Node Design Algorithm

Based on structural enhancements and the constraints of 3D-printing

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The optimization of discrete structural systems through form-finding methods often leads to geometric modifications, such as variations in the dimensions and orientation of structural elements. Such irregular geometries require nodes to connect elements at different angles. While the linear elements of a discrete system can be constructed using common bars, the design and manufacturing of the geometrically diverse nodes present challenges. These include connecting bars with different cross-sections or the design of an algorithm generating the geometry of individual nodes suitable for additive manufacturing. This study introduces a computational algorithm that produces structural nodes based on members with varying cross-sectional areas and orientation angles. The algorithm employs a finite element model of the discrete structure to size the bars based on a material definition and then to produce structural nodes at the axis intersection points proportionally to the adjacent bars. These nodes are composed of a generative core and predefined plugs at each axis connecting the core with the bars. This design enables adaptability since the generative node core adapts to the specific geometric situation while predesigned plugs retrieved from an internal library are scaled to the profile dimension. Thus, providing a modular and expandable system. The proposed algorithm was tested in a case study involving a regular cantilever truss and its optimized variant.

Keywords: *Structural Nodes, Discrete Structures, Topology Optimization, 3D-Printing, Additive Manufacturing.*

INTRODUCTION

In times of declining resources and productivity (Goldin et al., 2024), researchers and designers are challenged to develop methods of constructing more durable structures with fewer resources. Discrete structures based on form-finding principles enable lightweight constructions with the potential to contribute to sustainable architecture. However, such enhanced structures can present challenges since they often result in geometric modifications in the dimensions and orientation of structural elements. While the linear elements of a discrete system can be constructed using common bars, the nodes may be difficult to design and manufacture when their geometry varies in shape and orientation due to form-finding processes. Conventional manufacturing methods are only partially suitable for producing varying nodes as they rely on repetitive work steps for economic production. For additive manufacturing methods such as Selective Laser Melting (SLM) for producing metal or Fused Filament Fabrication (FFF) for producing plastic

objects, it does not matter whether the workpieces to be manufactured vary in shape. These advancements in additive manufacturing methods go hand in hand with research into the design of varying structural nodes to foster the implementation of structures based on form-finding principles. For instance, Raspall & Banon (2021) developed various node designs for research projects on specific topics. As part of a pavilion project based on a tetrahedron structure, metal nodes were 3D-printed to seamlessly connect to metal bars at different angles using a screw detail integrated into the bars. A canopy project by the same researchers utilizes machine vision to individually scan the profile shape of bamboo rod ends to connect the bamboo bars to FFF-printed nodes via a form-fitting detail. Also, the node design of Laufs (2021) for a canopy structure features a form-locking detail where metal bars are cut oval at the ends to be connected to the fiber-enforced structural nodes with a positive fit. The approach proposed by Morales-Beltran et al. (2022), in contrast, focuses on reducing the topology-optimized shape to its nodes by substituting sections with uniform cross-sections of the topology-optimized form with bars. The resulting topology-optimized nodes are then connected to standard bars using flange connections. The rationalization algorithm proposed by Vahid et al. (2020) focuses on optimizing topology-optimized nodes in discrete systems to enhance their manufacturability via metal printing. After generating the nodes at axis intersections within a spherical domain, the algorithm modifies the resulting topology-optimized geometry to facilitate compatibility with metal printing requirements. The 'smart nodes' in the curtain wall system of the Galleria Department Store in Seoul allow for the connection of various flat glass shapes at different deflection angles (Sangho et al., 2022). The node design addresses geometric challenges such as the vertex deflection phenomenon by minimizing the distance between the glazing and the structural system through optimized node configuration.

The proposed methodology builds on the experience of the reviewed research and aims to provide an extensible and universally applicable node algorithm for discrete systems with varying axes. The algorithm aims to be adaptable to different bar cross-sections and sizes without having to abstain from the advantages of uniform details. Moreover, the algorithm is foreseen to be customizable to enable the implementation of the details of designers to support their work. To test the applicability, we use a case study based on a regular cantilever truss and a topology-optimized variant as proposed by Kawamura et al. (2002). Consequently, we use the structures of the case study and connect them to the methodology step by step.

