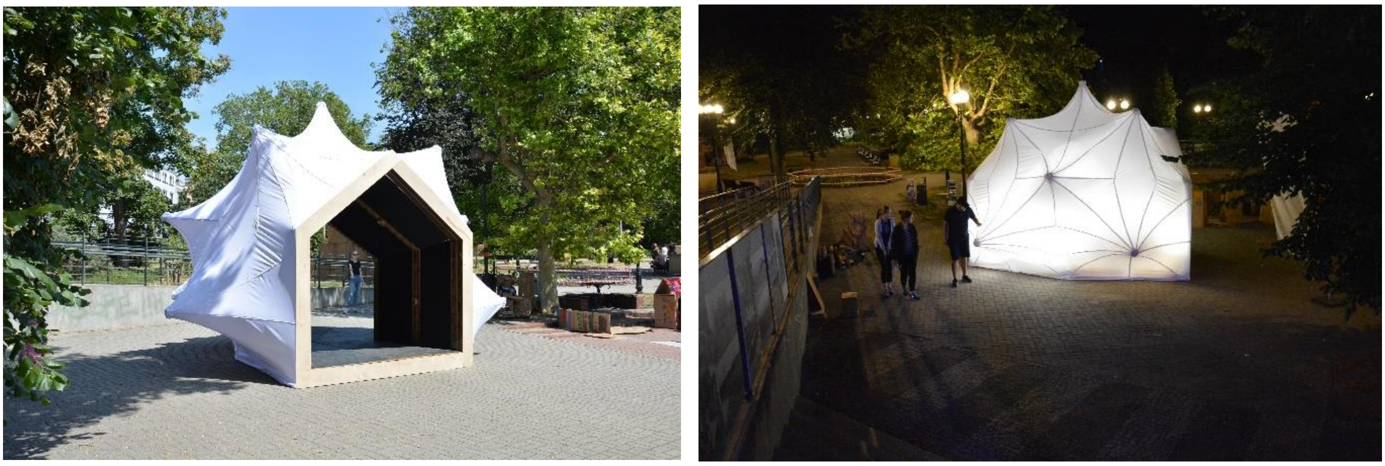


(b)

Figure 15. The pavilion details (**a**) plywood clamp that holds the membrane at the end side of the pavilion , (**b)** Fixation of the paper tube in the substructure.

The Obverse/Reverse Pavilion was exhibited at Plac Wolności in Opole for three days (Figure 16 and Figure 17). It was assisted with the cardboard chairs Bench-folks designed especially for this occasion.

The Pavilion was of considerable interest to visitors. Its surprising form brought the attention and as it was not obvious what kind if shape the structure was exactly, passers-by were eager to come closer, go through and even touch the outer skin.



(**a**) (**c**)

Figure 16. The Obverse/Reverse Pavilion (**a**) Pavilion in daylight, (**b**) Pavilion by night.

Figure 17. Obverse/Reverse Pavilion in the public space of Plac Wolności.

5. Discussion

The example of Obverse/Reverse Pavilion showed how even small pop-up structures in the urban area can bring attention and create a new positive value. The pavilion due to its unconventional form and used materials become a temporary sculpture. It was erected in one day, and was exposed in primary location just for three days. The temporary character of the structure and the assembly process enhance public attention, and by that interest of the citizens and tourist to the other events within International Day of Architecture. The behaviour of the passers who went through the pavilion, walk around, touch its outer skin allows the authors to conclude that the pavilion has fulfilled its role as a push-pin in an urban fabric of the city which corresponded with visual and haptic sensory system.

The limited colour palette i.e. black, white and natural colours of timber and cardboard were in a contradiction to the overwhelming amount of information which needs to be absorbed in the city centre. The only information was a 50 x 50 cm poster hanged on the inner wall, that explained the project idea and used materials.

The structural system composed of structural frames and outer membrane skin stretched on the structural rods allow to create a volume by the use of void. Thanks to that, the amount of the materials, and thus the budget were minimalized. The use of paper and timber-based materials presented how a new and unconventional structural solutions can be adopted in architecture. The outer membrane was made of polyester, therefore not very ecological friendly material. On the other hand polyester is one of the most common textile which can be recycled.

