APPLYING GENERATIVE MODELLING TOOLS TO EXPLORE ARCHITECTURAL FORMS

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Abstract: The paper relates to contemporary architectural explorations of complex, curvilinear surfaces in the context of generative modeling. Traditional ways of representing geometry, based on descriptive methods, favor formal language of "flat elements" easy to map in a rectangular coordinate system and built using traditional technology. In advanced generative modeling techniques used in the architectural digital design objects are not "drawn”" but they are calculated, which means that the designer does not model directly the external form, but its internal generative logic. This allows automatic generation of variations of solutions, and digital production of "difficult" components of architectural forms using CNC technology. The digital generative methods open up new areas for exploration of formal and tectonic features, accentuate form's ability to emerge and adapt. "Architecture is recasting itself, becoming in part an experimental investigation of topological geometries, partly a computational orchestration of robotic material production and partly a generative, kinematic sculpting of space” [9]. Topological transformations have primary impact on mutual relations and the geometry of the resulting form. Innovative architectural designs around the world have shown that the use of generative modeling has great design potential and requires the ability to go beyond the traditional architectural and designing workshop. This ability for future generations of architects may be a subject to competitiveness in the global market.

Keywords: geometric competence, topological surfaces, parametric models of geometry, associative models of geometry

1 Introduction

„*Without tools it would not be possible to realize ideas, and without ideas tools would remain dead*” [5].

Forms of free, curvilinear geometry appeared in the Baroque architecture but the design and the realization of the objects which could not be clearly depicted by descriptive methods, were for centuries a major challenge. A textbook example from the 30th is Endless House by Friedrick Kiesler, a visionary design of a house – sculpture which has never been built. His concept of flexible spaces is still an inspiration for generations of architects and designers. Also, an attempt by John. M. Johansen to construct Spray House - a home of non-linear form (project 1955) ended in failure. Problems with the geometrical calculations forced Jørn Utzon – a designer of the Sydney Opera House (1957) - to simplify the unique roof shell elements, originally intended as irregular shapes of geometrically identical segments of the sphere.

Only the progress and support of modern information technology makes the design and completion of these "too difficult" form possible nowadays. Pathfinder in the use of computers in architectural design Frank O. Gehry recalled[1]: ”*I started designing shapes that*

[1] In 1992, Frank O. Gehry pioneered utilization of Catia software for realization of metal form called "Fish" (Barcelona)

were difficult to draw. This led me to the computer and software Catia, through which I realized with what degree of accuracy documentation can be drawn up and relationships defined". The experience with Catia software (originally intended for the aviation industry) led to further Gehry's conclusion that *"the control of architectural processes with an accuracy of up to seven decimal places allow you to change architectural practice and will lead to the new buildings having a more" exciting, "sculptural forms"* [6].

In subsequent years, NURBS[2] modelling technology (derived from the applications for aerospace, automotive and yacht industries) has become widely used, offering previously unimaginable precision and flexibility of modelling curved forms (by way of mathematical description of the geometry). This technology brought a renaissance of interest in organic shapes of the free-form geometry and the change in a formal architectural language.

Parametric modelling techniques developing rapidly in the last decade have become a milestone in the development of architectural design tools. They facilitate the exploration of options for formal solutions and the optimization of geometry in terms of structural, aesthetic and economic solutions. Generative advanced computational methods are not used for direct modelling of the external form of the object, but they "calculate" form on the basis of defined internal generative logic. The essence of digital design moves from the creation of forms to searching it. New areas of formal and tectonic exploration open up accentuating the ability "to shape up" and "to adapt".

2 Euclidean geometry vs. topological structures

„*The nineties began angular, and ended curvilinear. In architecture they began deconstructivist and ended up topological*" [7].

Digital design is classified according to the processes of digital computational morphogenesis used to generate and transform shapes. B. Koralevic distinguishes strategies based on concepts such as topological structure, isomorphic polysurfaces, kinematics and dynamics, keyframes animation, parametric design, genetic algorithms, performance, etc. Computational methods for creating 3D surface models, modify, stretch and bend without breaking any geometric logic and continuity, allow for exploring topological space. „The notion of topology[3] has particular potential in architecture as the emphasis moves from certain forms of expression on the relationships that exist between and within the existing location and the proposed program. These dependencies are structuring and organizing the principles for the generation and transformation of the form" [5].

