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ALGORITHMIC THINKING

8

Integrated evolutionary strategies on structurally informed complex grid morphologies

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Abstract

This paper is attempting to present an on-going research investigation performed on a PhD level, which addresses the notion of algorithmic thinking in architectural design that can re-create efficient integrated design strategies. It focuses, in particular, on the notion of structural complexity and attempts to interpret it as a 'bottom-up' property that can inspire and facilitate the design of non-standard forms in architecture. This is primarily observed through an evolutionary procedure that informs and transforms in a recursive manner the form-finding process and fosters the emergence of complex bio-inspired architectural forms, with particular interest in the case of irregular grid structures.

The investigation is taking into account theoretical approaches, as well as bio-inspired paradigms that excerpt self-organizational procedures in the determination of the morphological process and is performed through the research method of digital experimentation. More specifically, the experimental approach attempts to investigate a series of parameters that can dynamically affect the form-finding procedure of an irregular grid system and aims to generate evolutionary strategies on structurally informed complex morphologies. The informative parameters include the determination of specific geometrical shapes, the subdivision type of distinct irregular grids that are bio-inspired by natural structural patterns, the present dynamical possibilities and finally the mechanical properties of the material composing a structural form.

Conclusively, those parameters are examined through their combination on a set of digital simulations, while the whole process is being computationally encoded and performed within the environment of Grasshopper.

Keywords

'bottom-up'; Grasshopper; bio-inspired paradigms; design strategies; evolutionary; parameter; digital simulation.

Background

Presently, we may observe a “digital shift” in the architectural practice. New principles are embedded with the ongoing architectural theory enhancing the idea of form and structure with terms like complexity, complex theories, dynamical systems, non-linearity, non-standard, digital tectonics, leading to a hybrid perception of the architectural discourse. These new confrontations have received from extent enthusiasm to severe criticism concerning their possible impact on architecture. We may speak of an impact, not only engaging with the degree of benefits put forward by digital technology on design, but more on the transformations architectural discipline and discourse is starting to follow.

One of the significant events that have led to an alternative way we interpret architectural theory and experience design is the rise of the epistemology of computer science in conjunction with the theory of cybernetics. The appearance of the Alan’s Turing “algorithm” and in turn gradually to “algorithmic design” (Terzidis, 2006) constitutes in fact a conceptual evolution in architecture, leading to a new state of thought and design, that of ruled-based relational thinking. Form and design is now generated under the co-existence of a relational system and rules that define it, being not singular and static, but multiple and dynamic. We may speak of technological artifacts that were not seen only as a means of executing commands, but also as digital entities that could produce data, relationships and ideas (Parisi, 2013). Moreover, terms such self-organization, as part of a complex system and a key concept, plays another important role in design, trying to give a further explanation to the inner organization, with concepts such as inner dynamics and constant evolution (Karabaj, K, 2006).

This in fact triggered questions such as the relation between scale and tectonics (Pico, 2010), form and structure and the way they interpolate in design. Beliefs such A. Picon’s reflects a paradoxical effects on the transition between the screen and reality, with famous examples, such as the Mediateque or Frank Gehry’s projects being impressive and ornamental form expressions, but giving at the same time little regard to any structural restraints they entailed. Nevertheless, we may observe the emergence of a “new materiality” that has influenced the conventional structural constraints followed before the advent of computational era. Regardless if the structural parameter was at a secondary stage in the design process, it has undoubtedly challenged the norms towards a new attitude in the technological techniques that would perform such revolutionary geometries. This has identified initiatives, such as the “informal” of Cecil Balmond (Baldmon, 2007) and Greg Lynn “animate form” (Lynn, 2011) that attempt to give this alternative dimension of a structural expression in the morphological generation.

On the other hand, biological paradigms and the recent investigations on several natural structural patterns have become living examples towards this direction. We may observe several natural constructions that are examples of self-organization systems and products of evolutionary processes that incorporate dynamical parameters. The most representative example is the microstructure of the cancellous bone that reflects this adaptation in both tensional and compressional forces as seen in the figure previously (figure 2). Specifically, the microporous inner system re-adapts its cohesion and thickness according to the external stimuli that take place (Weinstock, 2006).

Simulation procedure: description and implementation

Main description

This “new materiality” confronted by the digital architecture along with several bio-inspired examples that indicate the ability to adapt to severe stress conditions and self-organize into a more stable organizational system as mentioned and observed in biological examples, can re-generate design

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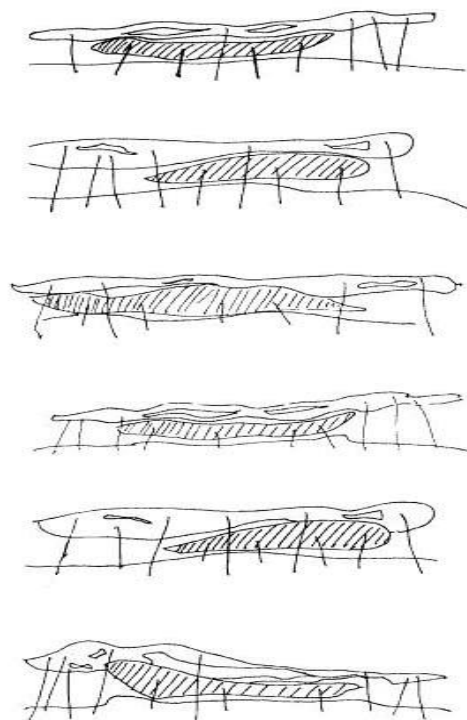


