The computation turn in structural performance based architecture design

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Abstract. It is necessary for an architect to engage closely with structural design, to interpret their design idea thoroughly, and it requires carefully collaboration between architect and engineer. The structural performance based design is not only to obey structure principle but to explore different possibilities of engineer and architectural innovation. Architects could apply this method in the earlier stage of design, and it could provide the efficient solution for structure, create a new spatial experience and further improve the construction quality in the later phase of development. In comparison to structural performance-based design in history, the computational technology has made it possible for architects to implement further the structural knowledge in more dynamic and sophisticated environment. This paper will discuss the history development and current transformation of this method. Three research project will explain the current experimental design process and back the idea of this method.

Keywords: Computational Design, StructuralPerformance, Finite Element Analysis, Evolutionary Algorithm

1 Introduction

The traditional or the age-old structural performance design method was a hands-off design approach that mainly focused on realizing the requirements of not only the structural laws, but also the structural regulations. As such, for the majority architects, it was difficult to convert their free design forms into construable structures without detailed structural design knowledge. Besides having to seek frequently consultation from the structural engineer, who not only verified and assessed, but also approved designs so as to certify that constructions comply with the setup performance prerequisite.

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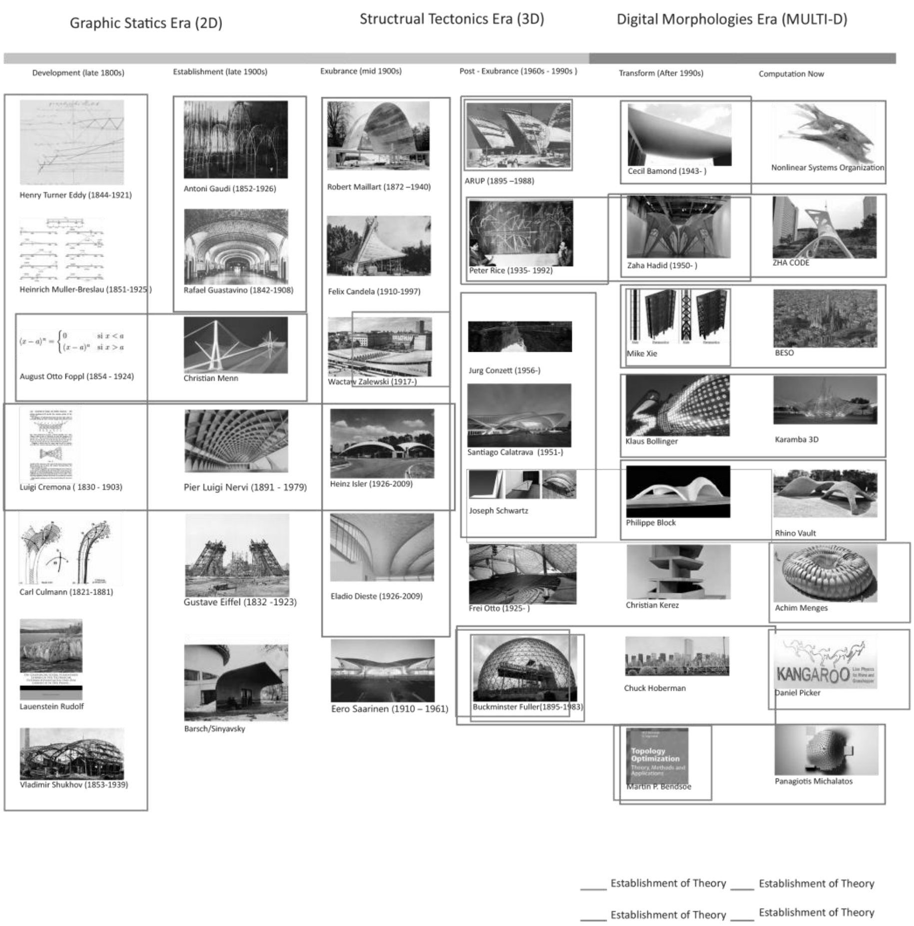
1.1 Background

With progress in computational force and speedy prototyping technology over the last ten years, a new structural performance-based architectural design methodology materialized. Consequently, Pedreschi highlights this has offered the architects the option to explore the new form-finding technique that could be in projecting the structural performance within the early design stage (Pedreschi 2008). Accordingly, the structural execution of architecture may be simulated, evaluated and enhanced. This has made it easy for architects to work closely together; a factor that has not only helped push the limits of architecture design, but also generating diction between the structural and spatial architectural quality.

Table 1 Diagram of Structure Performance based Architecture History (Yuan & Hu, 2014)



1.2 The Three Eras

From the perspective of an architect, the process of developing a structural performance-based architectural design is usually a nonlinear process comprising of numerous sections and layers.

Chronologically, it may be split into three periods or eras, including the structural tectonic, the graphic statics and the digital morphologies era (Yuan & Hu, 2014).

