Parametric Poetry-Integrated solutions for complex geometries with structure and skin

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This paper describes our integrated parallel approach to optimizing structures, using generative computational modelling systems, working alongside our clients, structural engineers and construction companies. Nowadays, there is a move towards integrated design systems in contemporary design. Here we describe our design for a pavilion, where structural elements were optimized not only in terms of their structural stability, but also production, thereby reducing costs. This integrated approach allowed us to simultaneously examine, on one hand, the architectural impact of the structural elements and the associated covering membrane, and on the other, its structural stability and the extent of material required. The process led us to set up a parametric system to study the pavilion's architectural geometry. A similar system then analysed its structural integrity, and another, the production costs. The resulting system of components form an interrelated whole, where each has a direct impact on the other. To test out various pavilion geometries, we undertook an iterative mathematical analysis, based on the logic of evolutionary calculations in three dimensions. Following that, several potential pavilion forms were examined and weighted according to various factors: architectural, structural, material and financial. The resulting structure – a system of wooden ribs combined with an outer membrane – was then further tweaked to optimize it as an integrated structural system. Compared to a traditional design approach, which is more or less consecutive and creates a loop, the advantage of this process is that the constitutive elements are always considered in parallel. This speeds up the design and analysis process, and is an efficient method to determine the final production cost. In the case of the pavilion, this meant we were free to experiment with various designs, while always keeping costs in mind. We were, for instance, surprised to discover that through optimizing the integrated rib and membrane structural system, the dimensions of the structural elements turned out to be far smaller than we had originally envisaged. All this affects the production schedule, the material flow and ultimately, the final cost of the pavilion.

Keywords: Computational Design, Integrated design systems, Optimization, Parametric modeling, Complex geometries, Wooden construction, Membrane systems, Evolutionary optimization.

Fig. 0 View of the Frankfurt Pavilion, Frankfurt Book Fair 2018

1 Introduction

Humans have come a long way since they inhabited natural shelters, as exemplified by the complexity of architecture today. In prehistoric times, humans fulfilled their need for shelter by finding a naturally appropriate location, like a cave or an overhanging cliff. Later, hunter-gatherers began to live a nomadic life and to create settlements that led to the appearance of the first constructed shelters. One might argue that this episode marked the birth of the tent – a temporary shelter, assembled within a short time span and later dismantled and carried to the next location. This portability became necessary due to the nomadic nature of society and Bedouins in Arab countries epitomise this form of lifestyle, and still practice it today. The tent represents the most rudimentary form of portable architecture, and it is based entirely on two primary attributes – a structural frame, and a skin. This concept has remained constant in the entire genealogy of the tent throughout the passage of time. The construction principle of a modern tent hardly differs from that of a primitive tent.

The tent-like works of Frei Otto in the latter part of the 20th century show an unrelenting desire to further the boundaries of using structure and skin in a single integrated system. The Multihalle Hall in Mannheim, Germany, designed by Carlfried Mutschler together with Frei Otto (1975) (Fig.1), offers one of the best examples to demonstrate how this principle can be stretched to the limit, in terms of form and structure. The design system is based on a wooden rib structure covered by a membrane skin. The most fascinating aspect of this system is the form-finding principle that is embedded in it. This wooden structure was dictated by the parameter of the membrane and wooden elements acting as a single structural entity once the elements are brought into position. The final form of the roof thus derives from an organic form-finding process that is influenced by a combination of structural forces and the desired spatial quality.

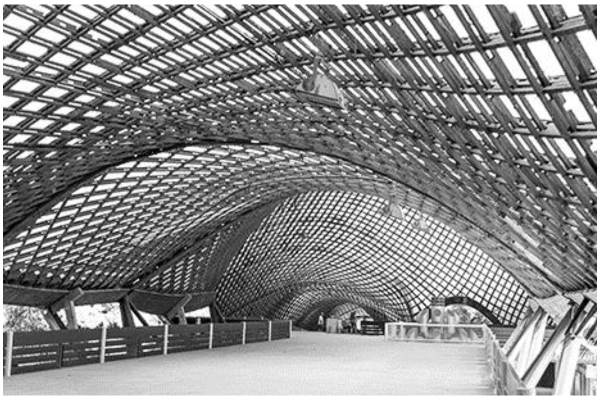

Fig. 1 The Multihalle in Mannheim, Germany (Carlfried Mutschler with Frei Otto)

