SETSCI Conference Proceedings
10, 215-224, 2019

4th International Symposium on Innovative Approaches in Architecture, Planning and Design

November 22-24, 2019, Samsun, Turkey

https://doi.org/10.36287/setsci.4.7.054
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Curvilinear glass technologies in the historical urban environment. A new glass city-event in public space

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Presentation/Paper Type: Oral / Full Paper

Abstract – The paper is deals with Glass Structures, used as a component of nonlinear shaping architectural forms in historical urban environment. These forms are treated as a city-event per analogies to Bernard Tschumi's theory of „event cities". In this theory, the essence of space is to animate the movement and actions, which strengthens the social and ecological or political dimension of architecture. In the first part of the paper the possibilities of glass technology now and historically is discussed. Buildings with non-linear shape force relationships between geometry and material which are different than before. Virtual free surface imposes such technical solutions which question the traditional thinking about glass components in architetcure. A few selected examples glass city-events will be presented and discused. The second part presents of the academic research program undertaken at West Pomeranian University of Technology in Szczecin by Krystyna Januszkiewicz. The program was focused on designing an city-event with using freely curved glass panels (3D). This is an innovative spatial product invented in Poland. In conclusion it is emphasized that when dealing with transparent surfaces, is not only rooted in the geometrical definition of the surface, but depends on the correct coupling of the glazing technology with the structural constraints. Curvilinear glass technologies opened into the new territories for the study of the cognitive form, its tectonics and space, changing the existing axioms design.

Keywords – Architecture, curvilinear glass technologies, free-forms, glass city-event, historical urban environment

I. Introduction

In the 21st Century use of glass structure in a historical context grows enormously. The digital design tools, which are interfaced with the production of computer technology, have opened the new opportunities that not only are shaping the architectural objects, but also interferencing in the buildings' structures. With the emergence of large-scale architectural free-form surfaces the essential question arises of how to proceed from a geometrically complex design towards a feasible and affordable way of production. Curvilinear glass forms entered the public space, radically transforming facades and coverings into a low resolution computer display, a "communicative display surface ", fusing architecture, technology and information.

II. Materials and Method

In the last decades the digital design tools, which coupled with the computer technology production, have opened new possibilities, not just in shaping the architectural structures, but also interferencing with the existing building structure. The curvilinear architecture of free geometry has already been implemented in various places in the world and is becoming increasingly popular due to the rapid development of robotics and CAD/CAM technology. The digital design tools based on the NURBS curves and surfaces have released the architects' imagination from the simply drown forms.

Published by Architectural Design in 1993 essay *Architecture Curvilinearity: The Folded, the Pliant, and the Supple* written by Greg Lynn is still the canonical position for architectural theory, dominated by the digital design tools and manufacturing. It was the first attempt discourse of architectural theory position of curvilinearity in architecture, designed in the digital topological areas. Greg Lynn's essay provides a basis to agree that "curvelinearity cemented the shift in architectural thought by identifying and highlighting this new architecture of smoothness"[1]. The publication of Lynn's essay in Architectural Design coincided with the extension of the Waterloo Station in London (fig.1), located in the historically stratified city tissue. The glass canopy platforms 400 meters long smoothly pushed into the dense buildings. Nicholas Grimshaw, in preparing the geometry of the roof covering applied the parametric model. Soon, after Grimshaw went Norman Foster, Massimiliano Fuksas, Renzo Piano, and other well-known designers. Not without a reason, therefore, Gilles Deleuze in his book *Le Pli. Leibniz et le baroque*, which was published in 1988, predicted an inevitable shift towards the curvilinearity in various art genres [2]. For Deleuze *le pli* (a fold) is the principle of the world construction leading directly to the notion of the continuity, nowadays so eagerly used by architects. The continuity is included in the definition of *le pli* and is to be understood not as the straightforwardness, but on the contrary, the curved maze of the continuity. It is assumed that there are no breaks, fractures tears in the matter world that in the immaterial level means there is no conflict and contradiction. It is different in the tissue of old towns, where the substance has layered for centuries. The old techniques are in a constant conflict with the newer ones, and the evocative content of the forms and their associations contradict each other in the dialogue of history. However, the preserved buildings or their remains represent the state of consciousness of the eras in which particular styles were born. Historical continuity is perceived through the complexity and contradiction of various interventions performed constantly on the body of the city. In the maze of streets and squares, daily life is lived, which no longer corresponds to the spirit of the past and requires new technical and spatial solutions, new forms at the point of contact. According to Leibniz's idea, Deleuze's maze of matter continuity corresponds with a maze of continuity in the human soul. The two planes communicate because "the continuity of matter raises the soul" to the next level [2]. Is it then possible to treat curvilinear architectural forms as a special event in the urban fabric?

A. What the term "city-event" means in architectural and urban design

The term "‘city-event" has emerged as a useful way to encapsulate the still somewhat fuzzy concepts of an ideal relationship between people, governance, built environment, infrastructure, living ecosystems, resource use (e.g. energy). In architectural and urban design, the term refers to Bernard Tschumi's concept of "event space" in the city. For Tschumi, space is "created" by an event taking place within it; and architectural space is defined by the activity taking place inside/in front/around – in any spatial relation with it [3]. The term has become commodified in recent years, and is now regularly applied to corporate various activities in public space with use architectural temporary or mobile objects. However, there is an interpretation of this concept; as a common ground or infrastructure, which can be freely used for a multitude of activities or functions.

Nowadays, the experiment conducted by Tschumi in the park La Viellete has entered a completely new phase. These structures are often a tool for manifesting ecological values and possibilities of new technologies in the urban landscape. Through their specific exhibitions and programs a sites for interaction and integration is created. This site can be called an "eco-event" in the city. Adding this specific urban element to the discussion, Lefevbre's phrase “the right to the city" [4] captures individuals' rights of access not only to physical public spaces, but also to the public spheres of discursive participation which should be enabled by such sites today. The "city-event, this is real realm is a space where various activities take place.