Figure 1.
Cecil's Balmond Sketches on Chemitz Stadium, ("Structure and The Informal", 1997)

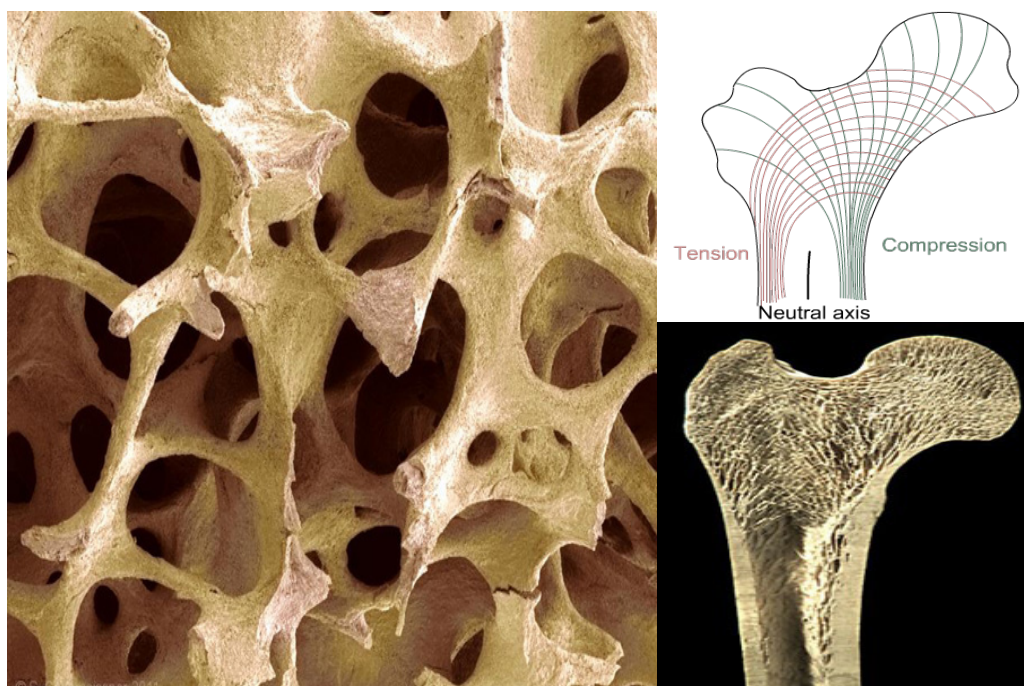


Figure 2.
The microporous system of a bone's inner structure generated according to external loading conditions

strategies. These strategies may have the capacity to respond to the changing built environment and be optimized accordingly, such as optimization procedures and evolutionary algorithms. When referring to architectural form and materiality, those concepts of adaptation and self-organization are transforming their external reference factor to a building's conditional system. Loading conditions, such as gravity, wind, lateral, and live loads, thermal and earthquake loads shall be taking place, whilst the way that material, form, and structure are organized becomes important too.

Therefore, we may investigate on and form morphological processes in architecture that will be able to respond to the present structural challenges and constraints using at the same time the digital tools offered by the recent technological advancements. This process is what this research is mainly investigating and can be described and divided into three main stages. The first stage includes the geometrical generation of an irregular grid, the second one informs with structural elements and real cases loading scenarios the whole model and while the third one evolves and adapts the model by using self-organization processes. This is performed in a recursive manner and converges when reaching an equilibrium point.

Computational Environment and Language

The whole procedure was established through the computation-friendly environment of Grasshopper. Grasshopper (www.grasshopper.com) is a very popular program used in architectural design that gives the opportunity to engage with the geometry parametrically. Developed as a built-in plugin for the design program Rhino 3d, it gives the opportunity to visually program/compute a design process, with limitless potentials. Moreover, structural analysis programs were necessary that could perform a structural evaluation, therefore, since the whole process intends to function in a recursive way, Karamba plugin (www.karamba3d.com), an extension of Grasshopper, would serve as the structural analysis aid tool that can be combined in a parametric manner. Particularly, Karamba is able to assist with a number of functions that can calculate, assess and analyze the structural performance on a variety of geometries, from grids to shells structures. It can also provide the opportunity to evaluate any structure under a number of feasible conditions, such as gravity load or even temperature effects.

Non-standards Structures and the definition of irregular Grids

The investigation was mainly focused in defining the generation of non-standard grid morphologies. Thus an attempt to understand their generation process as well their formal representation was also necessary.

