IOP Conf. Series: Materials Science and Engineering **245** (2017) 082042 doi:10.1088/1757-899X/245/8/082042

Nonlinear Shaping Architecture Designed with Using Evolutionary Structural Optimization Tools

Krystyna Januszkiewicz[1], **Marta Banachowicz**[1]

[1]50 Piastów Ave., 70-311 Szczecin West Pomeranian University of Technology in Szczecin, Poland

martabanachowicz@wp.pl

Abstract. The paper explores the possibilities of using Structural Optimization Tools (ESO) digital tools in an integrated structural and architectural design in response to the current needs geared towards sustainability, combining ecological and economic efficiency. The first part of the paper defines the Evolutionary Structural Optimization tools, which were developed specifically for engineering purposes using finite element analysis as a framework. The development of ESO has led to several incarnations, which are all briefly discussed (Additive ESO, Bi-directional ESO, Extended ESO). The second part presents result of using these tools in structural and architectural design. Actual building projects which involve optimization as a part of the original design process will be presented (Crematorium in Kakamigahara Gifu, Japan, 2006 SANAA"s Learning Centre, EPFL in Lausanne, Switzerland 2008 among others). The conclusion emphasizes that the structural engineering and architectural design mean directing attention to the solutions which are used by Nature, designing works optimally shaped and forming their own environments. Architectural forms never constitute the optimum shape derived through a form-finding process driven only by structural optimization, but rather embody and integrate a multitude of parameters. It might be assumed that there is a similarity between these processes in nature and the presented design methods. Contemporary digital methods make the simulation of such processes possible, and thus enable us to refer back to the empirical methods of previous generations.

1. Introduction

The works created by Nature have been an inspiration for building forms since time immemorial. These forms have represented a kind of bridge between men and their natural environment. In the digital age, this bridge seems to be essential both for architects and scientists alike, and a diverse development of research interests concerned with new materials and technologies to re-inform the built environment has emerged. The Nature can provide 'models and processes for the creation of artificial systems that are designed to produce forms, and perhaps even real intelligence' [1]. Today we learn from Nature about efficient energy and material management, we find effective engineering solutions and structural designs for new building materials. We also learn the ways in which the natural and built environments could best interact with each other connecting art and science. Digital instrumentation of the evolution, morphogenesis and emergence processes, along with the proposed methods and techniques, provide a possibility of using these models in the architectural and structural design. It is a key concept, which is important both for the theory and methods of digital design [2]. The interest of architects and designing engineers is increasingly focused on the use of Evolutionary Structural Optimization (ESO) in nonlinear shaping of structures. Their aim is to identify and expand the applicability of these methods in architectural design.

2. Evolutionary digital optimization tools

In the digital age architects and structural engineers often use 'evolutionary' design strategies and genetic algorithms to optimize structures and define shapes [3]. Evolutionary Structural Optimization (ESO), was developed specifically for engineering purposes using finite element analysis as a framework. ESO is based on the simple idea that the optimal structure (maximum stiffness, minimum weight) can be produced by gradually removing the ineffectively used material from the design domain [4]. The original ESO method did not allow deleted elements to be restored. It differs as such from other optimization algorithms which were often based on a general mathematical approach and now have a wide variety of applications. ESO, on the other hand, is purely limited to shape optimization and has very straightforward principles guiding it. It is for this reason that the term 'evolutionary' is an inappropriate, perhaps incorrect adjective to denote this algorithm.

This method has become well known after Mike Xie and George P. Steven (both RMIT) developed it in the early '90s of the 20th century [5].

The basic principle of the ESO is to discretize a volume (or area), define forces acting on it and carry out the FEM analysis. With the data obtained from the analysis, the ESO algorithm performs the deletion stage, which aims to remove the material which is "least useful" in constituting the structure. In basic terms, ESO develops a topology, or shape by removing inefficiently used material based on the finite element analysis. It continues to do so until some optimum is found between the stiffness and volume of the shape. The results show organic, sometimes skeletal structures to be optimal, which was probably the reason for attributing the same qualities as natural evolution to this algorithm. The organic shapes are of course much more complex than conventional rectangular shapes. This has led to limited applicability of ESO outside academic circles [6]. In the following paragraphs some examples that do exist are shown. Since the early '90s ESO has been improved upon and adapted because of its advantages. The algorithm is fast and can easily be understood due to its goal-oriented nature. The development of ESO has led to several incarnations, which are all briefly discussed:

a) Evolutionary Structural Optimization (ESO) works by starting from a dense finite element ground mesh. Material is removed based on stress criteria. In other words, material that is hardly stressed is simply removed, increasing stresses elsewhere until maximum stress is achieved. The result is a 'fully-stressed design'. One of the more famous results of ESO is an animation of the algorithm, which, using certain constraints and optimality criteria, leads to the shape of an apple (Fig.1).

