FURNITURE DESIGN USING CUSTOM-OPTIMISED STRUCTURAL NODES

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Abstract. Additive manufacturing techniques and materials have evolved rapidly during the last decade. Applications in architecture, engineering and construction are getting more attention as 3D printing is trying to find its place in the industry. Due to high material prices for metal 3d printing and in-homogenous material behaviour in printed plastic, 3D printing has not yet had a very significant impact at the scale of buildings. Limitations on scale, cost, and structural performance have also hindered the advancement of the technology and research up to this point. The research presented here takes a case study for the application of 3D printing at a furniture scale based on a novel custom optimisation approach for structural nodes. Through the concentration of non-standard geometry on the highly complex custom optimised nodes, 3D printers at industrial product scale could be used for the additive manufacture of the structural nodes. This research presents a design strategy with a digital process chain using parametric modeling, virtual prototyping, structural simulation, custom optimisation and additive CAD/CAM for a digital workflow from design to production. Consequently, the digital process chain for the development of structural nodes was closed in a holistic manner at a suitable scale.

Keywords. Digital fabrication; node optimisation; structural performance; 3D printing; carbon fibre.

1. Introduction

Recent developments in the field of computational architecture and new developments in fabrication technologies reveal many possibilities to generate complex designs with a high degree of visual differentiation. Increasing demand for intricate geometries and mass-customized building components opens the opportunity
for individualized expression of structures in architectural design processes. Over recent years, new applications of additive fabrication for the design of structural components were developed and custom-optimisation of structural nodes were tested on a scale pavilion to show first glimpses at the design potential of these design methodologies (Williams et al. 2015; Prohasky et al. 2015; O’Donnell et al. 2015). Innovation of structural component design, developed in the research presented here, uses a novel custom optimisation approach based on cross section optimisation for the improvement of the structural performance during different design iterations.

During the research project, a design process based on a closed digital process chain for custom optimized structural nodes was explored and implemented on a furniture scale. After development of a concept design, a virtual prototype of the design was developed to review the aesthetic appearance and the feasibility of the fabrication system for construction. Multiple iterations of optimisation of the structural system were carried out on multiple scales to reduce the material needed for the structural nodes. As a result, a significant reduction in cost and fabrication time were achieved.

The close collaboration with the structural engineers during the design process in design development allowed short iteration cycles and lead to a streamlined design process. In the meantime a collaborative parametric model was built in the design team, so that structural as well as design input was reflected in the model simultaneously. Above all, the constant communication during the design process created the potential for novelty and innovation during the design process, and led to a design outcome with a holistic aesthetic appearance, material reduction through the custom optimisation of the structural nodes, and a reflective approach to fabrication constraints during the design process.

2. Background and Critical Review

Recent developments in the field of computational architecture and new developments in fabrication technologies revealed many possibilities to generate complex designs with a high degree of visual differentiation. Increasing demand for intricate geometries and mass-customized building components opens the opportunity for individualized expression of structures in architectural design processes. Over recent years, new applications of additive fabrication for the design of structural components were developed and custom-optimisation of structural nodes were tested at a pavilion scale to show first glimpses at the design potential of these design methodologies (Williams et al. 2015; Prohasky et al. 2015; O’Donnell et al. 2015). Innovation of structural component design, developed in the presented research, uses a novel custom optimisation approach based on cross section optimisation for the improvement of the structural performance during different design iterations. Here following observations have been made:

- **MATERIALS**: Whereas ABS and/or PLA prints do not have the structural integrity needed in the construction industry, printing in metal as outlined in the research by Galjaard et al. (2014) which would fulfill the structural requirement is currently still an expensive undertaking. Projects such as the ones by
Williams et al. (2015) rely on 3D printers on an industrial scale and the cost of the use of such equipment is still high compared to conventional manufacturing technology for structural nodes like on site welding or steel casting. Currently most 3D printers are in a table top format. This is the case for popular types such as Makerbots, Flash Forge or UP printers using ABS and/or PLA as well as metal and other substrate printers. Particularly cost effective are the products that use plastics for the additive manufacturing process. As a consequence, the fabrication process for the structural nodes in the presented research used conventional table top printers for PLA.