The parametric method of project development allow the authors to create an organic and soft, i.e. friendly and inviting shape of the outer skin.

Due to the use of computer representation of the project in every design phase from the conceptual design throughout the production, it was possible to foresee the potential mistakes such as a wrong type of connections or structural elements parameters. It also allowed the authors to develop a three dimensional tensile membrane which was possible to be divided into flat patches and relatively easy to produce.

Even though modern membrane structures have been known and used in architecture and civil engineering and for over half a century, there is still a wide range of their application not yet explored s. Rapidly evolving design tools and methodologies are more ergonomic and accessible from a designers' point of view and therefore allow them to emphasize creative aspects of their works. New, morphologically complex membrane structures are possible to be form found, which had not been possible before using natural form-finding processes [33].

Membrane structures are also nowadays explored toward finding new applications for them, e.g. as lost-form/scaffolding and reinforcement for shell structures and as formworks of free-formed concrete structures, that impose the necessity of production of otherwise expensive and material-consuming formworks [34].

Parametric design tools, used by the authors as well as all others that allow for easy design of complex structures, play currently an important role in education complementing the understanding of materials' and structures' behaviour, previously learned about and recognized by architectural students by physical contact and experimentation [35]. However, the improper usage of those tools without the essential background and understanding of particular material properties or structural systems may lead to unexpected and dangerous results. The dark side of "Bilbao effect" was commencement of the fashion of the so called "blob architecture, which had soon been criticized for not meeting the aesthetics, durability or predictability expectations and therefore this trend fell into recession [36].

The construction of Obverse/Reverse pavilion allowed us to emphasize those issues and embed mature approach among the students we cooperated with during the design and construction process.

6. Conclusions

Contemporary world is characterised by immensity of events that most often have a temporary nature. An enormous amount of information is sent to every user of public spaces. This information has to be absorbed, processed, synthesised and later a user decides which information is important and which can be ignored. The architects and artist, especially when work with temporary structures search for new unconventional material and formal solutions in order to win the battle for citizens' attention. The use of computer aided architectural design especially with its parametric potentials allows for creation and optimization of unexpected free forms.

Abstract form-finding methods have now their renaissance and using them frequently opens the way for world class awarded architecture. Studying the background of modern Pritzker Prize laureates it becomes clear that pursuit for innovative ways for obtaining structural and material efficiency plays an increasingly more important role. Especially in times of a growing awareness of resource scarcity and environmental conditions. A special type of cooperation between engineers and architects that results with architecture with capital A, with emergent quality, is the cooperation between structural engineer Cecil Balmond, whose design philosophy is based on abstract factors, mathematics, emergence, fractals and for whom structure as conceptual rigour is architecture. The strength of such an approach is emphasized by the fact that this structural engineer cooperated with many Pritzker Award winners (Toyo Ito, Daniel Libeskind, Álvaro Siza Vieira, Eduardo Souto de Moura, Rem Koolhaas, Shigeru Ban (Centre Pompidou-Metz), James Stirling) and resulted with structures of unprecedented values.

Most of novel structural systems such as taut structures (membranes, pneumatic and cable structures), bending-active structures, reciprocal frame structures or shells, which are less common in permanent architecture, attached to orthogonality, promise a very good factor of costs and material consumption to span/volume of such structures. They are usually also convenient for prefabrication and quick assembly. On the other hand, they require a deep understanding of the theoretical background of their design, since in form-found structures it is not the designer who decides on their form, but the structure itself.

The Obverse/Reverse pavilion was an example of a surprising and organic form made of simple, low-cost, and pro-ecological materials such as paper tubes, cardboard honeycomb panels, timber-based boards, and polyethylene membrane. The formal effect was achieved by the use of a parametrically designed outer skin in the form of minimal surface, stretched over the substructure.

Membranes are suitable for temporary objects thanks to their lightness and low production costs, but on the other hand, designing and implementation of membrane structures require additional skills and knowledge from the designers.

The implementation of parametric design methods allows for the achievement of a spectacular form of an architectural object despite a limited budget and tight schedule.

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