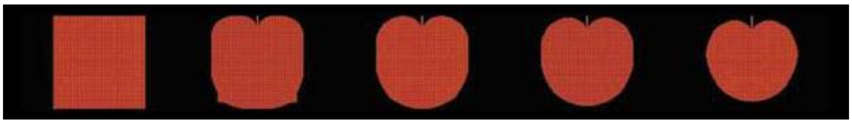

Figure 1. ESO made famous by optimizing towards an apple shape [7]

b) Additive ESO (AESO) works by starting with a very small, minimal amount of material and adding it near the areas of high stresses until maximum stress criteria are met [5].

What distinguishes AESO from the original version is the reversed logic of the process. As optimization using ESO begins with the volume, to remove the excess material from it, AESO has its origin in selected points in space, adding the material in places where it is most needed (depending on the optimization criterion) in the subsequent steps. The ESO method has proved, however, to be not fully effective, producing optimal solutions only in some cases (in others they are correct, but the use of the material is too large) [6].

c) Bi-directional ESO (BESO), a method combining the principle of optimization of ESO and AESO. This method allows elements to be removed from the least efficient regions at the same time as elements are added to the most efficient regions. Hence, a variation of optimised structural solutions can be designed by the constraints of loads, supports and material property (Fig. 2). It combines a possibility of adding or removing material, depending on the adopted criteria. The algorithm is able to decrease the number of calculations and reduce the risk of hitting a local optimum. The rate at which material is added or removed is determined by inclusion of evolutionary ratios (IR/ER) and a rejection ratio (RR). Recently these ratios have been replaced by a single dynamic parameter, the Removal Rate of Volume

(RRV), that can produce different optima with equal volume which are compared based on, for example, stiffness. A description of the improved BESO algorithm ESO was published in 2006 by a team led by Mike Xie, from RMIT (one of the founders of the basis of the ESO method)[5].

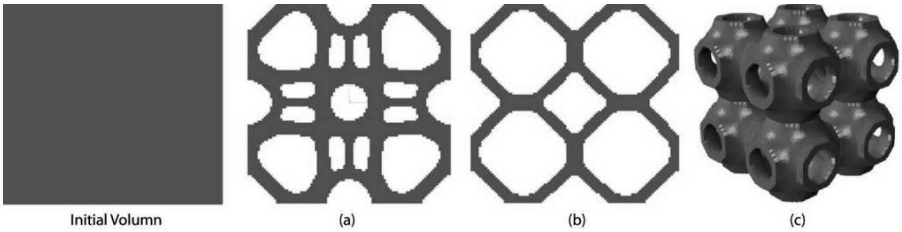

Figure 2. Microstructures and effective elasticity matrixes of two-dimensional and three-dimensional (3D) material cells with maximum bulk modulus for various volume constraints: (a) 50%, (b) 30%; (c) volume fraction is 30%. [7]

d) 3D Extended ESO (EESO). It is an extension of the ESO method used only to generate the form. EESO uses stress contour lines for two-dimensional problems and stress contour surfaces for three-dimensional problems. EESO, thanks to the introduction of the evolutionary process, allows to generate reasonable 3D structures. Shape analysis is based here on an iterative process, whose aim is to achieve optimal structural solutions. These solutions can be adapted to the limitations imposed by the architectural design. Computation is used here only for the calculation of compliance of a form with stress and deformation. The evaluation is interpreted by introducing interactive analysis which is based on the topology, and not the geometry alone. The resulting form retains the same method, topological relations [5]. Japanese structural engineer Mutsuro Sasaki developed this method based on the principles of self-organization in nature.