One of the first manifests of topological approach in architecture was an essay by Greg Lynn titled "Folding in Architecture" from 1993, inspired by the philosophical theory of "fold" by Gilles Deleuze[4] who introduced to the discourse the idea of a smooth connection of form as a denial of *deconstructivist* idea of conflict and contradiction.

The consequence of the topological approach is a departure from discrete objects of Euclidean space represented in the Cartesian system the so-called "rubber sheet" geometry. The continuous curves and surfaces are mathematically described in the commutation procedures of as NURBS (surface is a very important concept in topology). „*Because of their intrinsic property of one-sidedness, topological structures such as the Möbius strip and the*

[2] Non Uniform Rational B-Splines) are used for constructing NURBS surfaces that are defined by a network of curves (splines). The shape of the NURBS can be controlled directly by manipulating the control points, their weights and position of the nodes.

[3] Object subjected to deformation in a continuous manner (not torn and punctured) is topologically homeomorphic to the initial state, though its geometry changes.

[4] In his published work in 1988 tilted "Le pli - Leibniz et le baroque " Deleuze interprets the term "fold" as a form of unity, connecting and merging separate segments and surfaces into continuous lines and solid.

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Klein bottle, have a potential for an architecture in which the boundaries between what is interior and what is exterior are blurred, an architecture that avoids the normative distinctions of "inside" and "outside" [5].

An example of manifestation of a topological approach to architecture is the design of station area Arnhem Central Station (UNStudio 1996-2007). The program objectives include: a masterplan of the area covering infrastructure (including two tunnels) and the transfer hall with a car park, a bus station, retail and management offices.

The station area is the transfer place for passengers traveling by various means of transport - trains, buses, taxis, cars, bicycles and pedestrian traffic (an estimated flow is about 110000 passengers per day). By creating a diagram of traffic, authors of the project moved from the analysis of two-dimensional planes into single three-dimensional surface or "layered space, which added to the available communication space, while avoiding bottlenecks (elevators, escalators) resulting from the need to connect the different levels." [8] The designed ramp system was equivalent to a diagram in which all lines were drawn and bent towards the empty center without their collapse and unification. The idea of continuous and coherent journey with multiple starting and ending points is translated into a topological manifestation inspired by spatial logic of the Klein bottle[5] - nonorientable continuous surface, which is smoothly transformed from the surface into the hole and back, combining different levels of the station.

The designer of Arnhem Central Transfer Hall, Cecil Balmond (Arup), adopted a topological approach to solve the problem of vertical and horizontal structural consistency and continuity of the connections in the building containing a public hall which transfers-connects neighboring shops, restaurants, parking lots and housing units. "We drew a line that moved up from the foundations to loop and coil over space. How to keep the curvature as a natural consequence of the concept? For that, a merging was needed, connecting roof and floors into one network" [1]. The result is a topological spatial object recognized as the Seifert surface - continuous, and oriented surface, which edge defines the adopted knot[6]. At a later stage of the project, using a proprietary software tool, the idea of the project was transferred into a shell-like model of the roof and the architectural shape of the surface with optimal parameters was selected. "The idea keeps relations and vicinity, not the shape or dimensions" [3] (Figure 1).

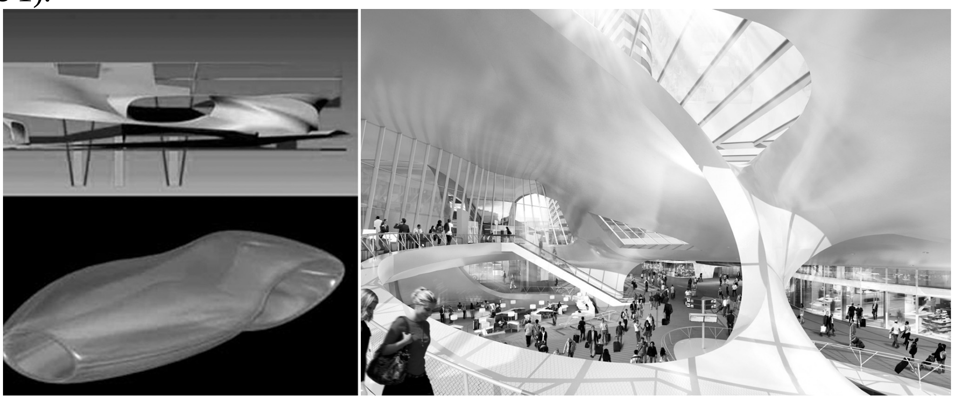

Figure 1: Structure models (left), with a clearly visible inside twist (right). Arnhem Central Transfer Hall, UNStudio

[5] Klein bottle - a one-sided surface that is nonorientable, two-dimensional manifold, with no boundary. Described in 1882 by German mathematician Felix Klein.
[6] Karl J. H. Seifert proved that each knot in 3D space can be represented as a constraint of a consistent, orientable surface with boundary.