The graphic statics period started in the 18th century, with the discovery of steel construction and improved concrete technology. This facilitated the construction of curvature buildings, high-rises, and big foot prints by engineers. Consecutively, architects also attempted to delve into the form-finding opportunities offered by the new materials, as well as the modern construction methods. This early form of the structural performance-based method (graphic statics) thus became a significant tool for both architects and engineers to share, collaborate as well as experiment with.

According history, this particular theory was developed by Karl Cullmann. On the other hand, it was his fellow scholars, Müller Bresalu and August Föppl who developed and practiced the method. Müller Bresalu lectured in Berlin while August Föppl lectured in Munich. Alternatively, with increased researchers in graphical statics in English as well as the publications in analytical geometry by Henry Turner in 1874, these particular works came to be widespread in the United States. Afterward, Professor Lauenstein produced a summary of the findings approximately 100 years back in his “Die graphischeStatik” book. His course books can still be located in libraries. Jerome Sondericker, on the other hand, published his book, “Graphic Statics”at MIT, which deliberated on applications to arches, beams and trusses(Jerome, 1903).

As soon as this theory was established, many architects attempted to advance the structural-based architectural design techniques. Rafael Guastavino Jnr, for instance, advanced the graphic statics concept to another level by employing equilibrium analysis methods, hence contributing to the graphical study of domes (Fangary&Aly 2010). Guastavino Jnr was among the pioneers to apply innovations in the utilization of graphical methods in not only his design but also construction projects.

Gaudi further advanced the graphic statics concept when he employed it in determining directions of thrusts that spring from the bases of vaults (Torrelles, 2011).Gaudi afterward aligned supportive columns along these lines of thrust, an action that enabled him to evade creating buttresses that he deemed not natural. He thus developed a modern architectural design or style that was not just original, but also simple and artistic. Overall, the engineers’ significant input to architecture, the structural performance-based technique within the graphical statics period, served as an important verification tool for architects to acquire an improved comprehension of structural prerequisites and react to them. They also had vital roles during the structural tectonic period’s structural execution design.

Structure-based architectural design began receiving significant interest during the mid-20th century.In particular, due the rapid progress and reconstruction after the Second World War, the thin-shell construction design began to be increasingly significant. The thin-shell design has thus had an increasingly significant role ever since the year 1940s.Firstly; the advanced graphic statics structural knowledge facilitated not only the yielding of reliable outcomes from architects, but also made the architects satisfy the structural prerequisites of large civil projects (Asmaljee, 2013). Secondly, the thin-shell design adheres to geometric and clear structural principles. Lastly, it has a cost-effective benefit in terms of the labor resources, the utilization of materials, and the construction period has been cut to the least.

The concept of framing social interaction also offered architects with an opportunity to carry on probing the historical lineage or bases of design research within the physical form-finding domain, including the soap films, the hanging chains, among others, which were pioneered by individuals such as Felix Candela, EladioDieste, Frei Otto, and Heinz Isler, and others. Nonetheless, there were debates regarding this particular method (Kotnik&Schwartz 2011). To begin with, this particular method was argued to be producing unique outcomes that are not repeatable. However, this inadequacy in terms of the number of repetitions of experiment could result in unwanted outcomes. Furthermore, individuals argued that these designs were being generated in exceedingly defined ways, a factor that is argued to lower creativity of the design process.Finally, there were arguments that these particular methods only offered a limited number of outcomes. As a result, making it problematic for architects to obtain not only potential structural or artistic solutions and optimum materials. These particular shortcomings have driven architects to seek not only new tools and technologies but have also improved the design methods.

Alternatively, during the digital structural performance morphologies period, it became significantly fundamental and indicated prospects, besides its analytical value that goes beyond its instrumentality. The graphic static model has, on the other hand, been converted into algorithms. Consequently; architects could now have a better understanding of this particular long-established structural analysis, which could not only assist them improve structures, but also attain improved structural performance with an economical budget.

Architects also advanced it into a form-finding tool so as to produce high performance as well as create adaptive and dynamic structural systems. Moreover,it offers solutions for the new algorithmic design including agent-based design practices aimed at finding significantly sophisticated as well as adaptive/flexible structural solutions to the hyper-complex geometry. For instance, the finite element method helped an engineer such as Mike Xie and an architect such as Mark Burry to decrypt Gaudi's mystifying geometric design as well as comprehend the construction works of Sagrada Familia. The topological optimization model, on the other hand, acted as an inspiration to architects such as Panagiotis Michalatos who manufactured software such as the Millipede plug-in and BESO used by architects to help them understand the topological optimization concept at the start of a design process .

