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Digital design and fabrication of adaptive metal nodes for timber space frame structures

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Abstract

This study proposes a new approach to sustainable timber construction, focusing on repurposing leftover round timber for the construction of space frame structures. It introduces digitally designed and fabricated modular metal nodes as connectors, and, as such, addresses timber shortages amid Europe's increasing timber construction sector. Central to this approach is the enhancement and optimization of wood resources, and the development of a corresponding connection technique, being suitable for non-standard material systems, while, at the same time, emphasizing architectural simplicity and structural efficiency. The connection technique and respective connectors need to be geometrically versatile while ensuring optimal architectural and structural performance. This paper explores the design, development, and fabrication of (metal) node connectors optimized for round, leftover timber elements, considering two variants: individually topology optimized nodes produced via lost-foam casting, and a modular approach facilitating efficient assembly, mechanical adaptability, and serial production. The research framework encompasses defining parameters, detailing the iterative design and fabrication process, and presenting a 1:1 architectural prototype. Through this framework, the study demonstrates integrating leftover timber into digital design and fabrication practices, reshaping sustainable timber construction and potentially expanding the art of structural design.

Keywords: Space frame structures, metal nodes, leftover timber, digital design, CNC milling, non-standard construction, lost-foam metal casting

1. Introduction

The need to build in a climate-friendly and material-efficient way is becoming more important than ever, with particular regard to resource depletion, growing world population, and increasing climate extremes. As such, it is not only important to utilize sustainable materials, but also to activate sustainable materials that are currently disregarded [1]. A key example is leftover timber which is hardly used in building construction and is mostly used for heating. Leftover timber is generated in many areas of timber processing chains, which often occurs as unprocessed round timber, for instance as crown residue or weak wood during thinning. Here, traditional building systems and workflows are considerably limited, since they are developed and applied for standardized construction processes, and, as such, for the usage of standardized building elements [2]. However, introducing custom-designed (yet serially fabricated) connection systems, such as modular metal nodes, allow the usage of leftover timber, and leads not only to a significant repurposing of material, but also to foster the development of digitally integrated building processes and the construction of non-standard timber frame structures.

This research is in its infancy, and presents many theoretical, practical and methodological challenges. Obvious examples are wide-ranging and include the need for advanced computational design routines and interfaces, constructive systems and non-standard assembly of building parts, and the integration into a unified building process[3]. In order to develop a schema for addressing these challenges, a first experimental setup and prototypical process to explore and outline the architectural potential of using leftover timber through computationally designed and fabricated modular metals nodes was developed.

In Section 2 we present the context of our work from both a material and a constructive perspective. Section 3 discusses our method, and suggests parameters for investigation, including design and fabrication. Section 4 presents a detailed description of first experimental results. Our conclusions are presented in Section 5, including an outlook for further research.

2. Background

The approach developed in this research combines multiple directions and constraints. As such, we first discuss the material context of our research, and then, second, the previous attempts to develop constructive systems that allow the usage of leftover timber for timber space frames.

2.1 Material context

Due to the increasingly fluctuating temperature and precipitation values in Central Europe, the forestry industry is increasingly focusing on a transformation to robust mixed forests. A particular case is Germany [4]. Here, the aim is to cultivate more diversified and robust forests, and, at the same time, preventing mass tree extinction events. However, timber construction is only partially prepared for this future change in the supply of local hardwoods; here, construction methods using softwoods dominate. Only beech, and products such as "BauBuche", is still used to some extent as a structural construction material. In the construction industry, the proportion of softwood in Germany is 85.6%, the proportion of hardwood is 12.6% and the proportion of tropical wood is 1.8% [5]. Against this background, it becomes clear that there will be a considerable supply of weak hardwood in the future. This is related to the so-called "thinning practice": In commercially cultivated forests, substantial attempts are made to maximise the timber yield, for example, tree density is gradually reduced over the years until only the best, straightest trees remain. As the rotation period of hardwoods is longer than that of softwoods, this weak wood will also make up a larger proportion of the wood supply in mixed forests. Currently, this weak hardwood is mainly used for energy production, and heating in particular.