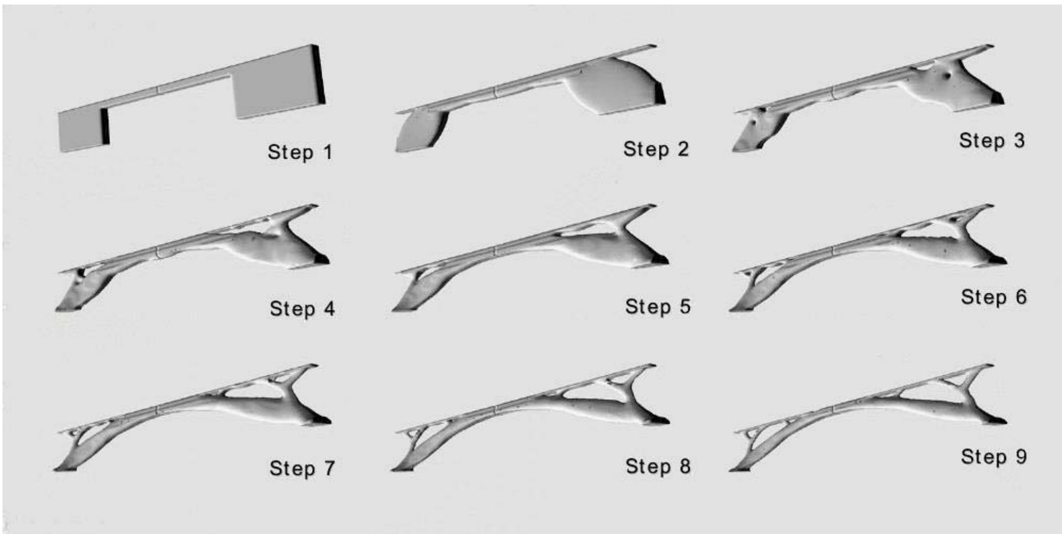

Figure 3. EESO in action, from initial design space to final solution for a bridge structure [7]

3. Shape optimization ESO of building structures for architecture – the case study

The research of natural structures and mechanisms conducted by multidisciplinary scientists has provided new ways of defining geometry and its behaviours. Even more exceptional than manufacturing considerations in structural optimization are actual building projects which involve optimization being part of the original design process. In these instances, ESO did not include manufacturing in an explicit manner, but was used as a tool during initial stages of design.

3.1. "Illa de Blanes" in Blanes, Spain, 2002

One of the first attempts to use ESO digital tools in architectural design was a project of a multi-space cultural and tourism structure called Illa de Blanes in the seaside town of Blanes (Costa Brava). It was executed in the years 1998-2002 by Isozaki & Associates with the help of a Japanese structural engineer Mutsuro Sasaki (Fig. 4). Isozaki created load transfer columns as a tree form using an optimization program starting with virtual block of concrete. The forms which were generated here, of a unique shape, were to become an icon of this seaside resort. However, due to budgetary constraints, the work on the project has been suspended. A large seaside structure with mixed commercial, public and recreational functions was proposed, providing an attractive 75,000 m² of usable space. Besides organically shaped columns, the design also features a roof that was created using 3D Extended ESO [7].

Figure 4. Arata Isozaki and Mutsuro Sasaki, "Illa de Blanes" in Blanes, Spain, 2002

3.2. New train station in Florence, Italy, 2003 and the Qatar National Convention Centre in Doha, Katar, 2008

An extension of the train station *Santa Maria Novella* in Florence, also by Arata Isozaki, in cooperation with Matsuro Sasaki was executed in 2003. It is the largest railway station in Italy, serving 59 million travelers annually. It was the first attempt of an entry in an international architectural competition using ESO digital tools in design.

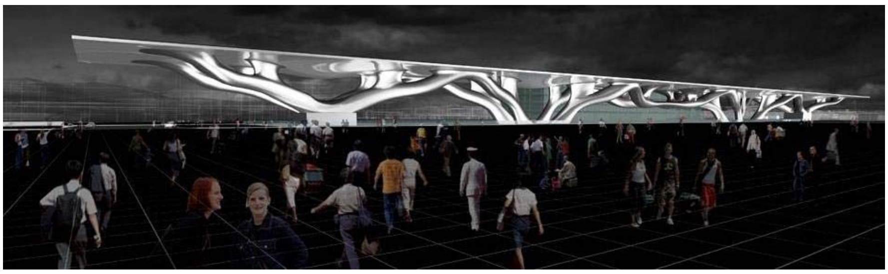

Figure 5. Arata Isozaki, Mutsuro Sasaki, 3D model of the train station *Santa Maria Novella* in Florence, 2003