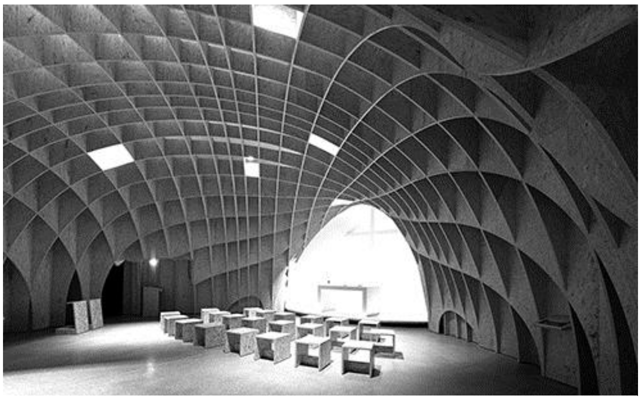

Fig. 2 Autobahn Chapel Siegerland, Germany 2009-2013 (schneider+schumacher)

The new pavilion designed by schneider+schumacher for the Frankfurt Book Fair (*Frankfurter Buchmesse*) embodies similar principles, and takes them to the next level, employing the computational tools available today. These allow one to combine the process of form-finding with form definition, and to thereby create an integrated design process. The factors governing the geometry are also those that will ultimately influence the final cost of the project, so an unprecedented level of optimization can be achieved in this integrated process. By analysing the hybrid configuration of structure and skin as a single entity, it is now possible to test how the independent elements influence one another and thereby to optimize each one of these elements, creating an integrated system.

2 Integrated design – form, structure, material and costs

The client's brief for the Book Fair pavilion was quite simple: the pavilion should be an iconic structure capable of seating approximately 300 people, primarily to be used for book readings, presentations and events. It should also allow some flexibility in terms of the use of the space. Another requirement was that the temporary structure should be capable of being erected and dismantled within a short space of time, and subsequently stored, then re-used annually over at least the coming 10 years. The approach to this project was inspired by another schneider+schumacher design – the Autobahn chapel in Siegerland, Germany. It was the inner dome of this chapel (Fig.2) that offered a starting point for the design process for the Book Fair pavilion, officially named the 'Frankfurt Pavilion'. In the Autobahn chapel the dome is constructed as a waffle system of intersecting wooden ribs, and it is a grid in plan, hence the structure is comparatively simple.

The design of the Frankfurt Pavilion, on the other hand, sought to amalgamate not only the notions of architectural space and a structural system, but also the philosophical connotation of a space which is intended to house book-related events. This involved experimenting with reinventing the concept of the bookshelf. As shown in Fig.3, a conventional bookshelf was subjected to an imaginative force, which then created a shell, thereby also transforming

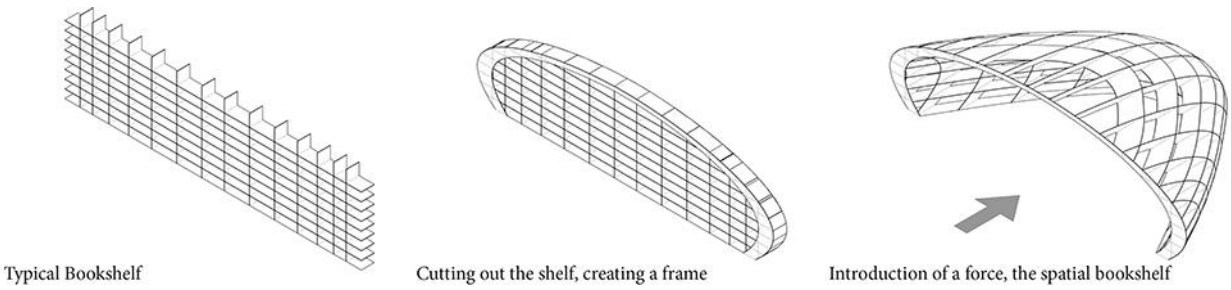

Fig. 3 Spatial transformation of a typical bookshelf into pavilion bookshelves.

the bookshelf in the horizontal direction, such that it follows the contours of the inside of the shell. This strategy brought with it a number of challenges, such as how to define the form, ensure structural stability and find appropriate materials, but also with regard to aesthetics, stability and durability. As Sanford Kwinter (Kwinter, 2006) comments in his essay entitled 'The judo of cold combustion': "The new materialism may well be the new expressionism.", the design process of the pavilion strives towards finding a point where form, structure and material fuse together to create a single homogenous entity.

3 Optimization – creating a hybrid construct with geometry, structure and skin

3.1 Geometry

The geometrical design of the pavilion is based on a simple principle of three identical shells, which together intersect to create a single space. The building envelope consists of three structurally independent, identical, monocoque systems that integrate the outer layer and its structural behaviour in one single-layered envelope. Employing a vertical grid to generate the waffle-like structural frame, means that horizontal ribs are created too, and these can also function as bookshelves, thereby integrating a third function within the building envelope as shown in Fig.4.

