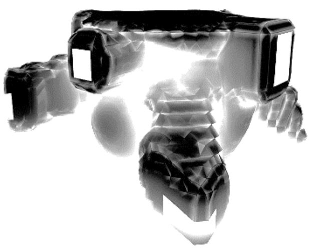
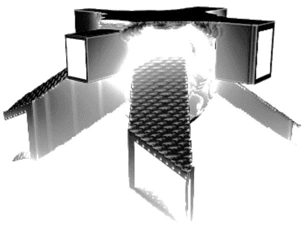
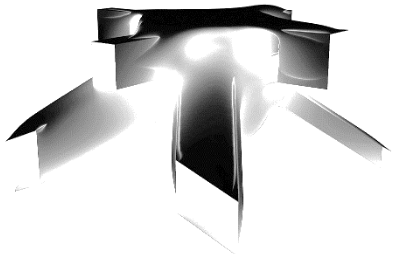
# TOWARDS ZERO-WASTE STRUCTURES THROUGH INTERGRATION OF RECLAIMED WOOD AND 3D PRINTING

BT Graduation Studio Master Thesis June 2024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# Preface

This report is the result of a graduation project at the faculty of Architecture and the Built Environment of the Delft University of Technology, within the Building Technology Master track.

At the time of writing, the Netherlands is in the shift towards a circulair economy before 2050. There cannot be any waste anymore, after service life the product or materials should be able to re-enter the economy. Currently the Dutch government is pushing the construction and usage of circulair hub where materials from demolition/dismantling can be stored for certain period of time before they re-enter the economy again. Simultaneously there is a material shortage for the building industry, where the materials are already responsible for a large proportion of the total carbon footprint. These drives up the demand for a renewable building material that will cause a lower carbon footprint. The recent trends in building with wood seem to address some of these problems. There is potential in better reuse of wooden elements as that could increase the quantity of available structural elements. Designers currently face difficulties with designing with irregular elements. Most of the time the potential for reuse is either overlooked or remanufacturing is preferred, creating a waste stream in saw-off loses. This research will aim for refusing waste, by utilizing computational design and digital production. The goal will be to create a new way of designing that will lead to a lower carbon footprint.

I hereby would like to express my gratitude to my mentors, Mauro Overend and Paul de Ruiter, for guiding me in the process of this research project and for advising me along the way.

# Abstract

In the pursuit of sustainable development, the construction industry faces the dual challenges of material scarcity and the environmental impact of its material usage. This thesis explores the potential of hybrid structures, specifically employing reused wooden elements, to address these challenges and transition towards a zero-waste economy. The research investigates the application of computational design and digital fabrication techniques in order to maximize the reuse of wooden structural elements without the need for remanufacturing, thereby reducing waste and carbon footprint.

Using the TU Delft modelling hall of the BK faculty, this study introduces a new approach that combines stock-constrained design with additive manufacturing. This approach utilizes 3D printing technology to create flexible, adaptable connections that accommodate the irregular dimensions of reclaimed wood, thus optimizing the use of available materials. The study evaluates the environmental impact through a life-cycle assessment. In the end it will compare the proposed method to the traditional construction practice and other methods that stimulate the reuse of wood.

The findings indicate that the proposed hybrid design methodology effectively reduces waste over the successive generations. However, the data also reveals that the carbon footprint has not yet decreased. Further research is necessary to identify the next steps for reducing carbon emissions and achieving a sustainable, zero-waste methodology. This study contributes to the body of knowledge by bridging the gap between theoretical design and practical application, offering a scalable model that can eventually be implemented in real-world scenarios to promote a circular economy in the building sector.

# Contents

# I. Introduction

## A. Context

Construction materials in the building industry are responsible for a significant share of total carbon emissions, contributing to climate change. Although wood presents a more sustainable option, its production is insufficient to meet the growing demand for construction materials. To increase the utilization of wood as a construction material, it is essential to address waste management issues and enhance the reuse of wooden structural elements. However, the reuse of these elements introduces design complexities due to a fluctuating stock that necessitates adapting to varying optimal geometries and complex connections. The extended design time and increased energy requirements further pose challenges to the widespread adoption of wooden structural element reuse.

## B. Problem statement

The reuse of wooden structural elements has not yet been widely adopted by the industry. A significant challenge faced by designers is the increased complexity brought about by a fluctuating stock compared to working with standard "off-the-shelf" elements. To address this challenge, digital stock-constrained design tools have been proposed. However, these tools introduce their own set of issues. They often result in complex compositions requiring irregular connections and create flexibility in the elements by resizing them, leading to saw-off losses. The remanufacturing required for saw-off and the production of customized connections deter designers from utilizing this waste stream.

From the background research conducted, the following problems have been identified:

- The construction industry operates as a linear economy, producing substantial waste and carbon emissions.
- The reuse of wooden structural waste elements is underutilized.
- An ever-changing stock of elements increases the complexity of the design process.
- Complex compositions often necessitate complex connections, adding to both design and manufacturing complexity.

## C. Objectives

Objectives:

- Create an alternative stock-constrained design tool that enables the extraction of essential information to further develop the connections.
- Develop a topology optimization method that can generate connections meeting the requirements of both design and additive manufacturing.
- Establish a streamlined workflow that optimizes structural design towards minimal footprint and maximum future reuse through efficient manufacturing processes.

To achieve these goals, this paper undertakes essential research to provide a comprehensive understanding of the root causes and propose strategies for achieving the set objectives. The following research question is attempted to be answered:

*"Can stock-constrained digital design combined with 3D printing support the reuse of wooden structural elements without saw-off losses in a sustainable way?"*

To answer this research question, the following sub-questions have been developed:

- What are the primary obstacles faced by designers in the process of reusing wooden structural elements?
- What prevents stock-constrained design tools from improving the reuse of wooden structural elements in the current environment?
- Can a rationalized connection between stock-constrained design and additive manufacturing of structural connections streamline the development of projects?
- How should this connection work to produce functional joints?

## D. Scope

Several factors impact the scope of this research paper. The most prominent ones are listed below:

1. **Structure type: Space frame**

To limit the scale of the study, the focus has been placed on space frame structures. Space frame structures are suitable for this research due to the high number of elements that are often of limited size. This variety allows for a wider range of configurations, making it ideal for testing stock-constrained designed structures.

2. **Case study: Modelling halls roof faculty of architecture TU Delft**

The roof of the modelling hall at the Faculty of Architecture, TU Delft, has been chosen as the case study. This selection further constrains the study by providing a real-life example, facilitating the investigation of its scalability potential. With this real-life example, it becomes possible to benchmark different scenarios against each other:

- The current situation
- New construction using new timber
- New construction using a combination of used and new timber with current stock-constrained design
- New construction using a combination of used and new timber with current stock-constrained design and structural optimization
- New construction with the newly developed workflow

3. **Additive manufacturing: 3D printing**

The additive manufacturing sector is rapidly evolving and introducing more alternatives. To maintain focus on answering the main research question, this paper will solely consider 3D printing. Among the various additive manufacturing techniques, 3D printing is the best-known and widely used. The availability of 3D printers at the Faculty of Architecture, TU Delft, makes it possible to test and validate the entire workflow of this research.

4. **Optimization objectives: Structural of quality and minimized carbon footprint**

There is a wide range of possible optimization objectives, both structural and environmental, which are of equal importance. Structurally, it is crucial that the generated structure stays within the desired limits set by the designer to produce a workable design. However, staying within these limits will suffice for this process. Additional objectives such as minimizing bending, minimizing elements, or maximizing element utilization will be left outside the scope of this research. Instead, to compare different variations, the carbon footprint will be the benchmark, measured in kilograms of CO2-equivalent. This will encompass all of the building's life cycle assessment (LCA) stages according to EN 15978.

## E. Approach & Methodology

The research will begin with a literature review, which will serve as a knowledge base for the design and manufacturing research. The purpose of the literature review is to build on existing knowledge, understand what has been previously done, and identify gaps to generate new insights. Existing research provides an understanding of the topic's complexity without needing to discover everything anew in this paper.

A comprehensive literature review will be conducted, focusing on key topics:

- Reuse of wooden structural elements
- Stock-constrained design
- 3D printing
- Typology optimization

*Design and manufacturing research*

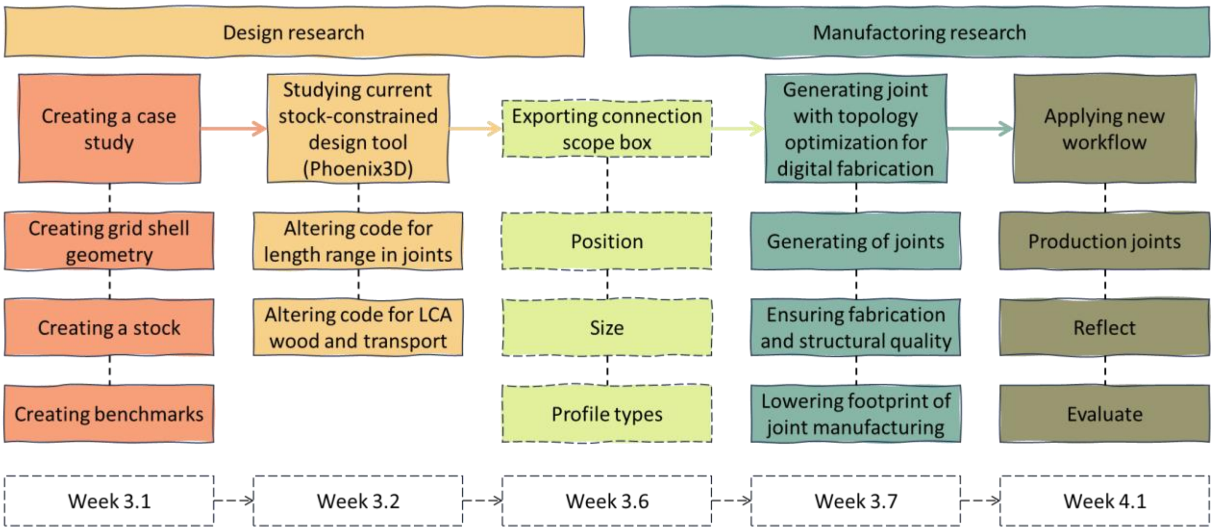



*Figure 1 – Workflow for conducting the research*

By designing and developing the proposed workflow it becomes possible to gather information about its functionality along the way. Each step offers an opportunity to validate the previous work by applying the created pieces of the workflow. The process will start with the development of the stock-constrained design tool. Using the created benchmarks, a feedback loop will be established to evaluate the impact of alterations. Once the desired changes are achieved, the next step involves data extraction necessary for creating the connections. This process will overlap with the stock-constrained design tool and the generation of the connections, as it is responsible for facilitating communication between the two. During the joint generation phase, the focus will be on ensuring functionality while minimizing the total footprint. Finally, the complete workflow will be tested and evaluated through both physical and digital testing.