The new train station project is 400 meters in length, 42 meters wide and 20 meters high (Fig. 5). A roof encompassing this entire complex provides a huge lower space for facilities, while the roof itself is a landing strip for light aircraft. The design entry by Arata Isozaki features a flat roof, supported at several points by organically shaped columns, designed through the use of 3D Extended ESO (Fig. 5). The vision was that supports, with their shape resembling tree branches, would be made of reinforced concrete with a box profile. The project was not implemented because the entry won second prize and lost out to a different design by Norman Foster. It was only in 2008 when the project of The Qatar National Convention Centre (QNCC) in Doha was adopted for the implementation, when there was a real chance to implement this innovative structure. Together with Buro Happold, an executive design was developed, in which the concrete construction has been replaced by a steel one [7]. This design includes a giant structure resembling two intertwined trees to support the building's exterior canopy. The forms are symbolic to reference the Sidra tree which is an iconic symbol in Qatari culture (Fig. 6).

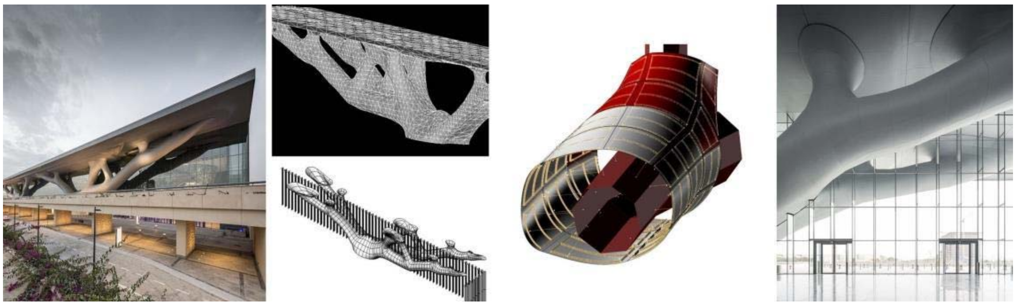

Figure 6. Arata Isozaki and Mutsuro Sasaki, Qatar National Convention Centre in Doha, 2008

Design and engineering of this 250-metre-long and 20-metre-high signature entrance structure was a challenge in various ways: geometric rationalization and engineering, as well as fabrication. First, Isozaki‟s office sent Buro Happold their own complex geometry of organic forms shaped using 3D Extending ESO. Buro Happold then used Rhino to rationalize it and break it down into cladding pieces that could be fabricated in Malaysia. The tree structure has two main components. Its visible exterior skin is a complex curved form. Underneath it is a structural core of octagonal tubes, each tube itself composed of flat steel plates. The whole tree is made up of 70 percent single curvature panels and 30 percent double curvature panels [8].

3.3. Akutagawa River Side in Takatsuki, Japan, 2004

The first example of computational morphogen-process or ESO put into practice is the Akutagawa River Side project in Takatsuki City. This office building, four-stories high, was completed in late April of 2004. It is aimed to rejuvenate the shopping arcade, which runs from the north front nearby Takatsuki Japanese Railway station, and of course this particular urban area as a whole (Fig. 7).

Figure 7. Akutagawa River Side in Takatsuki, Japan, 2004

Extended ESO method (improved ESO method) was adopted to the shape determination of the walls in this building. Two of its side walls, those facing west and south, were optimized using EESO and built of reinforced concrete. It succeeds in bringing out unity configuration of the design and the structure in facade. Typical dead and live loads, as well as dynamic earthquake loads were taken into account. The results of the evolutionary design were verified afterwards in an elastoplastic numerical analysis based on deflections and cracking patterns.

3.4. Crematorium in Kakamigahara Gifu, Japan, 2006

For Toyo Ito's Crematorium in Kakamigahara Gifu, the curvilinear reinforced concrete roof shell free form, only 18 cm thick, was evaluated using Sensitivity Analysis, a systematized method for analyzing curved surfaces to determine an efficient structural shape (Fig.8). Ito's envisioning, a white concrete roof billows up to 11.5 m above a travertine platform beside small lake. Freely dispersed columns drop seamlessly from the undulating ceiling, while the interior is marked off by walls of 19 mm thick glass.

The roof's form is the outcome of a balance between functional, servicing, structural and aesthetic requirements, achieved in collaboration with structural engineer Mutsuro Sasaki, who used digital programming 3D Extended ESO in order to define the most efficient form for the undulating surface. Toyo Ito and Associates worked with Sasaki Structural Consultants to digitally optimize the structural design of the building and its landscape.