- TOOL DIMENSIONS: Any structural node is limited to the size of the printer. The application of a custom optimisation process for structural nodes on the furniture scale offers the possibility to test the use of custom optimized nodes in a final product and therefore provides first insights in a design and fabrication process suitable for commercial use. Commercial activities in future additive manufacturing scenarios attribute great value to product customisation (Bertling & Rommel 2016), as attractivity of Direct Digital Manufacturing increased (Gibson et al. 2015).

- EVALUATION OF OUTCOMES: Before additive manufacturing can be introduced on an industrial scale to construction processes, adequate material testing, norming and issuing of code for the application of these fabrication process need to take place. In contrast, the experimentation on the furniture scale leads directly to potentially commercialisable design outcomes. This consideration points towards the potential for future development, while recognizing the current limitations for additive manufacturing (Naboni & Paoletti 2015).

Thus one can observe that even additive manufacturing has continuously advanced over the last decade with most 3D printers still have their limitations when it comes to printing custom-optimised structural components. This is the case for currently used materials and their associated techniques. Thus 3D printing has not yet had a very significant impact at the scale of buildings other then a few experimental projects such as the one by Williams et al. (2013), O’Donnell et al. (2015) or Galjaard et al. (2014) to name but a few. As argued above, scale, cost and structural performance have also hindered the advancement up to this point. Based on these observations, the research presented here describes experiments of an application on a furniture scale along with the presentation of a novel approach to custom optimisation of structural nodes.

3. Methodology

The researchers describe a design strategy for custom optimized structural nodes in the context of furniture design along with a novel approach to custom optimisation of structural nodes based on cross section optimisation. In summary, the following iterative design research methodology was used to design and fabricate:

- Concept design based on sound and water waves as reaction on site
- Virtual prototype of the preliminary table design
- Micro-scale optimisation of structural nodes
- Macro-scale optimisation of the structural system
Multi-scale structural model for custom-optimisation of structural nodes
Fabrication of the Opera Bar Table as a final product

Here a bar table was designed that used Karamba for optimisation of the overall structure and structural nodes. Designed for a music event, the preliminary design sketch mimicked sound waves as a first form iteration. The resulting NURBS surface was broken down into triangles in order to use timber members for construction. Each beam was connected to a node with a minimum of two and a maximum of six beams connected at specific points. The nodes were designed via La Placian smoothing based on the results of the cross section optimisation process. With this initial design approach, multiple optimisation cycles took place during the design development.

4. Case Study - Sydney Opera Bar Table

The Sydney Opera House (1959 - 1965) in particular the constructions of the shells of the Opera House challenged architects, engineers and construction firms at the time and “the enormous challenges in construction demanded pioneering applications and many new materials as well as building and engineering practices” (Sydney Opera House, 2016).

DESIGN PROCESS: Bachelor students of the Computational Design degree at the Faculty Built Environment / University of New South Wales, Sydney were challenged with the question: “What would a contemporary equivalent in design and construction that ‘demands’ed pioneering applications and many new materials as well as building and engineering practices’ in a way similar to the Sydney Opera House (2016) description in its historic outline”.

Figure 1 shows the selected design concept developed in the two week Karamba workshop. The design at this stage existed as a preliminary design that had been, in a first iteration, optimised in Karamba. Still the design of the nodes and the overall structure needed further optimisation iteration cycles to meet the fabrication constraints given by the additive manufacturing process.

Instead of designing an opera house as such, and dealing with spatial and or-
ganisational matters the students were asked to test and explore the challenge on a furniture piece. The motivation for the design of a bar table came from being commissioned by Opera Australia to develop a VIP area centre piece for their up-coming opera 'The eight wonder' that had the design of the opera house as theme. Each student used the design challenge to learn the Karamba plug-in for Robert McNeel & Associates’ Grasshopper® to design a table that somehow mimicked ideas and concepts of the Sydney Opera and optimised the structural system.

OPTIMISATION ITERATIONS: During the development of the case study, multiple iterations for the structural simulation and optimisation were carried out. The experimental setup and the results of the design process are provided in the next section to provide knowledge about the development of the overall and component geometry.