B. Glass "city-events" – selected examples

Glass is an ancient material with unique properties and diverse applications. Glass comes in many forms as a function of chemistry and process. Of the many silica-based glasses that exist, ordinary glazing and container glass is formed from a specific type called soda-lime glass, composed of approximately 75% silicon dioxide (SiO_2), sodium oxide (Na_2O) from sodium carbonate (Na_2CO_3), calcium oxide, also called lime (CaO), and several minor additives[5]. The most familiar, and historically the oldest, types of glass are based on the chemical compound silica (silicon dioxide), the primary constituent of sand [5].

The transparency and translucency of glass has historically given an aesthetic quality to architecture like no other material. Joseph Paxton’s Crystal Palace (1851), a bold building for 19th century was embodying the technological spirit of the Industrial Age and it's heralding the future of steel and glass buildings. Today also takes on new meaning the Glass Pavilion (1914) by Bruno Taut (1880-1938). The expressionist work was a pineapple-shaped multi-faceted polygonal designed rhombic steel and glass structure.

Nowadays, the new technology of building glazing, which has developed over the last two decades, has found an application in the conservation design process for historic buildings. Modern glass is introduced into the interior during modernization and adaptation works, not only in the form of window glazing. Glass has opened new possibilities of protection and shaping of historical spatial arrangements and elements of architectural composition to create new quality of public space.

Flat glass panels as a component non-linear building envelope: One such example is the Courtyard the Museum of the History of Hamburg built in the heart of the old city between 1914 and 1923. The 50 meters long roof is L-shaped in plan and consists of two singly curved barrel-shaped shells 14-17 meters in span and one doubly curved spherical dome at their intersection [6]. The conventional solution at the time would have been to roof each arm of the L with barrel vault. Barrels and domes, predominantly build out of masonry and concrete in the past, were now discretized in quadrangular grid elements and built out of steel.

Fig. 1. Volkwin Marg + Partner, Courtyard Roof of the Museum of Hamburg, Hamburg, 1989-1991

Unconventional shape of the roof was challenge for designers (fig.1). Schlaich saw it as a most welome opportunity to demonstrate the ability of the system used at Neckarsuim to adept to a free and complex form. The courtyard roof led to the development of translational surfaces, a technique through which planar faceted gridshells could be developed using the property that translated vectors stay in a single plane [7]. This technique led to a series of Schlaich Bergermann and Partner glass gridshells in the future, such as the House of Hippopotamus in Berlin.

The first structures designed in parametric digital spaces such as overlap the Great Court at the British Museum, London and the courtyard at the Smithsonian Hall (2004-2007) in Washington, designed by Norman Foster were pioneering structures, which showed how to integrate space of historical features into new functional areas. They are like Leibniz wants, "strained to immaterial internal body program events"[2]. The conception of glazing the Great Court at the British Museum in London dates back to the 19th century, when an English architect, Charles Burry proposed a roof supported by 50 columns [8]. Designed by Foster and Partners, the new roof over the Great Court covers a rectangular area of 70 by 100 metres, containing the 44-metre diameter Reading Room (fig.2). The glass roof is supported at the edges, with 50 columns concealed in the façade of the rotunda. The shape of the grid is made up from 3,312 unique triangular windowpanes[9]. The complex geometry of the object is based on parametrized fragments of a torus, one smoothly passing into another. The curves are rationalized by the radial geometry of the sphere, cones, cylinders, and rings, which approximates the complexity of the curves of the designed surface[9]. Triangulation is the most commonly applied form of planar tessellation. In order to prevent overheating of the structure, more than a half of the windowpanes are partly tinted. The construction daylighted the atrium, and aggregated the impression of lightness and spaciousness.

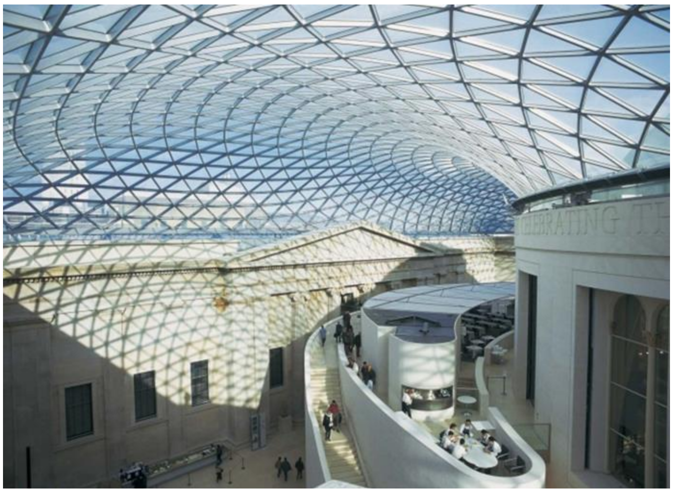


Fig. 2. Foster and Partners, Great Court at the British Museum, London,1998-2000

The new Court connected all the wings and impressive stairs linked all the floors. The redevelopment revived the image and structure of the historical building, increasing the social and cultural values, without altering the original values of the building itself.

The largest single glass envelope in the region is Golden Terraces (2000-2007) in Warsaw, designed by The Jerde Partnership International. The facility is located in the city near the Central Railway Station and the Palace of Culture and Science. The concept of creating Golden Terraces was

Fig. 3. Jerde Partnership International, The Golden Terraces, Warsaw, 2000-2007 – support structure under construction

created thanks to inspiration from the historical parks of Warsaw. The center was to be the next "park" in the capital, an integral part of the city. The idea of the roof covering the central part of the complex has evolved from the beginning of design works on the center from the large glazed shed, through the elliptical dome to the wavy, organic shape. The multifunctional complex has a glass coating 10,250 square meters surfaces (fig.3). The roof of glass and steel covering the central trading area was provided by Waagner-Biro. The roof consists of a wavy geometrically folded net of welded steel elements supporting the triangular panes. The average size of one triangle is about 2.5x2.5x3 m. However, there are no identical panels in the dome. Their contour depends each time on the exact dimension of the mesh of the steel web - i.e. the three steel elements that bind each glass panel. On the roof of such elements there are over 7,000. The connecting elements in the steel structure are the nodes. Six triangles meet in these places. Like the glass panels, each of the 2,300 nodes is different. It had to be designed separately and cut from steel sheets by digitally controlled machine tools. Arup engineers imported the basic geometry of the Jerde roof grid with AutoCAD and manipulated it with additional software to orient each RHS element perpendicular to the bisector angle of the two glass panels it supports[10].