In this, according to the wood processing industry, hardwood is still viewed critically for a broad structural use, because it is harder to process and thus making production more expensive [6]. However, the research pursued in this framework attempts to use the logs directly as debarked round timber and to keep wood processing to a minimum. The timber to be used has two main properties: a short length (<2 m) and a small diameter (<20 cm). Here, space frame structures present a viable constructive approach of utilizing such material properties and dimensions, as the spatial typology capitalizes on timber elements that can be short and thin. Another advantage is the redundancy of individual structural members, which is ideal for an inhomogeneous, anisotropic material such as natural timber. The main disadvantage of space frame structures is the complexity of their nodes, and through that the assembly of (non-standard) timber elements into precise, efficient and performative constructive configurations.

2.2 Construction context

Initial research was carried out by Pieter Huybers [7], exploring the use of round timber in spatial trusses and applying metal connections. This proved that, in principle, the overall possibility of load-bearing structures through the combination of prefabricated nodes and round timber bars. Previous research has also shown that unsawn timbers have higher and less variable bending strengths than sawn timbers [8] [9]: First, there is an unbroken fibre continuity around knots, and, second, round timber has a favorable shape in bending compared to a rectangular shape. When working with round timber, however, there are various challenges in terms of connectability and precision. On the one hand, different degrees of drying can result in different degrees of shrinkage and thus varying dimensions. On the other hand, logs are by no means perfectly round or straight, but irregular and can be affected by knotholes, drying cracks

and other defects. A potential connection system must therefore accommodate these (non-standard) material characteristics, while preserving construction robustness and assembly efficiency.
Addressing these challenges, many concurrent approaches in the field of non-standard space frame construction use Additive Manufacturing (AM) technologies – since AM is particularly well suited to account for bespoke geometries and material-saving strategies. However, by individually customizing each node in the structure and/or during a buildup process, considerable efforts in regard to monitoring, modelling, fabrication and placement are required [10]. This prevents fast and efficient fabrication processes, especially when considering large-scale assemblies and real-world structures, where a material switch from (prototypical) plastic to (robust) metal nodes is often necessary. In fact, there are various 3D printing technologies available for additive metal processing – but are still out of range in terms of unit fabrication costs and time.
In this regard, developing a constructive system that capitalizes on leftover timber, while allowing robust constructions and efficient assembly routines is an inherently difficult and challenging problem. It is therefore difficult to obtain a universal principle, but it is possible, however, to isolate important constraints and describe new constructive avenues. For this reason, designing and manufacturing new modular node systems represent a viable solution, overcoming the pitfalls of extensive parametric or topology-optimized components, while, at the same time, fostering a robust, variable and efficient buildup of leftover timber into space frame structures that are sustainable in their entirety.

3. Method

Our approach therefore follows a modular strategy, linking digital design and fabrication of variable metal connectors, and satisfying the requirements for economic and robust construction, while providing a high degree of freedom for geometric differentiation. In this research, we are fostering an empirical-materialistic approach, developing a series of digital and physical 1:1 prototypes, which are incrementally and iteratively tested and validated, and, ultimately, defining the system's tectonic performance, fabricational feasibility, and the integration of respective components into a unified process chain (Fig. 2).

3.1. Digital design

For the digital design, we first extracted key parameters and constraints, such as the amount and angles of connection. The design was limited to flat space frame structures, as these feature a wide range of applications, and therefore foster a high potential for saving CO^2 emissions. The 3D modelling design was carried out in McNeel Rhinoceros 7.0 (Fig.1). In an initial study, a parametric space frame Grasshopper tool was developed that was linked with a FEM and topology optimization plugin to generate individually topology-optimized nodes. Initial prototypes were 3D printed and CNC milled for proof-of-concept-validations (Fig. 3). The foam blank for the lost-foam casting process was then developed from these findings. The milling path for the foam shape was created in Autodesk Fusion 360 (CAM) (Fig. 1) and the specific milling parameters for the foam were determined through iterative milling tests.