METHODOLOGY

This methodology (Figure 1) serves as a guideline supporting designers in producing structural nodes for discrete systems with varying axis angles and bars of different sizes and cross-sections. The crux of this methodology is that the structural nodes are split into two groups of parts. First, in a generatively created branch-shaped node core, and second, in predesigned connection plugs (Figure 1). The node cores are generated at each axis intersection of the discrete system according to the sizes of the adjacent bars retrieved from a Finite Element Model (FEM). For generating these cores, Grasshopper's Multipipe Tool is utilized, which produces branch-shaped node core geometries based on the dimensions of the adjacent bars calculated by the FEM. This reduces the generative part of the algorithm to the node core for adapting to the varying axes and bar sizes of the discrete system. The connection plugs, on the other hand, are designed and added to a library from which the algorithm can retrieve, translate, and orient them into position at each axis end to establish the connection between the node core and the adjacent bar. Using an internal library to select and orient the connection plugs according to the bar's profile and dimension enables the designer to add and change connection plug designs for customization. The restriction in the

design of these connection plugs is the use of a defined connection detail at the end of the plug oriented towards the node core. For this research, we utilized a screw connection, whereby the screw detail is implemented in the connection plug and the thread in the node core. Thus, for connecting the node core with the connection plugs through this screw connection (Figure 2).

3D printing is considered for producing the nodes, as additive manufacturing methods are indifferent to whether the fabricated components are uniform or variable. Selective Laser Melting (SLM) for producing the nodes out of metal and Fused Filament Fabrication (FFF) for thermoplastics are foreseen. The standardized connection plugs, which link the node core to the bar, can also be mass-produced using conventional manufacturing methods. This approach would integrate established manufacturing methods with digital fabrication within the methodology, promoting the production of optimized discrete systems based on form-finding principles. The following paragraphs explain the methodology (Figure 1) in four steps.

Stage 1 – Discretization

If the design domain is not inherently a discrete system, it must be converted while preserving its structural logic. This requires faceting curves into segmented axes or subdividing surfaces into triangulated or quadrangulated meshes. During this process, it is crucial to consider that a higher density of axis results in a greater number of nodes. After conversion, the discrete system must be assessed to ensure it aligns with the design intent. If not, the discretization process needs to be repeated, and necessary modifications implemented.

Stage 2 – Finite Element Model

To set up the Finite Element Model for structural performance assessment, the discrete structure from the previous step is connected to a Finite Element Method plugin. Therefore, Karamba (Preisinger, 2013), a FEM plugin within the Grasshopper visual scripting environment, is employed. The aim of this step is the sizing of the structural elements based on the structural constraint materiality (profile type - steel, aluminum), support location and types (fixed-, pinned, roller support, etc.), and load type. Once the structural constraints are defined, the Finite Element Model provides structural feedback, determining the required size of each structural element based on the specified constraints.