Figure 8. Toyo Ito and Mutsuro Sasaki, Crematorium in Kakamigahara Gifu, Japan, 2006

As Sasaki describes in his book titled "Morphogenesis of Flux Structure" (2007), "By means of the repetitive nonlinear analysis procedure it becomes possible to organically comprehend the evolution of structural form in the overall structure from the relationships between its shape and mechanical behaviour", [8]. These perspectives in turn shape the future of complex space, as well as suggest the realization of new paradigms for collaboration between design, structure, and environment. The full integration of structural engineering into the process of architecture does not guarantee good architecture or revolutionary space and forms, but enables their potential to exist. Now more than ever, engineers are embracing the natural world and poetically exploiting its logic to realize architecture's possibilities [9].

3.5. Rolex Learning Centre in Lausanne, Switzerland, 2008

The engineering and construction of the Rolex Learning Center at the Ecole Polytechnique Fédérale de Lausanne is highly experimental and innovative. Mutsuro Sasaki working with SANAA, Bollinger+Grohman and Arup implemented a new shape-analysis approach, described at the beginning of this article, that he called Extended ESO (EESO) (Fig. 9).

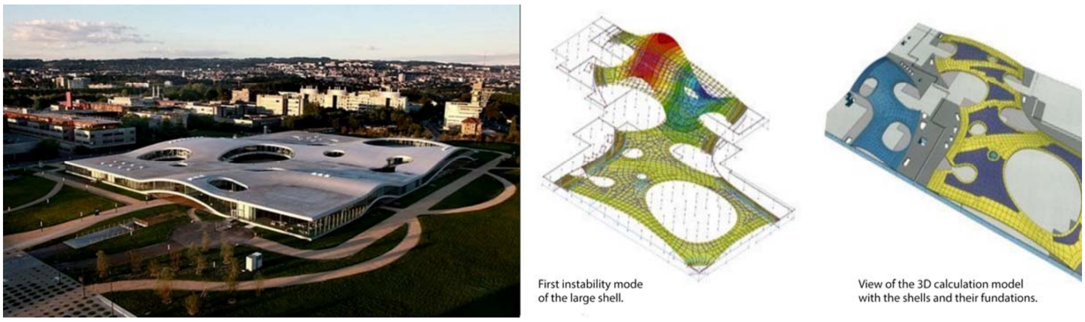

Figure 9. Kazuyo Sejima, Ryue Nishizawa SANAA, Rolex Learning Centre in Lausanne, Switzerland, 2008 [10]

Essentially, the building is made up of two complex geometry 'shells'. The main characteristic of this 160 m x 120 m structure is that the floor of the building follows the convex shape of the two shells of the project. Inside the two shells are 11 under-stressed arches. The smaller shell sits on four arches, 30-40-metre-long, while the larger shell rests on seven arches, 55-90 metre long. As this situation is extraordinarily rare, architecture is usually the product of a collaborative effort. Thus, even a shell can integrate a wide range of design criteria far beyond just structural aspects. Classic form-finding is superseded by processes of tracing performative capacities in the specific morphology. As the load-bearing characteristics vary across the landscape like articulation, no region represents a pure structural typology. The analysis also reveals problematic areas that would necessitate a disproportionate thickness of the concrete shell. Wavy tensile force progression, high bending movements and redirected forces combined with the lack of support points in the patio areas were addressed by redirecting the force flow between the shell perimeters through modification to geometry, size and location of the patios. Such an iterative process of tracking performance in collaboration with the architects entails ongoing design and evaluation cycles [10].

3.6. Students work inspired by the Rolex Learning Centre in Lausanne

Rolex Learning Center, a project at the Ecole Polytechnique Fédérale de Lausanne, is to create a fluid space for students to enjoy. This place is above all a library and learning space devoted to the cultivation of knowledge by an array of different methods**.** Topography of the place lends an extraordinary fluidity to the building's flexible open plan - a flow that is emphasized by fourteen voids in the structure, of varying dimensions. The seminal work is often recognized more as a landscape than an actual building. This idea inspires the students of architecture around the world to create their own design variations.