A special case is a trade house Benetton in the historic center of Rome, which occupies an eclectic tenement Unione Military Palazzo, which was built in the seventeenth century, at the intersection of Via del Corso and Via Tomacelli. The loss of the authentic substance causes the loss of monuments essential features, being the carrier of intangible assets and "the most important characteristics of matter is a form, texture and color, shaped by the creator and time" [11].

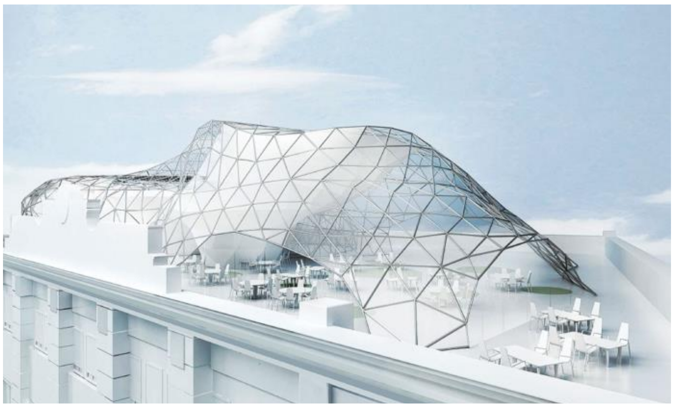


Fig. 4. Massimiliano and Doriana Fuksas, reconstruction of Palazzo Unione Militare, Roma, 2010-2013

The controversial redevelopment project was made according to the Massymiliano Fuksas design. Due to its historical significance, the architect could not reshape the facade of the Palazzo; instead, a new construction was built – steel, covered with a glass and steel façade rising from the roof (fig.4), adapting to the modern commercial needs and representation. The new architecture redefines the urban landscape of Rome historic centre according to contemporary taste. It's the steel and glass «Lantern» of the "Ex Unione Militare" building, situated between Via del Corso and Via Tomacelli, that crosses the four floors of the building from the ground-floor up to the panoramic terrace with a view of the dome of the Basilica of Saint Ambrose and Carlo al

Corso**.** The light rising towards the top structure penetrates tenement housing a staircase with two lifts, which are moving onto the roof of the freely formed covering uplifting to a height of 7.50 m [12].

A contemporary interpretation of the historic centre has led to a minor intervention on the outside of the building, whose original construction dates back to the end of the XIX century, focusing on the renovation of the interiors and roofing. The restoration of the outside has focused on the recovering and valorization of the original architectural features of the building. A steel and glass triangular-shaped structure that crosses the entire building and contains the vertical connections, the service and accessory rooms as well as part of the plants. The full-height void created by the "Lantern" generates a glimpse along the structure of the various floors, which are interconnected through gangways.

Undoubtedly, the redevelopment of Palazzo Unione Militare is a controversial approach to the character and values of a historical building. Every century had a different set of rules and views with respect to building renewal. It was done with a great deal of discretion in the selection of materials and planning concepts. After the adoption of the Venice Charter (1964), it is believed that the preservation of the original material is crucial to preserve the value of the monument. How did Palazzo Unione Military lose its authenticity and how much does it gain in terms of usability, aesthetics, and attractiveness? Answers to these questions will probably require multifaceted discussions and references to the unprecedented reconstruction of the Reichstag (1992-1999), adapted to the needs of the German parliament. panels it supports[10].

Examples presented above and other more recent fashionable projects have shown that triangle meshes are the simplest way of representing and realising a freeform shape with planar panels. These projects refer to triangularly facetted geometries based on discontinuous straight members connected by nodes which usually are rather complex. The challenge in the two-dimensional interpretation is to choose an appropriate geometric approximation that will preserve the essential qualities of the initial three-dimensional form. Which of the production strategies is used depends on what is being defined tectonically: structure, envelope, a combination of the two, etc. Approximation of the surface by means of tessellation and the use of different types of glass panels allows to find a balance between the visual smoothness of the coating and the cost of its realization.

Curved glass panels and a visual smoothness of the coating: Multiplication and deformation of the image on curved surfaces often leads to a curved and unreal reality. Smooth curvilinear forms are capable of creating unpredictable references and associations with a cultural context. The smoothness and transparency of glass has historically given an aesthetic quality to architecture like no other material. The smooth curvilinear, glazed envelopes are a new technical challenge in architecture 21th centuries. Freeform structures are a striking trend in contemporary architecture.

An excellent example is the department store *Weltstadthaus* in the center of Cologne (1999-2005) which was designed by Renzo Piano. It is the object of double curvature surface, which responses to changes in the environment (fig. 5). The form is the result of research adaptability. The contact with the past eras of architecture, establishes a relationship between the object and the existing urban fabric, which was destroyed during the World War II. The path with the direction of the mold is appointed, where the continuity and flexibility are the results of the surface computational relationship for the structure, function and form.

Fig. 5. Renzo Piano, Weltstadthaus, Cologne, 1999-2005

Weltstadthaus curvilinear architecture redefines not only the conceptual side, but also the building perception as being *per se* (fig.5). There is no developed in the past facade with its right articulation. It is divided through a sequence of parametric equations, determining the wooden ribs spacing of the individual curvature. These are mounted on the glass panels, each with a different curvature, and from the inside the shading system and sensors to the facade able to react to the sun's path, and also the rainwater is collected [13].

Traditionally, curved glass is manufactured from float glass that is heated above the weakening point and formed in a heavy curving mould. Since this technique is time and energy consuming and consequently relatively expensive. For this reason, a more affordable alternative has been developed. The technique is called a "cold bending process" because it is used to bend glass plates on the building site at room temperature. The process implies that toughened float glass laminates are gradually bent on a curved frame. Finally, the newly curved panel is mechanically fixed to the frame, which implies that the glass is continuously subjected to bending stresses during its lifetime [14].

