Parametric Design and Construction Optimization of a Freeform Roof Structure

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1. Introduction

The pioneering works by Poleni, Rondelet and especially Gaudì, shows how some structural principles related to the field of shape-resistant structures has been well-known for centuries. The design of structural shape has been approached differently; the more analytical way of engineering, such as the works of Dyckeroff and Widmann or the intuitive approach of engineering referring to the works of Torroja. The focus for the new structures was lightweight, large spans, functionality, efficiency and economy. This brought new developments of form-findings structures, i.e. a set of tools and strategies to find the form of 'structural minimum' - in shells where the surface is mainly stressed in the plane with compression, tension and shear. The research started with the development of experimental tools, or physical models, reaching a high point with the work of Heinz Isler [2]. However, this prosperous period has been concluded in about 20 years, since the rigid generative rules of shape-resistant structures brought to the rapid exploration of the complete family of potential shapes of shells during the 60ies.

Only with the development and introduction of computer technologies in architecture and engineering we assist to a renovated interest towards shells and shape-resistant structures in general. First, because the potential of exploring and representing any kind of complex geometry by means of NURBS extremely enhance the designer’s possibilities, bringing to the development of 'non-standard' and 'free-form' investigations [3]. Second, because with computer simulation the traditional form-finding can be approached in a numerical way, reproducing the search of catenaries and minimal surfaces as happened with physical tools, but also considering the design problem as a question of 'optimization', to be performed after the main architectural choices has been already defined.

In this paper, the design of a free-form roof structure is presented, approaching the problem in order to reduce construction costs and to define an efficient structural behaviour - see also Basso et al. [4]. The design process is supported by the use of a parametric tool, Grasshopper™, for the definition of an optimization problem related to shape-resistant structures, and then a Genetic Algorithm, Galapagos™, is used to explore/improve the shape of the 'a priori' defined structure, or better a parametric solution domain of tentative structures. Finally, a scripting interface between the CAD software, Rhinoceros™, and the FEM solver, Autodesk ROBOT™, is described as a rapid way to check and refine the structural behaviour of the overall roof.

2. The project

The optimization procedure described in this paper has been developed, starting from a design proposal for the new Historical Museum of North Jutland, in Denmark, as reference project. The program for this new museum has been defined both as a closed design competition and a design studio for master's students in Engineering, Architecture & Design at Aalborg University, during the fall semester 2010. The site of the project is located in the landscape near Fyrkat, Denmark. The main design issues to be addressed have been related to the topics of tectonic and Nordic architecture. The definition of a Viking Museum therefore focused on construction, structural and material aspects, as well as the perception of architectural spaces integrated into the landscape.

Therefore, the building has been conceived as a free-form ruin-like heavy concrete base, directly anchored into the landscape. The roof is in contrast a light free-form shell resting on top of the base, and is made up of timber panels assembled in a triangular faceted form. This would be perceived as a cave-like room from the inside, emphasized by means of large timber columns, which are cutting through the geometry as space defining elements (Fig. 2.1 & Fig 2.2).

Fig. 2.1 & Fig. 2.2 Exterior and interior rendering

3. Parametric definition of the morphogenetic problem

3.1 Mesh

The conceptual idea for the project gives the possibility to implement computational techniques. By considering structure, construction and assembly, it was possible to investigate and develop the free-form roof shell, with the means of a morphogenetic optimization procedure.
For this reason, the architectural element of the roof is initially defined in parametric terms with Grasshopper™ in order to investigate design variables and constraints. First, the reference geometry is defined by three guide curves, lofted to create a NURBS surface. Second, a Delaunay triangulation algorithm is used to construct a triangular mesh on this surface starting from a set of points in three-dimensional space. The solution domain can be finally explored varying the geometry of the three guide curves used to generate the reference surface, and the position of a set of points, a 'point cloud', placed in the plan is projected on the reference surface for the definition of the triangular mesh (Fig. 3.1).

