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The Relationship Between Geometry and Optimization Methods at Structural Design*

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Abstract

Thanks to the close relationship that the mathematics have established with various disciplines including architecture and the computer-aided design technology which has an expanding area of use with ever-growing development of the technology, it has become likely to use different mathematical models in the design process. Structure design through mathematical models has brought the geometry and material parameters forward.

It makes the load-bearing system a designable system that there are many parameters which are different from each other and the process of exploring the relationships between them. Geometry constitutes the form of this system and the first parameter that catches the attention. Each created form consists of geometry, and the structure design is required for the form to be able to remain standing. In architecture, the material along with geometry constitutes the main components in formation of the design texture, form and the appearance of the building. In those structure systems where mathematics create a model for, the electronically-created simulation has continued an interface which can be used jointly by architects and engineers, leaving the bothering and complicated calculation in the past.

For these reasons, the relationship between geometry and optimization methods has been analyzed through Arup optimizer, dynamic relaxation, evolutionary shape optimizer and evolutionary structural optimizer at the structural design in this research.

Keywords: Structural Design, Optimization methods, Self-organization, Geometry, Complexity Theory.

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1. Introduction

Structure is the general name of the bearing system and bearing elements which form the frame of a structure. Structure emerged with the existence of mankind, and developed with his evolution. Since the industrial revolution, people have started to design structures of engineered buildings in a clearly visible way, thus bearing systems have become definable. We can say that structure not only helps establishing an order and bearing loads, but also dramatically affects in most cases both the aesthetical and structural features of architecture (Bielefeld and El Khouli [3]). In the 20th century, the followings were experienced in construction techniques:

1. Emergence and evolution of structural theories. With this the opportunity of designing various types of structures with sufficient safety and sensitivity,

2. Abundance of high resistant materials such as steel and concrete, and drastic evolutions in materials,

3. Magnificence and change of new architectural subjects brought by industrial development, new and fast transports and social advancement,

4. Fundamental changes due to increased importance of economy (Nervi [12]).

Perhaps, the most important item among those mentioned above is the first one. Because, spread of structural theory knowledge has expanded the principals of structural problems over the entire field and saved architects from schemas and solutions which could lead to success only through a slow evolution. Historically, there are architects whose visions of aesthetics produce designs with very strong structural sensibility and innovative ideas. Such buildings have influenced the fields of architecture and engineering tremendously. Examples of these architects inclu-de: Buckminster Fuller, whose philosophical ideas about holistic design, synergetic and geometry led to innovative structures such as the geodesic dome; Felix Candela, creating thin-shell concrete structures which are efficient and beautiful (Figure 1), (Beghini *et al*. [2]).

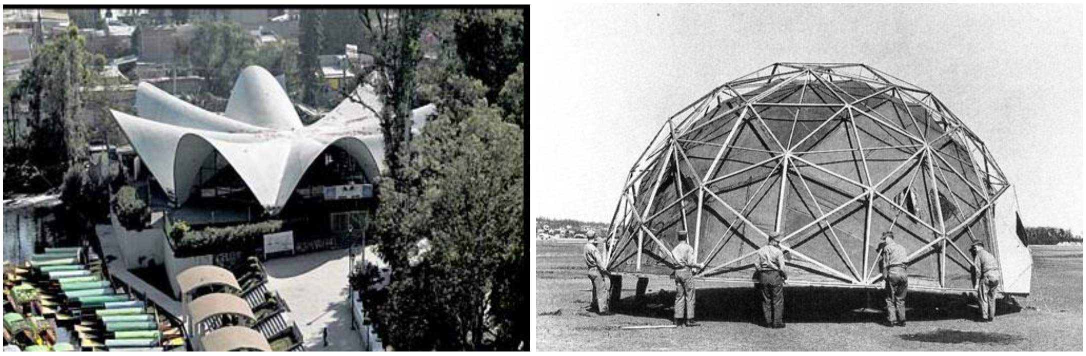


Figure 1: Felix Candela's Thin Shell Concrete Structure and Buckminster Fuller's Geodesic Dome

Source: http://mcis2.princeton.edu/candela/manantiales.html# and http://design.designmuseum.org/design/r-buckminster-fuller