We may observe a number of distinct non-standard structures, such as pneumatic, tensegrity, lattice structures and many more (Coenders, 2003). However, a further scrutiny shall be made on the case of grids, with special reference and interest on the irregular grids and their structural behaviour as a self-supporting system while re-define them through their distinction via their generative technique. Among the techniques that generate grid structures, whether these may refer to regular or irregular- ones, is the utilization of "tiling and packing" or "tessellation" technique. Tessellation is a method that accounts for its potentiality of subdividing space with the less or zero number of remaining unused areas. Specifically, it is a structural arrangement of inherent geometrical stability that finds expression in two (2) or three (3) - dimensional space. Additionally, de-

signer such as Lisa Iwamoto defines tessellation as a means of more close to fabrication patterning through a “collection of pieces that fit together without gaps to form a plane or a surface (Iwamoto, 2009). However, the research interest focuses in tessellation as a structural pattern utilization that is a pattern structurally stable and arranged in that way of offering self-supporting structures, as firstly applied by Buckminster Fuller. Thus, we shall take a short presentation of the types of tessellations, as well as the recent and more alternatives ways that have emerged through computation.

There are many alternatives of subdividing or tessellating space, such as regular tessellation, with standardized joints and member lengths. We may account for regular tessellation, that uses three main shapes and semi-regular tessellation with combinations of the above. Recently, contemporary architecture has started to explore the adoption of more recent mathematical inventions mainly influenced by the biological paradigm, including aperiodic tiling, patterns that have smaller in number or repeated units, but whose arrangements are such that the resulting patterns, unlike orthogonal or hexagonal grids, cannot be superimposed upon themselves through translation (Burry, 2010). A very interesting perspective is the interpretation of Farshid Moussavi in the “Function of Form”. These systems of grid distortion or variation, as mentioned by Moussavi, are an approach of transversal system, in terms of a system of cross sections with distinct topological variation (Pearce, 1990; Coenders, 2003). Because the base unit is not geometrically fixed, it may constantly vary and mutate when hybridized with other units, into novel and unpredictable forms that are spatially specific and capable at the time to adapt to external concerns. In other words, we may see a hybrid way of approach to a “non-standard” design that takes into account a bottom-up approach, from the properties of the system to the influence and performance of the whole. She also observed and made a relevant table with how a system, in terms of surface, dome, folded plates, shells etc, in accordance with a certain tessellation can have a variety of affects and effects in architectural form and structure. This may imply the numerous capabilities and complex behavior on this area of grid distortion research may offer.

These biomorphic and natural processes of subdividing space shall be generated by the use of a number of mathematical and computational three-dimensional representation, such as Delaunay triangulation, Dirinlet or Voronoi tessellations, Weairie-Phelan foam structure, Catmull-Clark subdivision, etc

Importing dynamical and structural factors

The next stage is to present how the model was informed with dynamical parameters and the structural evaluation procedure. A typical simulation of a structural analysis performance, requires a number of input elements. In other words, in order to generate a correct and valid structural model, it is necessary to indicate what is the current material and support locations, for it to become rigid and to have certain limitations in movement, and finally to set the preferable loading condition. This information is usually necessary to almost every evaluation or simulation program on structural analysis. The model, thus, must be translated into a model than can be identified by Grasshopper and Karamba3d.

Therefore, one of the first steps is to indicate what are the elements that compose this particular structure. There are two basic categories of structures that Karamba is making as a distinction. That is beam (grid) structures (or trusses) and shell structures. We shall interpret our structures as those that consist of beams and nodes, which is a grid structure.

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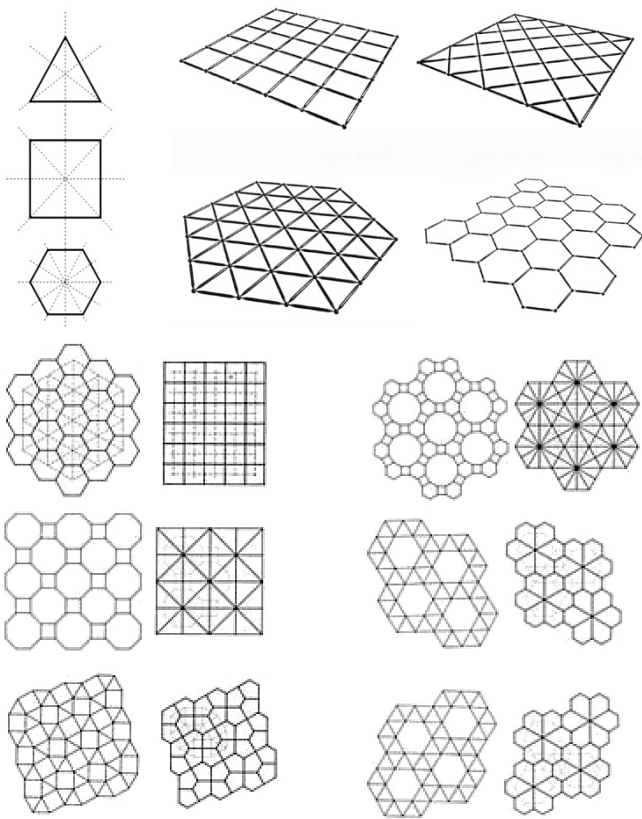