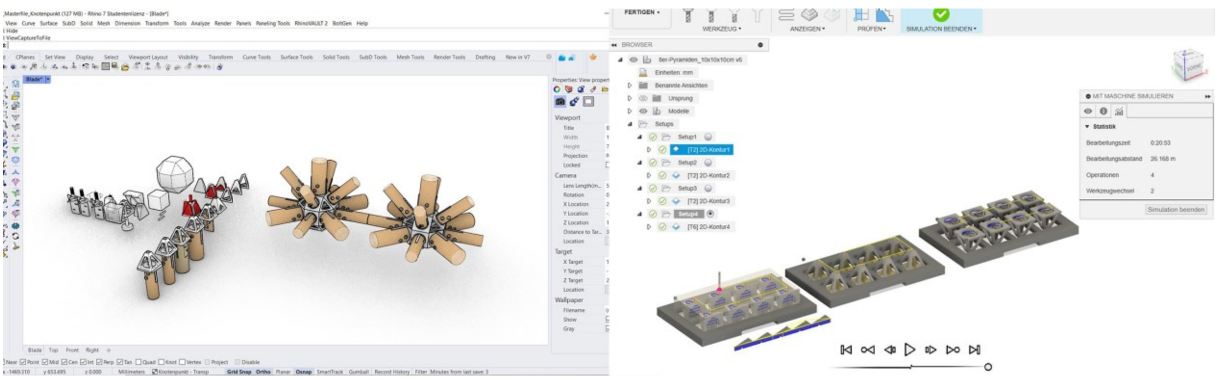

Fig. 1: 3D modelling in McNeel Rhinoceros 7.0 (left) and CAM simulation in Autodesk Fusion 360 (right).

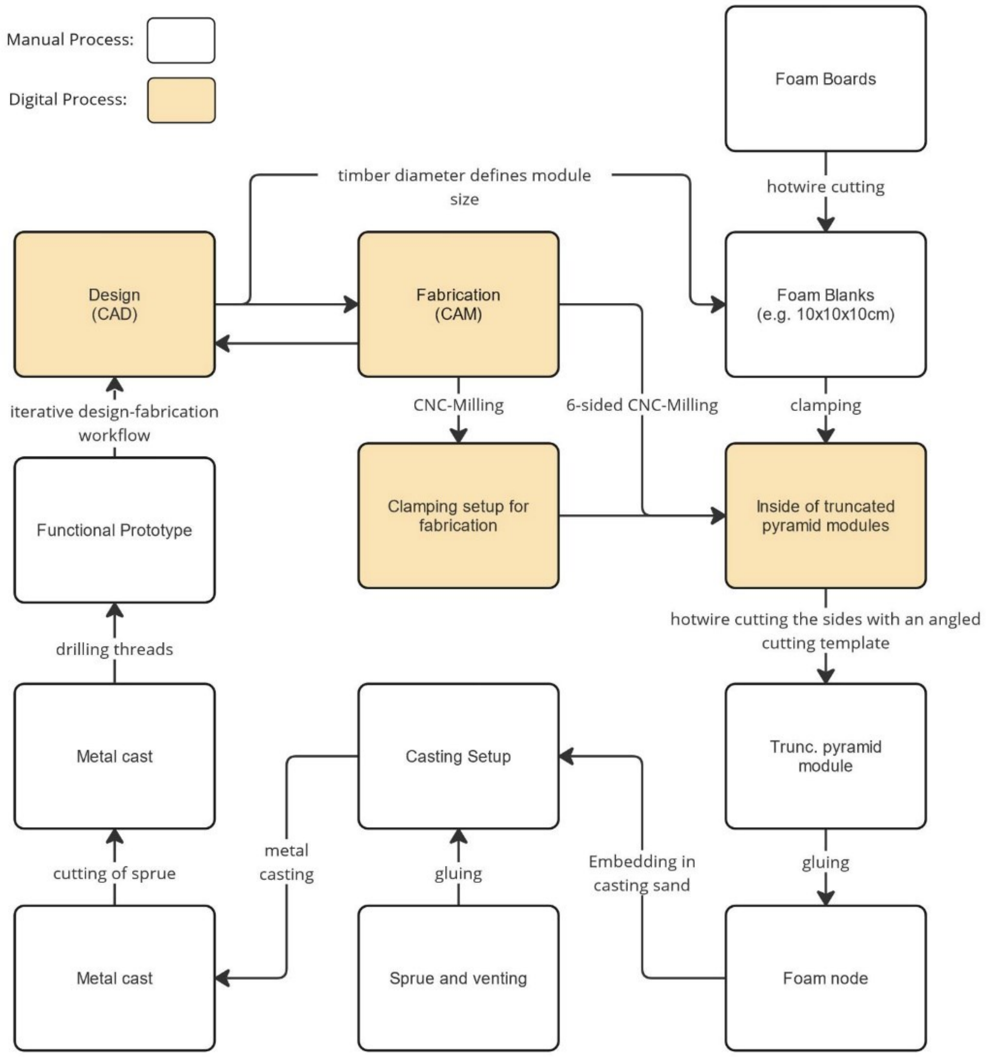

Fig. 2: Flowchart of the design and fabrication workflow of the metal nodes.

