INTEGRATIVE PARAMETRIC FORM-FINDING PROCESSES

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Abstract. The recent developments in digital technologies and contemporary design tools are initiating new approaches of form-finding based on parametric development of multiple geometries with simultaneous consideration of various aspects. This paper focuses on the use of advanced parametric CAD systems and reformulated construction logics to enhance the potential and possibilities of form finding processes. This approach is exemplified through the “Greenhouse Trauttmandorf project”. The project demonstrates a form finding approach which is based on defined parameters that not only fulfil aesthetic and functional aspects, but simultaneously take structural properties and the resulting sun shading behaviour into account. We will explore within this paper how – next to the functional and contextual building requirements – required illumination levels inside the greenhouse create a feedback loop between the structural system and its cladding system.

Keywords. parametric representations; digital technologies; digital fabrication; variable systems; load bearing construction.
1. Introduction

Michalatos and Kaijima underline in their paper ‘Structural information as material for design’ (2007) the importance to approach an informed design consistency and respect the “criteria of efficiency, architectural intentions as well as intrinsic properties of the geometry” rather than simple structural optimisation of a certain design. Our paper investigates this consistency between architecture and structure within the framework of parametric modeling, which requires architects, engineers and constructors to re-evaluate the feedback loop between how things are designed and constructed.

As Mario Carpo (2008) points out CAD and CAM technologies have overthrown the “Albertian paradigm” which claims that architects should not make things, but should just design and annotate them. As digital tools can be used to design and fabricate at the same time, CAD-CAM technologies have already started to bridge the gap between designers and makers. One of the most influential form-related factors on the lighting situation inside the building is – due to its shading behaviour – the dimension and position of the supporting structure of the façade. It is important to investigate these positions at the beginning in depth, since they serve as hypothesis for the entire planning process. In order to compare a catalogue of various design approaches and different designs in a timely manner, a parametric model has been built defining the rough form of the design.

2. The greenhouse project

The project which is used for the described approach is a Greenhouse in Meran, Italy, with approximately 370 m² gross area. The building has two programmatic parts: one smaller exhibition space and a big exhibition hall.

These two spaces are separated by technical rooms. The transition between the two main spaces is visible in the outer shell of the building: here the shell

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Figure 1. Model greenhouse project.
tapers and emphasises the transition zone. The section of the two exhibition halls varies. The arch system which is used for both exhibition halls has a maximum height of 10 m in the area of the big exhibition space and is 3 m lower in the area of the small hall. Therefore the arch system is more pointed in the big exhibition space than in the small. Towards the South the arch system rests directly on the concrete slab, whereas towards the North the arch system is lifted up by a 3m high concrete wall. Next to the structural system the second main feature of the project is a faceted skin which uses rectangular planar panels to achieve the double-curved geometry.

2.1. STRUCTURAL MODEL

All parameters of the NURBS based geometry need to be editable and accessible in the architectural design software and the structural calculation software. The initial design development follows a constant loop between texture, structure and massing – each form study undergoes the following automated definition of the geometric parameters.

1. parametrisation of the structural calculation model.
2. evaluating the structure versus light conditions.
3. looping back to 1.

The result of this parametrisation has been a rectangular grid of beams lying on a NURBS surface with editable grid densities, which is applicable to any given form. The structural calculation model contains not only geometry, but also loads resulting from various sources. Some of the loads directly result from the geometry, such as the weight of the structure itself. Others are indirectly related such as the weight of the glass panels, which depends on the grid size. As a consequence all changes in the geometry result in changes in the applied loads, the load distribution and lead therefore to a completely different model. In order to automatically create calculation models, loads must be realistically calculated and applied to the structure on the basis of algorithms. Additionally, further geometric information such as the element’s profile orientation has to be calculated. A computer program using the .Net interface has been self-developed to connect the CAD software and the calculation software. The final calculation models do not cover all loads and load combinations, such as wind loads, thermal expansion or imperfections, which had to be incorporated manually. As a result a set of different grids is structurally evaluated giving visual feedback to the dimension of the structural elements. Therefore it has been possible to compare the aesthetic of the design on the basis of realistic dimensions, while analysing also the lighting requirements.
2.2. DEFINITION OF GEOMETRY MODEL PARAMETERS

To be able to compare different designs in a timely manner, a parametric Grasshopper (McNeel Rhinoceros) model has been built, which defines the basic logic behind the structure of the given form. The final structure consists of flat steel elements aligned in a quadrangle grid. The grid consists of two different kinds of beam types: The primary structural beams, which span in the short direction and the secondary structural beams, which form a linear connection between two adjacent primary beams at several points. The secondary members correspond in size with the glass element, while the beam sections of the primary structural beams and the secondary structural beams may vary. To keep an even appearance of the structure the beam sections do not differ within the beam category.

The steel element sizes, the grid density and the resulting glass panel sizes have been explored under consideration of load bearing capacity and the resulting lighting condition.

The parametric model has been based on a NURBS Surface, representing the outer shell of the building. Onto the surface a rectangular grid of curves has been applied, which represent the axes of the beams. The main beam curves
are defined by dividing two opposing surface edges into a parameter controlled number of elements, resulting in evenly spaced division points. Through two opposing division points a plane oriented in z direction has been created and intersected with the NURBS Surface creating the main beam curves. The location of the secondary structural beams is defined by ISO-Curves in V Direction of the surface using parameters resulting from equal division of one surface.

2.3. ADDITIONAL DATA EXTRACTION

The parametric grasshopper model is used as a base to create a structural model within the calculation software R-Stab (Dlubal). In our case the calculation software only interprets nodes and lines between these nodes, representing section beams. Nonetheless information bases on surfaces would be very useful to the program. In our approach the section rotation degree has been calculated on the base of the surface and applied to the subordinate structural beams within the structural model.