Figure 3
Regular and Semi-regular plane tessellations
Source: Meijer J.H. and Coenders J.L., 2007

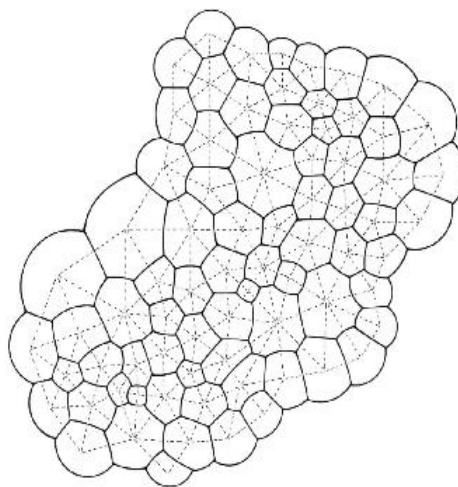
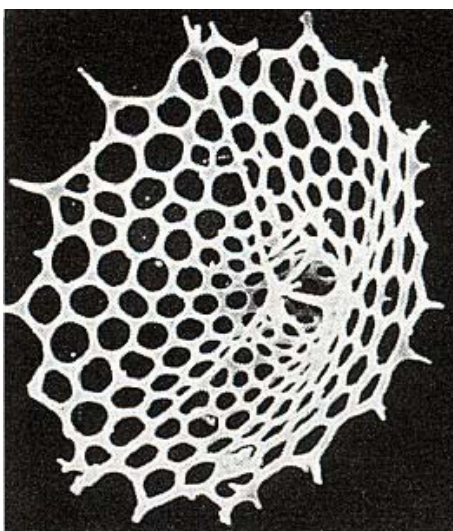


Figure 4.
Soap bubbles Array
Source: Left (Pearce, 1990) and Radiolara Shape right (Coenders, 2003)

At first, we shall transform the grid network, that for the moment is only consisted of a compound of points and curves, to a translation set of beams and nodes systems. It is also necessary to indicate the intersected points, or (or nodes) between the curves and to set the element type to beam. Karamba is able to provide with a list of possible loads that are engaged in a typical structure. This is performed through the indication of a load type or a combination of load types acting together. Several types were considered that were chosen in relation with the evaluated geometry. Thus, most of the cases were considered to be subjected to the following load combinations (Figure 6):

- Dead loads; -Live loads; -Wind loads (lateral forces); -Snow loads

Another information is the determination of the support locations. If closely noticed, we may observe that our structure should have its support locations only in the areas where it touches to the ground, or in other words when it is in contact with the 0 value in the z-axis. Therefore, all these points were extracted and provided in the support component of Karamba among with certain limitations in Rotation and Movement.

Since all the information is collected, now it is possible to proceed to the evaluation and assessment of the structural model. The assembled model is analysed and in turn computes some useful output information, such as total displacement, total mass in kg and Energy. The structural analysis method is mainly based on the first order theory (I), in order to compute a structural model behaviour.

Encoding self-organization into computational architectural design

Those biological models and material structural patterns have opened new possibilities for interesting morphological paradigms and advanced architectural design in computational architecture. They have informed several mathematical inventions, inspired digital techniques and can become the basis for physical investigations and digital simulations for new morphogenetic models in architecture. Moreover, this ability of material systems to adapt to severe stress conditions and self-organize into a more stable organizational system, can generate design techniques and advanced digital tools, such as optimization procedures, form finding and evolutionary algorithms, based on natural evolution.

Thus, it is important to make a relative comparison between the ideas behind natural evolution and adaptation, and those fostering computational ideas, such as optimization, form-finding and particularly structural optimization, and how those ideas have inspired and developed concepts in engineering and architecture.

As already mentioned in the previous paragraphs, computation is a mean of exploiting and investigating non-standard structures, as they entail extremely complex mathematical equations. Moreover, computation apart from its ability for advanced geometrical representation, it has also developed the ability of forms to self-adapt in certain restrictions and external loading conditions. This process is widely known in computational theory and practice as optimization.

In our case, the utilization of Galapagos plug-in gives us the opportunity to perform an evolutionary process through genetic algorithms. The basic steps to proceed to such process is to define the genes that will be taking into account and mutated, or in more simple words, diversified, and to define a fitness function, that is the number or mathematical function that will be maximized or minimized.

In this research investigation, the genome or genes are defined as the space generation of the initial set of points, therefore, the algorithms will attempt to search for different coordination values in order to locate the best combination of points in the specified design space.