2 Research Projects

To explain the development of computational design in structural based architecture design processes, Three research project will describe the current experimental design process and back the idea of this method. Firstly the multiple objective optimization could be achieved by setup design domain in the computer-aided design environment and with the help of algorithmic computational design tool, as a result, a flexible and optimum result could be developed. The second projects show a potential of escape from the static architecture structure and introduces dynamic balance in space, with the help of computational simulation and analysis. At last the research will explain how could this method improve the constructability and performance of algorithmic design that create complex geometric space such as agent-based architecture design.

2.1 Multi-Objective Optimization

The initial design purpose was to create additional space for extension of an existing building (Fig. 1). The extended space is formed by a planar grid that pushes out of the current facade. An evolutionary algorithm is used to attempt to maximize the volume enclosed by the frame, and the finite element method would help to ensure the structure can support the load. The input parameters specify a 2-D regular triangulated truss system with six members connecting at each joint.

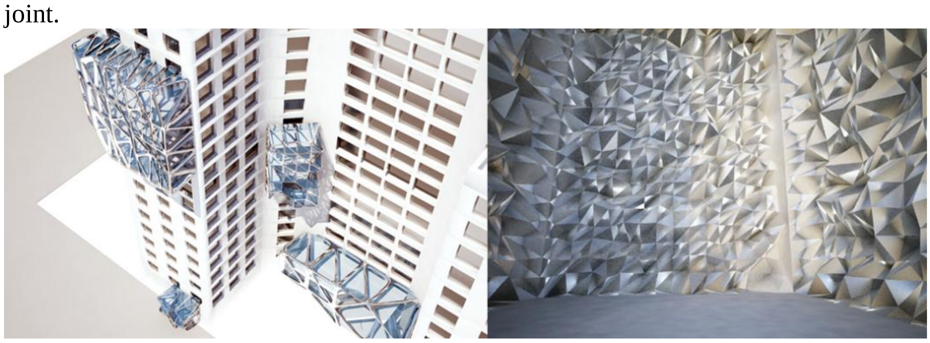
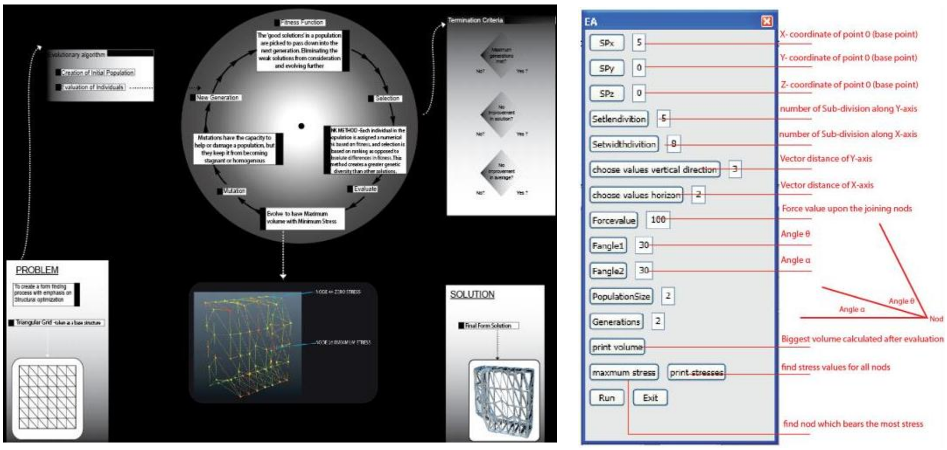


Fig.1. Exterior Rendering of project (Left) Interior Rendering of project (Right)

The overall structural form is generated in response to a model input by the user and can be adapted to individual design scenarios. It optimizes both the topology and geometry of a structure by minimizing the design objectives, e.g., material quantity for the given loads, while respecting the constraints. This is conducted in 3d environment of Rhinoceros with the help of the FEA optimization method (Roylance, 2001) and the Pyevolve, a Python Evolutionary Optimization Library (Perone, 2009) which has been import in Rhino Python. This project also aims to minimize member lengths while meeting all geometric constraints and to maximize the volume enclosed by the frame while meeting all geometric constraints.

The constraints of this projects are: Base points (the joints that need to connect to the existing building), the spatial limitations (maximum height, boundary lines, maximum cantilevered distance), the maximum number of members meeting in any one joint, the maximum and minimum lengths of each member, and the minimum angle between two members at any one joint. This design referenced these constraints as a starting point of overall structure generation.

The genetic algorithm is guided through all the steps of its process by an objective function. The fitness function that depicts the dynamics of genotype frequencies in a population for reproducing individuals, quantifies the prospective for the survival of any individual. A fitness value for a chromosome determines its optima in order to be ranked against all the other chromosomes in a population. The fittest chromosomes are those that are allowed to participate in the genetic process, producing a new generation that will be better (Fig. 2). The definition of the fitness function is not always a straightforward task, and there are cases for which is it quite difficult to come up with an absolute fitness function that will lead to the optimal solution. In this research project, the process was not always direct, but it was always goal-oriented: to reach the point where the tetrahedralized space frame with randomly distributed joints will perform as well as an engineered structure on an orthogonal canonical grid with the same number of joints. Towards that end, a couple of different fitness functions were experimented with, endeavoring to achieve the best results.



