P5 Reflection

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Background

Context of the research project
The main context of the research project is the Milan Expo 2015. A structure is designed and calculated in order to stimulate the research and apply the gained knowledge. According to the existing context the design concept is elaborated and several form-finding tools are developed and combined together to achieve the set goals.

Basic problem analysis
Dealing with digital form-finding techniques, there are two main issues that should be taken into account since the beginning. The first point regards the boundary conditions of the process, the fixed parameters determining the final shape. The second aspect concerns the process itself, the algorithm generating the final result according to the set boundary conditions. Those kind of processes can be direct or iterative, linear or non linear, and the level of accuracy of the final result is strictly linked to these aspects.

Problem statement

Main problem
Light-weight structures are strictly related to the sustainability of the building process. The material is minimized affecting the energy spent during the construction phase. The relatively small load transmitted to the soil makes possible to have less invasive foundation systems. Those kinds of structures have been always considered the most suitable for temporary installations. When calculating the overall “grey energy” of buildings with longer life-span, the lightness becomes secondary to the maintenance and the running costs. However the weight of the structure becomes one more time critical in the last phase of the building life-cycle, the disassembly. In order to build light-weight structures the building should be shaped according to the loads acting on it, both permanent and variable ones. The art of form-finding these shapes is nowadays strictly related to the development of new tools able to help the designer in drawing performing light-weight structures. Mathematical models are selected and translated into software able to generate and compare, in the early design phases, different variants of the same design concept.

Possible sub-problems
The first sub-problem is the selection of the existing form finding methods by evaluating their limits and potentials.

The second sub-problem regards the way of combining the different form finding methods in an iterative way.

The third sub-problem is dealing with the convergence of the combined methods into a unique result. This aspect is strictly linked with both the selected form-finding methods and their combination. However this issue will appear just in the last step of the algorithm development. In order to avoid any inconvenience, the convergence aspect should be taken into account since the beginning of the tool development.
Objectives

General objectives
The general objective is to elaborate a method to form-find structures composed by compressed arches and struts combined with tensioned membranes and ties. An algorithm will be drawn in the Grasshopper environment and several design tools will be developed for Rhinoceros users.

Sub-objectives
The first sub-objective is to select and/or elaborate form-finding methods.

The second sub-objective is to combine the selected methods in an iterative process able to preserve the fixed boundary conditions.

The third sub-objective is to guarantee the convergence of the iterative process to a unique solution.

A last sub-objective is to demonstrate the structural efficacy of the form-finding tool developed.

Final products
The main product will be the form-finding tools themselves and their design application.

The secondary product is the report explaining the tools background, their development, their final structure, a generic design application and its verification.

The third product is the elaboration of the supporting material for the oral presentation.

The fourth product is a DVD containing the all digital materials developed during the research.

The fifth product is a physical model of the designed structure

About the direction of the solution
The main direction of the solution is combining direct form-finding methods. Iterations should just be used to link different form-finding techniques into a hybrid form-finding algorithm.

Boundary conditions
A pavilion typology is developed in order to set the design boundary conditions. A clever structural concept is needed before the application of the developed tool. The parameterization of the pavilion according to its boundary conditions is the starting point to compare different form-found structures. The only shaping forces taken into account are the pre-stresses of the tensile elements and the self weight of the compressed ones. External loads, like wind, are not involved in the form-finding process but just used to test the efficacy of the designed structure by FEM analysis.
Research questions

Main research question
The main research question is how to design optimal arches in membranes and cable net structures. In order to do that a hybrid form-finding tool will be developed.

Sub-questions
The first sub-question is what the most suitable form-finding methods are.
The second sub-question is how the form-finding methods should be combined together.
The third sub-question is how and if a unique solution exists according to the set boundaries.
The forth sub-question is if the developed tool applications are performing as desired and if not what are the lacks of the developed method.

Background questions
The main background question is how a form-finding tool should be used in the design process.

Background sub-questions are about the stage in which these tools should be involved in the design process and their efficacy in improving the structural performances of the proposed design.