Today, the relationship of mathematics and architecture has evolved in a much more complex form due to computerized technologies. This evolution is not limited to topologies or complex geometries, but has also brought the sense of computerized design as a result of computerized thinking, and started to integrate also formal logic and axiomatic methods into design processes through computerized design rather than to obtain architectural mathematics, absolute geometry, parametric volume and surface relationships. In recent years, however, mathematics has stopped being seen as a search tool only for ratio or form for architecture, and been transformed into complex design processes in which various data are used as a design parameter and information of different areas of knowledge are integrated, as well as into a basic form of thinking which is a must of these processes (Sorguç [14]). Geometry has become important as a tool that associated different areas of knowledge to each other in these processes.

2. Geometry and Optimization

Optimization related to geometry is based on simulation results. These results are not linear. One aspect of optimization is evaluation of design drafts. Second aspect is creation of new and more promising designs. Thus, optimization contains both analysis (evaluation) and synthesis (production of new solutions) (Uzun [16]). Production of new solutions depends on optimization strategy. Formation of these strategies define the structure of the relationship between information and geometry. As traditional mathematics and static systems became insufficient in explaining the complex setup of the nature, many disciplines have started to define natural and artificial formations by computational theories and algorithmic thinking. In this search, computational theory is being transformed into theoretical frame through the way of thinking it presented, and into producing tool through the methods it presented (Erdoğan et al. [7]). This way, optimization methods brought by computational thinking enable us to understand the nature and its systems with new models.

As a result of the globalization that characterized the environment in the 21st century, developments in communication and information processing technologies, increase in the value given to human in a manner incomparable to the past and development of holistic systemic understanding in the assumption that everything is related to everything; a new idea has occurred and spreaded that the complexity approach would enable better understanding of businesses and organizations and their operation properties. The systems examining the complexity are the concept that defines both initial values of variables and their mutual interaction and non-linear relationship with each other and with outer elements (Çınar [6]). In that case, it is possible to form a mathematical or logical model which covers the components creating the system and their actions. According to Wang [17, pp.178];

"*Considering that structure of the system, complexity theory feeds from two main hypotheses. According to the first one, there is neither an objective method nor a predictable truth. Systems are open, fluid and complex. They exchange matter, energy and information with the environment surrounding them, but the parts of the system are so numerous that causes and effects are uncertain. Instead, there are constant feedbacks and feed forwards, and meaning of interactions depend on the receiver, not just the system. Moreover complex systems are self-organizing. This means they interpret the information in the system and project "emergent properties" that could not have been predicted from the component part, and these emergent properties feed back into the system and influence* *behavior. This brings us to the second defining feature of complexity theory: The whole of a system is greater than the sum of its parts."*

A key idea in complexity theory is that of small, simple parts, which are replicated, combined or changed, following simple rules. After a number of iterations, the result is a diverse system whose future state is not easily predictable (Burry and Burry [4]).

The chaos theory that developed with the complexity theory, is not a physical theory or a mathematical induction as a structure, but a method enabling explanation of components of physical reality as a whole. It has developed and gained popularity within the last ten years together with emergence of digital computers and screens which make their outputs easily visible. However, scientists have started to look at this subject skeptically when the impossibility of prediction in systems displaying chaotic behavior is combined with this popular image. But these suspicions are gradually disappearing as a result of the fact that the chaos theory and its extension, fractal geometry have recently found important areas of use in various fields from stock exchange to meteorology, to communication, chemistry and mechanics (Gleick [9]).

Chaos is defined by some scientists as equivalence of disorder and of the concept of not being able to find its ground. However, the so-called event that is called coincidence in chaos does not happen randomly, and predictability means not knowing the future exactly. Even though chaos expresses complexity and disorder when looked from outside, for scientists, it expresses a regular disorder, i.e. a complexity with a purpose, which cannot be foreseen and in which irregular but similar shapes are formed (Töremen [15]). Here, it is important to discover and interpret through parameters, which can evolve into the order that looks chaotic in the system and chaos intersection. Chaotic behavior shows the fact that the circumstances and events, which we observe during our lives, which seem to be unrelated to each other and give the expression that they are irregular and incidental, are in fact a part of an order when looked from a different point of view. Scientific definition of the concept chaos is expressed as "the order within disorder". Irregularity in chaotic behavior is not a simple disorganization or a complexity, and defining irregularity in such a way makes both chaos and order incomprehensible.