# II. Significance of the Study

## A. Closing the knowledge gap between stock-constrained design and additive manufacturing

This study aims to integrate the fields of stock-constrained design and additive manufacturing. By combining these fields, their respective strengths can be utilized to compensate for their shortcomings. This integration will create a workflow that encompasses the entire project cycle from design to fabrication, addressing the previous obstacles related to the design complexity of structures using reused wooden elements.

## B. Advancing timber construction towards higher circularity levels

By mitigating some of the previously stated design complexities, it will become easier to reuse wooden structural elements with minimal quality loss. Preserving these wooden elements in future structures will prevent any form of waste streams, thus advancing timber construction towards higher levels of circularity.

## C. Potential impact on the building industry's environmental footprint

By closing the waste loop of wooden structural elements, the share of wood as a construction material can increase due to its regrowth potential. This increase could reduce reliance on concrete and steel, thereby lowering the environmental footprint of the building industry[*]. Additionally, reused elements can potentially compete with new elements by eliminating the need for the manufacturing process. Collectively, these factors should positively impact the environmental footprint of the building industry.

[*] *Considering the demand for construction materials is static*

# III. Background information

## A. Building Industry’s CO2 Emissions

### Contribution of structures to the CO2 footprint of the building industry

The construction sector, constituting 40% of primary energy demand, stands as the most resource-intensive industry across industrialized nations. It generates a significant portion of Europe's waste, approximately one-third, and contributes over a third of anthropogenic greenhouse gas emissions globally (*PEFCR_guidance_v6.3-2.pdf*, z.d.). These greenhouse gasses accumulating in our atmosphere are a primary driver of human-induced climate change, which has numerous negative outcomes, including habitat loss, sea level rise, ocean acidification, and increased frequency of extreme weather events such as heatwaves, hurricanes, and droughts. This is a significant concern for world leaders, as highlighted in the UN Brundtland Report, "Our Common Future," which defined sustainable development as: "development that meets the needs and aspirations of the current without undermining the aptitude of forthcoming generations to fulfil their personal needs” (*5987our-common-future.pdf*, z.d.).

To meet these sustainability goals, each country has set policies to reduce CO2 output, including within the building industry. Portland cement and steel each account for 6% and 7% of total worldwide CO2 emissions, respectively (Al-Ghalib, 2020, p. 6). This indicates significant potential for the construction sector to contribute to sustainability efforts. In addition to producing substantial CO2 emissions, the construction sector also generates considerable waste and consumes vast resources. Over the last century, while the global population increased by a factor of ~4, the usage of construction materials increased by a factor of ~42 (Krausmann et al., 2017).

The construction sector consumes the largest share of materials globally (*Global Material Flows and Resource Productivity*, z.d.; Groupe d’experts intergouvernemental sur l’évolution du climat, 2014), and this consumption is expected to further increase in the future (Fishman et al., 2016). The enormous environmental impact of construction is becoming increasingly apparent and unacceptable to many structural engineers, whose designs typically account for the majority of a building’s embodied carbon (Hawkins et al., 2021, p. 1).

### Reaction of structural engineering to climate change

In the structural engineering community, which acts as a steward of the built environment (Cocke, z.d., p. 7), there has been a focus on sustainability in two primary areas: construction materials and structural design techniques (Al-Ghalib, 2020, p. 6). The construction sector aims to reduce embodied carbon energy, particularly during the production of its two primary structural materials: concrete and steel (Al-Ghalib, 2020, p. 6). Additionally, efforts to further recycle materials or use alternative materials for construction contribute to lowering the footprint of future structures (Al-Ghalib, 2020, p. 6). However, the choice of time horizon for recycling or reusing materials is subjective and has ethical implications when comparing different alternatives (Hawkins et al., 2021, p. 95). However, the choice of time horizon for recycling or reusing materials is subjective and has ethical implications when comparing different alternatives (Al-Ghalib, 2020, p. 6).

Quality reuse plays a crucial role because although recycling processes reduce embodied energy, material reuse reduces it even more (Al-Ghalib, 2020, p. 7). Designers should aim to design without loss of quality and optimize their designs to facilitate future reuse. By applying the principles of the circular economy to the design and construction of structures, it is possible to reduce the building industry's impact on climate change (Stahel, z.d.).

## B. Potential of Timber Structures

### Renewable resource and potential for CO2 reduction

The focus on making the construction sector sustainable lies primarily in two areas: construction materials and structural design techniques (Al-Ghalib, 2020, p. 6). Besides concrete and steel, wood is another material used for structures. Wood has the advantage of being a renewable resource that captures CO2 during its growth. However, the choice of its time horizon is subjective and can have a significant impact (Hawkins et al., 2021, p. 95). Hoxha et al. (Hoxha et al., 2020) Besides concrete and steel, wood is another material used for structures. Wood has the advantage of being a renewable resource that captures CO2 during its growth. However, the choice of its time horizon is subjective and can have significant variations (Hawkins et al., 2021, p. 93).

However, wood remains a resource with a production limit before depletion. The broader potential impact should be considered before replacing concrete and steel with wood. Planting new forests may be appropriate in some locations, but competing land demands for food production, urban space, and biodiversity must not be overlooked (Hawkins et al., 2021, p. 96). Additionally, climate change is expected to increase the frequency and severity of natural disasters such as wildfires, disease, insect attacks, and wind damage to forests (Hart & Pomponi, 2020). These uncertainties put more pressure on the future production of wood, making it unrealistic to simply replace concrete and steel with wood while meeting the building industry's demands. However, if wood is reused more effectively and can serve multiple life cycles, its share in the building market can increase. The advantages of reusing wood are promising and should not be overlooked. In 2010, 17 million tons of wood from C&D waste was available for recovery in the United States alone (Falk & McKeever, 2012).

Deconstruction and reclaiming wooden elements have the potential to reduce greenhouse gas emissions from the construction sector by (a) making more construction elements available to the market and (b) reducing the quantity of new materials extracted for new construction projects. Additionally, reusing wooden elements in future structures prevents greenhouse gases that would have been generated during manufacturing and disposal (Diyamandoglu & Fortuna, 2015, p. 22). Thus, timber building structures are likely to have smaller short-term climate impacts than concrete and steel equivalents. Over the longer term, carbon sequestration can further reduce the impact of long-lived timber structures due to replanting and regrowth of harvested trees (Hawkins et al., 2021, p. 96). However, to achieve this, the design system must allow for full dismantling and reclamation while maintaining quality so that the materials can be reintegrated into new products (Al-Ghalib, 2020, p. 6).

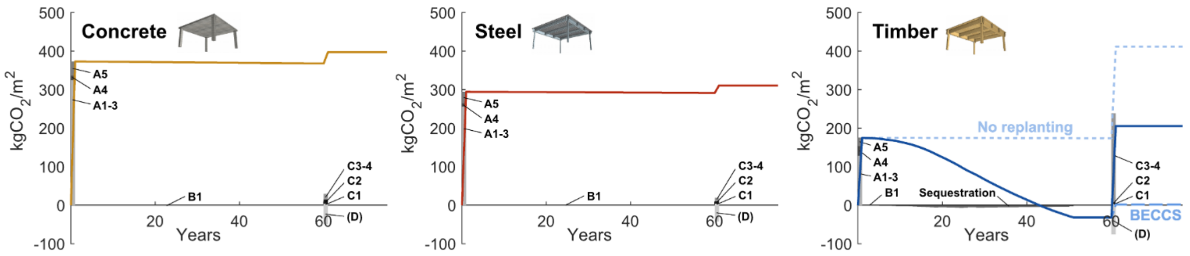



*Figure 2 Cumulative cradle-to-grave CO2 emissions for equivalent concrete, steel and timber buildings based on designs from a previous study carried out by Buro Happold, source: (*case-study-embodied-carbon-routes-to-reduction-20200406.pdf, *z.d.)*

## Government initiatives promoting reuse in construction

To stimulate the building industry towards a sustainable future, various government policies and initiatives promote the reuse of construction materials and cleaner construction practices. The European Union (EU) pushes for greater reuse of building components as a sustainable movement (Didier, 2018). Additionally, timber that is not sustainably certified has been made illegal to trade in the EU due to the European Union Timber Regulation (EUTR) (Hawkins et al., 2021, p. 93). This is part of the EU's transition towards a circular economy, seen as a solution to achieve a sustainable economy (*A New Circular Economy Action Plan*, z.d.).

Although there is no universally agreed-upon definition of a circular economy (Kirchherr et al., 2017), it generally aims to keep manufactured goods in circulation as long as possible through closed loops, which include repair, reuse, and recycling (Brütting et al., 2019). In this way, the circular economy maintains economic growth while limiting the input of new materials, waste production, and manufacturing processes (Savini, 2019, p. 675). However, the circulation of waste materials has been fragmented and unbundled (Graham & Marvin, 2001, p. 33). This fragmentation has made waste processing costly and unable to compete with primary materials, rendering waste processing largely unprofitable (Davoudi & Sturzaker, 2017). Recycled materials have remained secondary to primary materials partly due to their lower quality (Savini, 2019).

Reusing structural components outperforms recycling in this aspect. When detailed correctly, reuse allows the same structural elements to be used repeatedly (Al-Ghalib, 2020, p. 6). Reuse, unlike recycling, extends the service life of the component rather than the material, preventing the manufacturing process and the creation of additional waste while maintaining quality (Baker-Brown, 2019; Ghyoot et al., 2018). One way to facilitate the reuse of structural components is through the development of "circular construction hubs" by companies and governments (Tsui et al., 2023). These hubs collect, store, and resell building components (Marin et al., 2020).