Fif.2. Algorithm Logic Diagram(Left) Interface of Algorithm in Rhino (Right)

The basic rule of the algorithm calculation is a regular grid system. The selected planar surface or mesh should be divided into regular sections as shown; identical faces will be formed through the division (Fig. 3). In Python scripts, a loop is needed to get the faces of the picture and append them to a list. Several points need to be extracted from the faces: the starting and the ending points of the mesh/grids, all joining points, and the midpoint of each division.

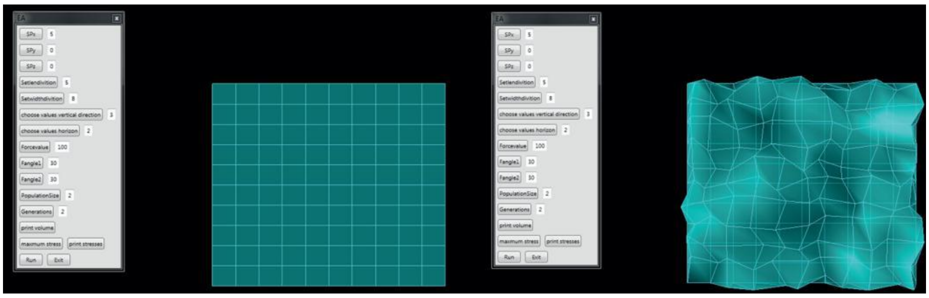


Fig.3. After set up basic grid and before run Algorithm(Left) After run Algorithm (Right)

The vertices of the mesh are decided by the starting point that will be determined by the user. For this reason, the mesh could be formed through two parameters: faces and vertices. - Change mesh Each point will be assigned three parameters: X-coordinates, Y-coordinates, and Z-coordinates. Paths of the nodes along Y-Z plane will be limited according to the set rules that then will be applied to the scripts in order to solve the overlapping problem.

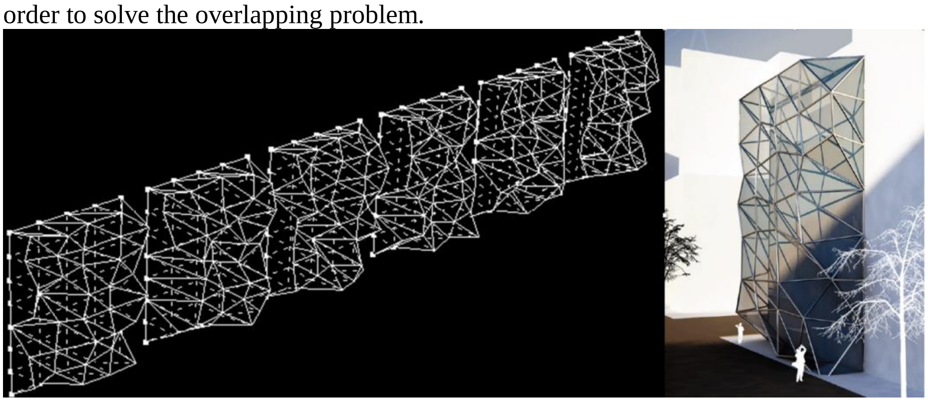


Fig.4. Different result from this design(Left) Project render (Right)

2.2 Dynamic Equilibrium Optimization

Located at London Canal riverbank, The Buffer-Zone house is a project that attempts to tackle the problem of modern dwelling architecture’s conservative static lifestyle and radical detachment from nature (Fig. 5). Enabled by a contemporary structure optimization method and construction technological solutions such as the pre-stressed tensile system, the house itself aims to blur the boundary between nature and living space, to create a more dynamic-balanced, unexpected, and reconnect nature with living experience.