The recent study of dynamic systems, related to theories of chaos has advanced progressively over the last fifty years due to the technological capacity for computer simulation (and calculation) of trajectories of complex geometry and random definition (Gausa et al. [8]).

With the computability theory becoming an interface, cooperation of architecture with biology, genetics, information technologies, mathematics and many other disciplines has become stronger. This approach has first enabled the information flow setup to be analyzed by universal structure of the computability idea, then led to suitable, necessary and correct reconstruction of the analyzed information in the concerned area. In addition, computability theory supports the interdisciplinary realization of information flow without limitation to a specific area thanks to its universal structure. As an interface, the idea of computability transforms into a study area in which architecture establishes interdisciplinary cooperation and takes place in holistic information flow. Identification, re-evaluation of variables or redetermination of their relationships in design may cause holistic design to develop and change. Thus, it is possible to develop the understanding of performance-based architectural design in defining parametric design processes and to have more control over the process. All these developments have brought along productive approaches that can consider different variables in structure designs of buildings.

The generation of these systems is practically buildable based on a recent, more engaged approach in architectural design to digital computation and the possibility of rapid iteration. In some cases, it is a deep faith in this bottom-up, systemic approach to meaningful pattern-making (Burry and Burry [4]). These pattern-making in self-organization raises the question of control. This raises questions about geometric discrimination.

2.1. Geometry and Self-Organization

Self-organisation is a final phase in the processes of relations between systems that allows solutions for adaptation. It is a form of dependent, inconstant grouping, fluctuating according to variables in the system in which it is implanted or to which it responds as stimulus (Gausa et al. [8]). Self-organization is an internal process. It is the process of organizing the system itself for a special function without external guidance and management against environmental factors. For instance, thermites are arachnoids living in colonies whose numbers reach up to millions. They obtain a solid and durable material by mixing the secretion in their mouths with soil. They can build their nests up to 6 meters high and 12 meters wide. They build special corridors inside their nests to obtain air circulation and can filter air through the pores they form. Each thermite species build nests that are compatible with the conditions of the environment it lives in. Some thermites living in rainy regions build mushroom-like nests that have special projecting roof. Some species shape their nests according to the magnetic field of the world. Some living in Sahara on the other hand, get about 40 m lower than the surface and enable water to reach the nest located above through vaporization. Thick walls of nests ensure preservation of the humid inside. These creatures act by repeating this complex system with simple steps and evaluating natural parameters (such as humidity, heat and magnetism). We can evaluate this social system from many aspects. Every single unit of the system acts with simple setups algorithmically. When the system is examined, it is seen that unit automats (one thermite) ensures continuity of the existing system through simple directives. An open-ended, productive and prevalent system is observed (Çıltık [5]).

According to Hensel [10, pp.6];

"Complex adaptive systems entail processes of self-organization and emergence. However, both concepts express very different characteristics of system's behavior. Self-organization can be described as a dynamic and adaptive process through which systems achieve and maintain structure without external control. The latter does not preclude extrinsic forces, since all physical systems exist within the context of physics, for example, deploy the self-organization of material systems exposed to physics to achieve optimization of performance capacity. Self-organizational systems often display emergent properties or behaviors that arise out of the coherent interaction between lower-level entities, and the aim is to utilize and instrumentalist behavior as a response to stimuli towards performance-oriented designs."

In conclusion, complex systems, self-organisational systems and collective intelligence concepts are merged with one another. While mentioning these concepts, we can say that the main ideas underlying these systems are open-ended, self-repeating, parametric, productive and prevalent. In the studies carried out on the aforementioned systems, algorithms are used for their solution. Algorithms can produce complex systems by using simple directives as in thermites. Algorithms that can produce a complex system can also be used for solution of existing complex systems (Çıltık [5]).