Stage 3 – Node Core Generation

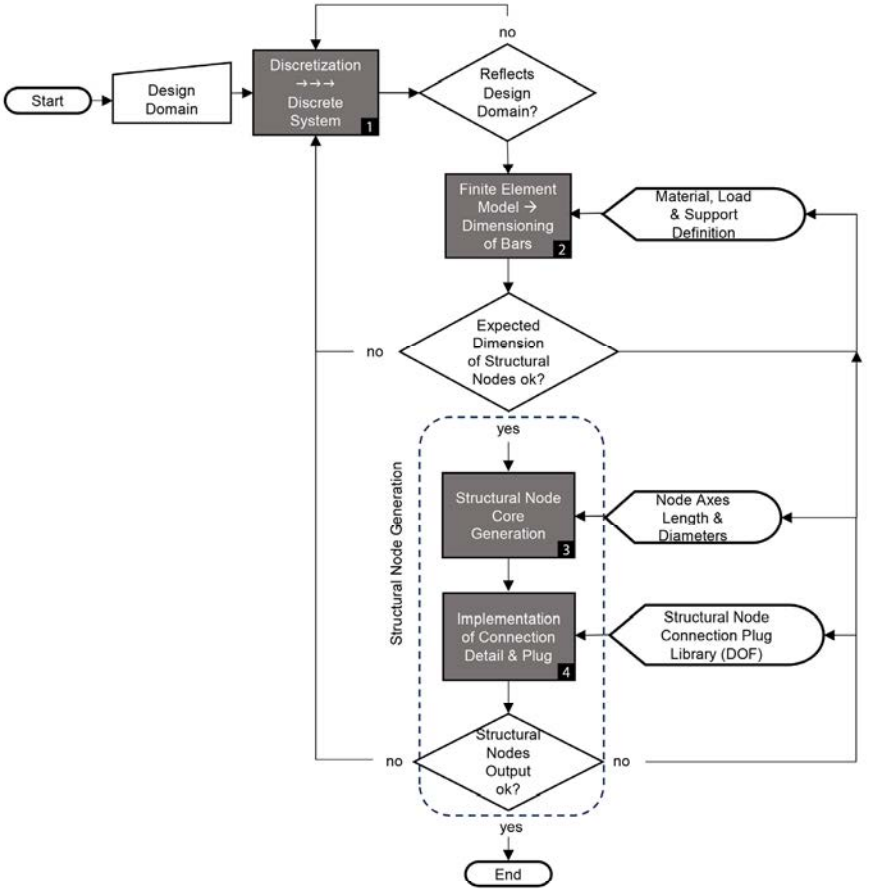
Once the bars of the discrete system are sized based on the FEM, the algorithm identifies all axis intersection points of the discrete system to generate branch-shaped node cores around them (Figure 2). Therefore, the Grasshopper Multipipe Tool is utilized, which generates the size of the branch-like node cores according to the sizes of the adjacent bars.

Stage 4 – Implementation of Connection Detail & Connection Plug

After the algorithm produces the branched node cores using Grasshopper's multipipe tool, a Boolean operation is employed to create voids at the end of each node core's branch. Threads of a screw connection detail are implemented into these voids and merged with the node cores to establish a connection with the node plugs, which are screwed into the node core's threads (Figure 2). The predesigned node plugs are selected according to the size and cross-section of the adjacent bars and retrieved from an internal storage or library for translating and orienting them into position at each node core's axis end. These steps can be carried out by the algorithm if suitable node plugs of the correct size fitting the cross-sections of the adjacent bars are available in the internal library. If not, unavailable node plugs need to be designed, labeled according to their profile dimension, and added to the library.

Evaluation of Nodes

A review of the produced structural nodes allows for subsequent adjustments regarding the selected connection plugs, geometrical adjustments of the



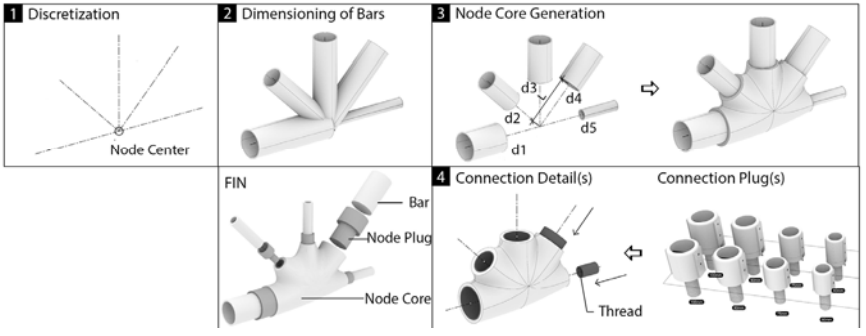


Figure 1
Methodology
Flowchart

node cores by manipulating the node core's parameter d or L (Figure 2), FEM, or modifications to the discrete system. If no adjustments are required, the nodes are ready for production using additive manufacturing methods such as FFF or SLM.