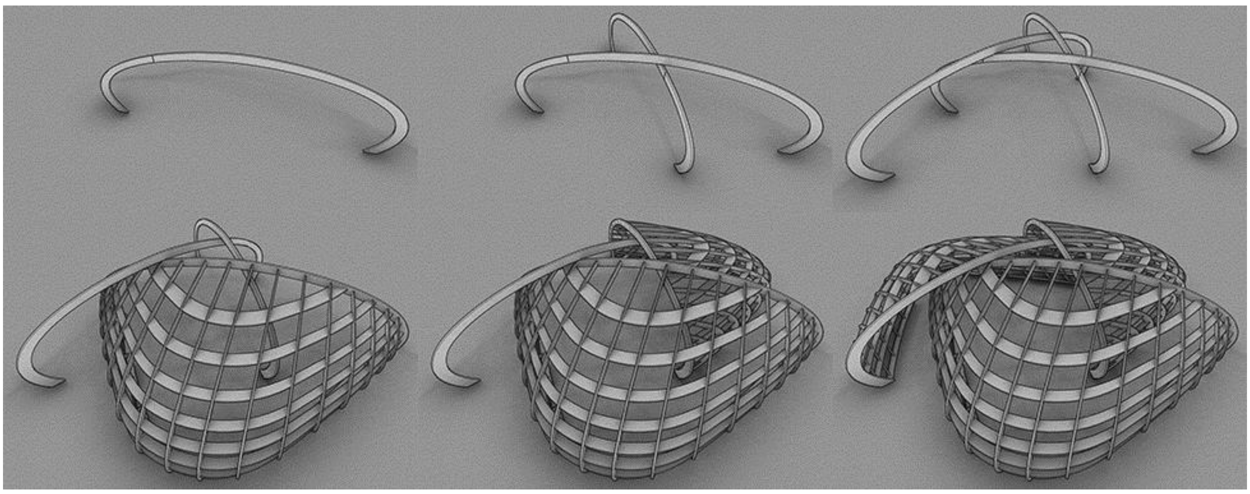

Fig. 4 Design logic of the pavilion

Contemporary architecture employs digital tools in design, analysis and production and these digital aids are helping to break down the linearity of conventional architectural processes. By using a combination of various computational tools it has now become possible to create a more fluid interactive process between the various contributing factors that produce an efficient and optimal design solution. The authors of this paper have been researching various aspects of integrated design systems over the past few years. In several schneider+schumacher projects they have focused on the potential and the limits of fluid design systems that combine feedback logic between geometry, structure, and materials. Among such experiments in this series is the bus-stop shelter “Parapluie”. Here the limits of Ultra High Performance Concrete (UHPC) was tested so that, by combining geometric effects in form, and material effects in structure, the ultimate form resulted in a very thin concrete shell (Eisenbach, Vasudevan, Grohmann, Bollinger, & Hauser, 2014).

3.2 Computational integrated system

For the Frankfurt Pavilion, a computational system was created to control the overall geometry, employing the simplest parameters. By constructing just one shell and then triplicating the system, only one shell had then to be analysed (see Fig.4). At the same time, the client’s spatial requirements were kept carefully in check throughout the process. Since the three shells are identical, a single lateral displacement plus a rotation of 120° and 240° generates the entire space, and three entrances result from this displacement and rotation. The shell itself is a part of a larger geometry that is controlled by tangents and their intensities (see Fig.5). The upper three images show the global geometry and the resultant shell as part of it. The diagram describes the logic of the creation of the form. The two curves are generated by vectors (v_{a1} and v_{a2} for the outer surface and v_{b1} and v_{b2} for the inner surface). The angle of the vectors v_{a1} and v_{b1} to the horizontal are ‘a’ and ‘b’ respectively, and the system is built with the condition that b > a. The difference in the angles then also defines the structural cross-section depth at the thickest part of the rib. The combination of vector intensities and vector angles were the controlling parameters for the geometry of the pavilion. The outer curve subsequently also defines the geometry of the skin. This is one of the key integration aspects, since both structure and skin are defined by the same parameters. As a result, the system is capable of re-