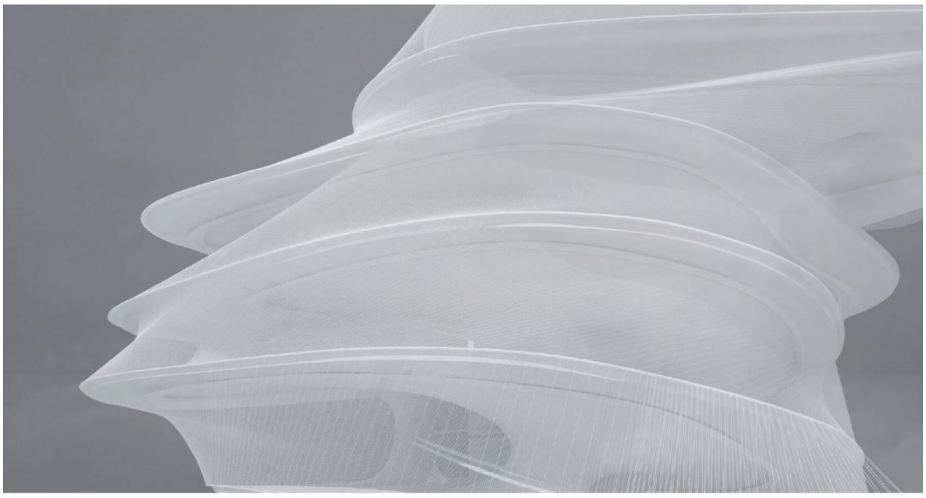


Fig.5. Render of exterior

Torsion of Domino House: After analysis, arguably the primitive model of the modern house, the prototype that was designed by Le Corbusier, the structural problem of torsion has become the central focus of this design. Torsion, in many cases, is the main latent hazard in extreme natural disasters, such as earthquakes and flooding, as is foundation erosion (Fig. 6.1). It will cause structural distortion and even structural collapse. The main cause of this is the geometry centroid and structural center of buildings are not at the same location.

Torsion Orientated Optimization: Through a torsion-reduction orientated optimization, the structure of the house turns to a compound system and the spatial condition of the house turns to a continuous spiral for the movement(Fig. 6.2). Also, the twisting effect of torsion generates spirally helicoid geometries. Thus, we decide to drive the helicoid geometry and composite structure member and circulation together to counter torsion and provide continuous movement. To strengthen the overall result, the handle geometry was introduced to provide natural light and encourage interaction between different levels.

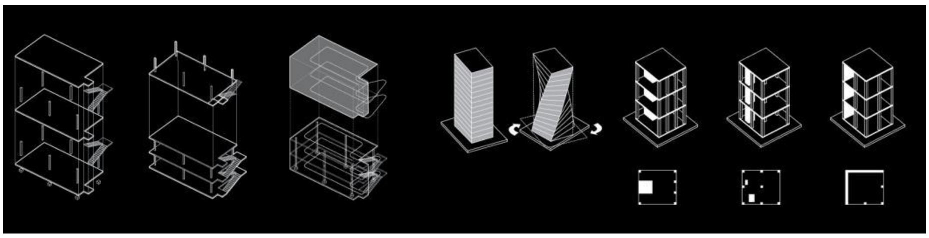


Fig.6.1 Analysis Diagrams of Domino House

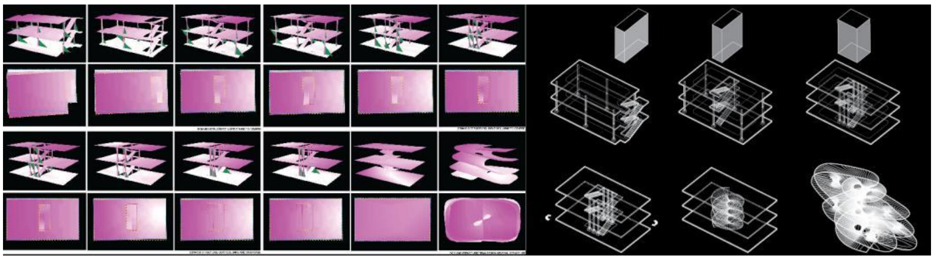


Fig.6.2. Diagrams of structure formation

Helicoid Geometry: Empowered by a pre-stressed tensile system, the structural envelope of the house becomes a non-standard, open-air, tightly-wrapped, tensile structure consisting of opaque pre-stressed carbon rods. Guided by pre-stressed tensile system joints, the rods connect with each other and all the way to the ground. Through connecting and bonding the rods with the top of core building structure with pre-stressed tensile system fittings, the load is continuously transferred through rods, and then the loads are distributed to the ground (Fig. 7). The pre-stressed rods provide sufficient structural support and helicoidal reinforcement for the overall geometry; at the same time, they also refine the quality of the helicoid geometry and create a blurred and soft yet dynamic balance for the building facade.

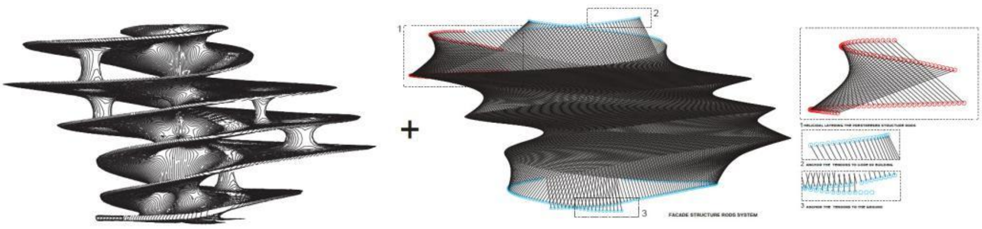


Fig.7. Structural facade diagram

Feather-skin Facade: The bird feathers display the possibility that, by closely arranging special thin line elements, the skin could have waterproof features and, at the same time, remain breathable and transparent. In this case, the ETFE thin line has made it possible for the facade to breath and prevent humid site conditions. Sewed with structural fabric and bundled at a very close distance, the ETFE lines fit around the exterior rim of the house (Fig. 8). The pre-stressed tensile system makes it possible to control the ETFE thin line system by guiding and locating the structural fabric.