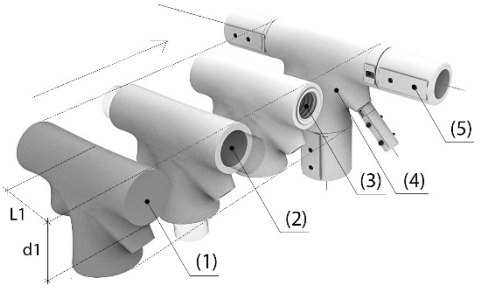


Figure 2
Node Core and Implementation of a Thread for the Connection Plug

(1) Generated Node Core (Multipipe Tool)
(2) Node Core with Void Opening implemented
(3) Node Core with implemented Thread
(4) Node Core with Connection Plugs
(5) Connection Plug

L1... Branch Length
d1... Branch Diameter

CASE STUDY

The case study applies the methodology to a regular cantilever truss, referred to as Case 1 (Figure 3). For practical reasons, the bay spacing L is set to 100cm for fostering the production of the node samples using an FFF PRUSA XL desktop printer with a build volume of 35x35x35cm.

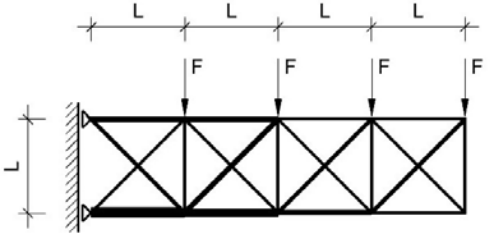


Figure 3
Regular Cantilever Truss

Stage 1 – Discretization

The geometry of the regular cantilever truss is discretized by drawing the axis lines and converting them to curve parameters within the Grasshopper environment.

Stage 2 – Finite Element Model

The curve parameters (axis) of the previous step are defined as structural elements within Karamba. The four point loads (F) are set in position at 10 kN each. The supports are defined as a fixed support at the upper support location and as roller support at the bottom. ISO aluminum tubes are selected as a material. After entering the load, support, and material definition, the FEM responds with structural feedback. Thus, providing the required diameters of the aluminum tubes necessary for the following steps.

Stage 3 – Node Core Generation

The algorithm identifies all axis intersection points of the discrete systems and generates node core geometries around them by utilizing the Multipipe-Tool of Grasshopper. The size of each resulting node core geometry is set proportional to the diameters of the adjacent bars. This resulted in branched node core geometries aligning with the adjacent aluminum bars.

Stage 4 – Implementation of Connection Detail & Connection Plug

Connection plugs, adapted to fit the bar diameters, are designed, labeled, and incorporated as a 3D model into the algorithm's internal library. Each plug is equipped with a screw detail to connect to the node core. Therefore, the algorithm creates a void at each branch end of the node core and implements a thread to connect to the connection plug. Subsequently, the connection plugs from the library are translated and oriented to the node cores to complete the structural nodes.

Evaluation of Nodes

Except for two structural nodes, no adjustments were required. To address this, the core branch diameters (d) were adjusted to enable the Boolean operation for the thread implementation.

The case study applies the methodology to a topology-optimized cantilever truss of Kawamura et al. (2002), referred to as Case 2 (Figure 4). The optimized cantilever results from research utilizing a stochastic search procedure based on modified genetic algorithms to generate near-optimal variants of load-bearing truss structures. This procedure altered and enhanced the geometry of the discrete system, enabling it to sustain the same load conditions as a regular cantilever truss, as employed in Case 1 (Figure 3), while utilizing less material.

Stage 1 – Discretization

The geometry of the topology-optimized truss is discretized by redrawing its axis lines from the reference paper and scaling its dimensions based on a bay spacing of 100 cm. Subsequently, the cantilever's axis is converted into curve parameters within the Grasshopper environment.