Approach and methodology

Research questions and objectives definition
- Research of study material
- Selection of study material theories

Design tool developments
- Mathematics, mechanics and scripting studies needed to achieve the set goals
- Translation of the theory into design tools for the design algorithm
- Structural concept elaboration for a generic pavilion
- Translation of the concept into a parametric model with its BC (boundary conditions)

Design tool application
- Combination of the form-finding tools with the structural concept of the pavilion

Structural verification
- FEM analysis of the design pavilion
- Reflections and considerations
Relevance

Societal relevance
Designing a building according to its structural performances requires the collaboration of both engineers and architects since the first steps of the design process. However, especially in the early phases, the communication between the parts is hard and time consuming because of the undefined boundary conditions of the design concept.

Digital tools are developed to give to the designer the independency to investigate different possibilities from an aesthetical as well as a structural point of view. Since calculations are run by the tools, a clever structural concept can be translated into a performing structure by just understanding the boundary conditions and the forces governing the form-finding process.

There is a societal relevance in the developing of these kinds of tools. The designer is free to explore both the aesthetics as well as the structural performances of the proposed shape without the need to involve specialized structural engineers in the early stages. The designer becomes an “archi-neer” controlling the overall process from different aspects by using the engineering knowledge contained in the digital tools as well as its own architectural and technical background knowledge driving the design concept.

In the age of specialization and fragmentation of the design process, digital tools can give back to one person the possibility to draw, investigate and choose between different design variants.

Scientific relevance
The project is about a new tool to form-finding the supporting arches in tensile structures. In the past century a lot of research has been done on the form-finding methods of both tensile and compressive structures. The first digital form-finding were inspired by physical experiments, used by designers like Antoni Gaudi and Heinz Isler.

Limits of physical methods are the accuracy of the models and their measurements. Even more limitations are given by the form-finding environment. For instance a hanging centenary can be used to form find arches while soap films or elastic surfaces and cable nets can describe the shape of membranes. However combining different physical methods is hard and not always possible.

A membrane shape depends on the internal pre-stresses as well as on the geometry of its supports. If we connect a pre-stressed membrane to an arch, the reaction forces of the tensile structure are affecting the thrust line of its support. In a physical model it is not possible to form-find the membrane together with its edge supports. That’s because in hanging models the geometry of the arches should be mirrored while the membrane form finding methods, by the use of elastic materials, depends on the exact position of its supports.

In a digital environment the two described form-findings can be combined into an iterative process able to give back a structure where the pre-stressed membrane generates only pure compression into the designed supporting arches.

There is scientific relevance into the developing of digital form finding tools. The combination of different methods allows to form-find hybrid structures that are not possible to be described by simple physical models. The limits of the physical form-finding techniques are overtaken by the digital environment allowing the designer to explore new possibilities in the field of slender structures.
Considerations on the product

About the developed algorithm
The developed algorithm was built as a combination of two direct methods looped together. It is a complex structure of simple processes. All the shaping forces have been presented and the output geometries tested by FEM analysis. Results are showing that the form-found structures are working in pure axial stresses when no accidental loads are applied. The main goal of the research is therefore achieved.

The chosen methods have been selected because of their linearity. That makes the overall process easy to control in terms of convergence. The looped method can be stopped and adjusted in between steps allowing the designer to gradually achieve the final geometry. Optimization processes can be run in-between steps in order to control the arch proportions as well as its planarity.

The proposed method gives back a unique solution. However for a given set of shaping variables there can be more than one result. The sequence of the optimization processes is also affecting the final shape. To reproduce the same geometry all the intermediate operations should be repeated at the same step in the overall looped process.

All the final representations have been created thanks to the 3D model generated by the developed form-finding tools. These tools are the same that have been used to analyze and export the structure in a FEM environment to check its structural behaviors. It can be concluded that the strong relation between engineering and architecture has been successfully managed by the overall developed design process.

About components
The developed components can be used for other design proposes by combining them in other ways. Different kinds of optimization could be run by playing between the inputs and the outputs of single tools. For instance the 3D Arch Form Finding component can be combined with many other optimization processes. It could be reused to obtain a thrust line with a fixed height, a fixed total length or even a fixed maximum internal force. Every output can be optimized to adjust inputs according to specific needs. Therefore the described design application is only one of the possibilities in which the developed tools can be combined.

A further development could be done on the FDM components in order to faster generate the connectivity matrix from the initial geometry. The developed FDM Cluster component can take more than 5 minutes to generate a complex connectivity matrix. Saving this data into a .txt file and reading it in the next steps rather than recalculating, was a necessity to overcome timing problems.