Curved glass panels can be one of the world's most notable bent-glass structures is the Strasbourg Train Station Extension (2007) executed by the firm Seele. The glazed structure is a smooth double-curved envelope which involved a surface area of nearly 6,000 m^2. Like a giant cocoon (120 m long and 25 m high), the new glass shell wraps around the historic station building (fig. 6).

Fig. 6. J-M. Duthilleul, E. Tricaud, F. Bonnefille, Strasbourg Train Station Extension, 2007

The glass panels at Strasbourg were elastically bent into a cylindrical shape. According to this logic, the panels are long and narrow in order to maximize the longitudinal flexibility while still spanning transversally on a relatively short span.

The continuity of these elements refers not only to a structural logic but, also has the function of directly supporting curved glass panels. This approach is coupled with the overall geometrical concept and regularity of the envelope which, despite its appearance, is not a free form but a torus (of non circular section) inclined with respect to the horizontal plane in order to give a visual dynamism to a classical form[15].

The fact that the envelope is a surface of revolution implies that each glass element can be realised as a single-curvature panel of different radius according to its position along the section. The other key element is the production technique of the glass. For the Strasbourg project, the glass panels were not hot-bent, but cold-bent, i.e. elastically deformed to reach the desired curvature radius not after, lamination and in the end this technique was used for the totality of the glass panels due to the installation advantages.

In 2008, Frank Gehry was an early adopter of a "cold bending" process, when he transformed the downtown Toronto's Art Gallery of Ontario with a new convex glass façade. Later on, he used the same approach for the project of the Fondation Louis Vuitton (2012-2015) in Paris. The challenge in this project is to replicate the complexity of the Guggenheim Museum in Bilbao (1994-1997) while using transparent surfaces. In this case the geometrical complexity of the glass canopies has been extended with respect to the curvilinear geometries but at the same time contained, limiting the design only to developable (single curvature) surfaces. Under this condition each canopy can be approximated using only single-curved panels. During construction, Gehry has bent flat panels by using an innovative process in which workers shape the glass on-site. It is bent on site to adapt its curvature to the multitude of different radii required by the geometry: this two-step production technique permitted the maximum freedom of form using only a limited number of moulds.

Fig. 7. Zaha Hadid and Patrik Schumacher, Nordpark Railway Stations, Innsbruk, 2004-2007

Advanced three-dimensional geometries may involve bending along multiple axes rather than a cylindrical bend with a single radius. Nordpark Railway Stations (2004-2007) in Innsbruck, by Zaha Hadid and Patrik Schumacher, used heat-bending techniques to achieve double curvatures. (fig.7). The form of the stations used a combination of thermoforming and CNC milling, with panels developed by Bollinger & Grohmann and manufacturer Pagitz Metalltechnik and then made in China[16]. The feasibility of this project is the result of the integration and synergy between the glazing technology and the production constraints of both the fixing elements and the bearing structure, which twist in order to follow the surface. Of course, this complexity is managed using advanced digital tools that takes advantage of the parametric nature of the software.
Hot and cold glass-bending methods continue to evolve, architects' material repertoire is expanding to invite and transform light in ways that even fin de siècle visionaries couldn't have imagined. Today's glass-forming technologies are expanding the sculptural and functional possibilities of this distinctive material.

III. Research and Results

New geometrical forms in architecture and ecological concerns created the environment for search for new materials and new structural solutions. The use of curved shapes in architecture grows enormously. Architecture shows an increasing demand for uniquely shaped freely double curved panels, especially glass panels. Current production technique of such panels necessitates making a ceramic or steel mould, by milling or by forcing into shape (hammering, pressing) with much manual labour. This production technique offers, especially by milling, high accuracy, but the manufacturing, transport and storage of such moulds are costly. A new reusable and adjustable mould technology greatly reduces production costs.

These issues were undertaken by author (Leader of Digitally Designed Architecture Lab) and faculty member at the WPUT (West Pomeranian University of Technology) in Szczecin. The academic research program developed by Krystyna Januszkiewicz in cooperation with Proteh Innovative Technologies investigates the panelisaton and subdivision of surfaces for creating nondevelopable freeform surfaces without being limited by facetted solutions, to realize freely curved architectural forms.

A. *Glass Waves panels - Polish invention*

Glass panel system named Glass Waves is an innovative spatial product invented in Poland by engineers Bogusław Szarejko and Eugeniusz Ziołkowski. In 2012 they established Proteh Innovative Technologies company in order to manufacture freely curved panes from float glass for architectural applications. Some base materials can easily be transformed under pressure, by using advanced modelling equipment. However, the possibilities to transform glass panes are limited. Complicating factor is the minimal required temperature variation during shaping of the glass, to prevent surface distortion. With the process Proteh devel-oped, many limitations in transforming glass have been overcome with the help of (research of nanotechnology) Wojciech Sadowski's team (Gdansk University of Technology). This created an opportunity to accurately produce almost any desired curved shape.

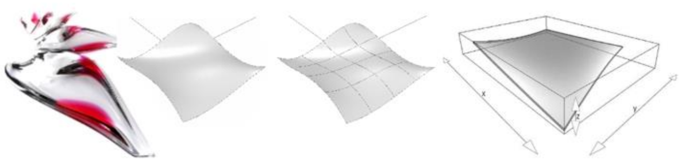


Fig. 8. Glass Waves panels - the main idea

The manufacturer mastered an innovative glass bending technique to create single and double curved glass facade panels directly from CAD data. The production process is enabled by the integration of Parametric design CAD software with automated software used to drive robotics. Proteh Innovative Technologies has a patent protection for the method of manufacturing Glass Wave panels W.122034. The conventional manufacturing of freely curved glass requires producing a unique mold for each glass panel, while implying a labour-intensive and critically complex process. The manufacturer production method is based on the application of an adjustable ceramic mold which is industrially developed by the extensive research and experience.

