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Smart Structures in Architectural Projects: Towards an interactive design framework combining multiscalar structural optimisation and custom-optimized structural nodes for generative design

Estructuras inteligentes en proyectos arquitectónicos: Hacia un marco interactivo de diseño combinando optimización estructural multiescalar y nodos estructurales optimizados de manera personalizada para un diseño generativo

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RESUMEN

La personalización masiva interactiva está cambiando prácticas en arquitectura, ingeniería, y la industria de la construcción (AEC). Los flujos de trabajo de sistemas de software en el futuro podrían abordar las tecnologías que incluyen interacción con usuarios y así aumentar las capacidades creativas humanas. Las primeras etapas de diseño requieren decisiones rápidas e informadas por datos entregados por tecnología de modelado de información de construcción. El diseño arquitectónico se ha transformado por la introducción de software de diseño, pero hasta hace poco el diseño en sí ha seguido siendo realizado por el arquitecto. Eso ha comenzado a cambiar con la exploración de marcos de diseño interactivo. La optimización de estructuras en múltiples escalas afecta tanto a la estructura general en dependencia de la geometría arquitectónica y la expresión local de nodos estructurales impresos en 3D. La investigación reportada exploró el uso de un algoritmo para cerrar brechas geométricas en el diseño generativo de componentes estructurales. Este algoritmo similar a la espuma permitió al artista y arquitecto diseñar en el estilo del Nuevo

ABSTRACT

Interactive mass customisation is changing practice in the architecture, engineering, and construction (AEC) industry. Future workflows in software systems could address human-in-the-loop technology to augment human creative capacities. Early design stages require quick and well-informed decisions in response to data available from building information modelling technology. Architectural design has been transformed by the introduction of design software but until recently the actual design has continued to be performed by the architect. That has begun to change with the exploration of interactive design frame works. Optimizing structures on multiple scales effects both, the overall structure in dependence of the architectural geometry and the local expression of 3D printed structural nodes.
The reported research explored an algorithm to close geometric gaps in generative design of structural components. This foam-like algorithm allowed the artist and architect to design New Structuralism style using a combination of different

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Estructuralismo usando una combinación de diferentes rutinas de optimización. Como resultado, el algoritmo SPUME se investigó para integrar varias partes geométricas en una forma orgánica para el diseño de nodos estructurales optimizados de manera personalizada. Como parte del estudio de caso, un pabellón con una estructura teselada y nodos estructurales impresos en 3D y optimizados de manera personalizada fue diseñado por un artista y un arquitecto para mostrar el potencial de aplicación del marco conceptualizado. Finalmente, un prototipo para conectar soportes y la forma optimizada por BESO de los nudos estructurales fue producido para combinar todos los aspectos de la geometría del nodo local en la representación tectónica.

Palabras clave
Humano-en-el-bucle; Inteligencia artificial; Diseño Evolutivo; Optimización del diseño; Diseño generativo.

optimisation routines. As a result, the SPUME algorithm was investigated to integrate several geometric parts in an organic shape for design of custom-optimized structural nodes. As part of the case study, a pavilion with a tessellated structure and 3D printed custom-optimized structural nodes was designed by an artist and an architect to showcase the application potential of the conceptualized framework. Finally, a prototype for connecting brackets and BESO optimized shape of the structural nodes was produced to combine all aspects of the local node geometry in the tectonic representation.

Keywords
Human-In-The-Loop; Artificial Intelligence; Evolutionary Design; Design Optimisation; Generative Design

INTRODUCTION

The key technology of human in the loop systems provides the architect with more design freedom in a supervisory mode, having access to the vast geometric potential of generative design. Concentrating and extracting the necessary data for decision making in early design allows well informed data driven design processes.

The customisation of design using interactive design methods is likely to transform the architecture, engineering, and construction (AEC) industry. Generative design is by no means a one step process leading to a finished product, even if it is considered an independent design stage in the AEC industry. A complex process chain from design to fabrication data needs to be applied for feedback of tectonics into generative design.

To be specific, architects want to get an overview of possible design solutions for a specific design case in the early stages of the design process. This need was addressed in a case study combining mass customisation and interactive design systems. A flexible and adaptive representation focused the complexity of the structure in custom-optimized 3D printed structural nodes. Therefore, designers were able to use standard structural members. This approach integrates mass customisation, standardisation, and structural expression as architectural techniques.