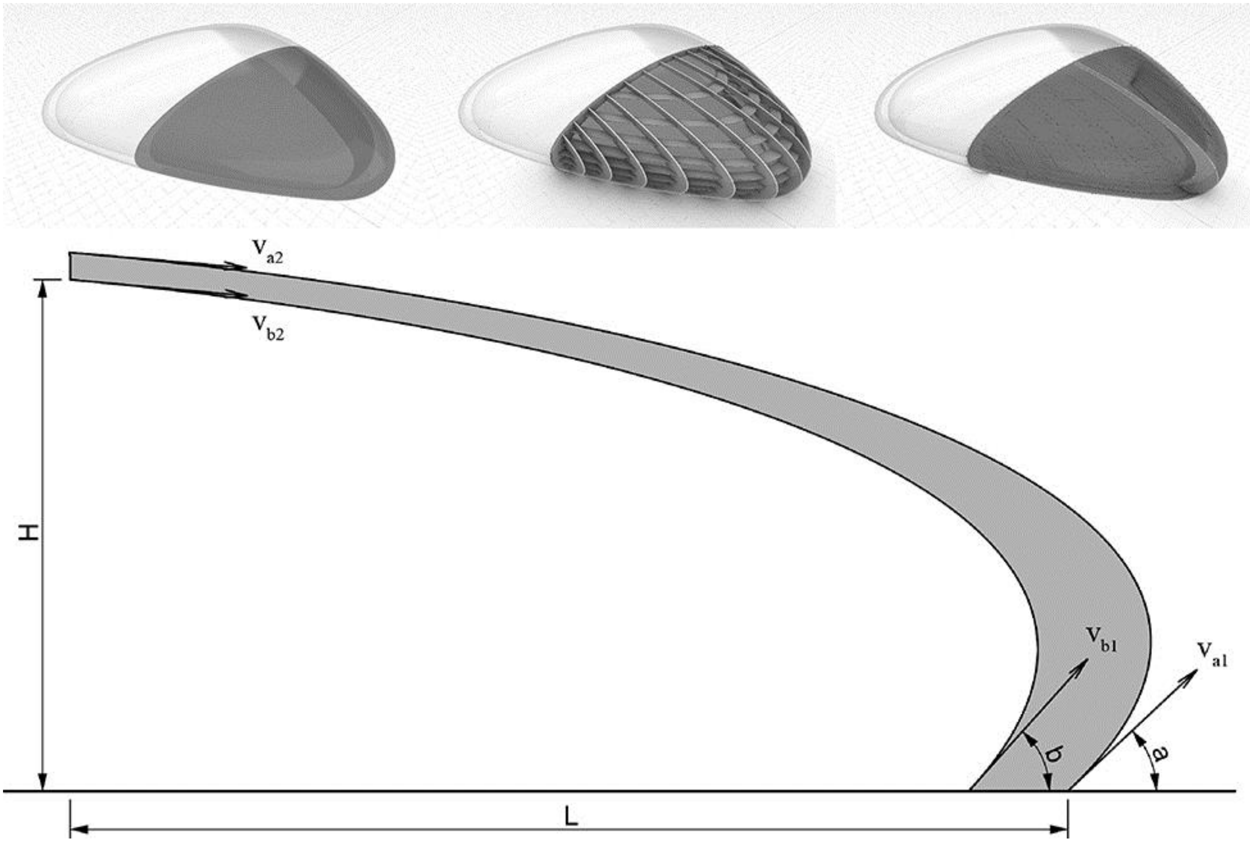

Fig. 5 Geometric system and controlling elements of the base geometry

sponding to minor changes so as to get the maximum out of the form and the material. A computational system needs to be designed to function responsively and efficiently in an integrated geometrical and structural system. This requires ensuring that the basic aspects of constraints, constants, variables, their interrelationships and hierarchies are fluidly controlled, so they are capable of maintaining the system responsive at all limits of the variables. A detailed explanation of such a system can be found in a paper on another schneider+schumacher project: “die Welle” in Frankfurt. In that project, double curved geometries were produced with roll bent aluminium plates. An ideal parametric system is clearly defined in the paper as follows:

“A parametric design system is a 3D mathematical model based on the various parameters of the design. The basic aspects of such a system are:

- Constants (relating to the design geometry and existing aspects in the site)
- Variables (the values that allow adjustments to the design)
- Interrelationships between the constants and variables
- Hierarchies between the interrelationships
- Boundary conditions (aspects from the site that restrict the design)

A parametric system is hence a combination of the design ideas imbibed into a geometric system with the aforementioned aspects as the basis of the system. The effectiveness of such a system is dependent on the possibilities offered by such a system to test various alternatives under different conditions so as to have a better understanding of the design.” (Vasudevan, Fahlbusch, Schumacher, Bollinger, & Grimm, 2016). This is crucial when the system is put through an optimization process. For the pavilion, the aforementioned logic was used to build a computational system that could be controlled by a minimal number of parameters. This ensured the stability of the system at all stages during the optimization process, which enabled a maximum number of variations to be tested, thereby producing a more diverse set of results.

3.3 Optimization through evolutionary mathematics

In the case of the pavilion, optimization was done using a 3-axes system for specific fitness criteria based on evolutionary analysis with a tool called Octopus (Vierlinger, 2014) for Grasshopper – a visual programming tool developed for Rhinoceros as shown in Fig.6 and Fig.7.