The original CAD files (3D Model created in Rhino-Grasshopper, Catia, Maya, Autocad, etc.) are converted to parametrically controlled format for analysis of geometry. In this way the Glass Wave allows for a free surface of building envelope in accordance with its curved geometry, deserved special attention The surface is then visually optimized to get high quality precision in contours and reflections before creating individual panels. The manufacturer can create a panel definition for surfaces by panelization or subdivision of original envelope with user defined rule set governing panel shape and size, orientation, split lines, minimum radius control, material selection, type of glazing, thickness of glass, fixing and substructure.

B. Designing Glass Waves Pavilion

The main subject of the research was the use of the first commercially available glass bend in three dimensions, produced by Proteh Innovative Technologies company. The aim of the research was to create a portable glass pavilion showing the characteristics and potential of the new building material.

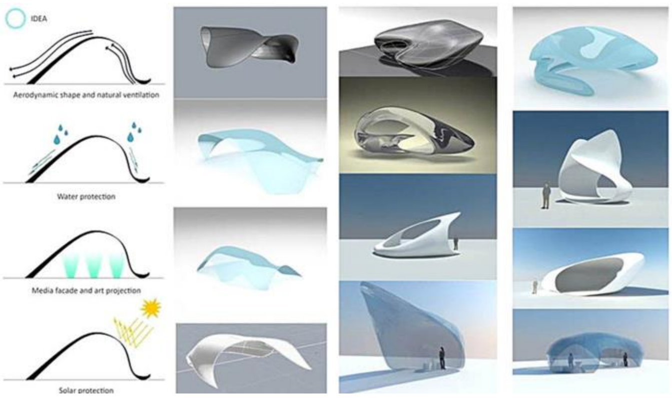


Fig. 9. Glass Waves Pavilion – research for architectural form

Finding the form: research on the form started from the study of the properties of rational curves (NURBS) and their capabilities. Free dragging of the control points and changing their position allowed us to obtain a variety of forms and planes, which in various combinations may intersect each other at the same time creating interior and exterior. Lofting profiles and changing the position of the control points can show geometric possibilities of the surface (fig. 9).
Knowing the capabilities of the digital tools for modeling work began the stage of the final form. The form was based on a solid shape, with the cross-section of an ellipse. Further the free formation tried to create the interior space through the notch. Finally, by using other forms of elliptical shapes, the notch led to the formation of an architectural form, which can act on the recipient in an intriguing and interactive way.

The primary focus of this research was to combine the material logic with the flexibility of parametric modelling. A surfaces lies in the complex interplay of different objectives related to geometric, aesthetic, and fabrication constraints that need to be considered simultaneously. Surface modeling often requires a visual assessment of surface continuity and surface curvature. The Zebra command is one of a series of visual surface analysis commands. These commands use NURBS surface evaluation and rendering techniques to help you visually analyze surface smoothness, curvature, and other important properties. The Gaussian command visually evaluates surface curvature using false-color analysis. These tools can be used to gain information about the type and amount of curvature on a surface. Gaussian and Mean curvature analysis can show if and where there may be anomalies in the curvature of a surface. Therefore, the parametric modeling integrates all steps of the digital fabrication process to produce patterns that allow the glass sheet to be formed into desired shapes without using additional resources.

The surface division: Proteh Innovative Technology produces precisely bent glass up to 300 x 550 cm format with a deflection curve of 80 cm (max). System provides bent glass panels with all functionalities known from the flat glass applications. The pavilion requires to be divided into panels that can be prefabricated by manufacturer and then shipped and assembled at different locations. The max dimension on each element should be no more than 2,5 m x 3,5 m (length of the edge curves).

Method 1: NURBS surfaces are a controlled by a set of control points and two parameters (u and v). By using these coordinates (U and V) each free surface can be easy divided in two directions. Then, each panel has a different shape and size. Adjusting the division of the surface so the lengths of the longest edge in U and V directions are 2,5 x 3.5 m or shorter and the height of the bounding box is 80 cm or less, manually merging panels that after the operation fit in the maximum dimensions.
Method 2: You can create a series of contour lines on any NURBS surface in Rhino. For contours running parallel to the x-axis, selected a point on the y-axis. For contours running parallel to the y-axis, selected a point on the z-axis. For contours running vertical, switch views to the right or front and selected a point along the z-axis. Then was selected the distance between contours respectively to wanted size glass panels.

The paneling task is a key component of the rationalization process for architectural freeform designs. The approximation of a design free surface by a set of panels that can be manufactured using the Proteh technology at a reasonable cost, while respecting the design intent and achieving the desired aesthetic quality of panel layout and surface smoothness. In this case approximation of the surface employing tessellation and the use of different shapes of glass panels allows finding a balance between the visual smoothness of the coating and the production capacity.

Glass Waves Pavilion - final design: the pavilion has to be made entirely of glass, without any constraints about the form. A shape of form should provide dynamic emergence of spaces varying from a half open-space, through a semi-enclosed space to a fully separated one.