Stage 2 – Finite Element Model

To ensure consistency with the regular truss in Case 1 (Figure 3), four point loads (F) of 10 kN each are applied. Aside from the reduced number of structural elements resulting from the topology optimization, the load, support, and material definitions remain identical and are applied accordingly.

Stage 3 – Node Core Generation

The node core generation is applied according to the methodology and proceeds in the same way as described in Case 1. No deviations or errors were observed.

Stage 4 – Implementation of Connection Detail & Connection Plug

The implementation of the connection detail and the connection plugs is applied according to the methodology and proceeds in the same way as described in Case 1. No deviations or errors were observed.

Evaluation of Nodes

The structural nodes of the topology-optimized truss were produced without errors. However, for three nodes, the alignment with the connection plugs was geometrically enhanced by adjusting the node core parameters (d) and (L), (Figure 2).

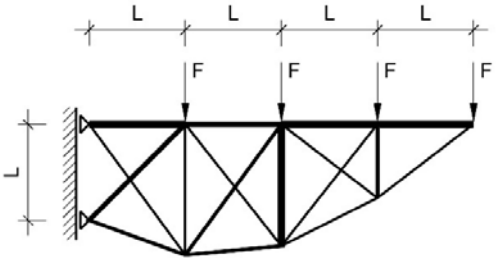


Figure 4
Topology-Optimized Cantilever Truss (Kawamura et al., 2002)

RESULTS

The proposed algorithm produced structural nodes for two case studies, the regular and the topology-optimized cantilever truss (Figure 5). Node core geometries were generated around the axial intersection points of the discrete systems, and predesigned connection plugs were incorporated into the nodes branches to establish the connection between bars and the node core. Based on the Finite Element Models of the case study cantilevers, the required diameter of each structural member was calculated, and this served as a basis for sizing the branches of the node cores. Subsequently, predesigned node plugs fitting the different diameters of the adjacent bars were designed, added to the algorithms' internal storage, and translated and oriented to the respective node axis. This resulted in structural nodes connecting bars of