By storing structural elements from deconstruction in circular construction hubs, it becomes possible to match supply and demand. Some elements from urban mining processes might not be needed for a year within the region, but storing them for longer periods increases the odds of finding a second function. This perspective is mainly adopted by demolition companies and their partners (Tsui et al., 2023). By storing structural elements from deconstruction in circular construction hubs, it becomes possible to match supply and demand. Some elements from urban mining processes might not be needed for a year within the region, but storing them for longer periods increases the odds of finding a second function. This perspective is mainly adopted by demolition companies and their partners (*TNO_2018_bouwlogistiek.pdf*, z.d.). Circular construction hubs have also gained geopolitical interest by decreasing dependency on the global market, a risk highlighted during the COVID-19 pandemic (Wuyts et al., 2020). Combined with sustainability advantages and job creation, circular construction hubs are mentioned in government strategic documents at provincial (*Actieagenda Circulaire Economie 2021-2025.pdf*, z.d.; *CW_-_Bijlage_3_CircE-actieplan_(PS2019-749).pdf*, z.d.; *Metabolisme-Noord-Nederland_20190131.pdf*, z.d.) and municipal levels (*Circular-Rotterdam-Report_23.11.2018.pdf*, z.d.; *strategie-amsterdam-circulair-2020-2025.pdf*, z.d.) in the Netherlands. Integrating circular construction hubs into the Dutch economy will assist the Dutch government in achieving a 50% reduction in primary material usage by 2030 (*klimaatakkoord.pdf*, z.d.).

## C. Challenges in Timber Element Reuse

### Limited stock and predetermined profiles

Despite efforts to better reuse existing wooden structural elements, the building industry still faces significant challenges before achieving desired sustainability outcomes. For instance, in the UK in 2022, 63% of all wood waste was used as biomass, 24% was recycled, 21% was exported, and only about 0.5% was reused (Smulian, 2023). Reuse can complicate various construction stages—design, assembly, and disassembly—all of which affect the quality of structural elements maintained into their next service life (De Wolf et al., 2020, p. 9).

Some current wood products, such as timber-concrete composite floor systems, have irreversible adhesive interfaces with non-timber materials, making them harder to reuse as wood (Hart & Pomponi, 2020). Another reason for the low level of wood reuse is the lack of information about potential reclaimed elements. Circular material hubs require details on wood quality, applied processes, and secondary products (Marin et al., 2020, p. 15). Currently, the quantity and quality of wood in existing building stocks can only be measured during construction or demolition, with future material supply only estimable (Sprecher et al., 2022, p. 2). The development of material passports could overcome these challenges in the future (Durmisevic, 2019; *Madaster-Press-Release.pdf*, z.d.).

However, increased design complexity due to imperfect "demand-supply" coordination remains a significant challenge. These gaps between supply and demand could persuade designers to prefer new materials over reuse (Gorgolewski, 2008a). Circular construction hubs can help mitigate this problem by storing elements between life cycles (Ghyoot et al., 2018), but designers will still be limited to current stock items. Designers need to become more flexible in working with an ever-changing stock instead of relying on "off-the-shelf" components. Computational tools designed to handle these complexities can help designers overcome these obstacles without losing productivity (Gorgolewski, 2008b).

*Figure 3 Reclaimed timber out of housing, source: (*Circulair bouwen*, z.d.)*

## D. Parametric Stock-Constrained Design

### Role in improving timber element reuse

As discussed in the previous chapter, designing with used structural elements differs from traditional structural design. In traditional design, structural elements are produced or purchased to meet the needs of the structural layout. In contrast, design for reuse involves creating typologies and geometries that make the best use of available structural elements. Traditional design methods prove inefficient or slow in such cases, often requiring extensive trial and error to devise workable designs or sometimes failing to find solutions altogether (Bukauskas et al., 2017). Depending on whether the stock's quantity and quality can fully satisfy the designer's needs, a hybrid of old and new elements may be used to obtain a structure with the lowest carbon footprint (Warmuth et al., 2021). To optimize the end result while complying with design requirements, certain boundary conditions and constraints are applied (Rozvany, 1992).

The process starts with creating a stock to work with. Digitalizing a stock of reclaimed timber elements as 3D models can be done using LIDAR techniques (Hackenberg et al., 2015). Reclaimed timber may have damage or irregularities, such as different profiles at the start and end, twisted components, or gaps. The structural behaviour of this representation can be easily analysed using finite element methods by treating each edge as a linear beam element with stiffnesses corresponding to the cross-sections defined at its adjacent nodes (Bukauskas et al., 2017).

To assist designers in matching finite sets of diverse structural elements into a functioning structural form, computational tools can be utilized (Bukauskas et al., 2017). This approach significantly reduces the designing time and complexity by leveraging computational power, thus removing a significant obstacle to designing with used structural elements. Phoenix 3D is an example of such computational tools (*StructuralXplorationLab/Phoenix3D*, 2021/2023), enabling designers to work with an interactive and parametric stock-constrained design workflow and visualize the results in the Rhino/Grasshopper environment (Robert McNeal & Associates, z.d.).

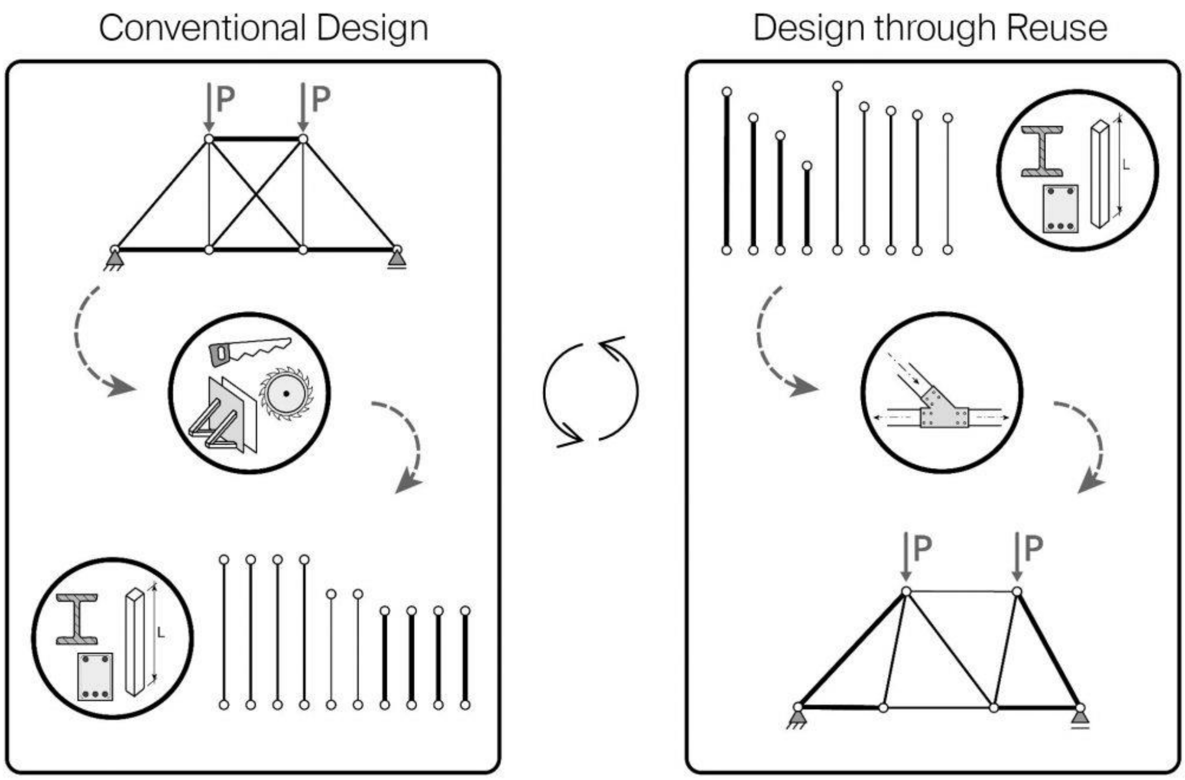



*Figure 4 Conventional design compared to stock constrained design, source: (*Phoenix3D*, z.d.)*

## Limitations of parametric stock-constrained design connections

Stock-constrained optimization design tools like Phoenix 3D currently search for elements of equal size or larger, resulting in some saw-off losses Consequently, some structural elements lose technical quality before entering their next service life. Additionally, impacts of refurbishment, storage, or creating the connections for the structure have been left out, assuming the impact would be minimal. Thus, only the elements used in Phoenix3D contribute to the calculated environmental impact (Brütting et al., 2019, p. 131).

Additionally, stock-constrained design often generates uncommon connection shapes. Conventional manufacturing methods for joints in traditional projects rarely accommodate these shapes, leading to high costs or ineffective resource usage (*Research on topology optimization of cross joint based on bionic substructure - CNKI*, z.d.; Zhang et al., 2021). The complexity of joint craftsmanship restricts common joinery to flat or right angles between pieces of wood, rarely connecting more than two elements in a single connection (Magrisso & Zoran, 2019, p. 442).

The design of the connection significantly influences the future reuse of structural elements, affecting the complexity of assembly and disassembly, the time required for reclaiming elements, and the quality of reclamation, which uses minimal drilling or cutting to maintain the highest possible quality

(Ma et al., 2021). Designing joints that do not damage structural elements and can fill in any missing lengths to prevent saw-off losses can keep structural elements in circulation longer, thereby lowering the overall footprint of the building industry. To make stock-constrained design sustainable and achievable, a link should be formed between design and manufacturing. This workflow should include missing information about the footprint and structural achievability, allowing for comparison with traditional construction.

## E. Introduction to 3D Printing in Construction

### Why to use 3D printing in construction

3D printing, also known as additive manufacturing (AM), is anticipated to play a significant role in the 4.0 industrial revolution and is advancing at a phenomenal rate ('Present and Future of 3D Printing', 2021). The phrase "complexity is free" often describes the main advantage of AM, allowing designers to produce any kind of geometric form without the constraints of traditional manufacturing, which is unfit for mass customization (VietnameseGerman University,, Vietnam, 2019, p. 27). Although AM was primarily developed as a tool for prototyping, it is gradually taking on a more significant role in several production processes (Felek, z.d.). 3D printing technology uniquely integrates design and manufacturing by effectively communicating between the digital and physical worlds (Han et al., 2022).

While most studies agree that AM can be more sustainable compared to traditional manufacturing, the extent of this benefit varies depending on its usage. When mass production is possible within the construction industry, the benefit is only marginal (*Sustainability and Environmental Impact of Fused - ProQuest*, z.d.; Tinoco et al., 2022). Larger objects, in particular, are not suitable for AM alone. Using a hybrid or heterogeneous system that combines other elements with the help of AM would be interesting (Jacobson, 2019). This approach is especially promising when combined with the prospect of enabling the use of reclaimed wooden structural elements in a new system. Exploring the possibility of combining 3D printed joinery with parametric stock-constrained design can bridge the gap between design and manufacturing.