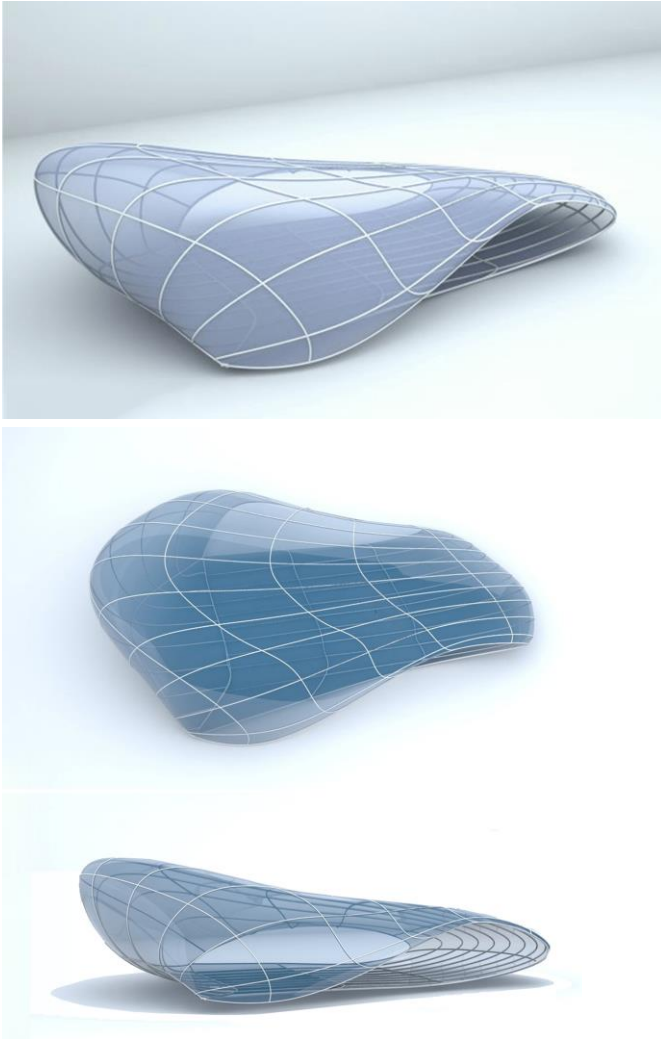


Fig. 10. Marta Banachowicz, Glass Waves Pavilion – final design

The shape of the pavilion resembles a curled ribbon. It is meaning lies in a surface that has neither beginning nor end (Fig. 10,11).

The pre-fabricated curling ribbon is designed to have carbon-zero emissions, collecting energy at daytime using it for media projection at night. It is a glass envelope which performs the following environmental tasks such as:
- energy storage (thin transparent film solar cells),
- art projection (media internal facade and floor).

The glass pavilion consists of a series of connected autonomous segments that can perform the division of a spatial division, but also places to connect, stands or sound and light sources. The object can be equipped with glass panels with variable translucency, with ranges of concentrations that are influenced by the function of enabling changes in settings from semi-translucent to translucent. In the OFF mode can also be used as a projection screen projection. Acting as a whole, the entire installation would exhibit the properties of the surrounding living body. In this way, it can provide adaptive spatial conditions, learning how to respond to variable information, including connections and indirectly from exhibition visitors and organizers.

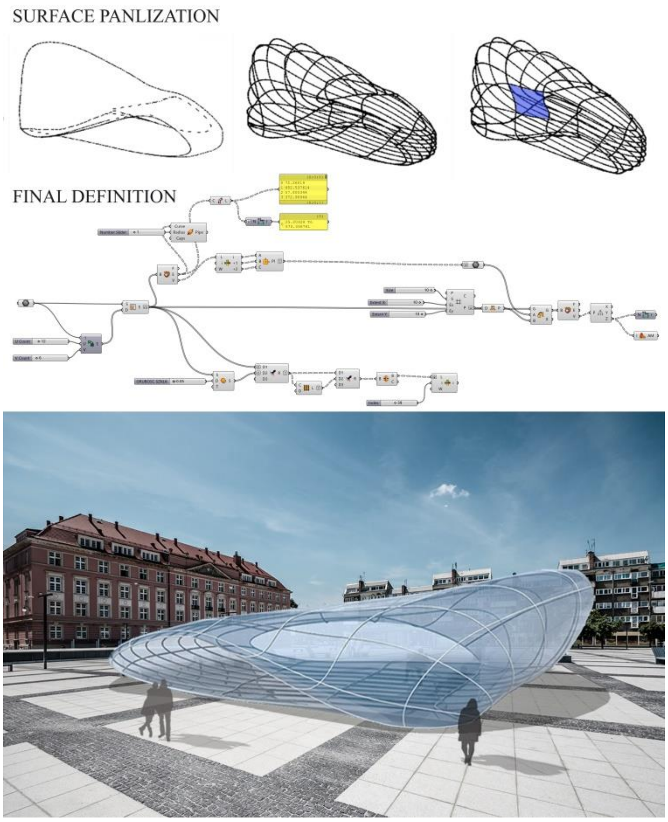
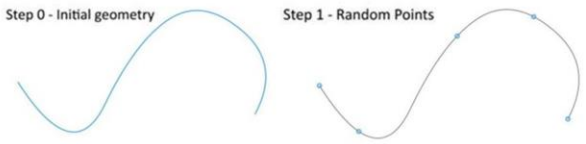


Fig.11. Marta Banachowicz, Glass Waves Pavilion – surface panelization

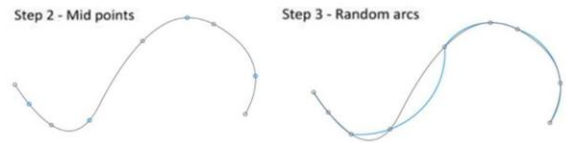
The load-bearing structure of the glass curling ribbon has been designed as bent metal pipes following curvature of glass panel's surfaces. These pipes should be hidden between the two layers of glass panels. Fabrication requires translation of remained elements into arcs. Usual approach would be a simple conversion of NURBS to an arc. Unfortunately, in order to keep the initial shape, lots of arc elements need to be used.

Support structure: The method of determining the geometry support structure for the Glass Waves Pavilion can be very easy. Konrad Zaremba's proposes to divide the initial surface into set of ISO curves which represent axis of beam. Curves are divided into smaller elements with a set of randomly generated points according to t-value of the curve. On shattered curves another point is computed with randomly generated t-value. Based on set of points random arcs are generated. This randomly generated geometry becomes search space for Genetic Algorithm (GA)[17].

In methods based on GA – a search space – is a number of all generated possible solutions. Solution space mustn't be too narrow, thus, algorithm can search in space of reasonable numbers of possibilities. However, a randomly generated population includes also a useless solution. In presented example number of bad solutions is limited in phase of setting up a search space. Additional random point is generated for a middle point of arc. This point allows adjusting generated arc to initial geometry. Therefore, more meaningful solutions can be generated (fig. 12).



Step 0 – Initial Curve b) Step 1 – Random Points



Step 2 – Mid Points b) Step 3 – Random Arcs

Fig. 12. Division curves ISO representative axis of support beam

The most important for GA method is proper set up of Fitness Function (FF). This heuristic function determines the value of the objective for each member. During optimization algorithm determines which members of generation are going to mutate according to FF. For described method 3 main objectives has been used: Deviation, Continuity, and Number of elements. Every set of arcs converted form curve will be different from an initial geometry. Deviation is calculated as a sum of distances between points generated from an initial curve and optimized arcs. It is calculated per load-bearing element (in this case 1 element). Axes of beams are sampled in distance of 20 cm. In presented example 50 points have been used. (fig. 13).