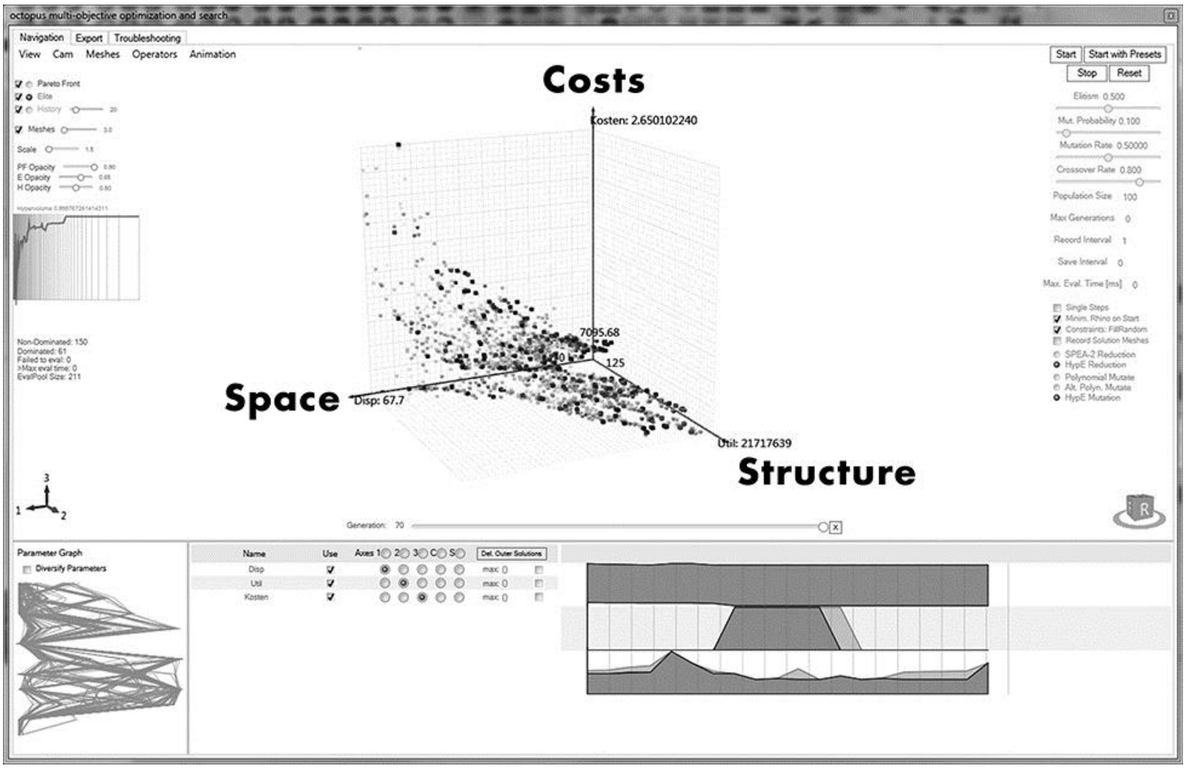

Fig. 6 The multi-objective optimization in Octopus

The first of these three axes was the parameter of the spatial requirement for 300 seats. Since the number of seats was integrated in the system, this could be verified with every iteration. The second axis was based on the results from the structural analysis of the geometry. This was integrated in the Grasshopper system with the help of a tool called Karamba3D, a plugin for Grasshopper developed by Clemens Preisinger in cooperation with Bollinger+Grohmann ZT GmbH in Vienna (Presinger, 2013)

The structural analysis for the pavilion was integrated by the structural engineers in such a way that any variation in the original geometry would be visible as a related consequence in the structural stability of the system. To analyse the structural stability in Karamba, all influencing factors were incorporated in the various load cases. This meant that the correlation between the wooden rib structure and the tension on the structure introduced by the membrane could be constantly checked and verified for every iteration. For the optimization process, a single fixed relevant combination of load cases was chosen in which self-weight, wind load, and membrane pre-stress were all taken into account. Specific fitness criteria consisted of structural aspects, such as the maximum deflection and the average maximum utilization of each set of members. The third axis for the fitness criteria was cost, as determined by the various geometrical elements. All the partners involved in the project participated throughout the entire development process. This included the consultants as well as the production companies – Holzbau Amann GmbH for the wooden structure, and Taiyo Europe GmbH for the membrane. This meant that detailed information on factors that might affect the final cost of the pavilion was constantly available. It was thus possible to include cost as a factor in the optimization process.