Various algorithmic modelling methods to define natural systems have emerged under the scope of shape-transformation concept. At the same time, these methods introduce new understandings of design to the architectural discipline such as use of digital tools and shape production. Key-shape animations, genetic algorithms and topological architecture can be given as an example of digital production methods provided to architecture with this point of view. In this regard, Kolarevic [11, pp.17] defined digital generative systems as;

"The digital generative processes are opening up new territories for conceptual, formal and tectonic exploration, articulating an architectural morphology focused on the emergent and adaptive properties of form. The emphasis shifts from the "making of form" to the "finding of form," which various digitally-based generative techniques seem to bring about intentionally. In the realm of form, the stable is replaced by the variable, singularity by multiplicity."

Non-euclidean geometries enabling development of modern geometry were built on the main ideas that the spatial space is curvilinear and multi-dimensioned. Among the non-euclidean geometries are hyperbolic geometry and fractal geometry (Figure 2).

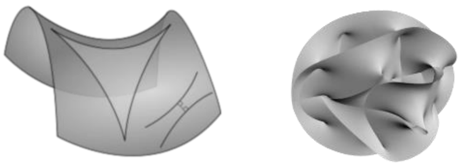


Figure 2: Example of Non-Euclidean Geometry

Source: http://en.wikipedia.org/wiki/Hyperbolic_geometry

Fractal geometry examines shapes which are self-repeating but diminishing infinitely, parts that form a similar object, or the whole of object of components. Irregular details or patterns are repeated in gradually diminishing scales and can last forever in entirely abstract objects. Natural models can be described realistically by using methods of fractal geometry. A fractal object has two basic characteristics: infinite detail in each point and a degree of self-similarity between parts of the object and its overall characteristics. Processes rather than equations (Gausa et al. [8]). Self-similarity is the common characteristics of fractal objects (Figure 3). Each one of the different groups in different magnitude scales is similar to the total entirety. When we proceed to the infinite small or large in the scale, object repeats and reproduces itself in parts. Fractal geometry parts always create objects similar to the total entirety. Use of this geometry enables reproduction and shaping of dynamic and chaotic forms of natural systems. It allows bringing order to chaos, finding the causes of randomness and determining the indeterminable.

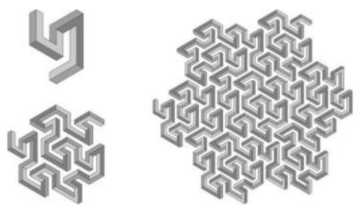


Figure 3: Fractal Geometry

Source: http://catherinephilosophie.wordpress.com/tag/fractals/

Describing spatial relationships of complex systems in geometrical way requires description of information within its relativity, i.e. topology, rather than within its certainty. In topological geometry, relational structures are defined based on values of object such as number of edges, corners and points. In topology-based designs, it is fundamental to establish relational logic between the shapes that belong to formal configurations. After the logic is established, making a dynamic design is possible by producing various formal alternatives which are open to transformations and are established on the same relational system. This dynamic design allows optimization, in other words reaching the best by decreasing or increasing.

3. Optimization Methods

The most basic analysis method used in solutions of optimization methods is finite element method. Finite element separate an element as infinite differential cubes and it is the analysis of these cubes through specific mathematical processes. The basic idea in the finite element method is to find a solution for a complex problem by simplifying it. An approximate result is obtained rather than a definite result since the main problem is simplified, however it is possible to improve this result for solution and get very close to definite result. In this part, improved optimization methods will be described based on finite element method.

3.1. Arup Optimizer

Interprofessional integration in Arup partners has been facilitated through work of different professional groups in the same environment, as well as computers. Computer system allows both engineers and architects work simultaneously in different terminals on different layers of a drawing. Thanks to this system, any change made by any engineer or architect is immediately reflected on drawings of other employees. It is the result of this rational approach of the company that enables net usable area ratio calculations of mechanic engineers, energy saving and cost analysts to shape buildings as much as the suggestions of architects (Aksoy [1]).