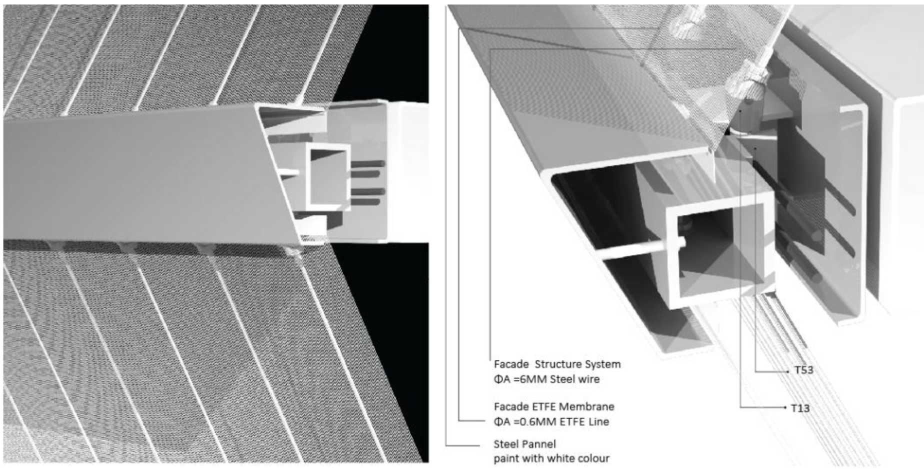


Fig.8. Facade Detail rendering(Left) ETFE Facade joints(Right)

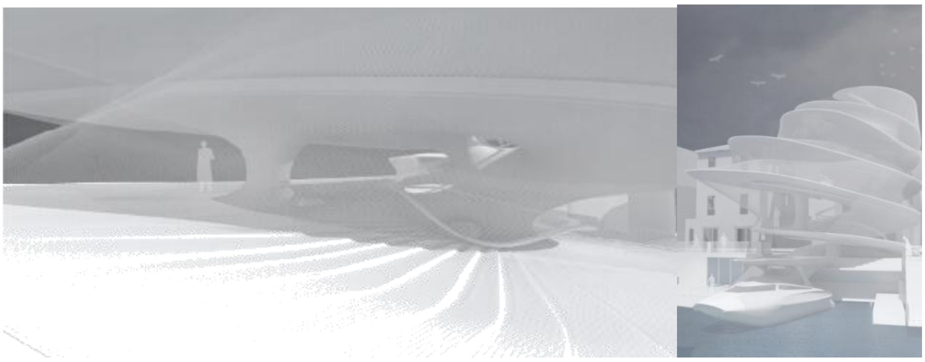


Fig.9. Interior rendering(Left) Exterior rendering(Right)

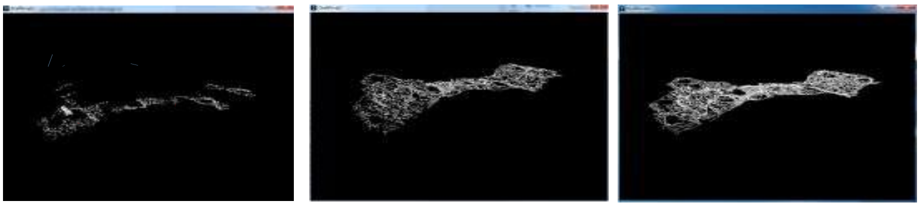
The boat and house are extensions of our movement and play important roles as spatial changing agents (Fig. 9). In different situation of car and boats the movement of building become varies.

2.3 Swarm Intelligence Optimization

It is important for agent-based architects to reclaim their right by applying a workflow that is more responsible for construction and the structural performance of the design. Many existing workflows only focus on post rationalize the structural computation(Hu and Li, 2014). As a complete solution to the practical problems, it's necessary to include pre-assessment, structure assignment, and post-optimization in this workflow (Fig. 10).