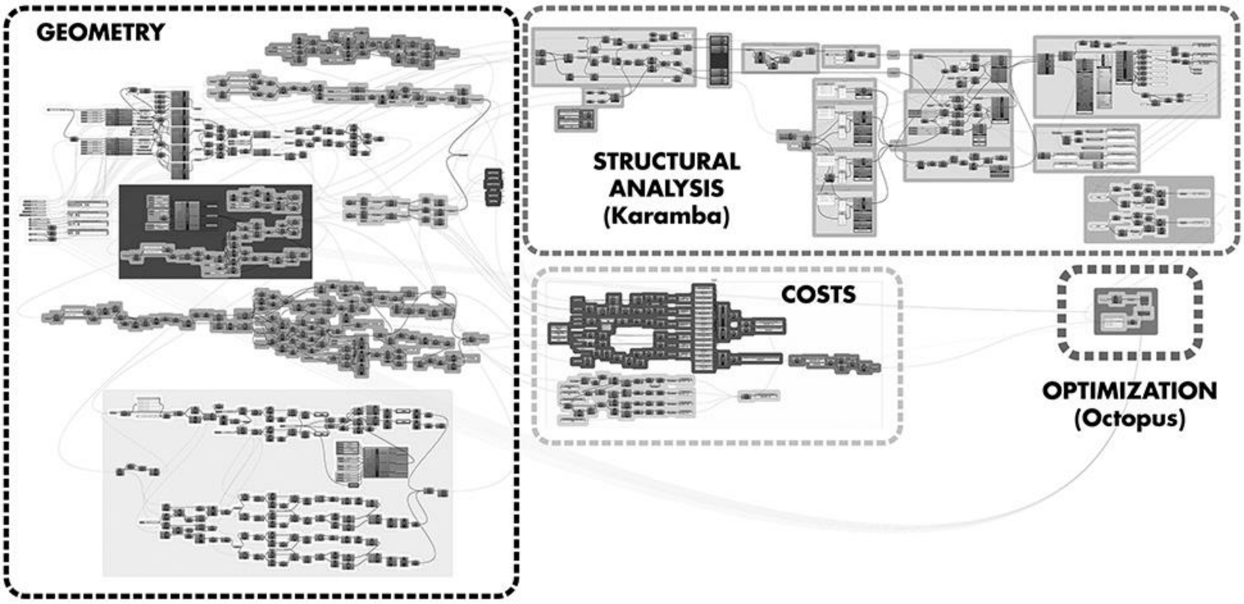

Fig. 7 The parametric system in Grasshopper

Fig.7 shows the combined parametric system, where the geometry of the pavilion, the structural analysis and the costs are all combined and influence one another in multiple feedback loops within the system. The optimization in Octopus works inside these feedback loops, analysing the pavilion with evolutionary mathematical algorithms in a multi-dimensional iterative process. During this process various combinations of variables are tested with each other and a large set of variations are produced and cross-analysed. Results that tend towards a more optimal solution then form the basis of the next generation. These iterations are then repeated until the solutions tend towards an optimal junction of all three pre-defined fitness conditions. This process has been well described by David Rutten in his work on evolutionary solutions for parametric design in Grasshopper (Rutten, 2010).

3.4 Materialising the optimized geometry

The pavilion's structural ribs are cut out of laminated veneer lumber (Kerto-Q) with a weight of 510 kg/m3. The three main arches (Fig.4) have cross-section thickness of 150mm. The ribs are built up in sizes as large as possible within the limits of standard transportable dimensions. The 14 vertical ribs for each shell have a cross-section thickness of 75mm and the 9 horizontal layers have a thickness of 50mm.

The resulting structure is extremely lightweight. Due to the dimensions of the vertical ribs, it was not possible to cut them out of a single plate. This meant that the ribs had to be subdivided, which then implied that the fibre direction would change along the length of the rib. The consequence of this change in fibre direction was a reduction in structural stability at the junctions. This meant that in the structural analysis thorough consideration had to be given to the material properties of the varying fibre directions along the length of each rib (Fig.8).