3.2. Material constraints

In this research, digital design and manufacturing is on a par with material research and specification. Exploiting this coherence requires the understanding of the properties of natural timber, for example, facing the problem of uncontrolled shrinkage cracks during the drying process. To overcome this problem, we suggest using the established approach of making a longitudinal cut (“kerf”) along the wood before the drying process has started, preventing additional cracks to form at undesired places [11][12][13]. At the same time this cut can be used to connect the timber and metal blade. Another option that has been researched is hollowing out the core of the timber and using the hole for a dowel-nut or glued-in rod connection [14]. By hollowing the core only minimal shrinkage cracks occur; however, this only proves viable on perfectly straight pieces of wood and is therefore disregarded at the current stage.

In this regard, the used timber for prototypical tests was salvaged from a central German hardwood forest. It was collected in spring after the thinning and debarked with an angle grinder and a woodcarving disc. After the debarking the timber has dried naturally for approximately a year.

Fig. 3: A number of prototypes were developed, ranging from topology optimized nodes (a, b) to the final modular approach (c, d).

3.3. Node typology

Constructively, a sphere is the best suited shape for a universal node as it can take loads from all directions and distribute them evenly. Furthermore, the axes of all members can pass through the center of the node, eliminating eccentricity loading at the joint; therefore, the joint is only under axial forces. This is the reason the MERO node and many other "universal nodes" are designed spherical and/or follow a spherical typology [15]. However, when working with diameters of (variable) wood instead of (standardized) thin metal bars, existing spherical node typologies are limited. To connect wood diameters of 10-20 cm, the size of the node needs to be considerably increased in order to fit the varying diameters. By hollowing out the knot, the higher material consumption of the larger node diameter can be minimized.

In this research, the spherical shape was approximated by a rhombic cuboctahedron (sphericity of 0,95408), which can be broken down geometrically into 18 identical square pyramids. These truncated pyramids form the basic module (Fig. 4a). This modular approach differs from fully-parametric node designs since it allows to compose the node only from the connection points that are actually required (Fig. 4), while, at the same time, preserving variation, scalability and mass production capability. The proposed node typology features uniform wall thickness and is optimized to be manufactured on a 3-axis CNC or respective subtractive machinery.

In order to actively compensate for the irregularity of the timbers, the knot consists of a screwable blade connection (Fig. 5) This is attached to the knot with an M20 screw and allows an adjustment of +/- 10 mm in the longitudinal direction of the timbers. The two metal swords can be easily inserted into the wooden slot thanks to their rotational capability. The metal blade is equipped with a slotted hole so that the connection angle can also be adjusted. The final fixing of the timber is achieved with two M10 screws in the first 1:1 prototype.