Micro-scale optimisation of structural nodes - The design of the structural nodes was informed by structural simulation during the development of virtual prototypes for performance evaluation. As the results of the simulation were based on a finite elements solver calculated by using Robert McNeel & Associates’ Grasshopper® and the Karamba plug-in, the geometry was generated directly in the parametric model. A novel custom optimisation approach was developed inside the parametric design environment. Based on the generative process for the generation of the structural nodes, different node sizes were necessary to provide all the fabrication data inside the parametric model. The structural system was divided into the structural nodes and the beams that represented the timber members through the subdivision of the connectivity diagram with spheres. In the next step the beams were sorted based on their topological adjacency to the positions of the structural nodes, so that a sorted list provided the basis for the assignment of materials and the generation of the node geometries.

Feeding the calculation results of the cross section optimisation into the Exoskeleton plug-in to generate a mesh as the basis for the Laplacian smoothing allowed a high level of variety in the node design, while a coherent design language was developed. This methodology has a number of advantages, such as the concentration of the structural complexity in the geometry of the nodes that provides a focus for the geometrical optimisation on the structural node. Another advantage is the small computational costs of a cross sectional optimisation as compared to other optimisation approaches that have been used in that context. The generation of all the node geometries was handled in one coherent parametric model that could update in a relatively small amount of time after changes were introduced.

The results of the optimisation process described are shown in figure 2 and figure 3 (left image). At this stage rather large nodes were generated, which did not satisfy the designer’s expectations about the printing time and use of material, while also violating fabrication constraints. Many of those node designs would have needed to be divided into several parts for the additive manufacturing process, therefore adding an additional step to the construction process.
Macro-scale optimisation of the structural system - After a first iteration of the custom optimisation process for the structural nodes of the furniture design, the overall shape of the table was assessed for design optimisation by the structural engineer. During this process a symmetric approach for the structural design was developed and applied to the structural system to provide better balanced table based on two ‘shells’ that form, preventing a potential tipping over when on site. Another step to improve the performance on the macro-scale of the structural system was the relaxation of the positions of the nodes on the design surface, so that an even distribution of the nodes was reached.

Through this process the length of the timber members was averaged, thereby balancing the utilisation of the structural members in reaction to the need of using the same cross section of the structural members over the whole structure. Here the total number of nodes was reduced as well as the size of each node offering improvements in cost and fabrication time. As a result, the node sizes were significantly reduced and a more coherent expression of the structural nodes were achieved as improvement to the overall design (compare changes in structural layout in figure 3).

The parametric model that incorporated structural simulation and optimisation in the design model, based on an ongoing collaborative design approach between architects and engineers, was adjusted to incorporate the changes in the overall geometry. In addition, the material properties for the structure were reviewed to ensure the structural feasibility of the final product. Further improvement was achieved by changing the material for the tabletop from glass to acrylic, resulting in a significant reduction in dead load of the structure.

Multi-scale structural model for custom-optimising of structural nodes - In another iteration of the optimisation process, the whole system - the beams in combination with the custom optimised nodes - was simulated to generate another set of structural nodes that met the fabrication constraints. Two load cases were introduced to reflect the impact of gravity and the total load live load of 100 kg/sqm that deemed to be appropriate for the use of the table in a bar space (final result in figure 3 right).
This last iteration applied in the design process was successful in reducing the size of the nodes to the print bed of the Flash Forge 3D printers used in order to meet the upcoming fabrication and handover-to-client deadlines.

FABRICATION AND ASSEMBLY: Following multiple optimisation iterations and the 3D printing of the 32 structural nodes, all connecting timber members were cut to size and the team assembled the table. The connection between 3D printed node and timber member was facilitated through the use of the FESTO Domino system as it created an invisible connection joint (see figure 4 and 5).

The whole construction process took place using unskilled labour, which would allow the application of the proposed design strategy for development of a commercial furniture system that would leave the assembly of the furniture to the customer. For this application, the tectonic detailing would need to be reworked, as it only incorporates a gap for the insertion of the dowel at this stage.