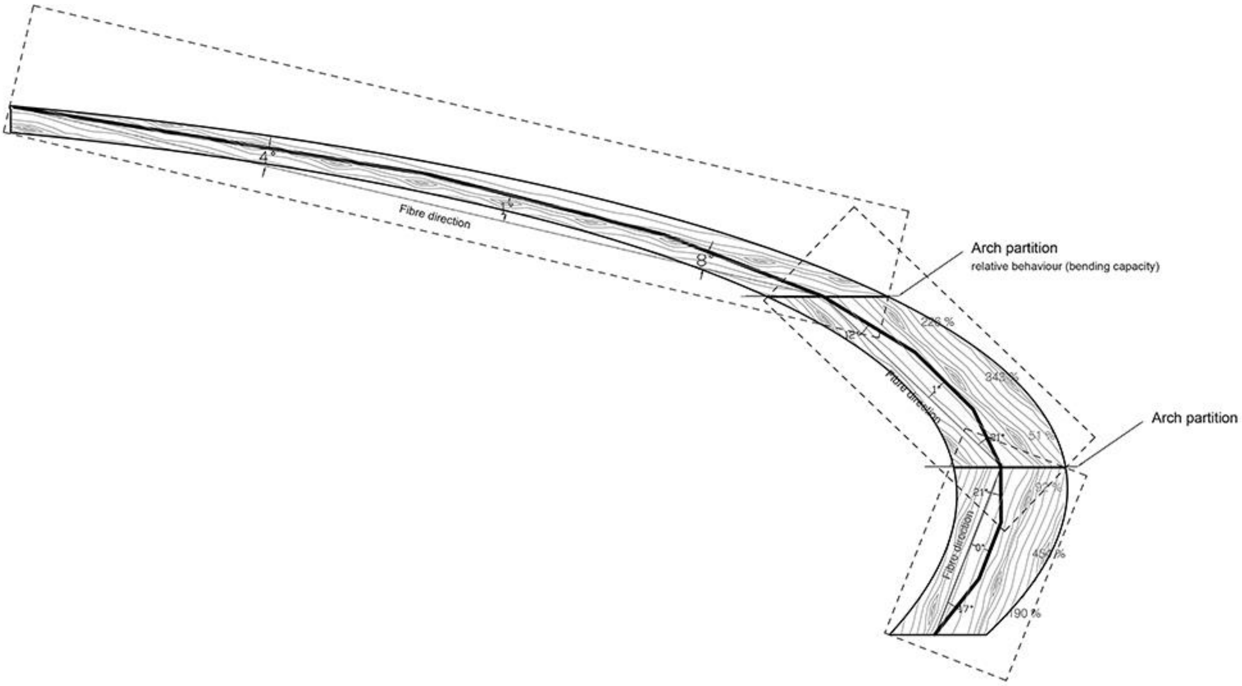

Fig. 9 A vertical rib showing sub-divisions, fibre directions and organization of the parts in the plates.

The pre-stressed membrane is made of PVC and produced by Taiyo Europe. The membrane forms the skin and also provides tension across the wooden members, thus keeping the entire structure stable. This membrane is fixed only to the main arch and to the floor. This means it glides over the intermediary ribs, thereby conveying its tensile strength only to the vertical ribs. The horizontal ribs are offset towards the inside, so they do not come into contact with the membrane. This creates a hierarchical system of dynamic force transfer throughout the system, as any element from one group of structural members is only in contact with the next group of structural members (Fig.9).