As a phase of the design process, multiple material systems can be simulated in the workflow using generative design for the formation of shape or structures (Cichocka, Browne, Neil and Rodriguez, 2017). A generative design system for both shape and structural optimisation needs a common representation, which was investigated and illustrated to address macro and micro expression of the tectonic system.

RESEARCH BACKGROUND

Mass customisation is based on industrial fabrication, off site prefabrication, and standardisation of building components, which have been constant research interests in architecture since Konrad Wachsmann published "Wendepunkt im Bauen" (1959). Architects and engineers consequently developed streamline workflows with current technological approaches like 3D-printing, digital fabrication, and low-skill construction.

The potential of 3D print to create complex geometry can be enhanced using topology optimisation. Since evolutionary topology optimisation increased the efficiency of 3D printed structural nodes, architects and engineers have applied this technology in different design contexts (Muehlbauer, 2021; Muehlbauer, Song and Burry, 2020; Seifi, Xie, O'Donnell and Williams, 2016). Custom-optimized structural nodes enabled the assembly of any configuration viable from a manufacturing point of view, independent from the complexity of the building shape.

Focussing structural complexity in custom-optimized steel connections reduced material use in structural systems (Abdelwahab and Tsavdaridis, 2021). Another trajectory of research was the application of structural criteria to the design of architectural geometries (Preisinger, 2013; Preisinger and Heimrath, 2014; Özdemir, 2021). Mass customisation using 3D print in architectural applications has been discussed in the literature as an area of application for computational design (Bertling and Rommel, 2016). In parallel, material research of 3D print in structural application took place (Gibson, Rosen and Stucker, 2015; Naboni and Paoletti, 2015, Martinez *et al*, 2019; Snijder *et al*, 2020).

Different computer science methods are basis for designing a human in the loop system driving mass customisation process. On another note, research about shape grammar for design application (Barros, Duarte and Chaparro, 2015; Lee, Herawan and Noraziah, 2012) pointed towards the use of grammar evolution for implementation of an interactive framework for optimisation of structural layouts. The associated workflows introduced user selection for navigation of the design space, *e.g.* as a contribution to the fitness function in evolutionary computation. Early work on interactive evolutionary computation reported the exploration of design spaces in a variety of generative design processes (Takagi, 2001).

However, research in optimisation of architectural systems used structural optimisation based on emergent representations for design of structural components in parametric design environments. In this context, research has focussed on collaboration in architectural design and engineering to gain better understanding of the integration of generative design in preliminary design stages of structural systems.

During the last decade research about the generative design of 3D printed structural nodes for application in architectural construction emerged and was showcased in research pavilions (Crolla, Williams, Muehlbauer and Burry, 2017; Prohasky, Williams, Crolla and Burry, 2015). Mass customized 3D printed structural nodes were uniquely shaped and adapted to their local position inside the structural system. This approach reduced the complexity of the structural system for non standard, non uniformly curved building enclosures. Consequently, the tectonic system was encoded, including connection details of the structural nodes and definition of all structural members.

Focusing the complexity of the design and manufacturing process of architectural geometries with and without its tectonic expression in the computational representation, enabled architects and engineers to use scripting as a design method that was subsequently extended towards algorithmic sketching. This principle was extended with simulation to a concept called virtual prototyping (Burry and Burry, 2016) and used as a design input for the investigation of material systems based on simulation.

A first iteration of the system was explored by collaboration on a project to produce unique product designs (Haeusler, Muehlbauer, Bohnenberger and Burry, 2017). In this instance the emphasis was on refining the optimisation routine. As part of the mentioned research, virtual prototyping was used to simulate the structural performance of the product in reference to specified criteria and to provide quantitative feedback to the designer. The resulting parametric representation needed an algorithmic extension reported in the following section to integrate BESO optimisation in a multiscalar geometric representation.

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METHODOLOGY

In this section the methodology of the research is described in its components, from the research design through the development of a parametric representation to its application in interactive evolutionary computation using genetic programming. A case study using the human in the loop system highlights features of the investigated guidance strategy for generative engineering, which includes all tectonic detail for manufacturing and construction of the structural framework.

Virtual Prototyping

A variety of virtual prototypes was developed as part of the design process to iteratively improve the performance of the parametric structural system. This system was based on the architectural geometry of the physical prototype and simulated structural performance during preliminary design to gain quantitative feedback for decision making.

Fabrication constraints, like the node size in reference to the built volume of the 3D printer and material specification of structural members, were incorporated in the parametric representation of the structure. In addition, engineers added all necessary tectonic details for the fabrication process.