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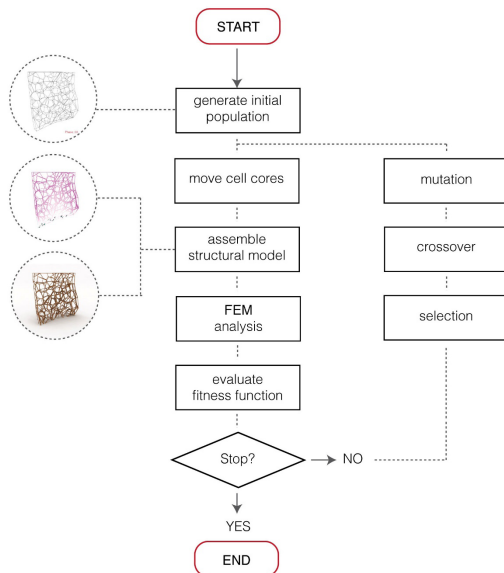


Figure 5.
Load combinations applied during the evaluation

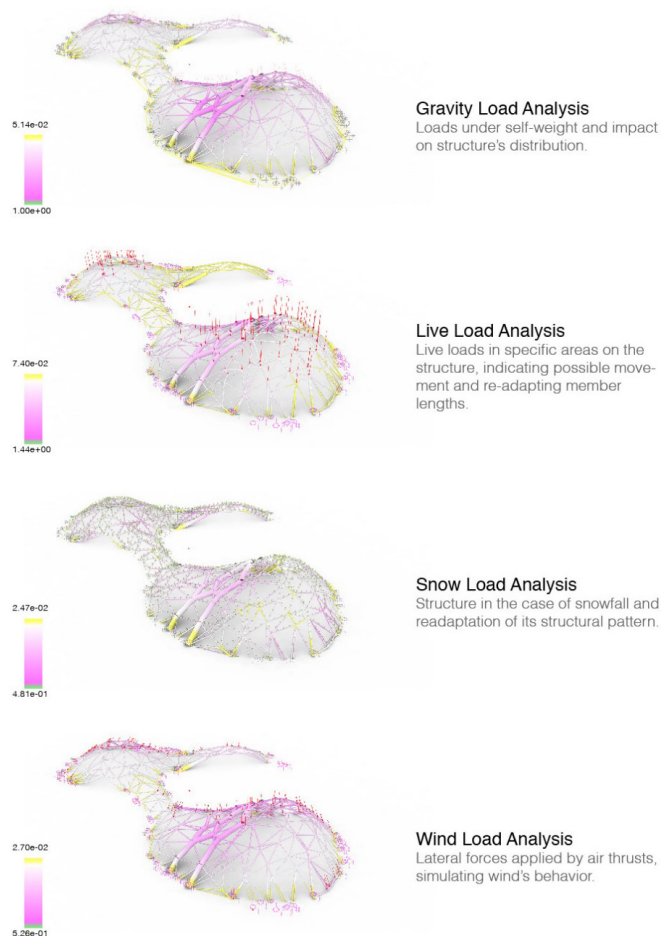


Figure 6.
Load combinations applied during the evaluation

Defining an optimization goal - Fitness Function

One of the primary goals before formulating an evolutionary approach on a form-finding procedure is to indicate an optimization goal, or in other words a fitness function. Fitness functions are amongst the most important parts on performing an optimization process, as it represents the ultimate goal the optimization seeks to achieve. For example, in structural optimization the goal is to have efficient structures. Efficiency in structural design is translated as a combination between less material and maximum stiffness. Although computer is the one that comes up with the final design, it is the human designer who has to design the fitness function. If the function is designed vaguely or invalid, the algorithm will either converge on an inappropriate solution, or will have difficulty converging at all. Moreover, the fitness function must not only correlate closely with the designer's goal, it must also be computed quickly. Speed of execution is very important, as a typical genetic algorithm must be iterated many times in order to produce a usable result for a non-trivial problem.

However, in our case, the goal is slightly different. The fitness function must be formed as a combination between two objectives, Total mass and Displacement. This can be illustrated in the mathematical function below.

$$\min f(x) = \sum_{i=0}^n \sqrt{((Dis_i * Mass_i)/n)}$$

This could be performed by either constructing a function that involves both of these figures, or either by using the Pareto frontier via an evolutionary approach, that can give a series of possible solutions covering the "Pareto curve".

Preliminary work & experiments

Some preliminary work during this research has been performed. This included a series of initial experiments in order to develop and specify a design strategy. The process included some basic research in structural patterns and their behaviour and in a next step, some further and more complex investigation on defining and generating this strategy in non-standard complex morphological geometries.

A random blob geometry was initially selected, which was later undergone to several and multiple evolutionary transformations that affected the structural grid configuration. Genetic algorithms were imported as a self-organization technique. Several experiments included the application of gravity loads in combination to random lateral forces in order to investigate the response and self-adaptation of the geometrical organization, as seen in the results by the evolutionary process in the figure below (figure 7).

The experiments were evaluated through the resulting of total mass and displacement and their evolution during the different experiments and thus optimized through the course of generations of the genetic algorithmic process.