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3 Parametric geometry definition

"*The main difference between the direct geometry modelling, and the associative model comes from the "topological effect" of the digital environment enabling re-configuration of the geometric structure.*" [2]

Parametric methods of recording geometry are characterized by a different relationship between the designer and the model if compared to the direct modelling (for example, manual manipulation of NURBS control points of the curve). A parametric model does not contain a description of a rigid form, but the definition of spatial relations, the principles of inheritance of specific geometric features by secondary structure elements, the method of allocation and method of generating successive levels of spatial relationships[7]**.** A pre-generated form may be modified by changing the value of certain parameters, until it meets certain criteria for e.g. aesthetic or structural.

The development of tools for parametric modelling was strongly inspired by SMART GEOMETRY GROUP established in 2003 – a nonprofit organization which has set itself the goal of creating an application for defining geometry and building into it internal logic and the tools for geometry optimization. Due to the SG activity Generative Components were developed and released - an application (which runs on MicroStation) enabling the creation of advanced parametric models of geometry.

An example of the object where the parametric design method was used to create the geometric elements of the whole structure, is the Mercedes - Benz Museum, also designed by the UNStudio (Stuttgart 2005) (Figure 2). The project concept was based on the composition of three circles, tangents and intersections to be reduced gradually to the geometry needed to create the object. The definition of the shape of each element of the building depends on the basic layout of the trefoil plane. Everything in this building from the ramp width and the dimensions of concrete slabs on the floor was coordinated and designed using a parametric model, which allowed analysis of all alternative solutions that meet the given criteria. Parametric modelling is particularly useful for modelling the geometry of buildings with a complex form.

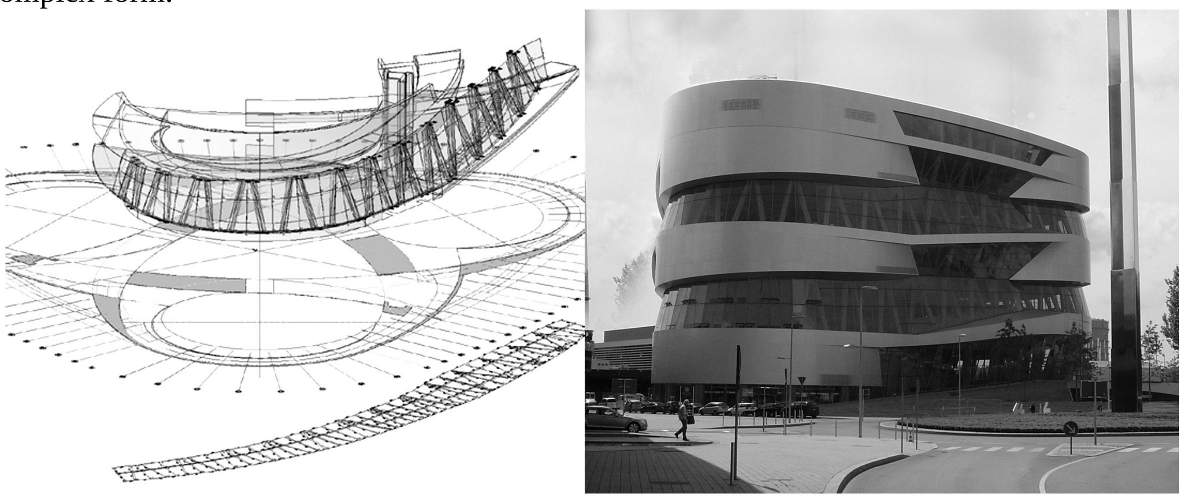

Figure 2: Mercedes-Benz Museum, Stuttgart 2005, part of the parametric model (on the left)

The geometry is generated on the basis of an algorithm stored by means of special applications, such as the already mentioned Generative Components, Digital Design, or

7 Parametric models generally alter principles of form designing and optimization by making use of simulation of physical phenomena, the impact of dynamic forces, fluid dynamics, etc.

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Grasshopper, or algorithmically by using scripting languages such as Visual Basic Script, MEL and Processing. By changing the parameter values it is possible to obtain components with different dimensions and curvature, but topologically homeomorphic.