Fig.10. The workflow of swarm Intelligence based optimization (Hu and Li, 2014)

Pre-assessment acts as a rationalization process before the agent-based computation runs. In many cases, an agent-based architecture’s structure can be rationalized into a structure primitive, which is the combination of several key structural features. Pre-assessment in the early design stage is defined with basic structural ideas that could inform structural poperies in the process of agent computation (Fig. 11). Furthermore, this helps the agent-based architect design a rational structure in the first place, which provides possibilities to maximize the freedom of design. Also, in later stages, it shifts to a structural tool that is able to provide an accurate analysis. This dual-stage method, which is not all-inclusive, prevents architects from overcomplicating structural setups in the processing, as many others attempt. The pre-assessment includes pre-setup, process-bundling, and pre-analysis. The agent set up should include pre-setup at the same time, such as supports, attachments, and base points before the agent generation process begins. The process-bundling is a process of agent simplification, and there are many existing algorithms to choose from. Lastly, the pre-analysis take place by analyzing the structural rebuild in the Rhino Grasshopper Environment. In the case of the above project, the original design is preset in the processing; the supports and attachments are placed according to the existing context. In the run agent process, the design agents lines are bundled, and a preferable design is chosen. In the later stages, the extracted lines were used as reference for rebuilding a spatial surface to accommodate the agent design result. In the analysis, the mesh was rebuilt as the overall structure in Karamba, an FEM-based structural plug-in for Grasshopper. The pre-analysis result shows that few cantilevered parts of the space have structural problems. The maximum cantilevered part is 30 meters. Through calculations, the maximum displacement of this design is 0.24 meters.



Pre-Setup Process-Bundling Preferred Result

Fig.11. Pre-Assessment of structure character for Design

Derived from the previous step, the result of agents based on process and structure information could be used as a starting point of structure assignment. Structure assignment ensures a precise simulation of one or multiple structure types, materials, and elements. Thus, improving the feasibility and even providing cost control for the final result. The characteristics of a defined structure type and material give rise to various constraints in the construction process. These constraints are often neglected in the agent-based design process which may cause unreliable results. In the work-flow, the structural, material properties, and even construction methods (such as optimizing, controlling, and reducing variation of elements and standardizing elements), are taken into simulation via converting them into geometric constraints, and so-called line and shell models in the structural analysis engine, as in Karamba. In this case, the main structure type has been chosen as 3D spatial steel frame structure, and steel has been chosen as the main material.

The structure has been built based on the agent-based line model. The extent of beam types, such as hollow beams, I-beams, and circular beams, is surveyed through experiments in the computer model (Fig 12). After selection, the specified material type, profile type, and structure type has been carefully inputted into the structural performance model and started to regenerate different structure models.

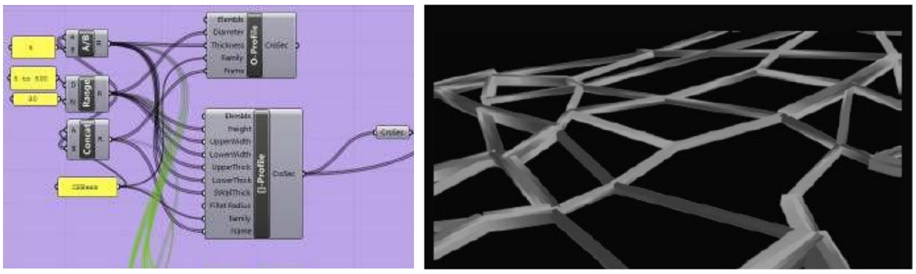
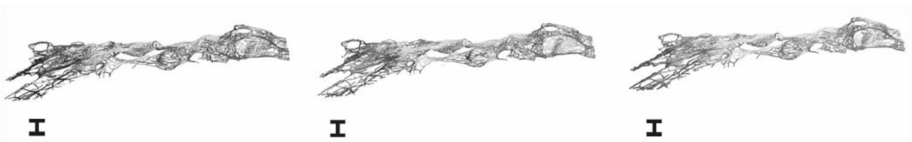


Fig.12. Profile Selection

After choose desirable settings, the next step is controlling the number of structure members. The range of sizes has been narrowed down to achieve optimum construable results, and the variations of elements have been optimized to find a balance between better structural performance and minimizing construction costs. As we can see from Fig.13, the different sizes of beams are applied to the model. The first one creates highly differentiated models that kept the most properties of agent-based models, but the 30 different sizes might need more cost infusion and joint types. The last one is the most economically efficient one, but the model is relatively too standard. Thus, the good solution is the one in the middle which allows for a limited number sizes of beams and balancing between cost and performance.



30 Sizes of Beams 20 Sizes of Beams 10 Sizes of Beams

Fig.13. Variations of Beam Sizes

The process of the structural assignment takes the form of transforming structural behaviors of the actual structure, material and construction features into their corresponding behaviors in the computational structural engine.

After previous processes, the well-established structural performance-based model has been set up. The advanced tool, Karamba developed by Clemens Preisinger in cooperation with Bollinger-Grohmann-Schneider ZT GmbH Vienna, enables architects to step further and make more detailed optimization of the structural frame.
Post-optimization includes the visualization and data management of the preceding result. It’s helpful for the agent-based architects to evaluate the quality of the space and structural result in seeking the solution to the construction issue. As a complete set of solutions, the visual feedback of the structure properties of the design is reflected in the present process (Figure 14), as well as some engineering related to structure drawing such as numbering and dimension.It’s also possible to export the statistical contents of the structure model to many different formats of structural analysis software, and it will be very advantageous for the structural engineers to design according to agent-based architects' requirements.