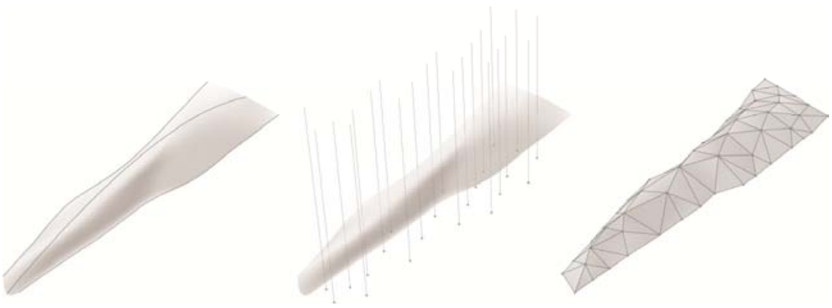

Fig. 3.1 From smooth surface to Delaunay mesh

3.2 Component

Each triangular element results from this first parametric definition of the roof and is used as a geometric boundary for the design of the final timber structural panels. They are studied in order to reduce manufacturing and assembly complexity and parametric adjustments are made according to the overall shape. Applying a recursive subdivision algorithm generates a structural element for each roof surface, following this procedure: First, each triangle is divided into four sub-triangles. Second, the respective edges and centroids are connected. It should be underlined that such a subdivision method uses the circumcircle centroid of each triangle, as well as the midpoint on each triangle segment to construct the components. The reason for using the circumcircle centroid instead of the area centroid of the triangle is to avoid joints with three-dimensional rotation. By keeping the joints two-dimensional it is possible to fabricate the elements on a 3-axis CNC milling machine.

In such a parametric definition of the roof structure a geometrical issue arises when a triangular component has obtuse angles, i.e. the circumcircle centre of a triangle does not lie inside the triangle. In this geometrical condition, the circumcircle centre will land outside the triangle, causing the subdivision algorithm to give an output that is not suitable for structural purposes, because of the non-perpendicular meetings (Fig. 3.2).

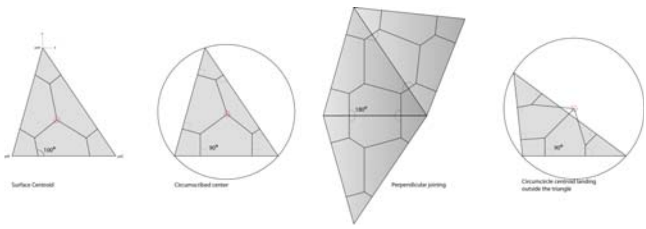

Fig. 3.2 The perpendicular meeting achieved by using circumcircle, and the problem when the corner angle exceeds 90 degree.

4. The optimization procedure

Solving this geometry and construction problem for each component in three-dimensional space requires the use of an optimization technique. In this case, a Genetic Algorithm [5] is chosen for a set of reasons. First, it allows a wide exploration of the solution domain by means of a metaheuristic search method, which can be easily followed by the designer and give inspiration and direct feedback during the optimization process. In this situation the goal is not to reach the optimal solution, but to define a sub-optimal solution to be considered as the best compromise after an in-depth evaluation of design criteria. Second, because GAs does not need the definition of an initial design proposal, i.e. a first tentative solution, but just a 'solution domain'. For the designer that means the formulation of a problem in parametric terms, their respective relations and range of variability. Third, because a new Genetic Algorithm called Galapagos™ has recently been developed and introduced as a tool inside Grasshopper™, providing a direct link to the parametric definition of the problem worth investigating.

4.1 GALAPAGOS GA

Galapagos™ [6] is a user-friendly GA, it allows for a direct definition of design variables and solution domain by means of Grasshopper sliders, and the definition of an objective function, or in GA technical vocabulary a 'fitness function' by means of a floating number, which can be minimized or maximized. No information is provided about types of selection. Crossover and mutation operators are used, and little control is given the user in relation to choice of the number of individuals per population, number of maximum generations i.e. iterations of the algorithm, and percentage of application of genetic operators (Fig. 4.1).