Generative Design

The management of this level of geometric complexity led towards the reasoning about the use of a generative process for the engineering of the structural system with an integrated interface for collaborative exploration of design variations.

During preliminary design, the level of detail was successively increased to account for the custom-optimized node system of mass customisation. From simple shapes to the adaptive positioning of the structural nodes in the system, the modelled geometry was chosen in response to computation time. Therefore, the unique expression of the structural system and each connector and strut was defined in multiple design steps.

A multiscalar representation for automated computational processes was explored. The integration of different optimisation strategies in the parametric model of the structural nodes expressed the intention of the artist and architect to explore a wider design space.

DESIGN PROCESS

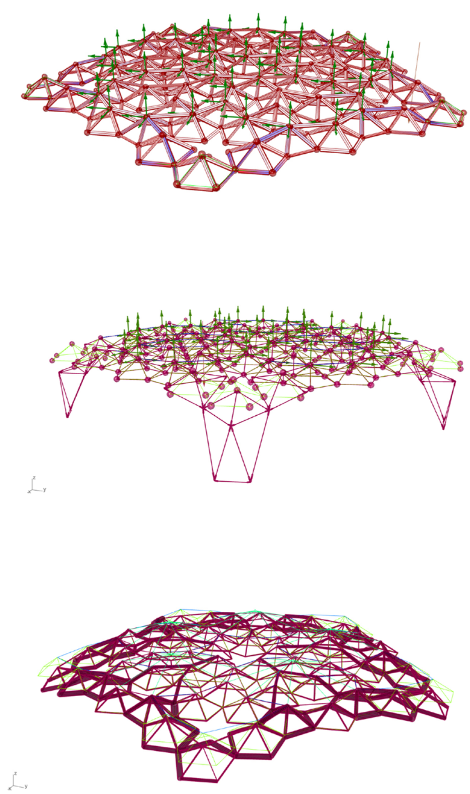
During the development of the design system, a systematic extension of the analogue top down design process was performed to gain insights into the considerations necessary to successfully develop a tectonic representation for a multiscalar structural system.

The initial design brief asked for a pavilion that uses 3D printed structural nodes in a tessellated structural frame. An innovative event space for artistic events was designed and planned by a multidisciplinary team led by an internationally recognized artist.

One objective of the design process was to integrate macro and micro expression of the structural system in a single parametric representation. The design considered different stages from node design using bidirectional evolutionary structural optimisation (BESO) to craft based artistic design of the overall building structure.

The middle part of the process focussed on structural simulation using Karamba 3D to gain an understanding of the overall structural behaviour (Figure 1) before diving into the task of designing custom-optimized nodes using Ameba.

Figure 1.
Structural simulation of the overall structure.



Source: *The authors.*

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Structural Simulation and Optimisation

Throughout the design explorations based on the parametric model, structural simulation was performed to evaluate the weight and displacement of the overall structure. The parametric structural model developed in Karamba 3D also showed the deformation of the structure and the different load distributions in the structural members (Figure 1).

Visual feedback for the designers was provided by the colouring of the analysis meshes based on the utilization of the structural members.

Because of the development of a virtual prototype, the mass of the structural system was reduced, and the node geometries aligned to a coherent design language.

This process revealed features of the structural system and reduced the need for time consuming modelling of the structure in computationally more expensive engineering software (Burry and Burry 2016).

At this point the materiality of the structure was still a hypothesis. The triangulated structural frame was determined as timber construction for the structural simulation. During the design of the connection details, the question emerged of how to integrate the connector bracket in the shape generated by the BESO algorithm.

Various design options were explored, and the design team chose a design that increased the thickness of thin branches of the BESO shape to the minimum needed for additive manufacturing.

The BESO shape was generated using Ameba plugin for Grasshopper parametric design environment in Rhinoceros3D computeraided design (CAD) system.