3.1 Example of parametric surfaces depicted in Grasshopper

Grasshopper, a popular visual programming language created in 2007 by David Rutten from the company of Robert McNeel & Associates (application runs on Rhinoceros), is mainly used for the construction of generative algorithms. Surfaces are described here using NURBS curves. The program is now offered for a free download without expiration dates but Rhinoceros version 4.0 or higher is indispensable. Geometry is defined by using the graphical interface without having to learn a scripting language. Generative algorithm is created by dragging components representing data or function to the work area.

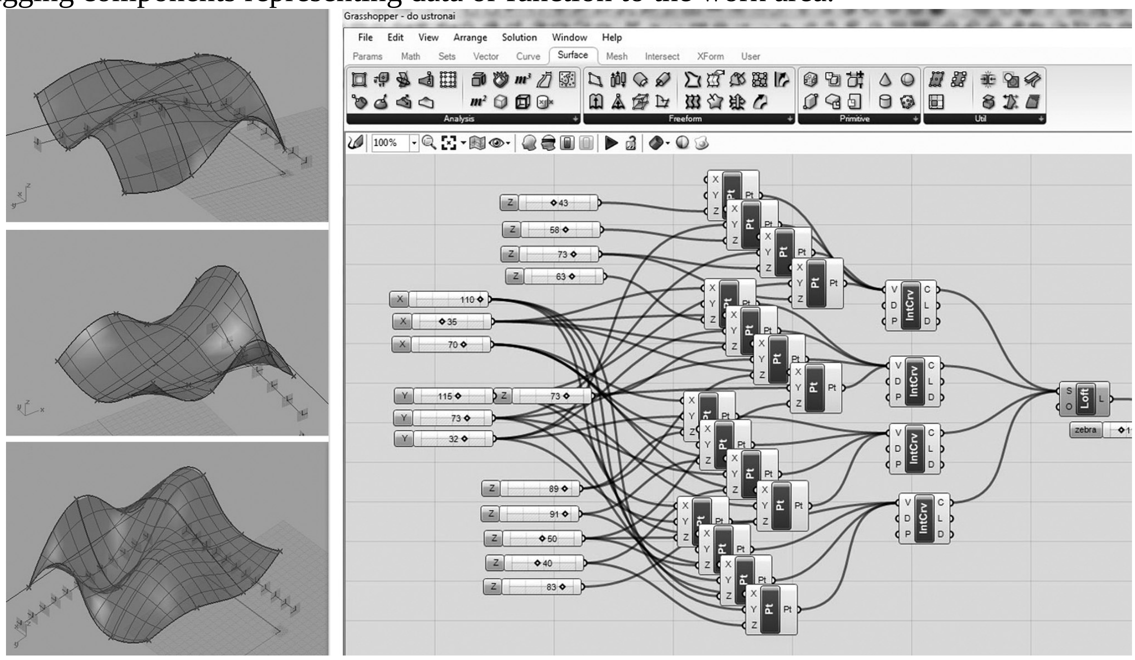

Figure 3: **A**lgorithm of parametric surfaces in the Grasshopper

The outputs of these components are then connected to the selected inputs of the following components. Some components are used to create 3D geometry, others to describe relationships between objects and to determine the behavior of an object under the influence of a particular transformation. This creates an associative model consisting of mutually coupled elements. Figure 3 shows a record of the algorithm generating a family of parametric surfaces, defined by sixteen control points which coordinates are interrelated. Changing the coordinates of control points and their weights (attractive forces) results in a modification of the surface shape. Grasshopper also allows you to generate data relating to the implementation of the framework structure and surface panelization, which allows direct transfer of digital data from the program to the CNC (computer numerical control) machines. Figure 4 shows the algorithm that allows the distribution of the form profiles of longitudinal and transverse sections on the sheets.