According to Burry and Burry [4, pp.253];

"In contrast to the traditional engineering method of deriving member sizes for stressed elements from tables and charts, it allowed iterative evaluation of the most appropriate member size for structural element individually. The optimizer works on the very simple principle of constraint satisfaction, which carries out design-strength checks for each individual member in a group. One constraint is active when a series of checks is being carried out. The system is very input-sensitive; it is important to select appropriate starting values for the member sizes to avoid finding local, rather than global, minima." (Figure 4)

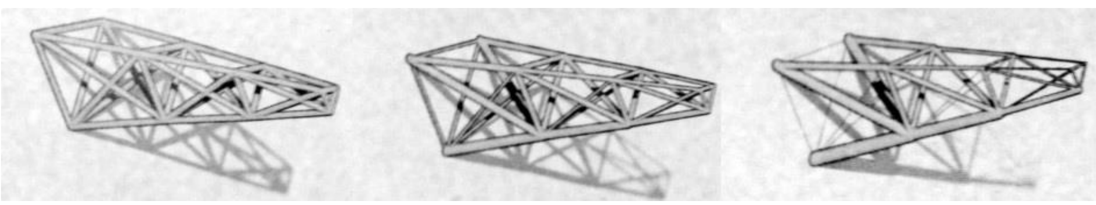


Figure 4: Arup Optimizer Basic Example

Source: Burry and Burry [4, pp.253]

Watercube swimming pool building built for 2008 Beijing Olympics were designed and made with PTW Architects and Arup partners (Figure 5). Based on the idea that walls and roof of this building are just like leather, designers put forward which structural topology can be designed homogeneously as 3D. For that, designers examine various examples of nature from living cells to mineral crystals and take as a reference the studies of Plateu and Weaire Phelan who took soap bubble as a reference in the 18th century.

Figure 5: Watercube Building, Ptw Architects and Arup

Source: www.arup.com/Projects/Chinese_National_Aquatics_Center/WaterCube_overview_1.aspx

While designing structural geometry, it is started with infinite foam rows and then a cube composed of 177x177x31 cubic meters as big as the building is made. This cube block is extracted out of the finite foam rows to form a geometric shape and an organic shape is given with etfe cushions. Building of the sensitive physical model is decided with 22000 structural elements and 4000 different coating panels. Since it is impossible to choose and calculate these elements manually, Arup optimizer determines the dimensions of the element which will ensure that the building stands. Arup optimizer automatically chooses the element dimensions through repeating optimization process (Figure 6).

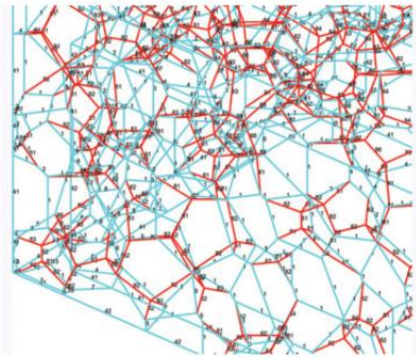


Figure 6: Water Cube Arup optimizer

Source: www.continuingeducation.construction.com/article_print.php?L=5&C=418

Istanbul Kanyon is designed to be a state-of-the-art live, work and play environment that caters to residents and visitors. Arup, took charge of the mechanical, electrical and structural aspects of the development. Arup also took responsibility for the civil, façades, acoustic, security, seismic, holistic and wind studies disciplines. A series of districts connected by an interior street, or Canyon, that traverses the site and includes a variety of courtyards and terraces. The districts include: Entertainment Sphere, Office Plaza, Garden Court, and Performance Plaza. At the heart of the project, the Canyon opens on to the Performance Plaza, an amphitheater carved from the base of the Sphere. A full height triangulated tubular steel lattice frame was used as an external shell for maximum stiffness. Reinforced concrete walls were placed at the back of the sphere to balance and transfer down the big tension forces from the inverted semi-sphere system. Internally, two inverted L-shaped brace frames added lateral stiffness to the structure, the diagonals of which were arranged to fit around corridors and doorways inside the building (Figure 7).