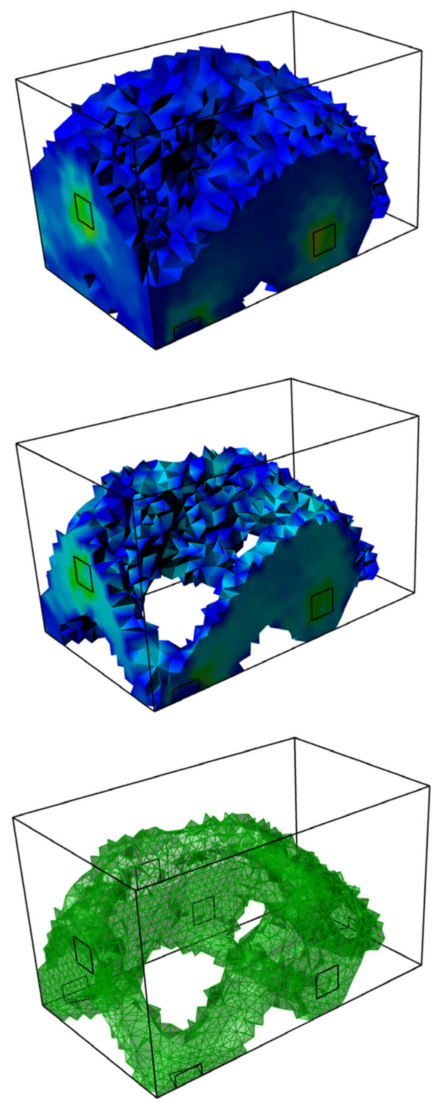
This cloud computation platform allowed the authors to address the form finding task based on generative design. The support points and the loads were defined to provide the constraints of the design task.

Next, the Ameba was used to generate a finite element mesh and calculate the force flows through the design space, adding material where needed and removing material in the areas without force flows.

In Figure 2 shapes with a volume fraction of 50% and 20% as target values are displayed. The bottom shape shows the unsmoothed result. After, the converged result of the optimisation process was used as input for a LaPlacian smoothing using Weaverbird plugin for Grasshopper.

During the design process the organic shape of the virtual prototype was investigated and reviewed for adding connection details. The tectonic system was constructed using a simple bracket as connection detail. The ends of the brackets were extended using a cylindrical shape with spherical caps.

Figure 2.
Stages during the BESO process.



Source: *The authors.*

Now, a novel algorithm was explored to generate an organic connection detail, which allowed the designers to create a coherent aesthetic expression.

The SPUME algorithm uses the simple mechanism of an attractor system to establish a smooth transition between the custom-optimized node geometry and the connector bracket.

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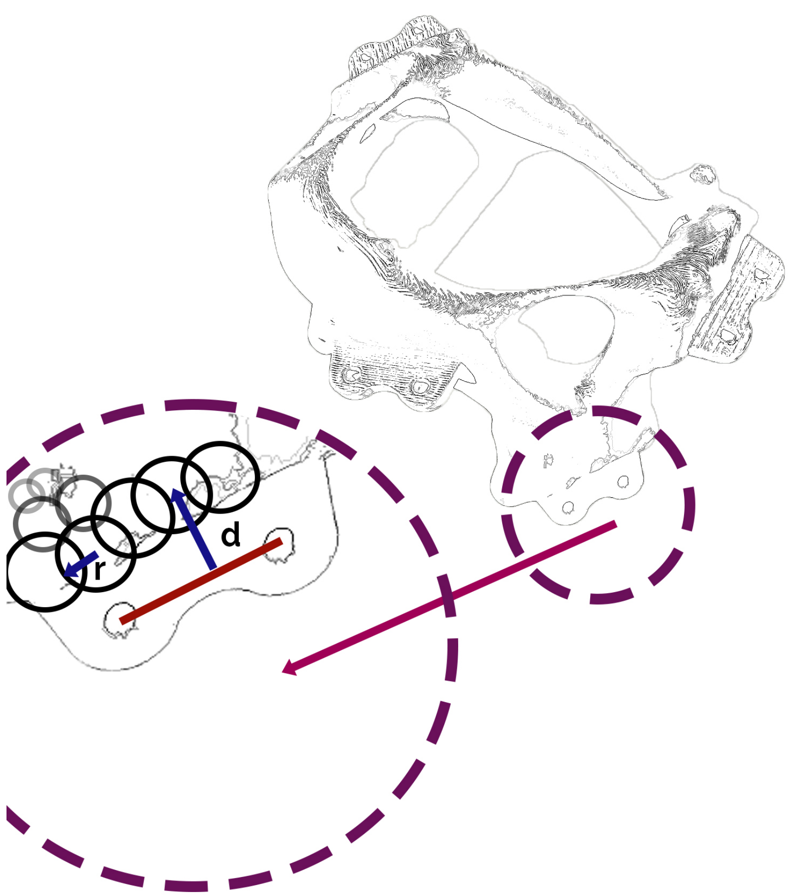
Spheres were used to populate the geometry of the structural nodes in a defined distance. These spheres were modulated proportional to the distance between the bracket's bolt holes.