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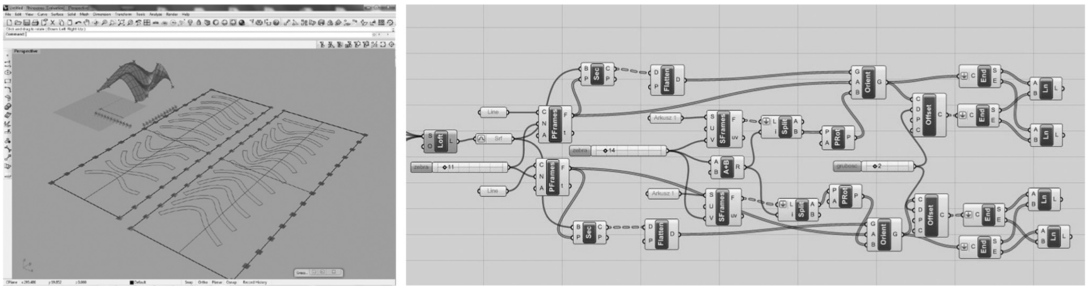

Figure 4: Algorithm that generates the digital data for CNC fabrication

Thanks to its non-deterministic nature, parametric description of forms of free-forms and organic geometry, allows for optimization in order to meet design requirements. "*These surfaces previously required mapping in plaster as a frozen moment, now, they can remain alive as part of the spatial continuum of changes*" [3]. Digital technologies tend to release from all the traditional formal boundaries.

4 Summary

Realizing how the computational potential of computers changes the role of digital media from a tool for visualization of design ideas to a tool for generating ideas, stimulate and inspire exploration. The core of architectural design has become defined in terms of the internal logic, a description of the geometric relationships between its components and the control of the dynamic process of generating forms. Designers get to their hands tools for creating forms of unique complex geometry and its optimization. Architects like Rahim Ali, Hani Rashid, Zaha Hadid, Farshid Moussavi, Greg Lynn in their projects explore topological space constituting an innovative contemporary architecture as the expression of social, economic and cultural era brought by information technology.

Only at a few Polish universities future architects may become acquainted with generative computational methods. Similarly, in the west they are domain of few renowned centers such as London's Architectural Association School of Architecture, the Bartlett Faculty of the Built Environment, the Institut d'Arquitectura Avançada de Catalunya and Universidad de Sevilla. Those universities have adequate parks of CNC machines for prototyping, consisting of laser cutters, milling machines and 3D printers. „*The computer is not only a tool to facilitate the design of the building, but an integral part of the design process, the door to the new worlds in which non-Euclidean forms are as natural as the cube and sphere for the previous*" [4]. Even in the difficult Polish economic situation some investors can be seduced by the unusual, visually interesting forms. But generative modeling techniques should not be reduced to tools only for forming "blobs"[8]. One should go beyond issues with aesthetics to the challenges of civilization, for which they can provide some solutions.

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[8] In fact, the cube is simply a very stiff-looking, very specific, very regularly shaped NURBS object. And the topological structure is not synonymous with curved surface.

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KSZTAŁTOWANIE GEOMETRII FORM ARCHITEKTONICZNYCH ZA POMOCĄ NARZĘDZI MODELOWANIA GENERATYWNEGO

Opracowanie dotyczy kształtowania architektonicznych powierzchni wielokrzywiznowych w kontekście narzędzi modelowania generatywnego. Tradycyjne sposoby zapisu geometrii, bazujące na metodach wykreślnych, sprzyjają językowi formalnemu „elementów płaskich”, łatwych do odwzorowania w prostokątnym układzie współrzędnych i wybudowania za pomocą technologii tradycyjnych. Zaawansowane techniki modelowania generatywnego wykorzystywane współcześnie w architektonicznym projektowaniu cyfrowym nie ”rysują modelu”, ale go obliczają. W konsekwencji projektant nie kształtuje bezpośrednio zewnętrznej formy, ale określa generatywną logikę wewnętrzną. Umożliwia to uzyskanie wariantów rozwiązań w sposób automatyczny, a także cyfrową produkcję „trudnych” komponentów form architektonicznych za pomocą technologii CNC. Dzięki cyfrowym metodom generatywnym otwierają się nowe obszary poszukiwań formalnych i strukturalnych, akcentujące zdolność geometrii formy do „kształtowania się” i adaptacji. „*Architektura przekształca się, stając się w części eksperymentalnym badaniem geometrii topologicznej, częściowo obliczeniowym sterowaniem zrobotyzowaną produkcją materialną i częściowo generatywnym, kinematycznym rzeźbieniem przestrzeni*.” [9]. Transformacje topologiczne mają przede wszystkim wpływ na wzajemne relacje i geometrię formy wynikowej. Awangardowe realizacje architektoniczne na świecie dowodzą, że wykorzystywanie technik modelowania generatywnego ma ogromny potencjał projektowy i wymaga umiejętności wychodzących poza tradycyjny warsztat architektoniczny i konstruktorski. Dla przyszłych generacji architektów umiejętności te mogą być warunkiem konkurencyjności na globalnym rynku.

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