Only one node was split in two parts for the additive manufacturing process. This allowed the researchers to evaluate the feasibility of gluing and screwing of the node as part of the assembly process. During the process, various glues were tested and a standard two-component glue used in during construction of the table. In the following all 32 nodes were printed and connected to beams to build a table with a 2.4*1.2 meter surface. The fabrication and construction process are described in greater detail in the next section of the paper.
5. Conclusions

This research has investigated the design process for custom optimisation of structural node for an application of such a system on a furniture scale and successfully introduced a novel custom optimisation method based on cross section optimisation. As a result, structural integrity, fabrication time and cost were significantly reduced during the design process. As a full scale application of the design process, the research provides first insights in the application of custom optimisation of structural nodes for the development of a marketable product. All of these aspects will be expanded on in the following conclusions.

CUSTOM OPTIMISATION OF STRUCTURAL NODES: In general the results show that the developed approach to custom optimisation of structural nodes based on cross section optimisation and La Placian smoothing can be used successfully to quickly iterate over multiple design options, as the process is computationally cheap. Another advantage of this process is the simulation of the whole structural in one coherent parametric model with different materials. In this respect, the process could easily be extended towards the use of different cross sections for the structural members and multiple structural materials.

At this point the structure has only been tested in a virtual model and through a rudimentary testing process in situ. In the physical testing the research team loaded the table with gym weights and sandbags. As these tests were made prior to handing over the table to the client we naturally did not go to the full loading of 100kg/sqm but stopped at 80kg/sqm.

FABRICATION TIME AND COST: The design methodology based on node optimisation and additive manufacturing has been a quick and cheap process for the generation of a complex design outcome that could be handled by a small design team. Hence we argue that the objective of developing a quick and cheap method of fabrication and construction has been achieved. The overall costs for the prints were under US$ 150 (a total of 4 rolls were used for the process), the printing times varied between 12 and 23 hours. Due to having six Flash Forge Printers available the total print could be completed in about a week. All nodes were printed solid in order to give them their maximal strength. Using ‘tree structures’ as support the amount of support material needed during manufacturing was reduced to a minimum as well, also reducing time required in cleaning the nodes.

The research in the construction process was limited in several ways. Mainly time and resource constraints needed to be accommodated. More research is needed in further optimisation of the tectonic details inside the parametric model to accommodate easier assembly without the use of glue, further exploiting the design potential provided through additive manufacturing technology. Although the study did not explore multiple approaches to the design of the assembly system, it tested the one (figure 6) in great detail and explored the potential application of gluing and screwing of nodes to accommodate limitations in meeting the fabrication constraints.
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Figure 5. Table assembled (left); detail view nodes (middle); and perspective table with several nodes (right).

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FURNITURE DESIGN APPLICATION: The findings add to our understanding of the development of furniture with complex topologies and geometries through the use of structural optimisation methods. We are aware of the fact that the introduction of this level of complexity into furniture design is open to criticism, but want to point towards the potential application of the design strategy for the design of furniture systems for mass customisation. These might be used to adjust this particular furniture design to individual taste through interactive methods.

Finally, the furniture scale seems to be the a well-chosen testing ground for the application of custom optimisation of structural nodes on a product scale as a vehicle for the exploration of commercial applications of the design strategy.

6. Next Steps and Future Research
The next iteration of the research will target the use of a robot arm for the wrapping of structural nodes with carbon fibre to introduce additional stiffness to the component design and enhance the capabilities of the structural node to perform under a variety of loads, especially under outdoor conditions. This composite approach to the fabrication of structural nodes will provide a new materiality for the use of structural nodes in the context of building construction, and test the method on a physical prototype to explore the associated fabrication constraints. Another step of the research project will be the evaluation of the material properties of the hybrid structure combining PLA and carbon fibre in the structural node in collaboration with material scientists and engineers. This paper provides a starting point for the development of novel optimisation methods in the context of mass customisation of structural components and associated fabrication methods. The nodes were designed via La Placian smoothing based on cross section optimisation instead of
using a topological optimisation approach, as the latter would result in geometry too complex for a carbon fibre laying robot arm to achieve a feasible outcome of the fabrication process.

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