In this way, the parametric system was able to generate an approximation of the organic shape imagined by the architect. At the next step, the geometry was compiled using Boolean union. Another stage of La Placian smoothing was applied at the end of the computational design process.

Both, the structural node, and the bracket geometry were added to the Makeprintable cloud computation platform to create a prototype geometry for additive manufacturing.

Figure 3.
Attractor system of SPUME algorithm.



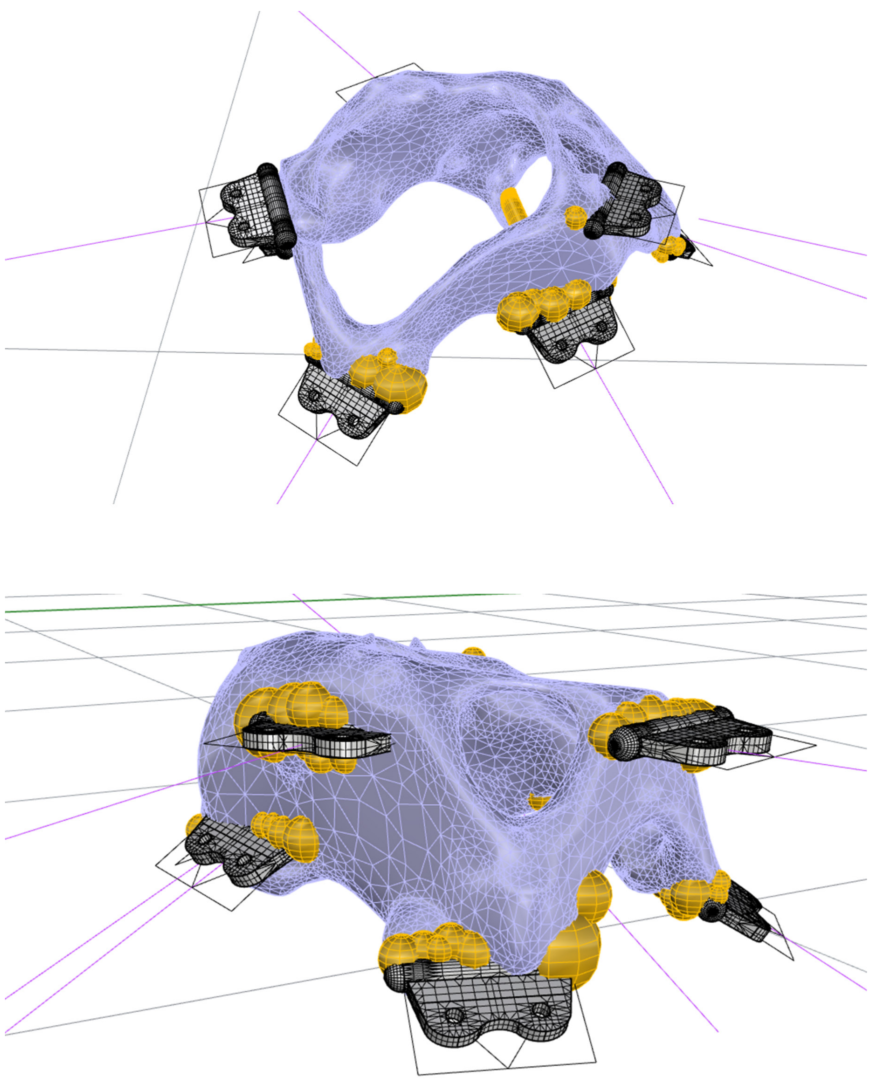
Source: *The authors.*

The SPUME algorithm (Figure 4) was designed to extend existing shapes for integration of non design space elements. This process is only necessary when an algorithmic framework is used that does not automatically integrate these elements into the form finding process.

Based on these considerations the digital workflow was designed to create a parametric design system integrating all aspects of geometry generation.

The homogenous expression of the structural nodes in the final prototype was achieved using mesh modelling libraries in Grasshopper for Rhinoceros 3D with the aim to create one coherent shape from the articulated detail illustrated in Figure 4.