*Figure 5 3D printed connection in wooden structure, source: (*3D-Printable Connectors Make DIY Furniture Assembly Easy - WebUrbanist*, 2014)*

## F. Topology Optimization in 3D printing

### Why topology optimization?

Traditional joint design heavily relies on the designer's expertise, resulting in high time and energy consumption (Y. Wang et al., 2021). This is especially true when each joint in a structure is unique, as often occurs in parametric stock-constrained designs. Additionally, engineers often use more material than necessary, leading to excessive mass and suboptimal geometric design. To address these issues, several researchers have explored optimization designs for joints using topology optimization methods (Galjaard et al., 2015; Huang & Xie, 2010; L. Wang et al., 2020).

Topology optimization aims to achieve the optimal distribution of material within a design domain (Bendsøe & Sigmund, 2004). This method determines how material should be distributed within a domain to form the most efficient structure (Sigmund & Maute, 2013). Using computational tools, topology optimization can generate shapes that meet specific requirements (Naboni et al., 2018). It enables the creation of designs with the minimal possible material footprint, based on geometry, material properties, applied forces, and fabrication methods.

Despite its benefits, topology optimization is less prevalent in architecture than in other fields (Selmi & İLeriSoy, 2022). Given the construction industry's increasing pressure to use materials more efficiently for sustainability, adopting this technique seems logical. In addition to reducing material usage, it could potentially streamline the design process, especially once fully automated, reducing the designer's workload. For complex, small-scale objects, computational power can offer a faster alternative. Researchers recommend a closer integration between optimization and fabrication procedures to streamline design, analysis, and fabrication stages (Aage et al., 2015; Søndergaard et al., 2016).

## G. Challenges in Fabrication of 3D Printed Timber Connections

### Material choice and fabrication method

Common materials for 3D printing include PETG, ABS, and PLA (Kumar et al., 2022). However, the 3D printing industry offers a wider range of materials, such as carbon fiber and steel. This list of usable materials continues to grow, each with distinct structural properties, carbon footprints, and end-of-life scenarios. Thus, the selection of filament type significantly influences the circular economy of filaments (Zhu et al., 2021).

This research will use PETG as the reference material. The choice is driven by its availability in the LAMA lab and the extensive literature on its behaviour in 3D printing. Understanding material properties is crucial to predict product performance and prevent design failures (VietnameseGerman University,, Vietnam, 2019). PETG has a lower carbon footprint compared to PLA due to its recyclability to a material level and the significant water usage in PLA production (Kumar et al., 2022). PETG’s ability to be recycled back into infill material enhances its post-service functionality, allowing the creation of new joints or products from used ones. The process can further improve by using cleaner energy sources (Kumar et al., 2022).

Besides material selection, the choice of fabrication method is equally important. It determines parameters such as binding strength of layers, design freedom, accuracy, and more. This research will use Material Extrusion for printing, a common technique available in the LAMA lab. This method affects the final product's strength due to the direction of the printed layers (Dickson et al., 2020). Additionally, the accuracy and strength of the final product are influenced by printing parameters such as build orientation, layer thickness, scan path and speed, and temperature (Zhou et al., 2013). Given the extensive range of parameters and the research's time constraints, translating these factors into the process will be deferred for further research. Nevertheless, it is important to consider their impact and role in the process.

# IV. Implementation

## A. The TU Delft modelling hall

After the former Faculty of Architecture burned down in 2008, an existing university building was selected for renovation and refurbishment to serve as its replacement. To expand the functionality and capacity of this building, two lightweight glasshouses were added in between the empty spaces of the building. The system comprises a lightweight steel spaceframe on a grid of 2,7 by 2,7 meters (*Faculty of Architecture TU Delft*, z.d.).

*Figure 6 TU Delft modelling hall, source: (*Faculty of Architecture TU Delft*, z.d.)*

This spaceframe was chosen as a case study to provide a reference for the structural capabilities required. Additionally, it narrows the research to one specific structural type: a spaceframe. Spaceframes consist of many smaller elements and have connections that can join up to eight elements. This structure is ideal for research that relies on many irregular or short elements, which create complex compositions and connections. In such a structure, computational design and digital fabrication can significantly impact the time required to design an altered structure to fit the available stock and the design and production of unique connections.

## B. The artificial stock

This research assumes the availability of a digital stock of timber elements derived from circular material hubs. By accessing these digital stocks, different options can be compared to determine the lowest footprint based on distance and compatibility. Unfortunately, such digital libraries do not yet exist. Ideally, a fully automated system utilizing LIDAR techniques would make irregular components accessible. For the purposes of this research, an artificial library will be created, which can be replaced when such a system is developed.

To simulate a scenario where such a stock exists, it is essential to make the artificial library as realistic as possible. This means the stock must contain similar irregularities to those found in a real scenario. Transportation costs will be excluded from this research. For this study, the carbon cost of transportation will be assumed equal for both new and reused elements, as the origin cannot be determined yet. This exclusion will influence the results, but it is expected that scale advantages will minimize the impact on the overall conclusions. Future research is necessary to verify this assumption.

## C. Raised roof structure

When designing a structure, certain external forces must be considered, as they will shape the final design. The loads can be split up into two categories: dead load and live loads.

Dead load is the constant load exerted on the structure by gravity. In the case study, this includes the weight of the elements used and the roof itself. According to the Eurocode, for a roof not used as a terrace, a load of 1 kN/m² per 10 m² should be considered. Although the overall roof load can be lower, most designers still use a load of 1 kN/m² (Arends, 2017). This value will also be used in this research.

Live loads are the variable loads a structure experiences during its service. For the case study, these include snow loads, wind loads (in the form of suction), and maintenance loads. Snow and wind loads are location-dependent, with Delft being the reference location for this case study. The maximum snow load for the Netherlands is uniformly set at 0.7 kN/m² (Arends, 2017). For suction and maintenance, values of -0.4 kN/m² and 0.4 kN/m² are chosen, respectively, as these are commonly used values (*Guidelines for calculations for Technoledge.pdf*, z.d.). Determining the exact values for the modelling hall was deemed too resource-intensive and not essential for the scope of this research."

These loads are combined into scenarios where multiple forces act simultaneously. The largest of these five load cases will determine the highest stress levels the roof will experience.

*Examples of the common stress-driven load cases for the roof used in the research, following Ultimate Limit State design (ULS):*

- *LC1 = 1.4 Fweight*
- *LC2 = 1.2 * Fweight + 1.5 * Fsnow*
- *LC3 = 1.2* Fweight + 1.5 * Fmaintenance*
- *(in a roof that there is a walkway for maintenance)*
- *LC4 = 1.2* Fweight + 1.2 * Fsuction + 1.2 * Fmaintenance*
- *LC5 = 1.2* Fweight + 1.5 * Fsuction*

## D. Materials and their properties

Multiple materials will be used in this research. Their mechanical properties are essential for both structural analysis and topology optimization for 3D printing, driven by the loads they experience. These mechanical properties include: Poisson's ratio, density, and Young's modulus. For the carbon footprint analysis, the carbon emissions of every step in the life cycle must be known. These steps are: extraction, processing, and recycling or end-of-life. Besides carbon emissions, energy and water usage are also considered. These factors are crucial for later explaining the carbon footprint.

It is important to obtain all of this data from the same source to ensure consistency in the calculations, allowing for accurate comparison of materials. For this purpose, the Ansys database of EduPack 2023 was accessed, as it contains all the materials and necessary data for this research.

## E. The scenarios

To create a reference point for the newly designed structure, several scenarios will be developed for comparison. There will be five scenarios in total, each containing one alteration compared to the previous one. This approach will provide an overview of the impact of each individual design decision.

**Scenario 1**

Scenario 1 represents the current situation in the modelling hall of TU Delft. It consists of steel bars interconnected with steel connections in a raised roof structure. The steel is new, and there are no plans for its end-of-life management.

**Scenario 2**

Scenario 2 will use wood instead of steel. This first design alteration will illustrate the effect of the different material choice. The connections will remain the same, and there are no plans for end-of-life management for this structure either.

**Scenario 3**

Scenario 3 will be constructed from reclaimed wood, while maintaining the same design. This introduces saw-off losses as waste. The connections remain unchanged, and the end-of-life plan involves reusing the wood in a similar fashion, assuming the same saw-off losses.

**Scenario 4**

Scenario 4 also uses reclaimed wood, but the design is optimized to fit the available stock, reducing saw-off losses. There is still waste, and the connections remain the same. The end-of-life plan is similar to its production, with the wood being reused in a similar fashion and assuming the same saw-off losses.

**Scenario 5**

Scenario 5 is the newly proposed method. Here waste is refused and instead compensated by the 3D printed connection. The structure is optimized to use as much available length as possible, reducing the length of the printed parts. There is no saw-off in this scenario. It is assumed that the wood will be reused in the same way the structure was built.

Each scenario will be measured using life cycle assessment (LCA) that includes energy, water, and carbon metrics. Additionally, the total amount of waste generated during construction and after the service life will be measured.

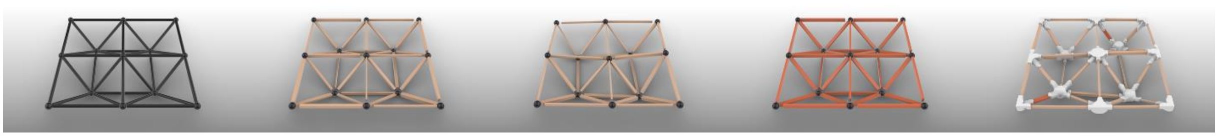


*Figure 7 Visualization scenario 1 to 5 for the research, source: own work*

## F. Programs used

To automate the workflow and design the suggested method, a programming software is required. This research will focus exclusively on Grasshopper and several Grasshopper plugins. Grasshopper is a popular platform, easily accessible to students (Selmi & İLeriSoy, 2022), and offers multiple plug-in that are essential for this research.

The Phoenix plugin provided several papers on stock-constrained design and its implementation, serving as an inspiration for this research. The Phoenix 3D plugin will be used to simulate current stock-constrained designs and will serve as one of the benchmarks for this research. If this benchmark is not sufficient, a custom stock-constrained design tool will be developed using Python within Grasshopper.