Figure 7: Arup's Istanbul Kanyon Project

Source: www.arup.com/Projects/Istanbul_Kanyon.aspx

3.2. Dynamic Relaxation

According to Burry and Burry [4, pp.256];

"It is a method of computational modelling for the form finding of cable and fabric structures. This method had to find the structural subdivision of the complex, curved dome into glazed facets. It assumes that all the mass is concentrated at the structural nodes. The system oscillates about the equilibrium position under the influence of loads. The iterative process is achieved by simulating a pseudo-dynamic process in time. At each iteration, the geometry (node position) is updated, using Newton's second law, where force is equal to the product of mass and acceleration. This is doubly integrated to give a relation between speed, geometry and residual force. Gradually the forces acting on each individual node are equilibrated. Finally, the friction component tangential to the surface at each of structural nodes via imaginary strings to its four nearest neighbors converges at zero." (Figure 8)

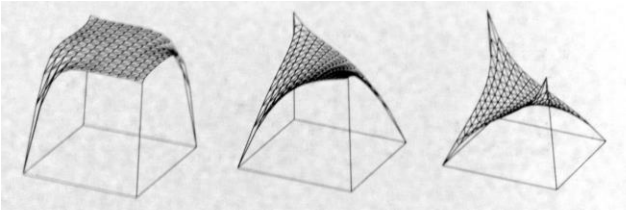


Figure 8: Dynamic Relaxation Example Diagram

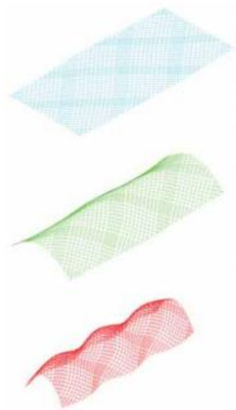
Source: Burry and Burry [4, pp.256]

Weald and Downland Gridshell Museum is built at Sussex in England and museum is designed by Buro Happold and Edward Cullinan. The design is based on dynamic relaxation method. This building is a example of wooden modern structures in rural areas (Figure 9).

Figure 9: Weald and Downland Gridshell Müzesi

Source: research.ttlchiltern.co.uk/pif294/tdk/case%20studies/structural%20engineering%20of%20the%20downland%20gridshell/01%20small.htm

The dimensions of the museum selected by optimizing the dynamic relaxation method will be the most economical and safe. Wood and timber sizes range from established and the future of the planting locations are marked. In the construction according to the value calculated by placing the computer it is allowed to take the final shape (Figure 11).



Şekil.10. Museum's Dynamic Relaxation Simulation

Source: www.ingenia.org.uk/ingenia/issues/issue18/dickson.pdf

Şekil.11. Construction Progress

Source: gridshell.blogspot.com/2007_04_08_archive.html

3.3. Evolutionary Shape Optimizer

Today, shape optimization is known as the structural optimization that deals with the research of the most suitable form of design. This is usually the first tried shape acting as the smallest (or the largest) aim function within suitable design limitations through moving its borders. Typical optimization parameters on the other hand are minimal weight, minimal compatibility (or maximum hardness), the most suitable eigenfrequency and maximum structural softness. The most suitable design limitations are generally material values, displacement, hardness, stress and torsional load.

According to Burry and Burry [4, pp.257];

"Evolutionary shape design by means of sensitivity analysis is the exercise of coming to understand how local and more global shape changes affect the mechanical performance of the structure in terms of its efficiency and low-strain energy. The strain energy is generally minimized when most of the loads are transmitted axially in the structural members, and there is very little bending. A global

minimum may represent very good solutions that are much closer to the design shape and to meeting all the other design criteria. Sensitivity analysis is study of how variation in the output of mathematical model can be apportioned, qualitatively or input of a model. The aim is to identify the relative weighting of sources of uncertainly. The understanding of the response to changes in its inputs is often obscured in mathematical models, but it is important in making correct and meaningful use of model."

An example for the evolutionary shape optimizer is Meiso no Mori Crematorium building of Toyo Ito in Japan (Figure 9). Wide concrete roof supported by columns hide inner blocks. As seen in Figure 9, the roof has the shape of a free form when looked from the plan. Design of the shell structure is optimized in order to find efficient structure type. Following that, structural nodal points are determined with the most suitable one of the repeating calculations in a manner so that the total strain energy will be minimum. In Figure 10, simulation of the roof is obtained as shown in the left of the figure, and displacements that occur as a result of placement of structure nodal points are observed and the most optimum shape is found in the geometry created after seventy repetitions. Nodal points are shown in upper right side, the curves passing through the nodal points, and the availability of the shape occurring in each change at the lowest graphic.