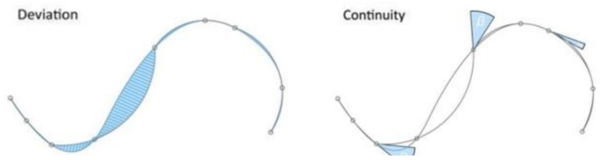


Fig.13. GA method and the Fitness Function – Deviation and Continuity

Randomly generated arcs does not generate continuous curve. In an initial geometry sharp kinks can be observed. Therefore, the FF of Continuity has been introduced. It is calculated as a sum of angles between tangents of neighboring arcs. By minimizing angles on endpoints, a final geometry is going to be as smooth as possible (fig. 13).

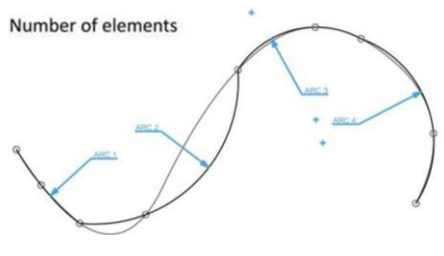


Fig.14. Deviation and Continuity for 6 structural members

Deviation and Continuity prefer structural members made from a higher number of elements. Therefore, function which is minimizing the number of elements had been introduced. The number of elements is determined in search space by additional value which is removing random number form 10 generated t-values in model preparation phase. Number of elements enables designers to see how Deviation and Continuity would increase when we use fewer arcs per beam. Fewer divisions per element will benefit in redundancy of generated structure and will decrease cost of fabrication. The number of elements is calculated as sum of arc elements in each beam. (fig. 14).

Optimization and results: both Gene-pools and FF values are input for Octopus engine. After algorithm procedure GA outputs optimized geometry in so-called Solution space. Octopus allows intuitive navigation through this space by mapping output in 3D space. Values of FF became X, Y and Z-axis. It is possible to map more FF in Octopus viewport, however, to minimize computation time for present examples three FF was used.

Evaluation of solution can be supported by visualization of the Pareto front which shows the best trade-off for different FF values.. Solution can be chosen based on information about advantages and disadvantages of each option.

For the presented experiment 300 generations have been computed. We can observe an exponential decrease of FF values. It indicates that further optimization will not be able to generate significantly better solutions. From solution space 2 curves had been chosen (fig.15).

Results had been compared with default Rhino conversion from NURBS to Arc. Both compared sets of arcs – optimized and converted - have the same number of arcs. Comparison is based on FF: Deviation and Continuity[18] [19].

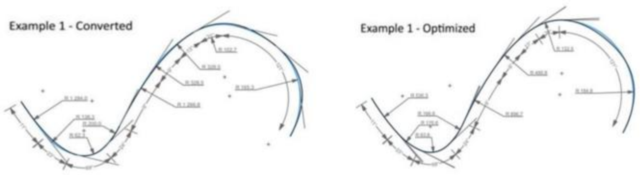


Fig.15. Optimization with Octopus engine

Example 1 – 9 elements

Converted: Simple converting produce set of arcs close to initial geometry (fig.15) Also; arcs are perfectly aligned to each other. The optimized and converted arcs have similar deviations.

Optimized: Continuity of optimized elements is not ideal. However, average error of 2 degrees per connection will not be visible in the structure. (fig.15).

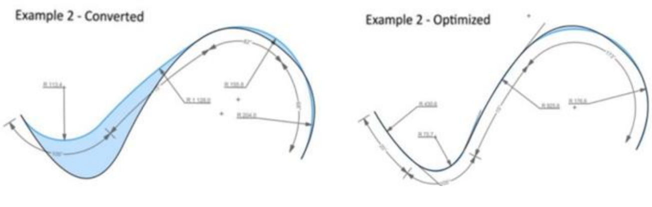


Fig.16. Results: Optimized curves

Example 2 – 4 elements

Converted: reduction of elements in converted members highly increases Deviation from initial geometry (fig. 16). Continuity between elements is close to 0.
Optimized: In optimized curves, we can still observe a bigger continuity value. Deviation from initial geometry has very low value comparing to converted arcs.

Method based on GA optimization is capable in rationalization of a complex freeform surface into a set of developable geometry, in presented case arcs. Elements are in acceptable tolerance from initial geometry and assure build-ability of structure. The optimization method allowed achieving various design solutions highly similar to initial geometry. Continuity of members after 500 generations has been acceptable for building industry standards. Overall method performance gives promising results. Nevertheless, the computation time for 500 generations (around 3 hours for 10 elements) needs to be considered as disadvantage of the method. Therefore, further research on performance seems to be relevant to popularization of GA usage.

The design highlights that it is possible to make new designs based on a glass as a building material and also being eco-friendly, self-sufficient, energy efficient. For these reasons, it can be treated as a city-event that integrates people and encourages social debate – as a place to develop and explore the novel theories, methods.