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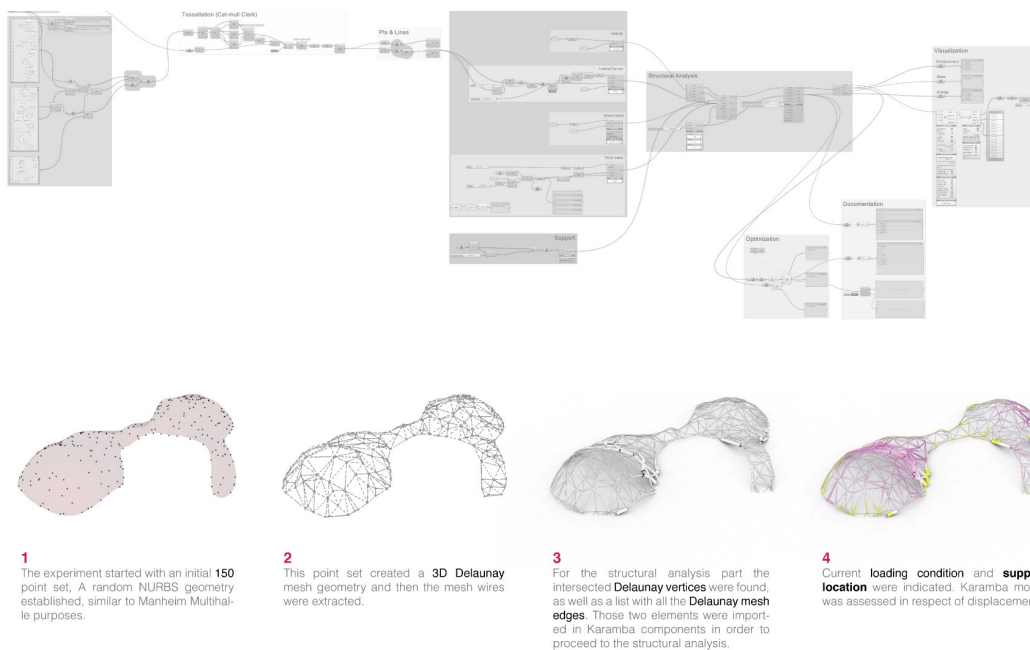


Figure 7.
Generative process un relation with Grasshopper code.

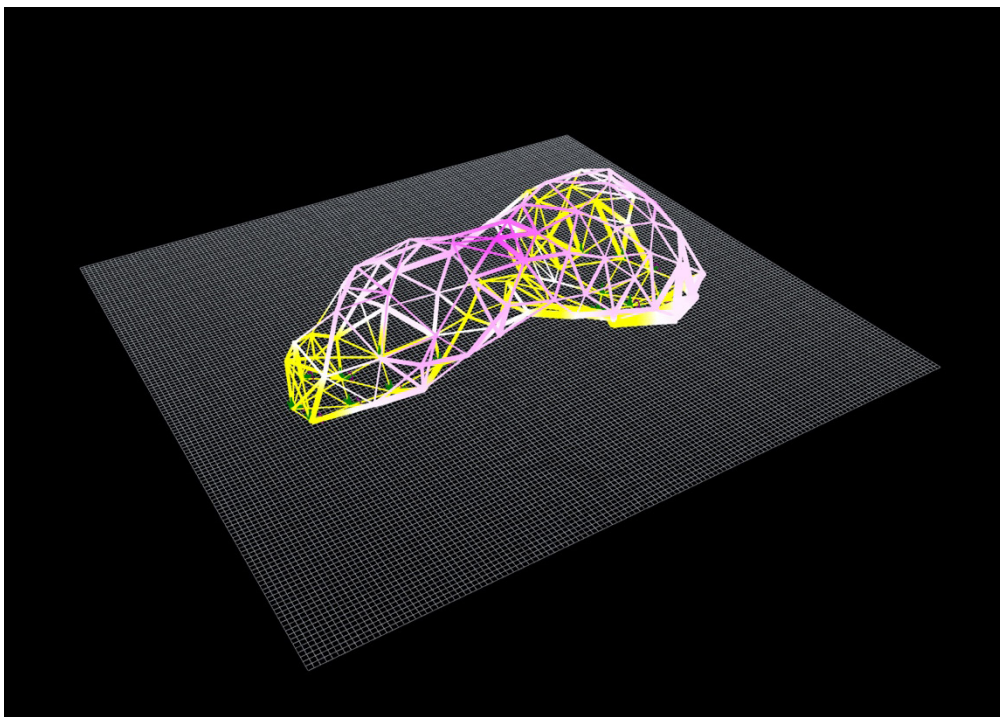


Figure 8.
Simulation process during the preliminary process of an evolved geometry

Simulation demonstration

Case Study 01: Wide-span NURBS surface

The first simulation is examining the paradigm of Mannheim Multihalle in Germany as a load-bearing geometrical shape with specific characteristics in terms of stability. This particular example acts as a sheltering, covering, wide span geometry, concentrating all the loads to the perimeter of its shape. This morphology has 3 out of 4 loading conditions in present, and in particular it is subjected, apart from self-weight, to wind and snow loads. It is being investigated in all three subdivisions, while adapting and optimizing the bar diameter, sizing and thickness, depending on the current stresses on each of those elements. The whole configuration is structurally evolved, using evolutionary algorithms, such as genetic algorithms, which have the ability to combine and solve multi-parameter problems. This particular example is structurally evolved in adapting the grid configuration and relocating the generation points of this grid, with criterion (fitness function) less deflections in combination with less material (lightweight). Regarding the material, steel is in default.