Figure 9: Meiso no Mori Crematorium, Toyo Ito

Source: http://www.ccaa.com.au/sub/cplusa/articles/issue/10/meiso-no-mori-crematorium/

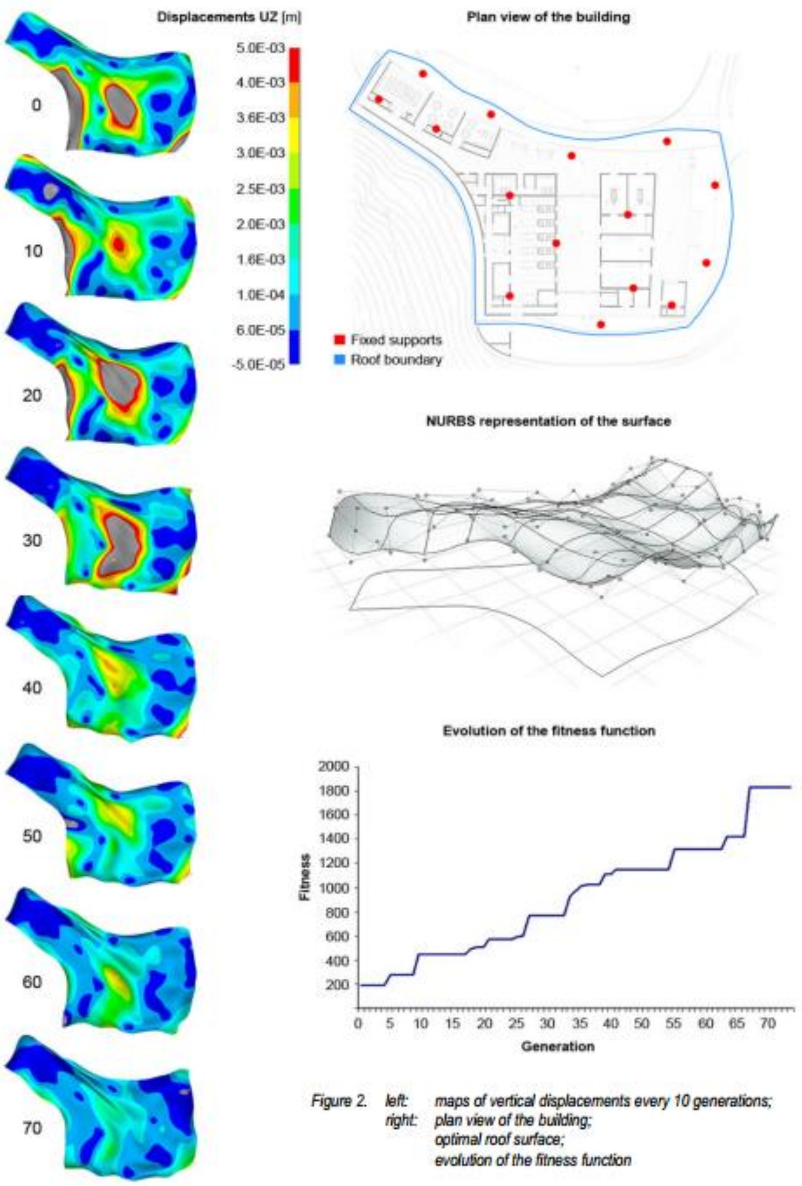


Figure 10: Graphics of Evolutionary Shape optimization for Crematorium

Source:vbn.aau.dk/files/38938688/Morphogenesis%20and%20Structural%20Optimization%20of%20 Shell%20Structures%20with%20the%20Aid%20of%20a%20Genetic%20Algorithm.pdf

3.4. Evolutionary Structure Optimizer

According to Burry and Burry [4, pp.257];

"Evolutionary structural optimization was originally proposed in 1992 by Mike Xie and Grant Steven. It is a recursive iterative routine that uses finite element analysis to discover the von Mises stress or strain energy in each element in a structure. A starting cube of virtual finite elements is given some real material properties, say those of stone, steel or concrete, and some loads and constraints are applied: gravity, support points etc. After analysis, the elements recording stress below a certain threshold. The analysis and removal of lowest stressed elements is then repeated on the residual form recursively many times over (50 to 100 in this example). This method will optimize a structural form to use the least material. The software was developed by Xie and his researchers to evolve tension-only structures, such as steel cable structures or compression-only structures like masonry, and a combination of the two. They have also developed bidirectional ESO, whereby elements are both subtracted and added during the evolution of the form. This is poetically close to such processes observed in nature as bone growth."