IV. DISCUSSION

The advance in the digital technology facilitating design (CAD) and manufacturing (CAM) has integrated the practice of erecting buildings with their design. There was a direct relationship between the creative idea and what can be realistically built. IT processes not only generate projects today but also implement them through the digital "files to factory" which are formatted according to the requirements of the CNC manufacturing technology. The coherent systems (CAD/CAM/CAE) permit for such development of the project documentation, which provides the desired, in terms of the shape and size, material processing its elements, and occasionally assemblies *in situ*. A well-known example may be the expansion of the German Historical Museum (1997-2004) in Berlin. Caesar Peii cleverly increased the baroque Zeughaus was built in 1695 by introducing new exhibition rooms below the ground level. Instead of a corner was a small tower accented with the glass panes with the varied curvature. The large glass used on the curved surfaces, which was made by the company Tambest Oy in Finland, specializing in the glass production for molds with complex geometry. Developed and taut on the steel skeleton transparent "skin matter" is the Liebniz's curtain between the levels – the higher for the arts and the lower for the road users. The glass scroll is rolled up and uplifted encouraging to enter. Despite the baroque idea, a new aesthetic quality was introduced resulting from the form, material and technology and in the opposition to the baroque style of the existing building and its context. New spatial conflicts were not created with the benefit to the urban public space. Glass structures used as a component of nonlinear shaping architectural forms in historical urban environment presents synergic relationship between a modernity and urban heritage. Glass structures used as a component of nonlinear shaping architectural forms in historical urban environment presents synergic relationship between a modernity and urban heritage

Architects, drawing complex curvilinear forms, are immediately drawn into the process of the CNC manufacturing technology. The coherent systems (CAD/CAM/CAE) permit for such development of the project documentation, which provides the desired, in terms of the shape and size, material processing its elements, and occasionally assemblies *in situ*. Architects, drawing complex curvilinear forms, are immediately drawn into the process of their manufacture. In this respect, there has been a return to history but in a a different technological condition..

V. CONCLUSION

We are witnessing the development of a new type of tectonics that expresses the potential of structure through advanced geometry and technological capabilities, which puts the aspect of tectonics in architecture elsewhere than ever before. There are attempts made to create a technological strategy that unites the "old" material reality and the "new" forms shaping the cultural symbol of the 21st century. The Curvilinear forms entered the public space, radically transforming their form fusing architecture, technology and information.

The presented examples of „city events" shows the ways of introducing an innovative formal language in the context of historical urban spaces that correspond to the contemporary consciousness in the era of information and digital technology.

Modeling software for designing and engineering free forms of complex geometries is currently widely available. Generative Components and Rhino-Grasshopper software are associative and parametric modeling systems that provided an efficient way to create free-forms and explore alternatives for the cladding system without building the detail design model for each scenario[20]. The form-finding processes of transparent organic forms entice the new generations of young architects with the freedom of design. They have changed their way of thinking from a flat elevational to surface concept of building skin that has developed a new digital tectonics design. Young students get familiar with thinking 'outside the box' by precedents created by digital avant-garde. The presented examples of „city events" shows the ways of introducing an innovative formal language in the context of historical urban spaces that correspond to the contemporary consciousness in the era of information and digital technology.

ACKNOWLEDGMENT

The authors would like to thank students: Grzegorz Baliński, Dorota Godlewska, Rafał Adamiak, Paweł Grabowski, Konrad Zaremba (PhD student), Karol Kowalski (PhD student) for their contributions to this work as well as for their efforts and enthusiasm throughout the WPUT Szczecin workshop.

REFERENCES

[1] [1] G. Lynn, Architecture Curvilinearity: The Folded, the Pliant, and the Supple, AD Vol. 63, No. 3-4, March-April 1993, pp. 9-15.

[2] G. Deleuze, *Le Pli. Leibniz et le baroque,* Editians de Minuit, Paris 1988.

[3] B. Tschumi, *Event Citeies 2*, The MIT Press, 1994, p. 12,

[4] H. Lefebvre, *The right to the city,* in: E. Kofman, E. Lebas, *Writings on cities,*: Wiley-Blackwell, Cambridge, Mass. 1996, p. 158.

[5] L.E. Bourhis , *Glass Mechanics and Technology* (2nd Ed.), Wiley, London 2014.
[6] A. Holgate, The Art of Structural Engineering: The Work of Jörg Schlaich and His Team, Editional Axel Menges, Stuttgart, 1997 p. 110.
[7] J. Schlaich, Jörg, and R. Bergermann. *High Energy. Berlin: Akademie Der Künst*e, 2010. Print.
[8] H. Schoenefeldt, The historic ventilation system of the house of commons, 1840-52: re-visiting David Boswell Reid's enviiromental legacy, The Antiquaries Journal, 98, 2018, 245-295.
[9] B. Kolarevic ed., Architecture in the Digital Age: Design and Manufacturing, Taylor & Francis Group, New York, London 2003.
[10] K. Januszkiewicz and M. Banachowicz, *Glass as a Component of Curvilinear Architecture in 21st Century* Procedia Engineering 161 (Elsevier Science Direct) 1490-1495,2016.
[11] Karta Wenecka (Międzynarodowy Kongres Architektów i Techników Zabytków) Venice Charter (International Congress of Architects and Technicians of Historical Monuments), Wenecja, 1964, Dokument 1 - Międzynarodowa karta konserwacji i restauracji zabytków i miejsc zabytkowych (Document 1 - International card conservation and restoration of monuments and sites).
[12] A. Boisi, *GuarDanDo Roma*, Interni 10, Mediolan 2013, pp. 44-45..
[13] K. Januszkiewicz, *Architektura performatywna w Kolonii* (Performative Architecture in Cologne), AV 2/2012, pp. 32-45.
[14] J. Belis, B. Inghelbrecht, R. Van Impet, D. Callewaert, *Cold bending of laminated glass panels*, Heron, Vol.62, 2007, pp. 123-146.
[15] H. Pottmann, A. Schiftner , J. Wallner,Geometry of Architectural Freeform Structures, Internat. Math. Nachrichten 209, 2008, 15–28.
[16] R. Vierlinger, K. Bollinge,r Accommodating change in Parametric Design, Proceedings of ACADIA 2014 Conference.
[17] K. Zaremba, *Application of the genetic algorithm for a geometry rationalisation of a of a load-bearing structure for free-form roof*, Procedia Engineering 00 (2016) 000–000.
[18] R. Vierlinger, .A Framework for Flexible Search and Optimization in Parametric Design', Rethinking Prototyping, Proceedings of the Design Modeling Symposium Berlin, Berlin 2013.
[19] J. M. Eigensatz, M. Kilian,, A. Schiftner, N. J. Mitra, H. Pottmann, M. Pauly, *Paneling Architectural Freedom Surface*, ACM Transaction on Graphics, Siggraph 2010
[20] A. Tedeschi, AAD Algorithms-Aided Design. Parametric strategies using grasshopper, Le Penseur, 2014.