Case Study 02: High-rise grid morphologies

The second simulation involves structurally evolved morphologies on a typical high-rise volume. Therefore, the experiment is focusing in the adaptation of the three grid configurations, in order to observe the effects that exhibits on the volume morphologically. The examination is realized both in a shell and a volumetric spread of points, resulting to grid-shells and three-dimensional grids respectively. A typical high-rise volume is mainly subjected in wind and live loads, which is in direct contact with the kind of uses it is designed for. Beam thickness is also optimized and grid formations are genetically evolved in both less deflections in combination with less material (Figure 12).

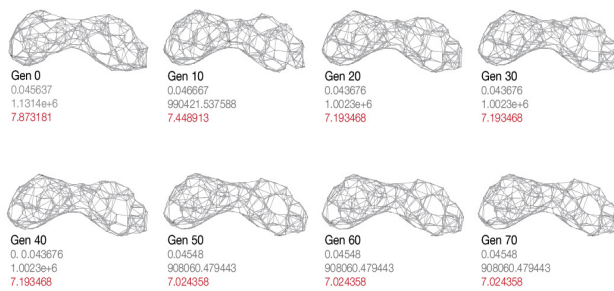
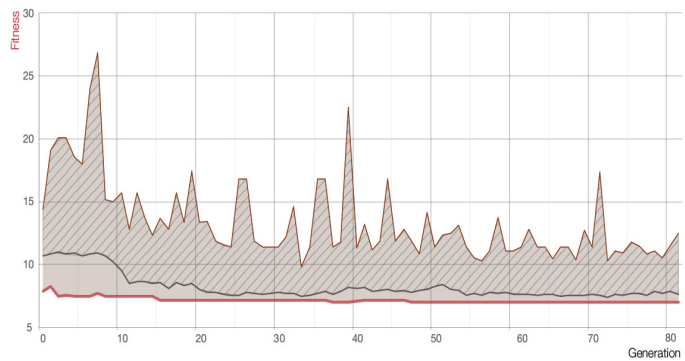
Material-based grid morphologies

The third and final simulation is experimenting in material-based grid morphologies that are adapted and evolved structurally. The initial geometry does not rely on a specified geometrical shape, but on a random NURBS curved geometry. Four (4) different materials are chosen (Figure 13), that have distinctive mechanical properties and resilience in stress and other forces, such as steel, wood, aluminium and concrete. The goal is to inform, through those properties and stress characteristics, the curvature of the surface by changing the control points, and determination of support locations, while adapting the configuration of grid generation point. The prevailing loading conditions is only based in gravity loads, while the optimization procedure is evaluating the structure under less deflections.

Discussion

In conclusion, this paper aims to present the development of effective algorithmically-based design mechanisms that enable and facilitate the design of non-standard forms exhibiting structural complexity. In particular, structural complexity is addressed as an integrated, bottom-up property that is able to affect dynamically the form-finding process of irregular grid structures. A number of digital simulations were conducted in order to form a performance-oriented design process focusing on structural efficiency.

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01
Delaunay
Triangulation
p: 450
d: 0.009425 [m]
m: 1.3409e+6 [kg]



02
Voronoi
Diagrams
p: 450
d: 0.032672 [m]
m: 1.4107e+6 [kg]



03
Cat-mull Clark
Subdivision
p: 450
d: 0.033632 [m]
m: 1.171300 [kg]



Figure 9.
Course of fitness function and resulted geometry every 10 generations in the genetic algorithm.

Figure 10.

Samples of several evolved irregular grid morphologies

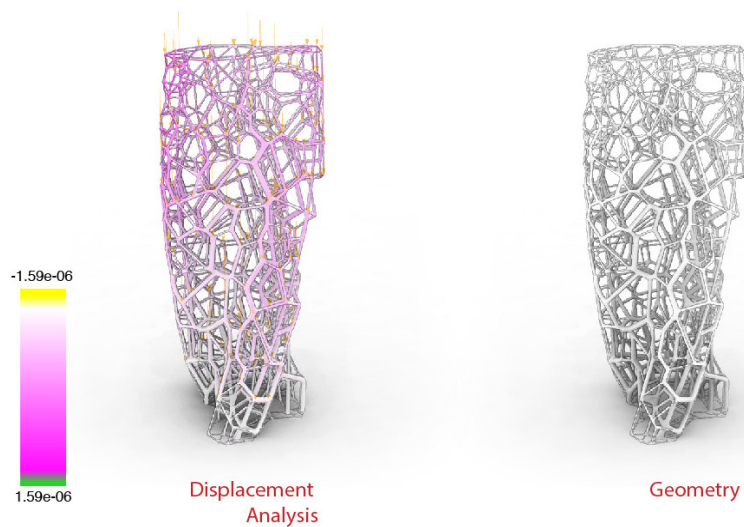


Figure 11.
Displacement evaluation and final geometry of a high-rise morphology.