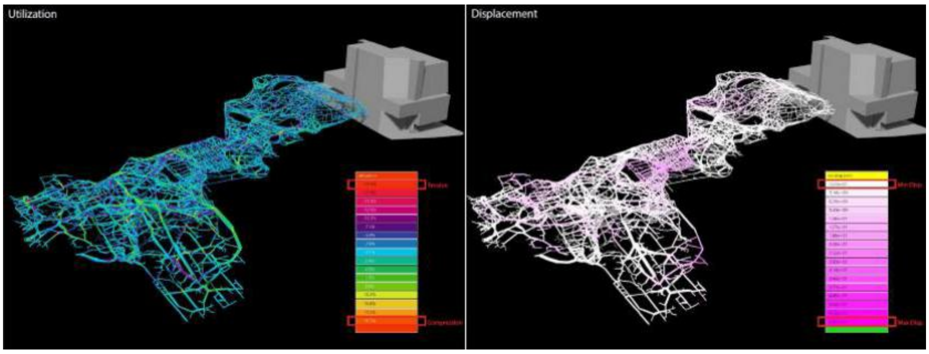


Fig.14. Visualization of Structural Utilization and Displacement

We could analyze, optimize, and solve a more specific structural and spatial design issue. In the example, the large cantilever parts have been optimized, and the structure has been enhanced to keep the original large-span, no-column space. This creates the necessary space for specific programmatic requirements such as auditorium and theatre space. More importantly, the structural informed space articulates structure ornament and function together, finally achieving the quality that agent-based architects desire.

We use a two-structure system to support an agent-based space: the traditional beam and column system and the structural performance design system. The two sections above present two entirely different space effects (Fig. 15). The traditional structural system limits space division and encroaches on the design’s initiative with elements that can stretch vertically and horizontally only. The structure also becomes a passive appendage to the building's shape. The most typical disadvantage is in large-span spaces.

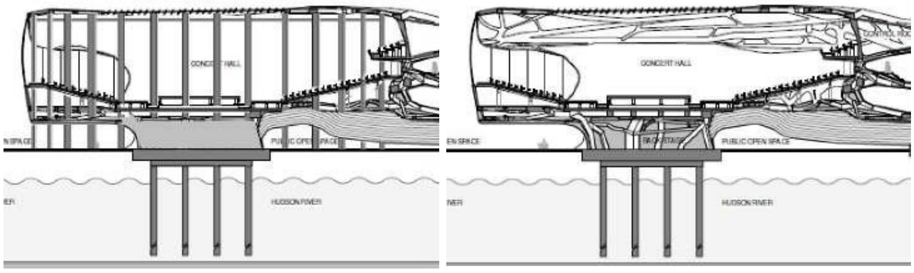


Fig.15. Section Comparison

Here in this left section, the large open space above the ground is divided into several small areas by traditional beam and column system divides into columns. The agent-based structural performance design system not only releases a large-span space but also provides reliable support with a structure system generating the shape generation development, which can fit the nearest part of building shape in any direction. It means, in this system, structure is congruent with building shape in every meaning.

3 Conclusion

At the outset, the structural performance-based design method advances and uses not only the computational techniques, but also the digital construction technologies in order to develop the inherent structural characteristics, as well as specific underlying per-formative capacities. By developing the structural systems, embedding their material qualities, their geometric behavior, assembly logic and manufacturing constraints within a computational model, the systems operation can be assessed vis-à-vis structural performance. Developing the structural systems also offers opportunities to reconsidering the predominant efficiency notion through the efficacy of the structural systems.

Secondly, the structural performance-based method neither employs the use of form-active structure primitives as the major design drivers nor the structural behavior properties as its established form-finding tools. However, it creates a new kind of between the architects and engineers; as a result, facilitating architects to design a multi-objective form-finding process through numerous hierarchies that describe complex/multidimensional architectural systems (Yuan & Hu, 2014). The structural performance optimization enables the design to be adjustable and more responsive. The performance-based innovative synergy outcomes materialize from its greatly differentiated morphology utilized with this particular method.

Lastly, the structural performance-based method is basically a method that facilitates or allows architects to have a more significant as well as an engaging task (role) in as far as the rationalization and execution of a multifaceted geometrical structural design are concerned. Alternatively, it also facilitates the improvement of project performance by architects. More significantly, however, the structural performance-based method could be employed by architects as means through which they can develop new forms so as to articulate structural members and structural space (Schumacher, 2014).

As such, we can argue that this particular method seems to be a requirement for not only building design methods, but also techniques aimed at form realization. It is actually meant to elaborate new possibilities in terms of designing new forms, as it is capable of articulating not just space, but also materials, social requirements, and architectural information with a significantly higher performance level than earlier possible.

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