Figure 4.
Articulated transitions between design geometry and connector brackets using SPUME algorithm



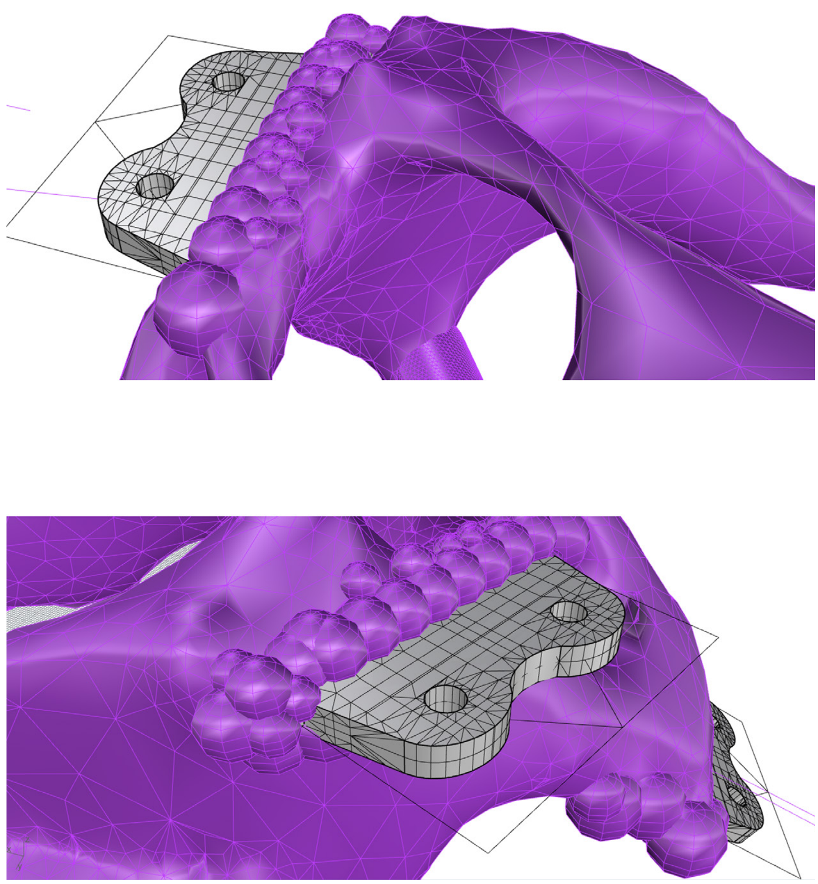
Source: *The authors.*

Prototype Development

The full scale physical prototype was printed on a desktop 3D printer PRUSA i3 MK3S with multimaterial upgrade 2s. Although simulation of the structural performance during the stage of the virtual prototypes gave feedback about the structural properties and the expected geometry, only the development of the full scale physical prototype allowed to experience the materiality of the structural node and test the fabrication process.

Consequently, a structural node was developed and fabricated based upon the above mentioned methodology. The dimensions of the custom-optimized structural node were 288mm x 232mm with a height of 124mm with 150.156 polygons in the 3D model. As material for the 3D printing, Polylactide was chosen due to its low costs and the performance requirements of the structural node, being used in an interior environment.

Figure 5.
Detail articulation of SPUME algorithm.



Source: *The authors.*

RESULTS

The 3D printed custom-optimized structural node as full scale prototype is presented in Figure 6. The 3D print of the prototype took 35 hours on the already mentioned PRUSA 3D printer. However, the fabrication process of the final product will need a denser infill. The infill chosen for the prototype was Gyroid with 15% volume fraction. In this configuration 329g of PLA filaments were used. Earlier research about application of ABS and PLA in additive manufacturing (Martinez, Souza, Santos *et al*, 2019) informed the choice of material. 44% of the material use went into the support structure. Here, the authors expect a strong optimisation potential.

The connection plate on each side of the node was 55mm x 30mm with a material thickness of 6mm. The bolt holes were located with 30mm between each other.

Next, the structural simulation was set up to extract the data about loads in dependency from defined load cases in the parametric environment of Robert McNeel & Associates' Grasshopper using the Karamba plugin developed by Bollinger + Grohmann Ingenieure GmbH. This plugin uses a parallel implementation of a custom finite elements solver (Preisinger, 2013) that allowed quick feedback during the evaluation of the virtual prototypes.

Figure 6.
3D-printed prototype of custom-optimized node.

Source: *The authors.*

The algorithm generated the final geometry as Rhinoceros native geometry from the artist's design in Grasshopper to simulate the structural performance. At this stage the structural nodes were abstracted as joints.

Finally, the parametric model delivered the fabrication data of the timber construction to provide feedback for the next design stage.