In order to be able to correctly use form-finding tools, the process governing them should be well known by the user. The designer has to be aware of the relation between the shaping forces and the final geometry in order to obtain satisfactory results. Therefore the mathematical and mechanical background theory should be studied by the user at least from a general point of view.
About structural performances of light weight structures

The found geometries perform optimally when the only applied forces are the same ones used as the inputs of the form-finding process. However in wind load conditions the membrane curvature and the pre-stress forces are the critical values in reducing deformations.

The arches, since they are rigid structures, will bend in case of accidental loads. To keep them as slender as possible stiffeners and ties are needed to prevent too high moments and deformations; bending stresses should be kept as small as possible.

It can be concluded that a light weight structure, performing very well in dead load conditions, doesn’t necessarily behave in an effective way when differently loaded. There are aspects that should be taken into account in the design process before form-finding the geometry. In the specific case of the presented design, they are the typology of the membrane structure, its Gaussian Curvature and the adoption of ties stiffening out the compressed elements.

About Form-Finding in the overall design process

Form-finding is a tool to be used in the overall design process. It is located between the design concept and the final design shape. The elaboration of more variants, to compare and select, is the best way to take advantage of the tools. New necessities could emerge during the design process affecting the shaping forces. The goal setting process and the boundary conditions becomes the most important factors to achieve a good quality of the final design proposal.

A clear example is the design application presented in the report. The membrane structural typology has been changed two times in order to reduce the wind deformations. That was not an operation affecting single parameters of the developed algorithm but it required resetting the entire algorithm structure.

The described form-finding technique is used to optimize the overall shape of the structure. However important issues can emerge during the detailing phase requiring compromises between the form-found geometry and its realization. In the specific case of membrane structures it is important to take into account the transmission of the internal stresses of single elements in its connections. Those aspects were not analyzed in this report but are an important parameter that the designer should be aware of.

It can be concluded that the proposed form-finding method should be used in the beginning of the design process in order to explore and compare different variants of the same concept. Testing the results will later describe the performances of the proposals. Sometimes it can even happen that the initial concept is modified on the base of considerations done on the FEM analysis results. That can affect the entire structure of the form-finding algorithm rather than just few parameters.

Form finding of supporting arches in tensile structures affects the slenderness of the compressive elements, especially in dead load conditions. However the critical aspect of designing this kind of structures is the choice of its structural typology related to the span and the accidental wind loads.
Conclusions

Learning from the process

In the first phases of the research a lot of interesting topics have been studied. However not all of them are discussed in the report. Papers about form-finding methods for tensile structures, tensegrities, arches and shells are listed in the report bibliography. Other more generic readings are also mentioned in order to understand what form-finding means and how it has been used since its early stages. The report itself is a selection of the research material in order to explain the developed algorithm and its design application. The aim was to support the final product and show the personal developments on the chosen topics rather than presenting the whole studied material.

A large amount of time was spent for developing the Arch Form Finding theory. The minimal complementary bending energy method, presented by Rik Rozendaal in his graduation report on Shells and Arches (2014), has been extended from 2D to 3D environment and from a simple vertically loaded structure to any kind of load case. That was the main creative process of the theory research. Another personal elaboration had been done on modifying the external loads acting on a 3D arch to achieve planar thrust lines. Only after those mathematical and mechanical explorations, the design tools have been developed.

The FDM components are all based on existing methods already used by other software. However there are not yet several FDM tools available in the Grasshopper environment. Because of that the first algorithm was built with the use of Kangaroo, a plug-in based on Particle Spring Systems (PSS). That was a fast way to explore the combination of the membrane with the new developed arch form-finding tools. The main reason because PSS has been substituted by FDM is because of its iterative structure. PSS is not a direct approach and a lot of intermediate solutions are converging to a final result that is actually never achieved. In fact the system keeps on moving in time reducing infinitely its translations. That’s why the FDM components have been developed. While scripting them it had been very helpful the VB-components developed by Daoxuan Liang in his research on “A Parametric Structural Design Tool (Grasshopper Interface) for Plate Structures” (TUDelft, 2012). Since he developed its own FDM components, reading existing scripts regarding the same topic was very helpful in building my own ones.

It can be concluded that, more than the final product itself, the research process was very important from a personal perspective. During the semester I kept on learning different theories as well as developing new skills rather than just producing a design tool with its application. The end of this graduation project is therefore a new starting point for future research, not necessarily strictly related to the presented topic but based on the different kinds of earned knowledge.