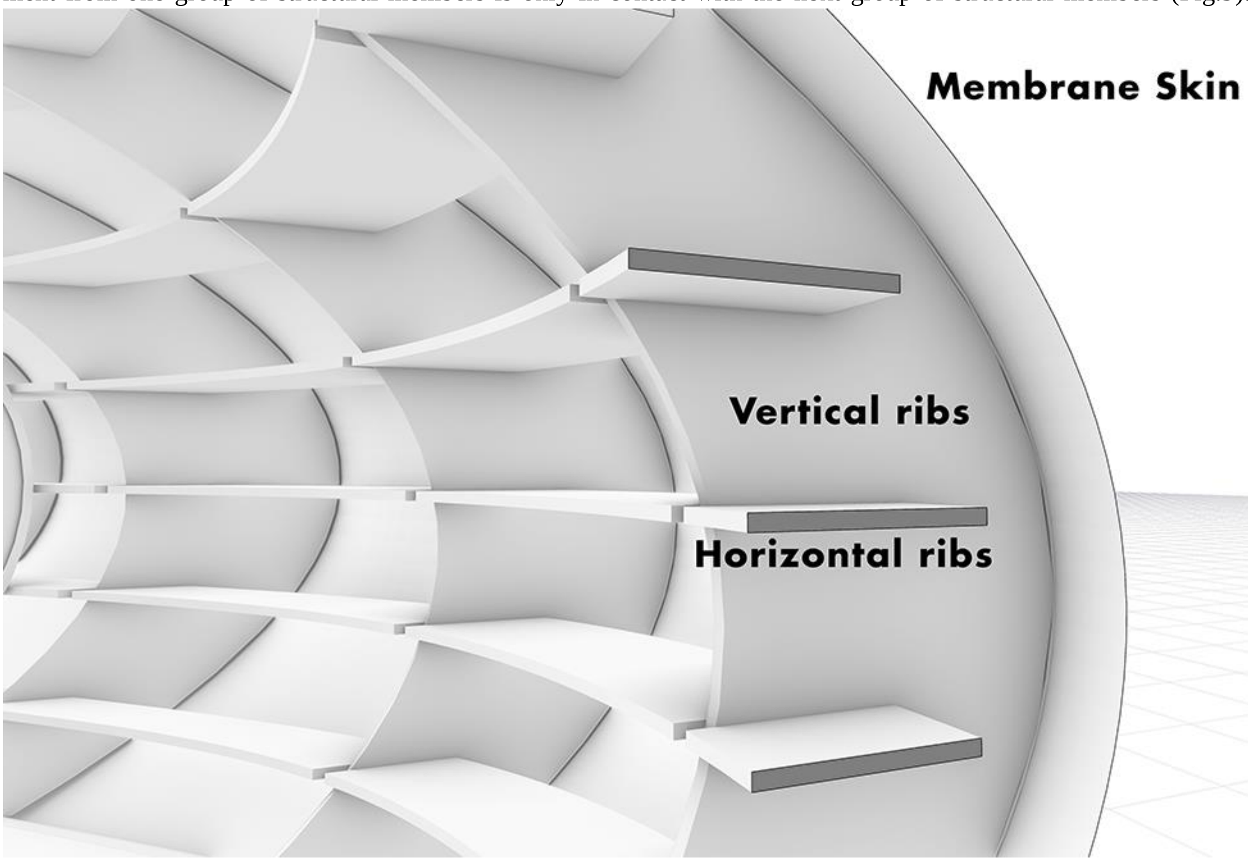

Fig. 8 Detail of the structural ribs and the membrane skin.

This ensures the durability of the individual elements and also reduces the possibility of wear and tear through minimised contact with the structural elements. Since the membrane is elastic and the wooden structure quite rigid, this hierarchy of elements ensures that the membrane is not damaged by contact and friction with a large part of the structure. This also protects the individual elements when the pavilion is erected and dismantled a number of times.

4 Resultant geometry through optimization

The entire optimization process was an autonomous procedure, which was carried out with a large number of iterations, so all possibilities could be considered before choosing the best one. In order to obtain a meaningful result from this process, it was essential to test the system to the limit, to be sure that during the iteration process, the system would not collapse. This is an essential and important aspect of all such computational systems, since it also

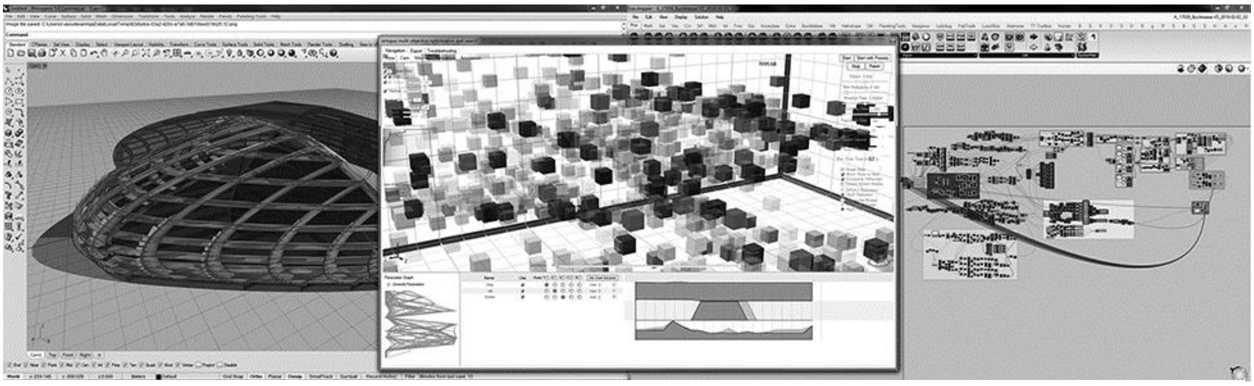

Fig. 10 Typical image of the resulting optimisation

defines the maximum freedom of optimization available to the system. It is also essential to keep variables to the bare minimum, since this allows an efficient calculation process that is fast enough to produce quick results. This is also evident from the simplicity of the geometrical logic used in the development of the pavilion. A typical view of the outcome of such an optimization process can be seen in Fig.10.

Fig. 11 View of the Frankfurt Pavilion at the Frankfurt Book Fair 2018

Once a particular solution has been selected, that solution is activated in the system so one can trace the exact parameters that lead up to that solution. Here it is interesting to note that some of the results were far more surprising than expected, and they deviated substantially from what one might have assumed to be correct. However, having cross-checked the results thoroughly in an independent process based on conventional calculations, it was confirmed that the results obtained from the optimization process were completely correct. It was also interesting to note that the process had pushed the geometry to the absolute minimum in terms of use of material, thereby creating a highly efficient system.

5 Conclusion

The entire design and analysis process for the pavilion provides an insight into the possibilities that current day computational tools can offer. When used efficiently, they help to reduce the costs of the production process by optimizing the use of material in conjunction with a particular geometrical configuration. Furthermore, such integrated systems reduce the cost of the design process itself by making it much more efficient. By combining all the pavilion elements into a single hybrid system – structure and skin – the resulting form can be regarded as having been optimally integrated. Ultimately such an integrated design system thus offers several advantages – not only in terms of increasing efficiency and saving costs throughout design development and in production – but also in generating spaces that directly reflect the process by which they were created. In October 2018, this process was tested in its entirety at the Frankfurt Book Fair 2018. As can be seen in Fig.11 and 12, the process described in this paper was executed successfully, which affirms the ideas that the authors set out to experiment.

Fig. 12 Interior view of the Pavilion at the Frankfurt Book Fair 2018

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