A few years ago this idea was undertaken by Krystyna Januszkiewicz (Leader of Digitally Designed Architecture Lab) and faculty member at the WPUT (West Pomeranian University of Technology) in Szczecin. Students of the architecture created a project inspired by the Rolex Learning Center in Lausanne. The main task was to find a free-surface Aqua Park project fitting into natural landscape. As the main architectural concept of the project was adopted the Rolex Learning Center’s spatial idea to a new public use. Spread over one single fluid space, it provides a seamless network of public services for leisure with free-located smaller open water courts. Thanks to this assumption, the building could function as a partially open or fully closed facility. The form of the building is achieved by contouring a traced.

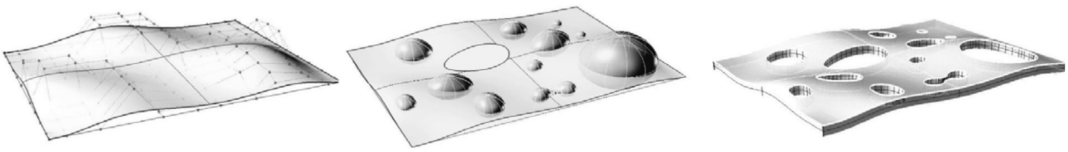

Figure 10. Modelling the free-surface with the Rhinoceros software

The Contour creates a spaced series of planar curves and points resulting from the intersection of a defined cutting planes. To create a terrain model was used for the command – Patch. The Patch option drapes a surface over the contour curves. These commands fit a surface through selected curves, meshes, point objects, and point clouds. In the next step terrain was duplicated to create thickness. As a result, solid shapes corresponding to openings and profile were created and terrain was trimmed. The two surface edges were then lofted to create a single slab and then grouped. This group was then duplicated using the edges of the two slabs, glass was created by lofting and offset commands to create thickness.

Models used to represent the intentions of a desired architecture visually can be in the form of diagrams, drawings, digital abstract or physical models and computer-generated images. This type of representation can be not appropriate for a “precise, unequivocal, and unique material reality’ and further states that ‘even the most convincing techniques of representation do not correspond fully to the experience of the built reality”, [11]. Therefore, a representation is usually a description of a material system rather than of a single material itself.

Nowadays, many different tools, including common architectural design tools such as Autodesk® Maya®, are widely used to visualise and construct micro and nano structures. There are the plug-ins which, combines the geometric principles of nano structures with finite element analysis, providing information about stability and assembly processes. The representational tools of an engineer are similar to those used by materials scientists. Due to their historical engagement with materials from structural points of view, over time, engineers have developed a repertoire of representation techniques that help to define and analyse a structure as well as to mediate the performance of the structural system.

4. Results and discussions

The presented works are the attempts to use ESO digital tools in an integrated structural and architectural design. The structural system is developed together with the construction method to realize the freeform geometry in rational and efficient manner. Such architectural and structural design that embrace a new holistic integration is also inspired by the internal structures of nature. This is a response to the current needs geared towards sustainability, combining ecological and economic efficiency. For example, the Rolex Learning Center is a highly energy-efficient building which, for its low energy consumption, has received the coveted Minergie label - the standard used in Switzerland for measuring environmental excellence in buildings. The imperative of environmental protection and sustainable development require, in fact, a re-examination of the problem of efficiency in the aspects of using raw materials, energy consumption, and ecology. This obliges to recognize and use the latest developments in all fields of science, engineering and technology, for research and implementation of new solutions. For structural engineering and architectural design this means directing attention to the solutions, which are used by Nature, designing works optimally shaped and forming their own environments. Structural designs that embrace a new holistic integration have also been inspired by the internal structures of nature.