For topology optimization of the connections, the tOpos plugin has been chosen. According to Selmi & IleriSoy (2022), tOpos offers the most realistic outcomes prepared to the other plugins. If tOpos does not perform as expected, alternative plugins such as Millipede will be considered.

Finally, the EPiC plugin will be utilized for parametric life cycle assessment (LCA) of the materials used in the study. Although EPiC provides its own library, it also allows for the manual creation of materials. For this research, the latter option was chosen because EPiC did not include all the materials used in the study. To ensure consistency in LCA calculations, all materials will be manually added using data from EduPack 2023, as previously described.

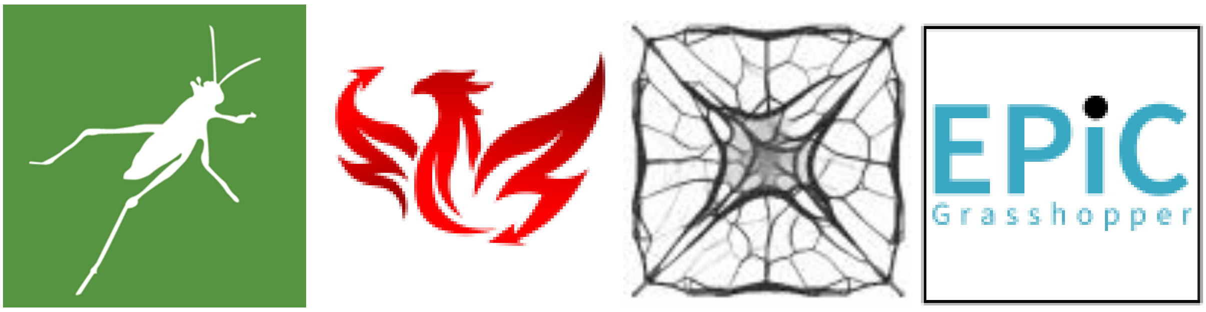
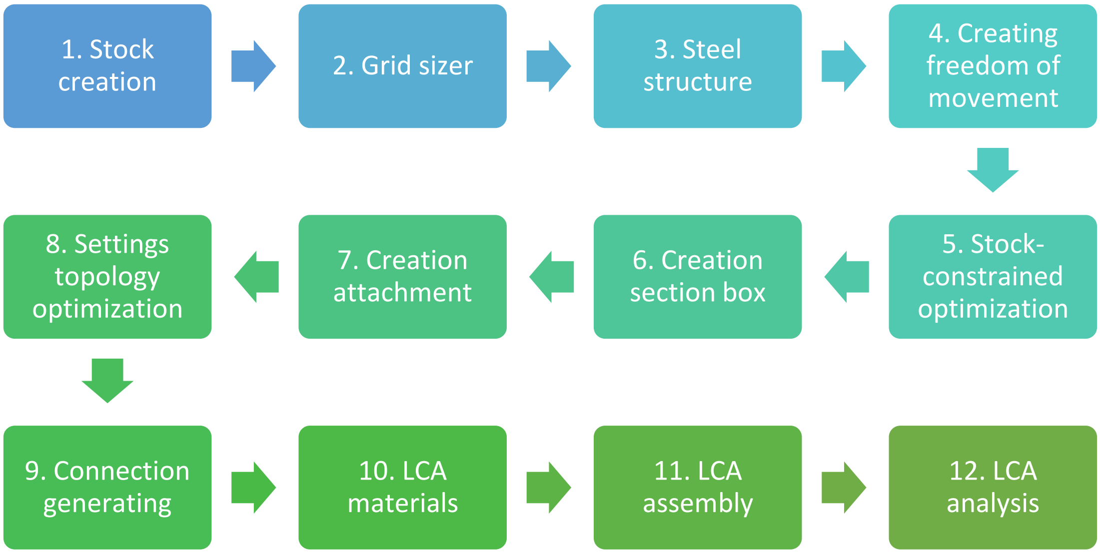



*Figure 8 Grasshopper logo, source: (*EPiC Grasshopper*, 2022;* Grasshopper*, z.d.;* Phoenix3D*, z.d.;* tOpos*, 2018)*

# V. The workflow

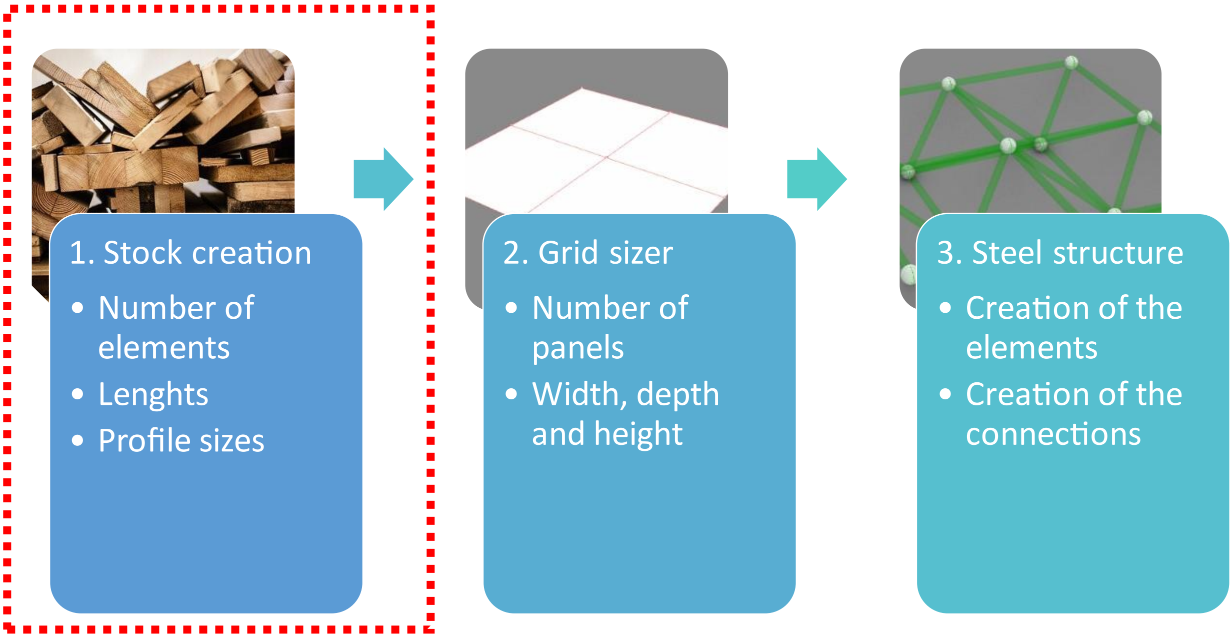
## A. Introduction

The workflow that was created in order to conduct the proposed research consist out of 12 steps: from stock creation to LCA analysis. In the following chapters each step will be discussed and explained.



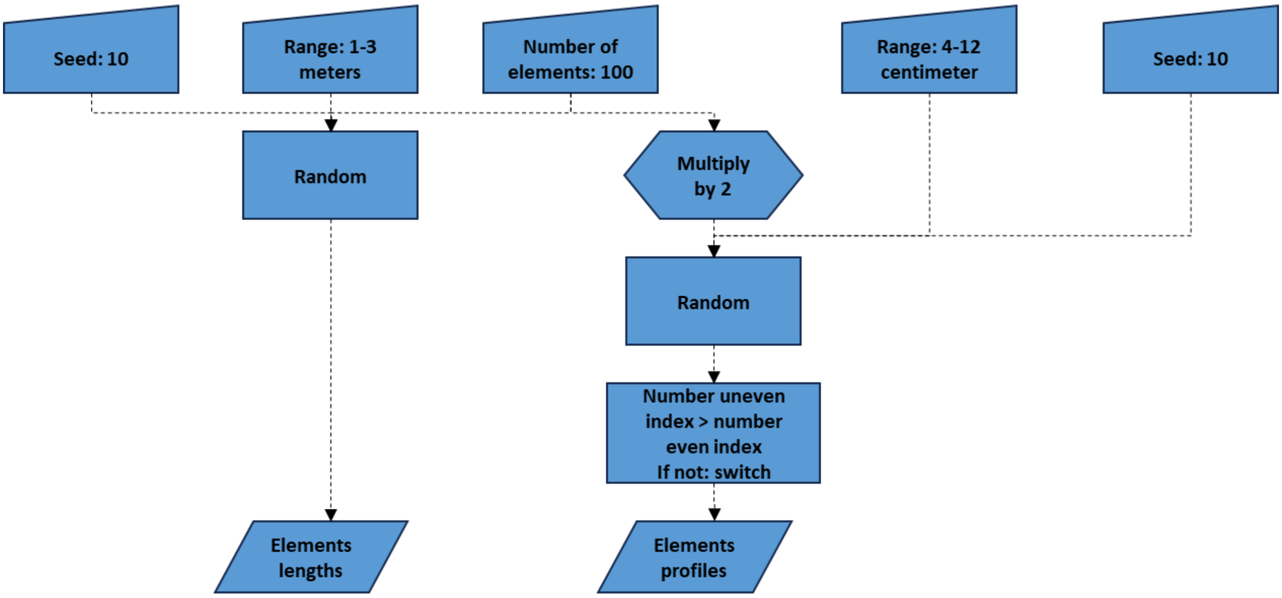

*Flowchart 1 The 12-step workflow overview, source: own work*

## B. Stock creation




When working with a stock-constrained design tool, creating a digital stock is essential to obtain meaningful results. Ideally, this would consist of a library of 3D digital copies of the actual members available within circular material hubs. However, for this to work, each member must be individually measured and registered in a database. Unfortunately, such a circular material database does not currently exist. Therefore, a component was created to simulate such a database in a way that is expected to behave similarly.