The building, in which a transfer is realized between all structural elements without bending moment, has the highest transfer efficiency and allows manufacturing with minimum material. This is the aim of the ideal shape resistance in spatial buildings where structural optimization is applied.

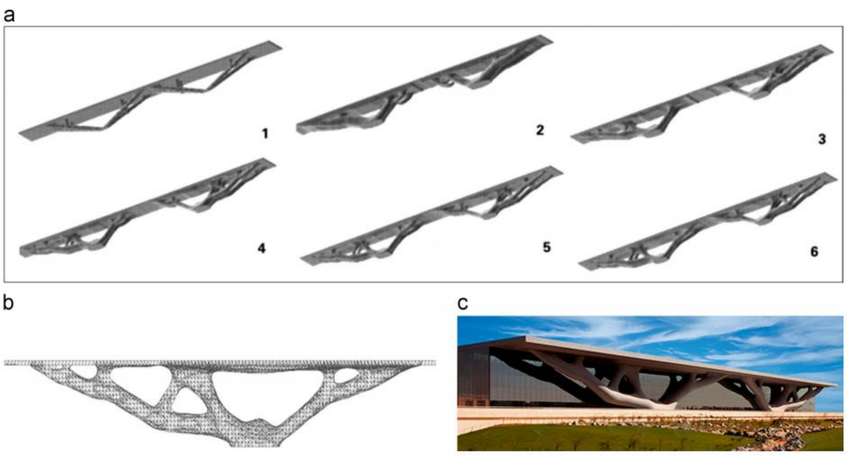


Figure 12: Qatar National Convention Centre (a) Form-finding by suing extended evolutionary optimization algorithm, (b) final shape after optimization, and (c) final construction in Doha

Source: Rian and Sassone, [13, pp.316]

Structural column of the entrance porch of the Qatar National Convention Centre in Doha (Figure 11) is one of built examples where an extended evolutionary algorithm was used for finding a form that can support a maximum length of the roof (Figure 12a). Constructed in 2011, its dendritic steel-made hollow tube structure spanning 250 m in the shape of the native sidra tree grows up to support the overhanging roof structure (Figure 12c). In designing a pair of a structural column, an initial shape and design parameters were taken as a starting point, and modified during the design process. So, as design parameters, the initial conditions in terms of height, volume, loads, support points or functional requirements were established. Then, using shape analysis methods, the initial system evolved into multiple directions with the purpose of optimizing its structural behavior. The design parameters were modified during this phase, and the optimal structure with the most interesting shape was chosen from the population of all final shapes of optimal structures (Figure 12b), (Rian and Sassone [13]).

4. CONCLUSION

Four optimization methods examined in this research try to ensure a physical balance between forces that allow the structural pattern to stand, and physical environmental parameters such as material, air flow and sunlight. Geometrical structure formed in computer environment organizes itself and reaches a new pattern; and thus a performance-based model is formed.

With the discovery of structural-based new possibilities which can generate parameter for architectural design; mathematics, apart from creating ratio or form in architecture, has been transformed into design processes, in which interdisciplinary information can be understood both by engineers and architects, and many data can be processed as design parameter through computer simulations; and buildings pointed by these processes. Structural design, in other words designing a bearing system with an aesthetical value contrary to the usual, allows the cooperating engineer to become an architect, and the architect to become an engineer. Discovering invisible parameters and making them functional through computers by using the experience obtained from here enables development of mathematical models.

Vectoral forces such as earthquake, wind and water affecting the structure which is obtained as a chaotic building have become better understandable as they can be simulated in computer environment as dynamic parameters. This has enabled development of geometry and appearance of non-Euclidean geometric forms. In structural designs, these forms create patterns by self-organizing themselves according to dynamic parameters. Topological continuity of the resulting pattern ensures the building to stand. This continuity is formed by optimizing the structure with the time and movement-dependent dynamic parameters. Thus optimization generates the topological information network that works according to performance and can be seen as a technique for innovation. This case help engineers and architects to direct their mental and intellectual actions to the area of design.

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