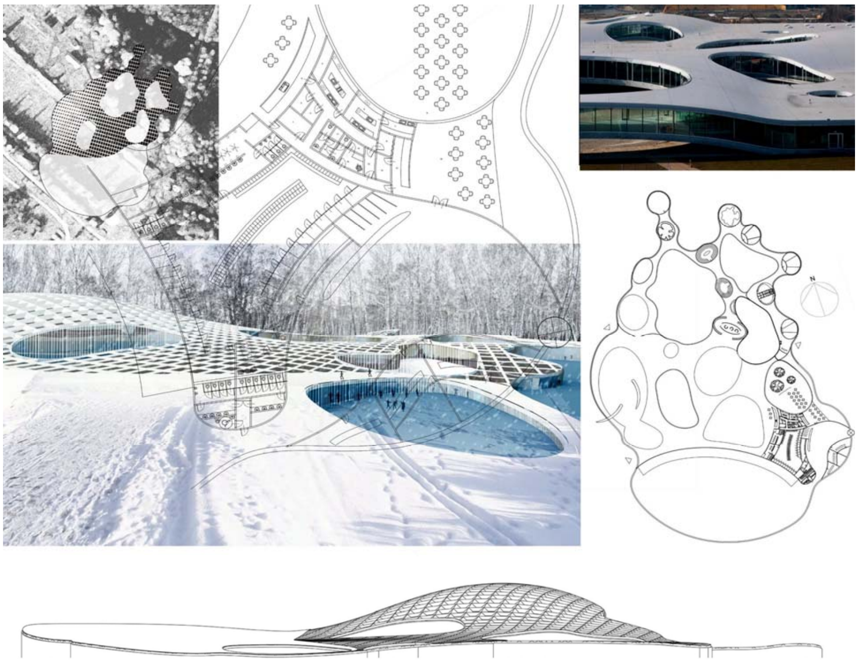

Figure 11. Katarzyna Dobrowolska, Aqua Park in landscape near Szczecin, Civil Engineering and Architecture WPUT in Szczecin, 2016

5. Conclusions

Architectural forms never constitute the optimum shape derived through a form-finding process driven only by structural optimization, but rather embody and integrate a multitude of parameters. It might be assumed that there is a similarity between these processes in nature and the design methods presented in this work. This can also be understood as an evolutionary method, one that is not limited by the availability of calculation and analysis methods. In digital processes, each individual structure needs to be fully defined and modelled in order to be evaluated. Cognitive form, its tectonics and space, change the existing axioms of design. The full integration of structural engineering into the design process of architecture does not guarantee good architecture or revolutionary space and forms, but enables their potential to exist. Now more than ever, engineers are embracing the natural world and poetically exploiting its logic to realize architecture's possibilities.

References

[1] M. Weinstock, "Morphogenesis and the Mathematics of Emergence", AD74, no 3, 2014, pp. 11-17.
[2] B. Kolarevic (ed.), "Architecture in Digital Age. Design and Manufacturing", London 2005.
[3] J. Coenders and D. Bosia, "Computational Tools for Design and Engineering of Complex

IOP Conf. Series: Materials Science and Engineering **245** (2017) 082042 doi:10.1088/1757-899X/245/8/082042

Geometrical Structures: From a Theoretical and Practical Point of View", in K. Oosterhuis, L. Feireiss (eds), "The Architecture Co- laboratory: Game Set and Match II; On Computer Games, Advanced Geometries, and Digital Technologies, Rotterdam 2006, pp. 271-279.

[4] P. Tanskanen, "The evolutionary structural optimization method: theoretical aspects", Computer Methods in Applied Mechanics and Engineering, Vol. 191, Iss. 47–48, 2002, pp. 5485-5498.

[5] Y. M. Xie, G. P. Steven, M. P. Nielsen, "A simple evolutionary procedure for structural optimization", Computers & Structures No. 49, 5/1993, pp. 885-896 also: Y.M. Xie, G.P. Steven, "Evolutionary Structure Optimization, Springer Verlag, 1997.

[6] K. Januszkiewicz, "Evolutionary digital tools in designing nonlinear shaping of concrete structures in current architecture", Central European Congress on Concrete Engineering, Concrete Structures in Urban Areas, September 4-6, Wroclaw 2013, DC full version: pp. 75-80.

[7] X. Huang, A. Radman and Y. M. Xie, "Topological Design of Microstructures of Cellula Materials for Maximum Bulk or Shear Modulus", Computational Materials Science 50, No. 6, 2011, pp. 1861–70.

[8] M. Sasaki, "Morphogenesis of Flux Structures", AA Publication, London 2007, p. 61.

[9] H. Ohmori, "Computational Morphogenesis. Its Current State and Possibility for the Future", Proceedings of the 6th International Conference on Computation of Shell and Spatial Structures, 28-31 May 2008, Cornell University, Ithaca, NY, USA, pp. 148-152.

[10] K. Bollinger, M. Grohman, O. Tessmann, "Form, Force, Performance. Multi-parametric Structural Design", AD 78, no 2–3, 2008, pp. 20–25.

[11] A. Picon, "Architecture and the Virtual: Towards a New Materiality", Praxis 6, 2004, pp. 114-121.