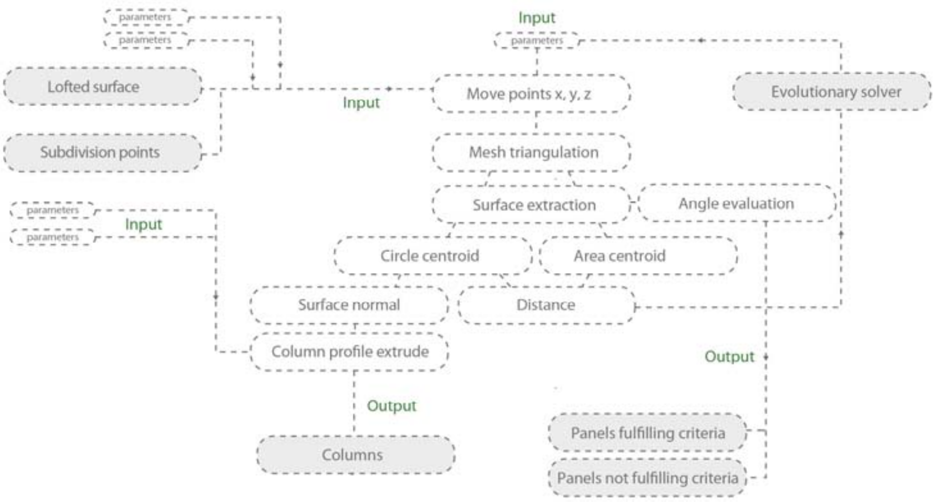

Fig. 4.1 Flow-chart of the optimization algorithm

5. Fitness Function and Solution Domain

The parametric definition of the roof with triangulation is used to define a solution domain for the Genetic Algorithm, Galapagos™. By decomposing each corner point, the triangles are then given a range of freedom, or variation in three-dimensional space. Such a limit is defined by the designer as a balance between desired form and degree of optimization. This allows Galapagos to modify and evaluate the overall shape according to the fitness criteria.

The fitness function has to be described in order to allow the algorithm to evaluate if each triangle fulfills the criteria for its angles. The fitness is the minimum distance between circumcircle centroid and area centroid, thus minimizing obtuse angles and avoiding the circumcircle centroid falling outside the triangle boundary. The distance is evaluated, for each modification on the point coordinates, and if it exceeds a given distance the solution is given a penalty by multiplying the distance exponentially. This guides Galapagos™ in selecting the fittest populations to further breed on and the population of fit individuals goes towards the best possible solution. (Fig. 5.1)