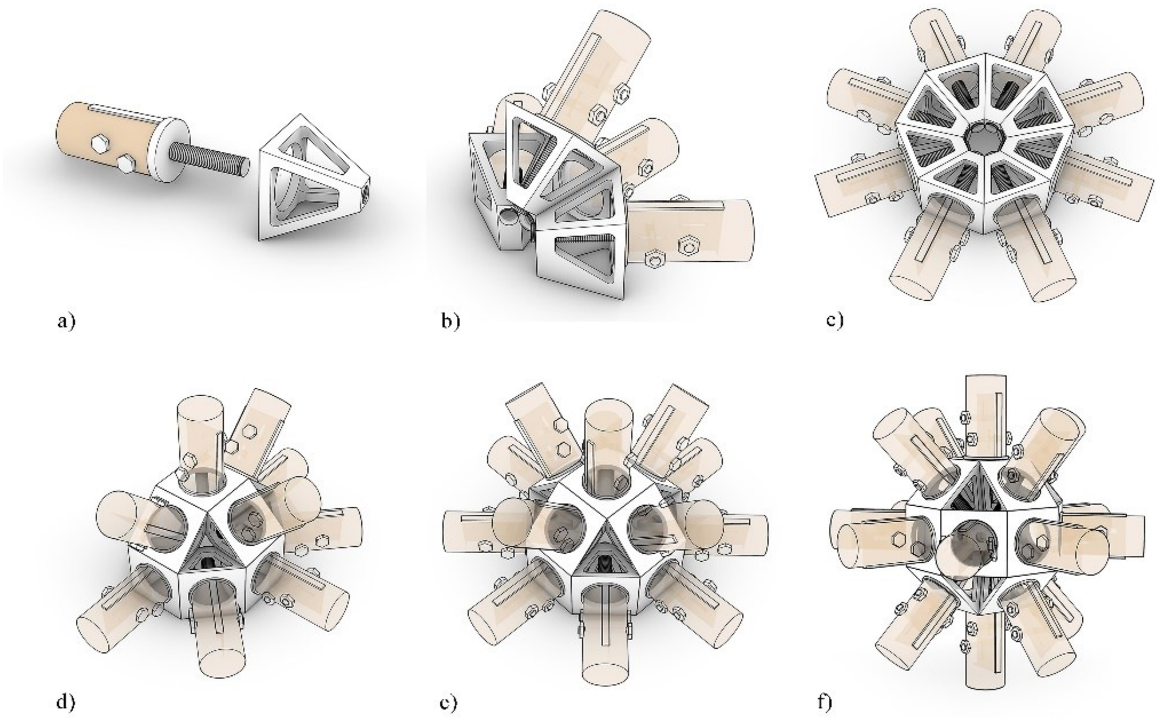

Fig. 4: Modular node system with a selection of possible configurations; a) basic node and blade module b) corner node c) flat node d) edge node e) top and bottom chord node f) multi-layer space frame node.

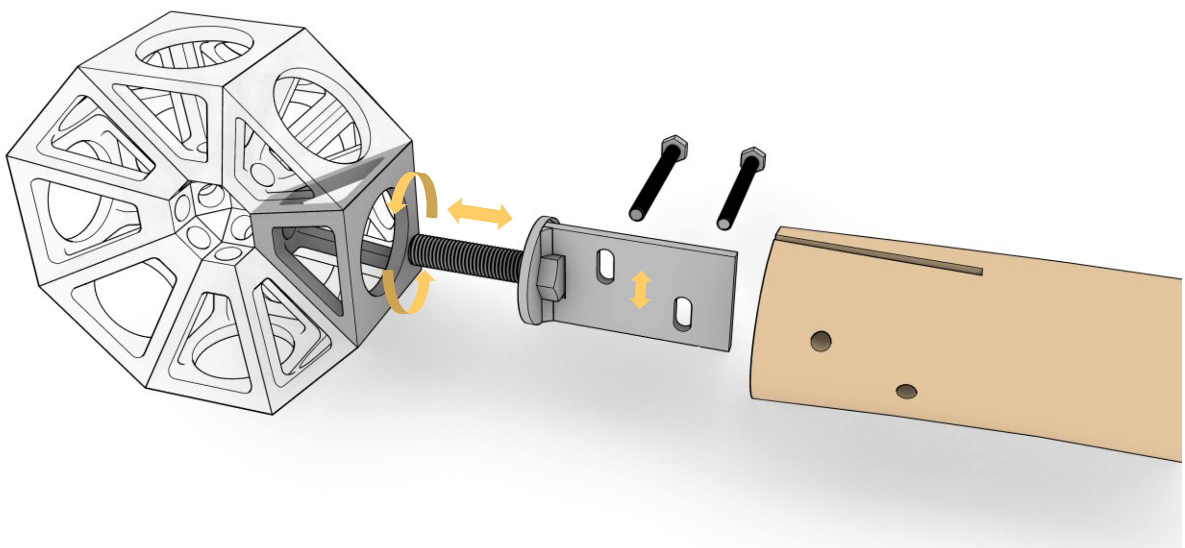

Fig. 5: Timber irregularity compensation through an adjustable, screwable metal blade.

3.4. Node fabrication

As the developed node has numerous undercuts and differently oriented cores, a production process using simple two-part moulds is not possible. Precise welding of the node from cut sheet metal would have also been very complex and elaborate. Combining the 18 different directions of the rhombic cuboctahedron in whatever configuration needed would mean that a large number of unique casting moulds would have to be produced beforehand. In lost foam casting the truncated pyramid can be glued together and cast in one piece thus reducing any additional expenditure. For this reason, the decision was made in favour of lost foam sand casting. The shrinkage of aluminum alloys is in the range of 1-1.5%, the casting sand used for embedding is simple quartz sand with a grain size of 0.1-0.5 mm. This sand was reusable even after repeated casting.