Other non-static, geometric properties have been defined to be interpreted differently in the calculation model. For example the start points and end points of the main beam curves are defined as hinged supports as well as the connection between the main and the subordinate structure is defined as a hinged connection. Next to the geometric information, loads resulting from geometric properties are reinterpreted and applied to the structural model. This approach has been used to calculate the distributed load of the panel weight and the snow load.
2.4. AUTOMATED LOAD CALCULATION

The structural model which derives from the parametric model has to be able to calculate the load cases by the parameter definition. The load cases which have been automatically created are:

1. own weight
2. distributed load of the panel weight
3. snow load

In addition to the automated load cases, load case combinations were automatically generated under consideration of the German standards (DIN 18800) and second order theory.

The own weight of the structure has been automatically calculated by the structural calculation program and only requires the sections as input. The weight is an important factor, because when changing the element section sizes, it significantly can change the outcome of the calculation. The distributed load of the panels though depends on the size of the panels and therefore has to be calculated for each parameter set separately. Based on each beam’s allocated load area intersection points have been calculated which results, multiplied with a predefined area load of the panel weight, in the distributed load. The calculation of the allocated load area though is not a trivial problem. In order to calculate the area for an intersection point in a quadrangle grid one need to know the four closest points in all 4 directions and their relative position to the point in order to connect them. There is the need to implement a sorting algorithm based on the geometry. The first step has been to sort the unsorted list of beams and store the adjacent beams for each beam, by evaluating the U value of each start point and connecting it with the beam object. So
the curves with the next higher and lower U value are the ones lying next to the main curve. All division points in the grid lie on a main beam curve and have different t-values. Their relative linear position is therefore defined and is separately stored in an index manner corresponding with the point location on the curve. Through the index of each point it is possible to get the next point \((i = i + 1)\), the previous point \((i = i - 1)\) and the points on the left and right with the same index on the left or right neighbor curve.

By knowing these four points, which all lie on the base surface, it is possible to get the UV coordinates of the points and create the new four corner points of the load area by overlaying the coordinates. The interpolated lines on the surface connecting the corner points define the edges of the load area surface.

To calculate the load area for snow load the surfaces simply need to be projected to the XY-plane. This approach does not consider snow sliding down the sides of the roof.

![Fig 6. Load area diagram.](image)

### 3. Workflow

After the creation of the parametric model and the setup of the interface to the structural calculation program a process had been manually triggered, which creates a structural calculation model on the basis of the current parameter set. The calculation model then is automatically calculated.

In an iterative process the section dimension is optimised to the applied loads. The result is saved in the native file format of the calculation program, giving a feedback to the dimension of the structural elements. With this realistic estimate of the structural dimensions a visual evaluation of the lighting requirements is possible.
3.1. ERROR AVOIDANCE

While automatically creating structural calculation models, it is very important to avoid calculation errors. A calculation error produced by non-diverging load combinations in later iterations leads to a back step in the section size.

3.2. QUALITY OF THE CALCULATED RESULTS

The created calculation models do not cover all loads and load combinations, such as wind loads, thermal expansion or imperfections. Nonetheless, the resulting section dimension is very realistic. The section optimisation process does not optimise the elements to the highest degree of stress utilisation of 100 percent, but a maximum utilisation of 70 percent. Therefore, there is a buffer of 30 percent, which is very unlikely to be exceeded. However, the result is not a complete structural analysis and additional load cases and load combinations would have to be added to reach the final state. The automatically created model, though, can be used as the basis for the final model. That alone is a great advantage in comparison to a non-automated approach, since the modeling of a structural calculation model is a time-consuming procedure, with a significant percentage of the overall editing time.

4. Roughening of the skin system

The structural system was used as a starting point for the modeling of the glass panels. Usually, tessellation is a phenomenon that architects and engineers try to prevent. In case of the glasshouse, an early decision was made that the tessellation of the skin needs a lot of intention. During the process, a solution has been found which does not hide the tessellation, but places additional emphasis on the facets of the skin.

A script has been written which always affects four points at a time. First, a plane has been created through the first three points and has been rotated outwards in direction of surface normal in order to increase the discontinuity between the adjacent panels. Afterwards, all four points were projected onto that plane, so that all four points meet in the same plane. This method ensures planar panels and creates an additional roughness of the panels.

The jaggedness of the skin is also affecting the main structural beams which now need to accommodate the jagged profile on the outside, whereas they can remain smooth on the inside. It is proposed to fabricate the main beams using water jet cutting technology.

The jagged main beams also allow attaching the glass directly to the structure. The insulated glass layer consists of laminated safety glass on the inside and toughened safety glass on the outside. The glass panel is glued to a support
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bracket which is connected to the structure. The additional roughening of the façade allowed integrating a sun shading device on the outside. Each glass panel has its own shading element.

5. Conclusions

Through this integrative form finding process, a set of different grids was structurally evaluated giving feedback to the dimension of the structural ele-

![Fig7. Facade section.](image)

ments. It was possible to compare the aesthetic of a design on the basis of realistic dimensions of the supporting structure and through that assure that the lighting requirements resulting from the structure are met.

However the described workflow could be further extended in many ways. Especially the automated load calculation leaves room for further development. The goal would be to reduce the amount of manual editing time, for example by defining different wind load application areas on the surface to which a parameter set can refer to and automatically apply wind loads to the generated structure.

Another promising approach would be to include illumination data as an additional numeric parameter by connecting an evaluation tool such as Ecotect
to the developed software. Both of approaches mentioned above are currently investigated by us.

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