Node optimisation for additive manufacturing

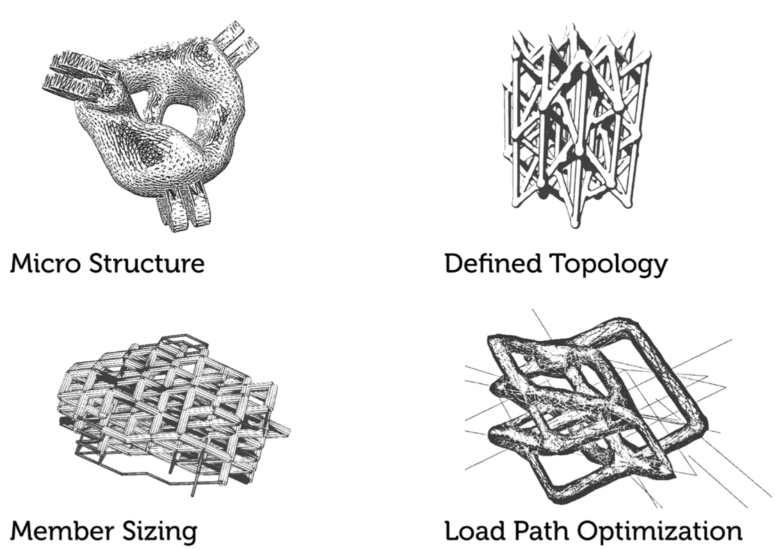
This research investigated different optimisation approaches for structural nodes on its way to integrating BESO using SPUME algorithm. The experimental exploration of representations for providing a design space during an interactive generative design process is reported in this section.

Different observations were made that must be addressed to reach an elevated level of multiscalar geometric representation of structural systems.

Four different design strategies for custom-optimized structural nodes are illustrated in Figure 7. The illustration compiles different approaches tested during the past eight years, in order to create a flexible geometric representation, which provides a sufficient range of design options for custom-optimized structural nodes as a basis for a generative design system.

These approaches were explored for their potential to enhance BESO. Especially aesthetic and fabrication constraints can be addressed using those concepts.

Figure 7.
Exploration of different optimisation approaches.



Source: *The authors.*

Enhancing BESO with complementary optimisation

During the entire process, four currently available optimisation algorithms for additive manufacturing of structural nodes were investigated for extending the current optimisation approach using BESO algorithm (Wang *et al*, 2016; Huang and Xie, 2010; Xie and Steven, 1993).

Micro-Structure

Application of micro structure was often used to generate infill. This application case is critical to structural performance and the results are difficult to test, so that the authors chose another trajectory of research. Next, the micro structure was applied to the exterior of the structural nodes. Finally, this approach was put aside to develop the missing piece for the integration of the BESO approach into a holistic geometric representation for generative design. However, the artist and architect concerned with the design decided to integrate this design stage in the next iteration of the project. In this way, the new plasticity of additive manufacturing in architecture (Teixeira *et al*, 2022) can be extended using an algorithmic approach.

Defined Topology

Another possibility was the introduction of a defined topology that can be used to add unique geometrical features. This approach can also be used to define the support structure for reduction of printing time and material use. Depending on the load case, it might also be necessary to add material to the central area of the node. In this case a defined topology will be added to increase stiffness of the overall geometry of the custom-optimized node.

Load Path Optimisation

It is apparent from the reported results that the proposed framework satisfies the criteria for mass-customized structural node fabrication. However, some areas of the geometry need to be enhanced using load path optimisation to respond to fabrication constraints. This approach was already tested in one area of the node, where the material thickness was too thin for printing. At the end, there were still some areas of the node prototype which need to be enhanced using load path optimisation for structural reasons.

Member Sizing

Both previously described optimisation approaches, Defined Topology and Load Path Optimisation, inherit the potential to be coupled with membersizing.

DISCUSSION

The authors were confronted with restrictions in computational power during the coupling of different optimisation algorithms. Some finetuning of the chosen set of algorithms will be necessary to define a feasible geometric representation that might be scaled to the macro level of the overall structure of the pavilion.

The goal of the presented research was to close the gap between shape and structure optimisation with the geometric foam of the SPUME algorithm. This development was necessary to provide a holistic geometric representation of the structural system as basis for a multiscalar approach to custom optimisation and mass-customisation of structural systems.

Another aspect of the mesh representation as output of the parametric design model was that even if a watertight mesh was generated for additive manufacturing, the result contained several manifold edges. The Makeprintable cloud platform closed at the end of 2022. Therefore, the next iteration of the Smart Struc-tures Project must incorporate a novel strategy for mesh joining, cleaning and repair.