The fabrication setup consists of a 3-Axis CNC milling machine (EAS Heavy 450) with a working area of 940 mm x 505 mm x 170 mm, a metal casting equipment for small metal volumes (max. 1.3 l), a thread cutter and a manual hotwire cutter. A water jet cutter and a welding machine were also used to quickly produce the 16 steel blades for the 1:1 prototype. The foam boards (EPS-VFG18) are initially cut into 10 cm x 10 cm x 10 cm cubes. These cubes are the blanks that are inserted into a clamping setup on the CNC-mill (Fig. 6a), whereas 8 of the pyramid modules can be produced in around 26 minutes (195 sec per module) at a feed rate of 2500 mm/min. After cutting all the insides, the angled sides of the pyramid are cut, while using a CNC-milled guiding aid to make sure the angles were absolutely precise (Fig. 6b). In preparation for the casting a foam sprue channel and feeder were glued on manually (Fig. 6c). From first casting tests it became apparent that some of the quartz sand had sunken into the thread holes and caused casting defects; this was subsequently prevented by filling these holes for the M20 screw with oil-bonded moulding sand. The foam is than covered with a thin layer of refractory coating, dried and covered in sand (Fig. 6d). The molten aluminum flows through the sprue to the bottom of the node and slowly rises evaporating the foam on its way (Fig. 6e). Finally, the cooled-down cast is cleaned in water and the sprue and feeder are cut off. Cutting the threads is the final step, because the detail of a thread is very hard to cast directly, especially with the lost-foam technique (Fig. 6f).