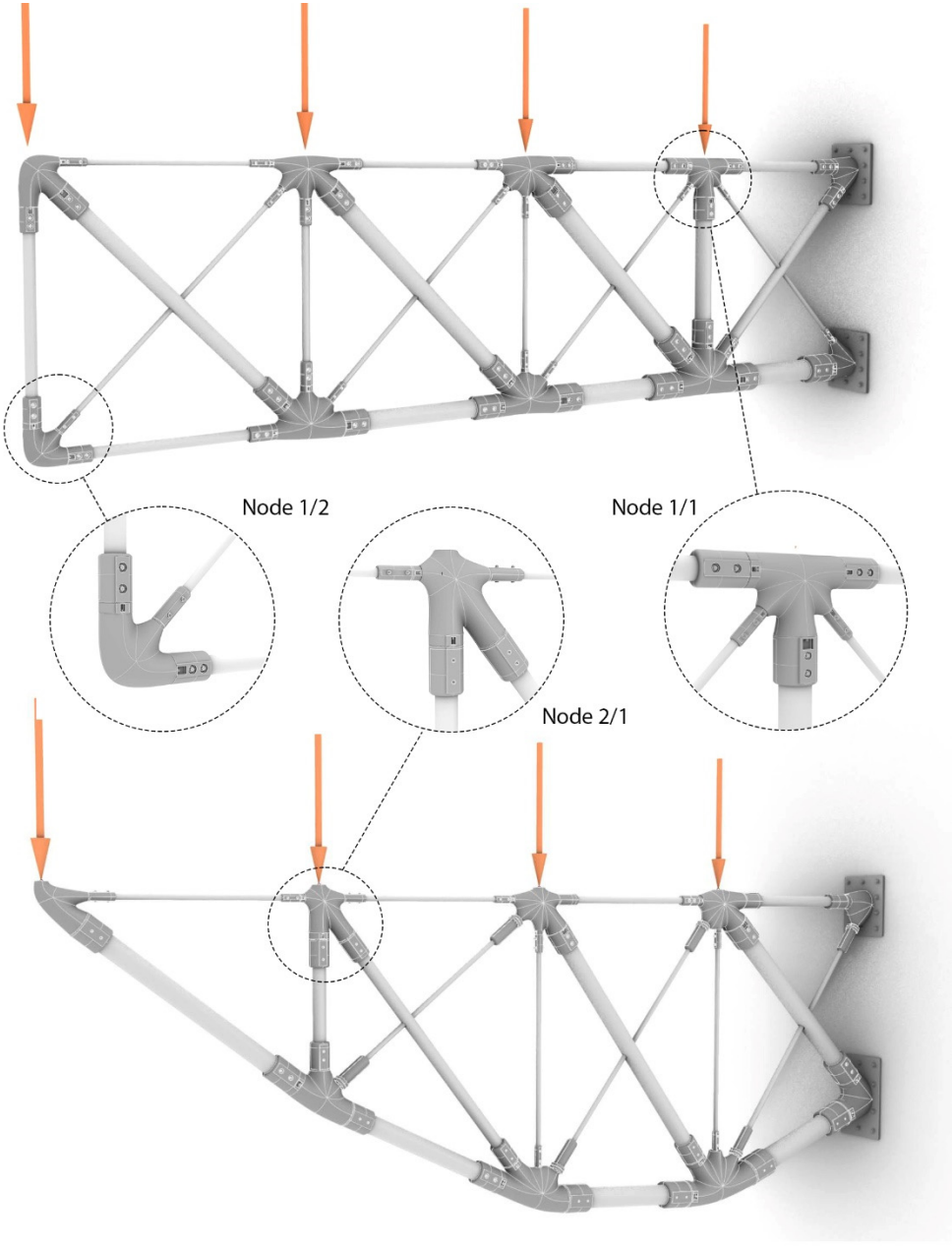


Figure 5
Comparison of a regular and topology-optimized cantilever truss with structural nodes connecting bars of different sizes

different sizes. The production of the structural nodes required the same effort for both trusses and proceeded without issues, with only minor geometric adjustments needed. However, the topology-optimized truss requires fewer bars and structural nodes than the regular truss and thus requires less construction material for supporting identical loads.

The proposed algorithm is applicable for a wide variety of discrete structures since connection plugs for various profile types and sizes can be added to produce structural nodes for enhanced structures. For the case study trusses, round aluminum tubes of different sizes were employed, and accordingly, connection plugs fitting the round profile type and bar sizes were designed, labeled, and added to the algorithm's storage. The connection plugs of the two case study cantilevers are designed as a fixed connection and enable the lateral accommodation of the round bars. The bars are connected to the node cores through these connection plugs, whereby one of the connection plug pairs enables axial rotation for easier assembly by aligning the plug with the bar (Figure 6). The node core and the connection plugs are separate parts connected through a screw connection. This connection makes the plugs exchangeable for adapting to various bar profiles and sizes or to replace them.

Although Selective Laser Melting (SLM) is the preferred method for fabricating structural nodes due to the higher mechanical strength of metals, three nodes from the case study were printed for demonstration purposes using Fused Filament Fabrication (FFF) with thermoplastic (Figures 7, 8, 9). Polylactic Acid (PLA) was used as the material for producing the nodes, utilizing an FFF Prusa XL desktop printer with a build volume of 35 × 35 × 35 cm, enabling full-size production. The node parts' internal stress direction was aligned with the printing direction to increase the mechanical strength of the parts (Lauff et al., 2019). Thus, since the bond between the layers in the vertical buildup of a printed object is less resistant against mechanical stress. Furthermore, the infill density of the nodes parts was set above 50% to further enhance the mechanical strength of the node components (Fernandez-Vicente, 2016). The round shape and the flattened areas at the sides of the node plugs parts (Figure 6) facilitated the printing process by reducing the need for support material to sustain overhangs during the additive manufacturing process. Overall, the production of the structural nodes of the case study trusses proceeded without incident and resulted in three full-sized varying nodes. The nodes were assembled and connected to aluminum bars of different diameters with bolted connections (Figure 7, 8, 9).