**Random stock generator**



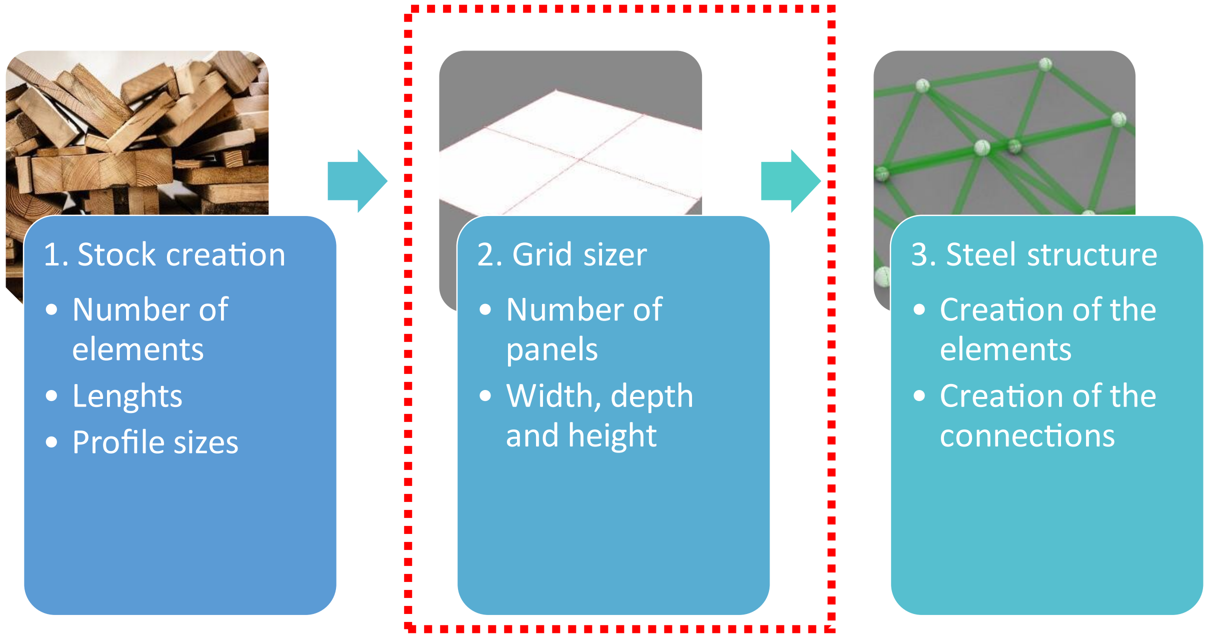

*Flowchart 2 Visualization of the random stock generator Grasshopper, source: own work*[*]

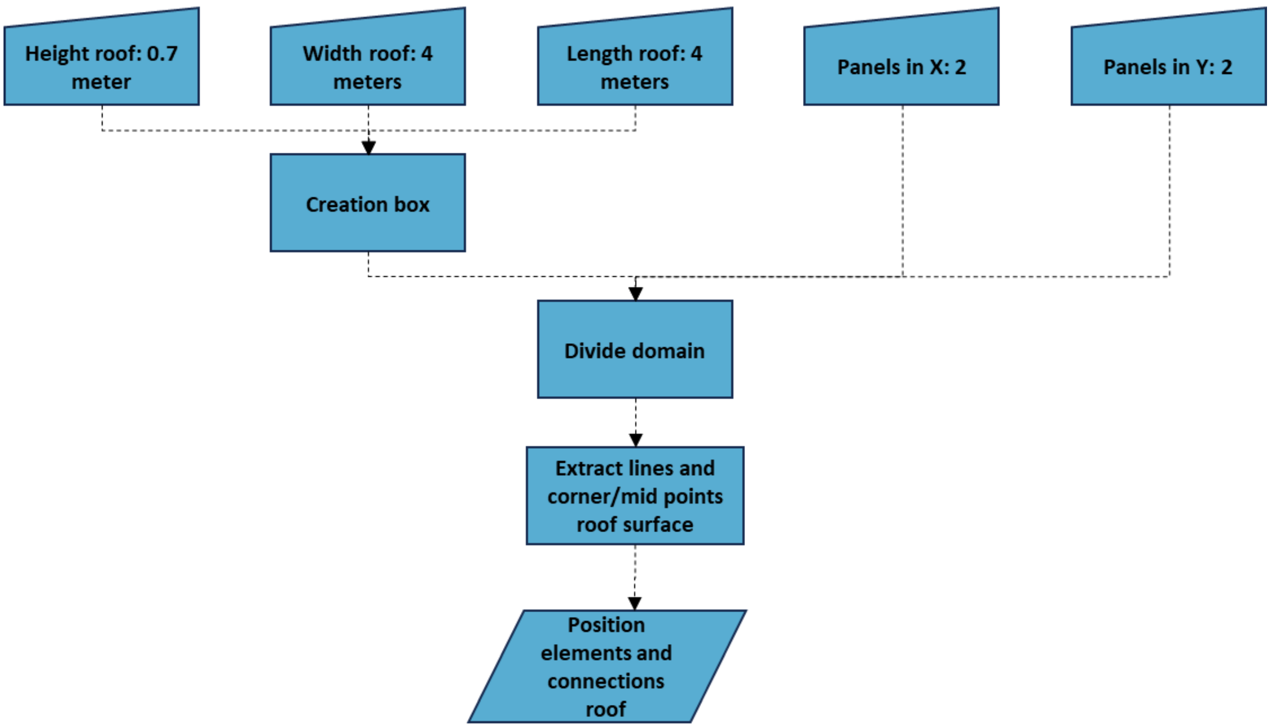
The random generator uses the random component in Grasshopper. By providing it with a range and number of elements, it generates a specified number of unique elements. For this study, 100 components were generated with lengths between 1 and 3 meters. By changing the seed number, different scenarios can be tested without manually altering any of the lengths.

This approach creates a stock with the uniqueness expected from reclaimed timber. This irregularity would typically pose significant challenges in a traditional design process but offers a potential stock that traditionally would not be used. The same process is used for creating the profiles. The only difference is that for rectangular profiles, two numbers are required. To ensure that the height of the profile is always larger than the width, a Python component was used to switch the numbers if the second one is larger.

[*] *The legend for how to read the workflows can we found in appendix D*

## C. Grid sizer




*Flowchart 3 Visualization grid sizer within Grasshopper, source: own work*

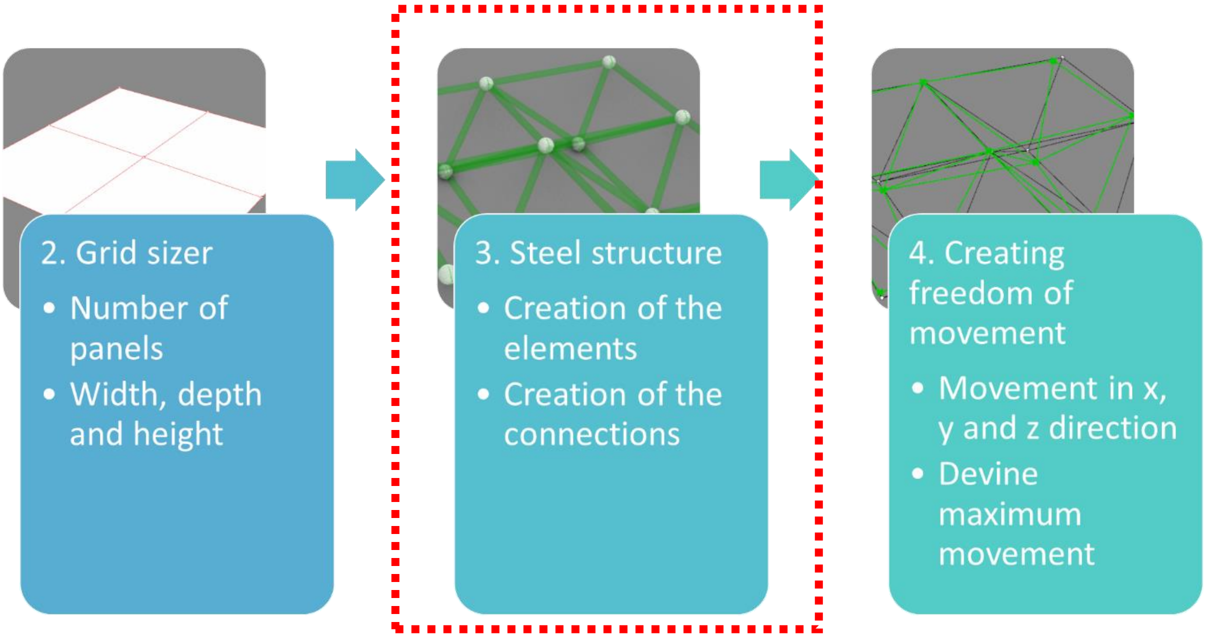
**Small scale model of 4 panels**

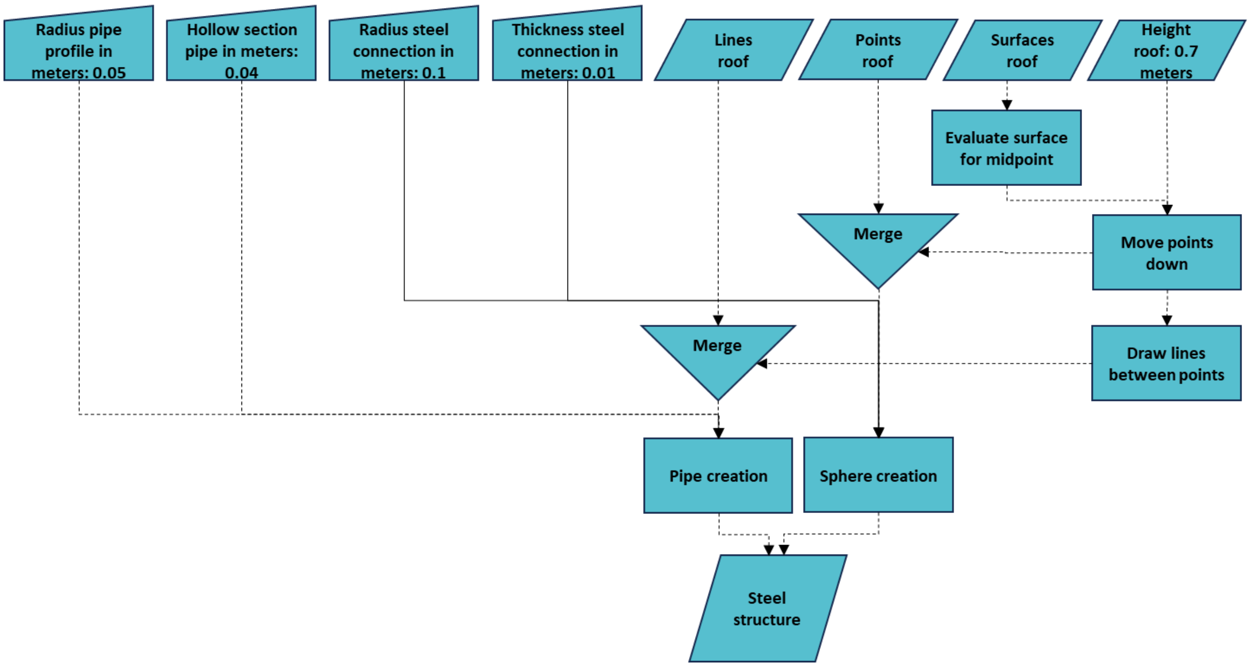
To limit the computational power required during the research, a small structure consisting of 4 panels was created. This structure requires 32 elements and 13 connections and includes all types of connections potentially present within a raised roof structure, combining 3 to 8 elements. The assumption is made that if the research is successful for a small structure, it will also be applicable when scaled up. Further research is needed to determine if the effects on larger structures with more variables are indeed similar, due to time constraints.