Additional optimisation of the support structure needs to be performed to reduce printing time, because the massive nodes necessary for the final installation make production material intensive.

However, the authors considered emerging limitations for the next stage of the research, especially in respect to the variability of node designs using four additional optimisation routines.

To extend this discussion towards industrial application, the custom-optimized building parts can also be fabricated on site, if necessary. Another benefit of integrated tectonics is the potential for dismantling and reuse of the building or selected building components.

Integrating the overall structure in the geometric representation allowed the authors to extract loads in dependency on chosen load cases from the parametric model. This step provided the constraints for local adjustments of the custom-optimized nodes to their respective position in the structural system.

The benefits provided by the design system based on the multiscalar representations were enabled using SPUME algorithm. This simple attractor based foamline algorithm had the potential to impact on the compatibility of different optimisation approaches. Other optimisation algorithms, like microstructure, fixedtopology, membersizing and load path optimisation can now be used to extend the geometric representation of the structural nodes.

Architectural envelopes impose additional requirements in weather protection, shading options, and static loads on the structure. Larger envelopes will profit from stronger modularisation, standardisation, and reduction of variety in geometric expression of the structural system. As a result, the artist and architect can further reduce construction costs by exploiting the advantages of mass fabrication while providing an appropriate level of geometric variability as the basis for the cusrromisation process.

As a result of the integration of tectonic details in the parametric model, the generation of fabrication data for 3D printing of the structural nodes and the respective timber construction for any geometric configuration was enabled. This integrated design process reduced the planning time for preparation of tender packs by providing a complete part list with accompanying 3D geometry for all parts of the structural system.

CONCLUSIONS

In conclusion, the presented research addressed the desire for individualized and customized building envelopes by exploring an algorithm to close geometric gaps.

Based on structural optimisation which integrated tectonic considerations in a multiscalar design process, an approach of geometric representation ready for automated workflows was envisioned. Additionally, the research explored the design potential of accompanying optimisation routines to extend BESO algorithms for custom-optimized structural nodes.

Combining multiscalar structural optimisation and custom-optimized structural nodes for generative engineering was explored as the basis for an interactive design framework for pavilions in a new structuralist style.

At the end of the process a prototype of the structural node and the associated virtual prototype using structural simulation were generated using the parametric design system developed for the design of the full scale prototype.

Further research will be necessary to scope the application of optimisation routines investigated during this research to fit computational power by actively restricting complexity. Having said that, the use of different structural features as part of the computational design process will be an option for the creation of the design space for evaluation of subjective preferences.

On one hand, the integration of structural simulation in the generative process will lead to stronger differentiation of envelope geometry. On the other hand, additional variability will be provided by the computational system by genetic diversification of the underlying representation. Furthermore, the introduction of a reference data base will reduce redundancy of designs during user evaluation.

In the context of design processes, the contentment of the user was the appropriate point of reference, as opposed to an optimisation that purely focusses on quantitative criteria (Akin, 1979). Even if basic cognitive processes during the design were similar for many designers (Akin, 1979), design intuition and personal preferences vary between different designers and change during the design process.

The transition of the design system from parametric definition into an interactive generative system is expected to provide noteworthy results regarding the encoding of structural systems. Consequently, tectonic expression of the micro level of the structure using custom-optimized structural nodes will be able to adapt to varying architectural geometries.

Next, a parametric design system based on evolutionary computing and machine learning will be applied using Biomorpher (Harding and Brandt-Olsen, 2018). This technology provides the basis for the development of an interactive optimisation system as a briefing tool for collaborative use.

Introducing an interactive optimisation interface to a generative design process like drone frame customisation (Bright, Suryaprakash, Akash and Giridharan, 2021) might increase the engagement of designers and engineers during collaboration, as well as their potential for real time collaboration on smart node facades (Na, Kim and Moon, 2022). Therefore, the likelihood of using these computational systems in an industry context increases, because of the possibility of direct application of design knowledge (Araujo *et al*, 2016) in the process.

Finally, the customisation of design using interactive design methods is likely to transform the architecture, engineering, and construction (AEC) industry. Novel CAD systems might integrate human in the loop aspects in their functionality in response to the increased need for quick decisions in early design stages due to the frontloading of the design process caused by building information modelling technology.

The next step of the project will be to investigate an interactive design framework that satisfies the criteria for mass-customized frameworks, as defined by Johnson (2012). One important aspect in this context will be to avoid fatigue of the user, especially in case of complex design geometries (Moustapha 2005).

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