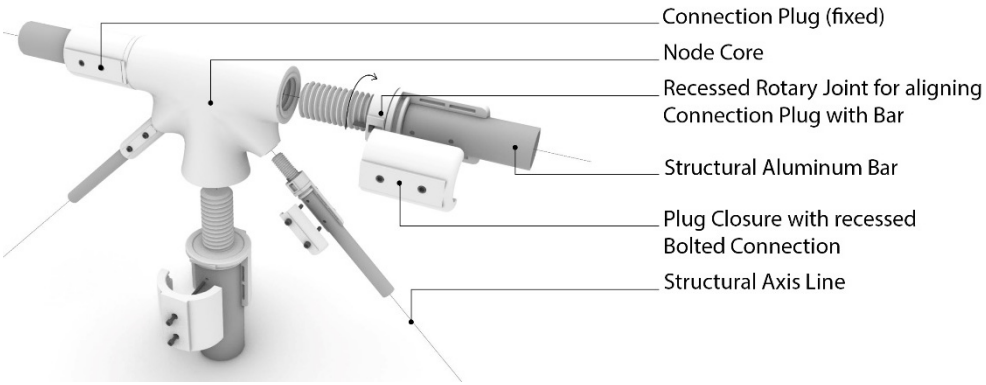
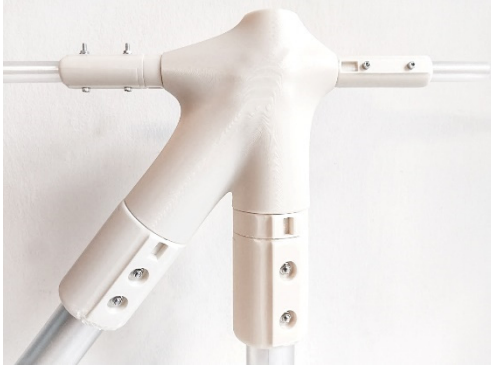


Figure 6
Structural Node Explosion Diagram

Figure 7
3D-Printed Node
1/1

Figure 8
3D-Printed Node
1/2

Figure 9
3D-Printed Node
2/1



CONCLUSION

This research presented an algorithm, which was tested using two case studies comparing a conventional truss with a topology-optimized version (Kawamura et al., 2002) under identical loading conditions. Although the loading condition of the case study may be ideal in comparison to real-world structures that have to withstand varying conditions, the case study highlighted the structural and sustainable potential of structures based on form-finding principles. The proposed algorithm provides a design tool to support designers in producing varying structural nodes for various profile types and sizes by integrating predesigned bar connection details, connection plugs, into this procedure. For both case study cantilevers, varying structural nodes incorporating aluminum tubes of different diameters were produced by utilizing this algorithm. The resulting geometry of the varying structural nodes is suitable for production, employing additive manufacturing processes such as SLM or FFF. This research thus fosters the construction of structures based on form-finding principles by providing a node design algorithm for creating varying nodes. However, since the proposed methodology's scalability is limited by the built volume of 3D printers for producing the nodes, further research is recommended to utilize other digital fabrication methods, such as waterjet or plasma cutting. Thus, expanding the applicability of node algorithms for producing large-scale structures. Moreover, the modular implementation of enhanced structures based on form-finding principles and varying nodes into conventional mass production and construction may be further investigated to exploit application potentials. This enables the comparison and combination of conventional and topology-enhanced systems, thereby leveraging the advantages of both. However, broader application requires appropriate training in computer-aided design in architecture and building construction education for future adaptability in evolving digital construction systems.

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