**Input sizes and height**

To create a raised roof structure, the height, total width, and total depth are first required. This roof surface can then be used for panelization, which in this research will be limited to a 2 by 2 grid for the beforementioned reasons. This approach can later be used by designers to create their own structures.

## D. Creation of original structure






*Flowchart 4 Visualization of steel structure within Grasshopper, source: own work*

Using the created points from the panels and a CenterPoint, it becomes possible to create a standard structure by drawing lines in between them. From this standard structure, the first two scenarios required for this research can be developed:

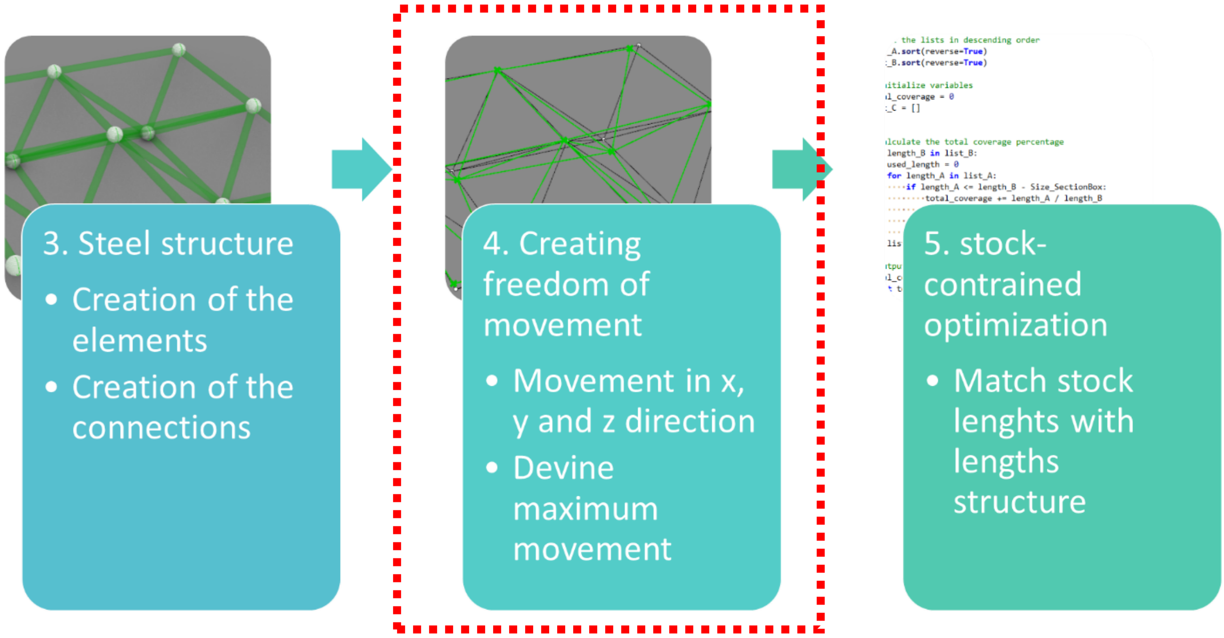
**Structure out of steel (scenario 1)**

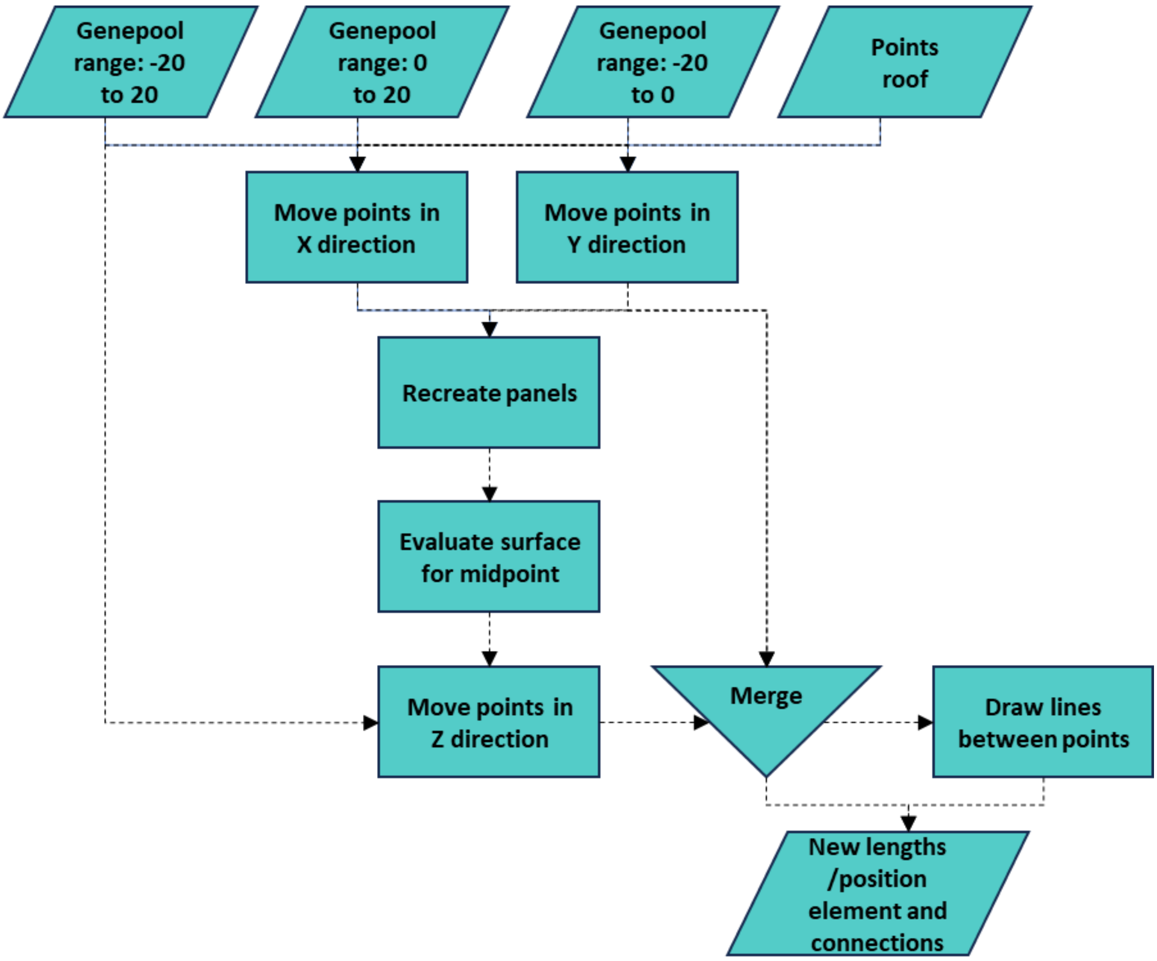
The first scenario will feature a structure made of steel, commonly used in raised roof structures, including the modelling hall of the Faculty of Architecture at TU Delft. This scenario will serve as the initial benchmark against which all alternatives will be compared. The estimated size of the profiles from the modelling hall is a 5-centimeter radius for the pipes and 10 centimetres for the connections. The measurements were performed near the orange staircase to approximate these dimensions. Through email contact with Peter van de Rotten (from Octatube) it was mentioned that the current steel structure weighs around 30 kg/m$^2$. With some trial and error, the ideal thickness for the steel components became 4 millimetres since this get the total weight the closest to the ca 30 kg/m$^2$.

**Structure out of new wood (scenario 2)**

The second scenario will illustrate the impact of using a different material for the structure. By changing only the material, it allows for a clearer understanding of the influence of this alteration. This structure will use virgin wood with steel connections.

## E. Creating flexibility in the structure




*Flowchart 5 Visualization of creating flexibility in the structure within Grasshopper, source: own work*

**Why creating flexibility in the structure?**

By not fixing the structure into a single composition but adding parameters that allow the structure to adjust the positions of its connections, it becomes possible to influence the lengths within the structure. Iterating through these parameters generates different lengths that are either closer to or further from the available stock lengths. By measuring these differences, optimization can be achieved using the Galapagos component.

**Height of the roof is set, underneath can change**

In theory, it is possible to give all joints freedom of movement in the x, y, and z directions. However, since the roof of a raised roof structure is most likely to be a flat surface, it was decided to constrain movement in the z direction for the roof. Limiting this movement also decreases the number of possible variations and reduces calculation time. The lower part of the structure, which is often freestanding, retains freedom of movement. However, in a real structure, some points might be attached to a support, and their movement should be restricted accordingly.

**Origin of the node always in the middle of the panel**

The raised roof structure can be envisioned as a series of upside-down pyramids attached to each other. To prevent the tops of these pyramids from extending outside the changing base structure, the centre point of the surface will always be the origin for the top of the pyramid. This ensures the point of the pyramid remains in its structurally most effective position, maintaining the integrity of the structure.