The research intends to adhere a holistic approach in relation with the subject of interest, examining all the possible loading conditions and formal applications in order to reach and form solid results. This can enhance architectural process with a valuable design strategy that can affect more efficiently the final design result.

Several conclusions can be extracted during the research process that could offer a valuable contribution to knowledge through their arrangement on three main directions. The first direction is conclusions in terms of architecture, which includes some observations and formal evaluations of the resulted morphologies, such as light, ventilation, aesthetics, as well as possible architectural uses that those grid morphologies may have.

The second direction are conclusions regarding the structural effectiveness of those forms, in terms of structural stability and rigidity. The deflection values in each case are compared in order to reach some conclusions. The third direction is towards the computational method of the evolutionary algorithms. The values examined are the time of convergence (optimum form) and comparison between genetic algorithms and simulated annealing as appropriate computational method in design.

Integrated evolutionary strategies on structurally informed complex grid morphologies

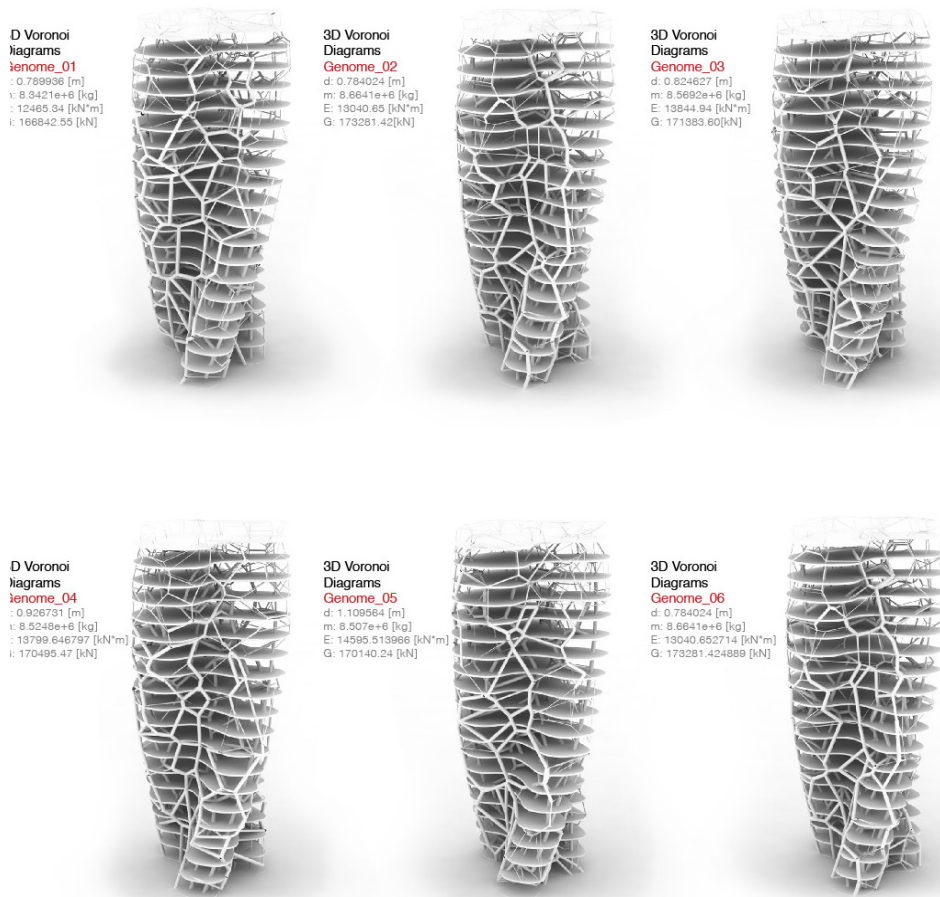


Figure 12.
Various samples on a volumetric Voronoi grid configuration

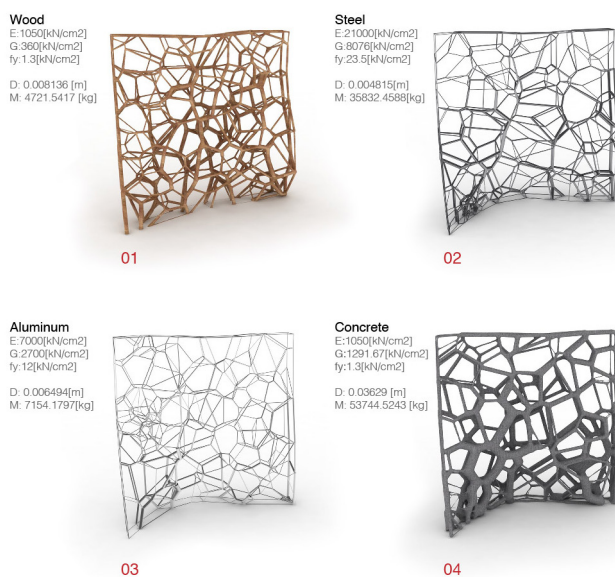


Figure 13.
Samples of material-based grid morphologies based on Voronoi diagram pattern.

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