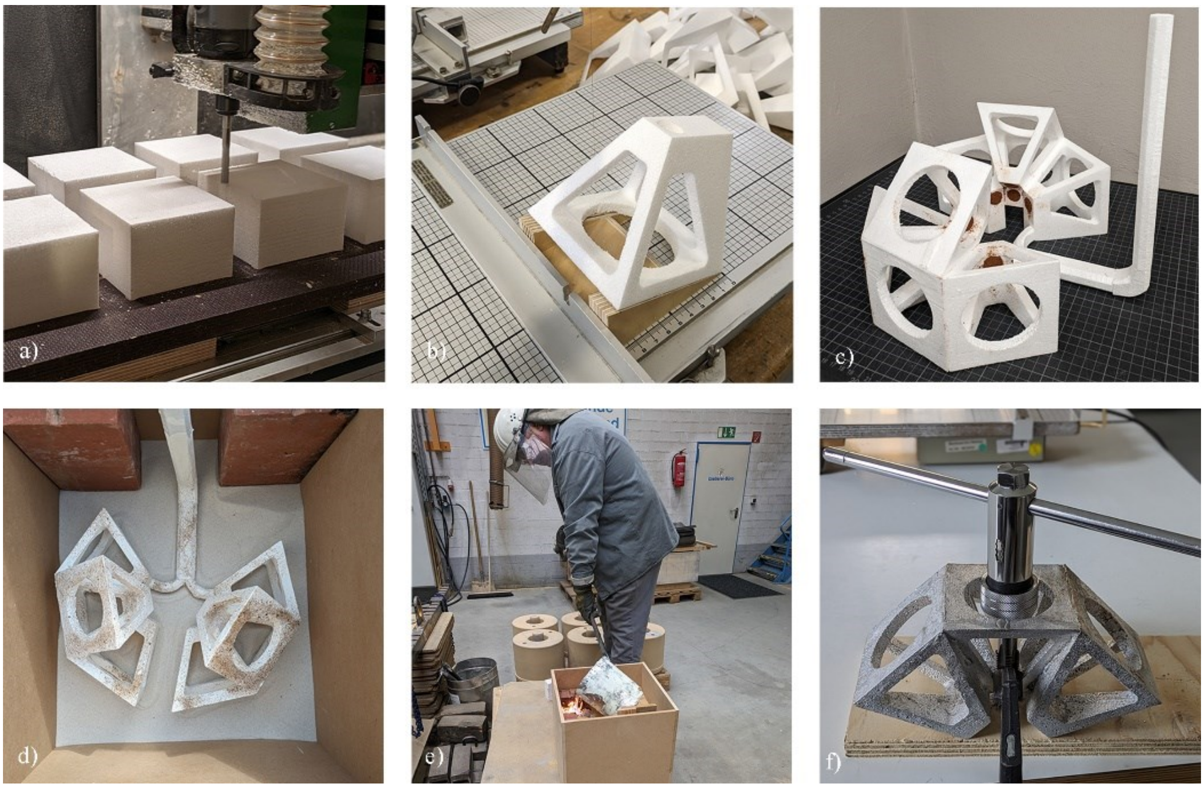

Fig. 6: Metal node fabrication workflow; a) CNC milling b) hotwire cutting c) casting preparation d) embedding in casting sand e) casting f) postprocessing and thread cutting.

4. Results and reflection

The general feasibility of producing modular metal nodes for timber space frames has been proven. The amount of postprocessing was considerably low and the casting sand was easily recycled. Only the thread cutting of the cast parts was time-consuming but could be automated in the future. Manually preparing the 8 timber logs (cutting and drilling) and connecting them to the nodes took about two working days for one person. Joining them was fairly easy because of the "designed" adaptability of the blade and node approach. The choice of metal (alloy) for the junctions is still subject to change; the advantage is that lost-foam casting is suitable for a wide range of metals and therefore does not require any adjustments in the moulding setup. There are various options for producing the foam blanks. For the production of the first prototypes, the foam was still processed subtractively using a 3-axis CNC milling machine, which allowed variants to be tested quickly. For mass production, however, this could also be done by foaming in 3D printed moulds (Fig. 7).

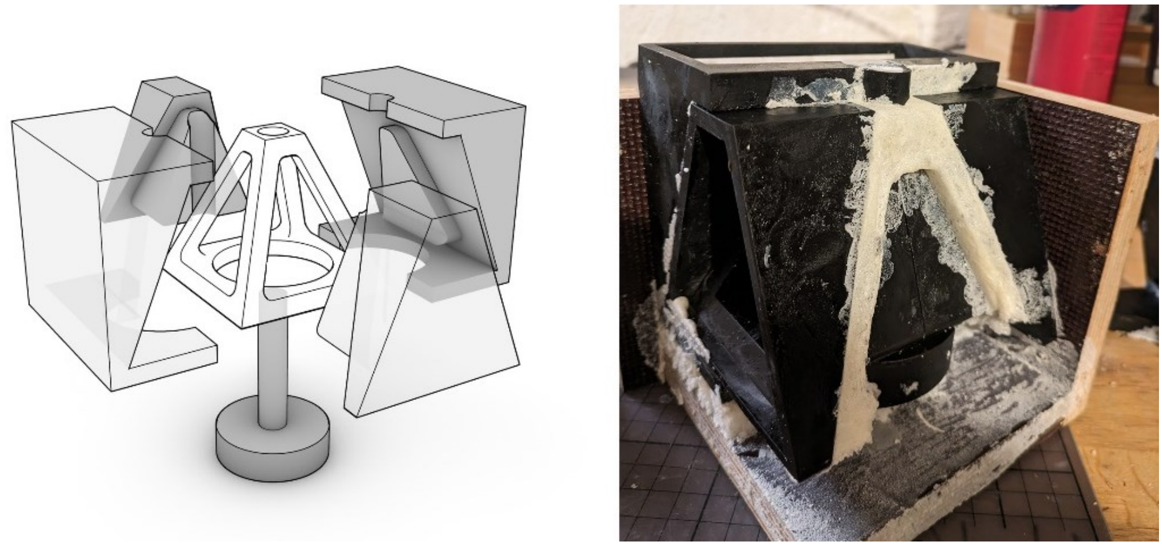

Fig. 7: 3D-printed mould, tested through using a PU-foam spray.

Foaming in 3D printed moulds was tested with PU spray foam, but the amount of foam sprayed into the mould was inherently difficult to control and subsequently the density of the foam as well. In industrial production pure polystyrene is mixed with pentane and can then be expanded with 110 °C water vapour. The advantage of foaming lies in its scalability and the smaller amount of waste produced compared to milling.