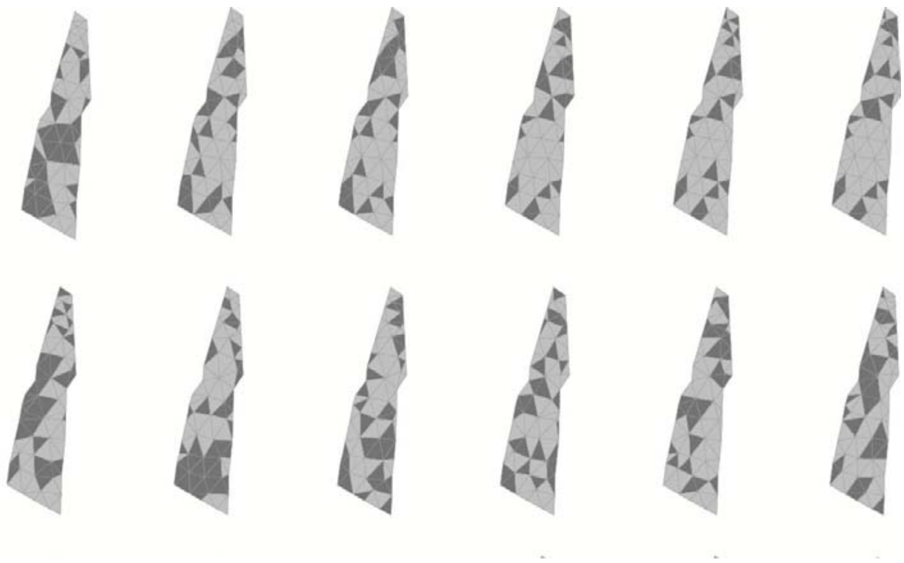

Fig. 5.1 Process of optimization, dark facets is the non-successful triangles

6. Results and further developments

The optimization focused on rationalizing the triangulation of a pre-established roof surface, with the constraint that is should respect the building plan as its boundary. The geometric optimization done with Galapagos™ allowed the archiving of a structure where 80 percent of the triangles succeeded in not having any corner angles above 85 degrees. This is a product of a very narrow space of freedom given to Galapagos™.

The advantage of a GA compared to a conventional linear way of solving lies in the variety of solutions generated. To reach a good result, it needs the possibility to operate on a broad range of solutions, but this also requires a considerable amount of time. From a design point of view it implies the possibility of investigating a broader range of informed design solutions and the possibility for discovering new and interesting solutions to a design problem. A potential for the GA is that it could be used as an active tool to explore new design solutions e.g. informing the form and plan of the building (Fig. 6.1).

The use of these in the design process relies on the designer's ability to set up the right solution space and fitness criteria. A way of investigating these possibilities could be through the setup of a solution space with a large flexibility in the modification of points, but also larger steps in between solutions enabling the solver to give a feedback on the widest possible solution space.

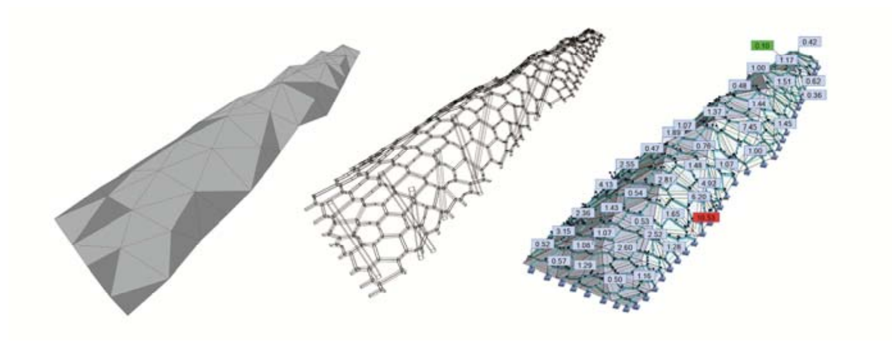

Fig. 6.1 Results of FEM structural analysis diagram

The optimization focused primarily on fabrication issues, but was also simultaneously during the design process evaluated for its structural properties. The procedure with GA showed that small variations in the node placements of the triangle corner could significantly reduce stresses in the overall structure. The Structural evaluation has been done with the finite element program Robot Analysis™ from Autodesk.

The open programming interface in the Robot API made it possible to program a direct link from Rhino to Robot making the Structural Calculations part of an Iterative design procedure enabling quick evaluations on the changes in the Structure. Due to time limitations, the investigation was solely done for uniform dimensioned structural bars (width and height).

A planned further development would involve letting Galapagos inform the dimensions according to obtained stresses in each bar member allowing a material optimization as part of the architectural expression.

7. Conclusion

As shown by this case study, the procedures of optimization by means of Genetic Algorithms and finite element analysis can be used in a parametric workflow to create an approach of integrated architectural design. Given the easy access to a GA in the form of the Galapagos solver in Grasshopper the designer now has easy access to a powerful tool, which can be used in an informed design exploration. The method can be directly implemented with the parametric model early in the process and requires most importantly the deliberate structure of the model.

8. References

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