5. Conclusion

In conclusion, the proposed node typology and production method allowed a strong material orientation and became an essential concept to repurpose leftover timber for architectural applications. The approach radically extends the traditional spectrum of timber construction and pursues a radical shift in resource efficiency where (non-standard) timber frame structures can be realized from a multitude of repurposed timber members, fostering redundant, distributed and versatile constructions. However, as outlined in this paper, the amount of available research on this topic is not abundant, and therefore the pursued studies, including the 1:1 demonstrator (Fig. 8), were essential to characterize key theoretical, practical and methodological challenges, thus providing an empirical basis for further research. This would include, for example, the refinement of the node geometry, the accommodation of specific material properties, the development of a robust design-to-fabrication workflow, and as such, the implementation of a comprehensive digital process chain. This would, ideally, involve 3D scanning, postprocessing and sorting of leftover timber, storing the information in a database and thus preserving information penetration across the entire workflow. In turn, this would allow, for example, (automated) parametric placement of the timber logs or computing the ideal element for each member of the space frame structure, or to alter or optimize the node geometry and its resolution. Parametrically adapting the metal blade to the respective diameter of the timber log could also be integrated into such a comprehensive digital process chain. Most of all, this would promote a new design method where a multitude of material and structural constraints as well as fabrication attributes are orchestrated from the very beginning and up to the different stages of prototyping until its final realisation – potentially opening up new ways of thinking about sustainable design and its materialisation.

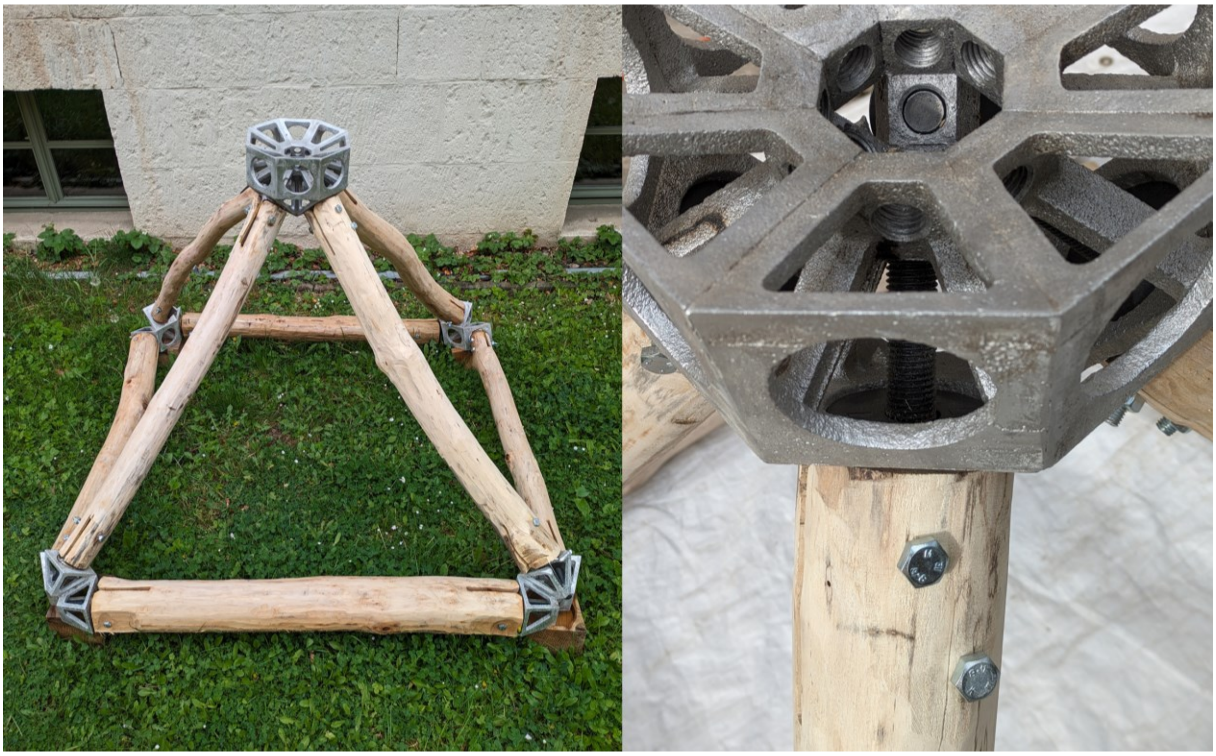

Fig. 8: Timber elements with a diameter of 6.5-12 cm, being joined through five metal nodes and forming a 1:1 truss prototype.

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Notes

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