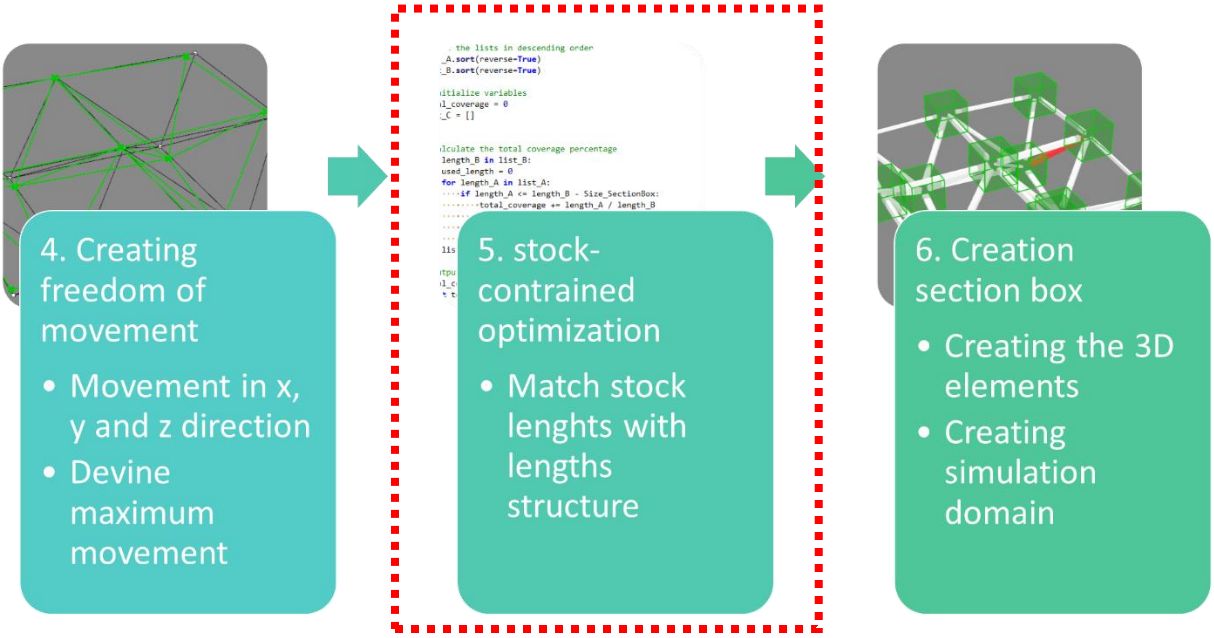
**Restrictions for movement in the edges**

To keep the structure within the designated surface, the movement of the connections at the edges must be restrained. This means the corners have only one-fourth of the total freedom of movement, and the edges have half the freedom of movement. This restriction decreases the number of variations and reduces calculation time by eliminating some possibilities.

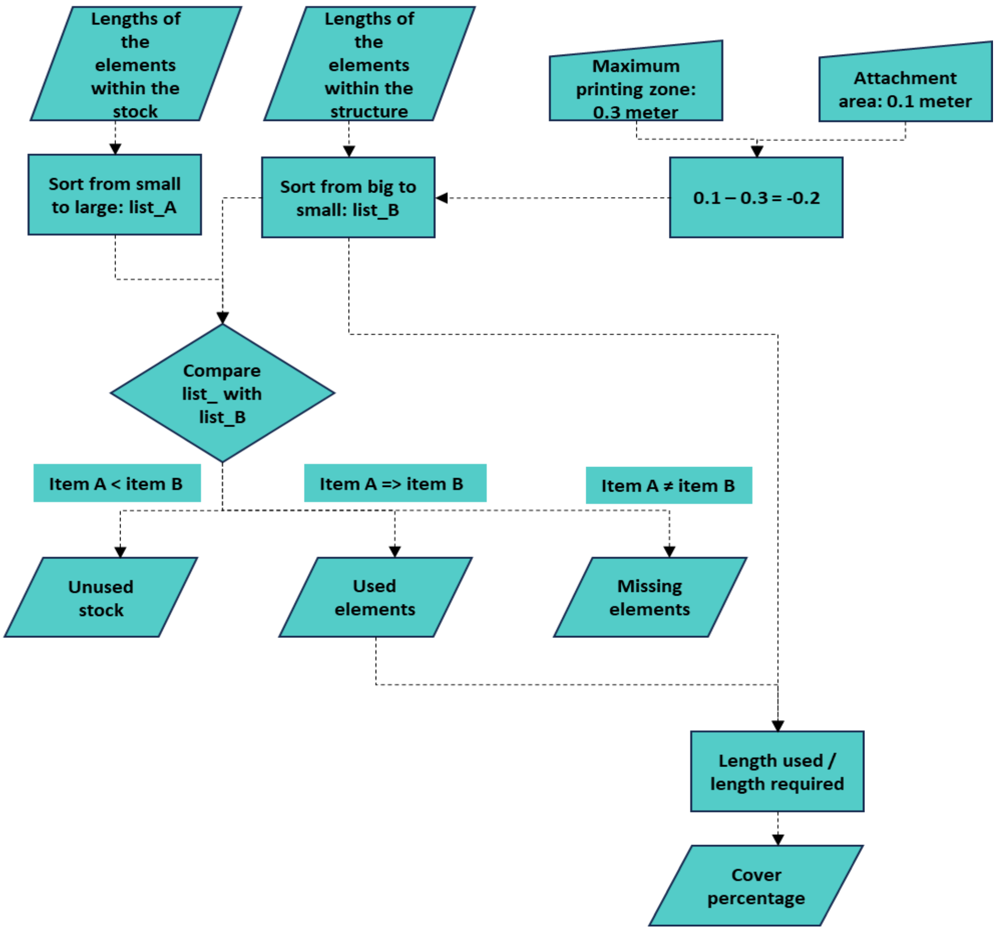
**Splitting the gene pool in three**

The beforementioned restrictions lead to three types of gene pools: a positive parameter, a negative parameter and a hybrid parameter. Initially, only one gene pool was used, with restrictions enforced by a Python command that made all numbers negative or positive where necessary. However, by splitting it into three gene pools, it was possible to eliminate some combinations altogether, rather than creating duplicates. This approach provides a more organized overview and reduces calculation time, making it a better solution for the research.

## F. Stock-constrained optimization




### Saw-off to create original structure (scenario 3 – reused wood)



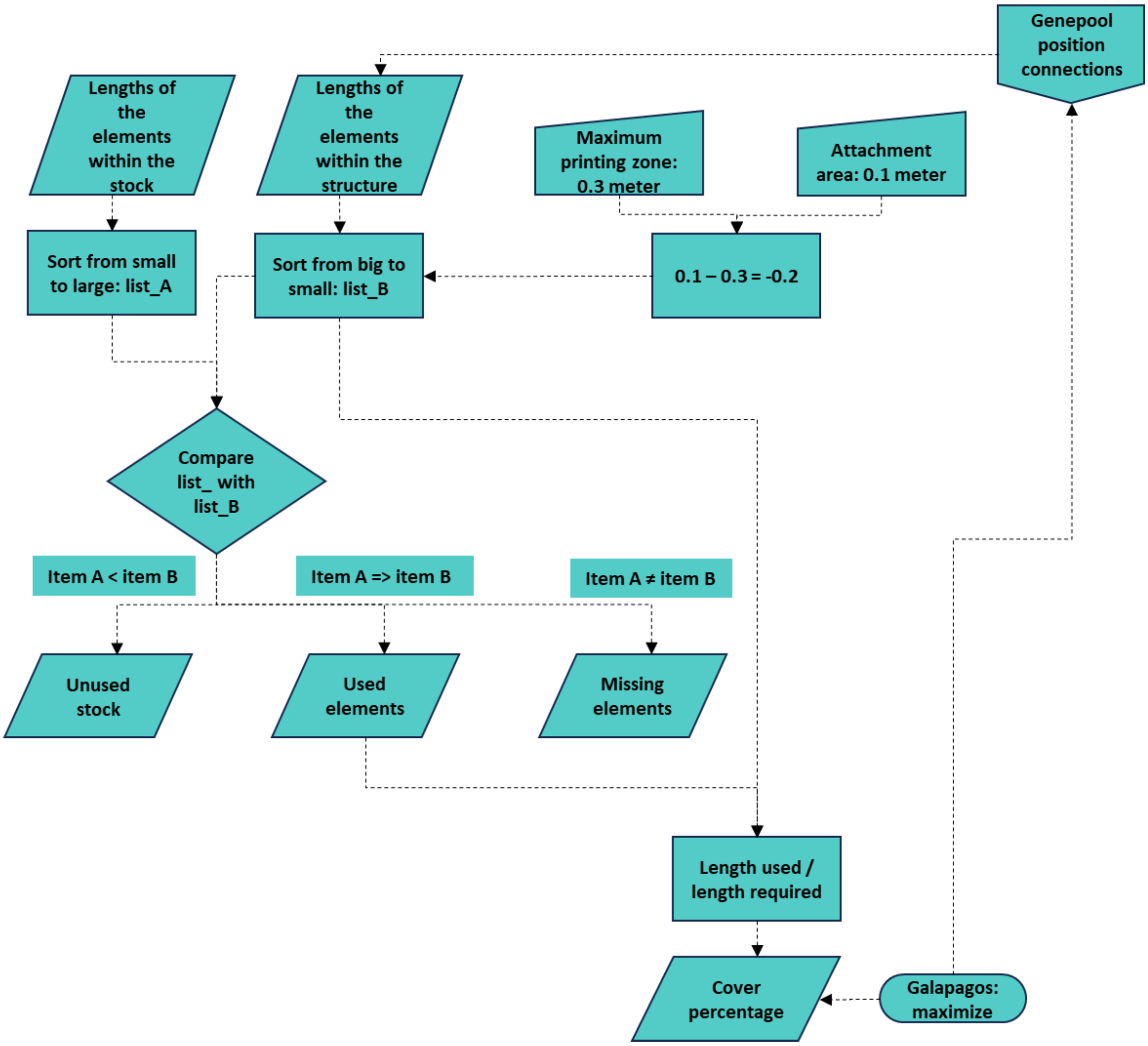

*Flowchart 6 Visualization of old stock-constrained design within Grasshopper, source: own work*

Scenario 3 will utilize the original structural shape but built with elements from stock. This scenario simulates traditional reuse through remanufacturing.

To efficiently accomplish this, both the stock and the elements in the structure are sorted from small to large. By sorting these lists, it is possible to find the closest match without iterating through the complete list each time. The sorted lists, list_A (stock) and list_B (elements within the structure), are processed by a Python command. The command runs through list_B, selecting the first element in list_A that is equal to or larger than its own length. Once found, the item is removed from list_A, and the process continues with the next item in list_B. The output, list_C, contains the lengths of the stock elements used in the final structure. The differences in length between the required and used lengths indicate the saw-off length. However, this does not account for profile dimensions; the saw-off volume will be calculated later. If elements are missing (i.e., lengths within the stock are smaller than the required components or the stock quantity is insufficient), new components must fill the gap. The missing components are identified by comparing the lengths of list_C and list_B. The difference determines the split between reused and new elements.

- Sort stock and elements in the structure from small to big
- Use element in stock that are >= element in structure
- The difference in total length is the saw-off loss

### Shape optimization with saw-off (scenario 4 – Reused wood optimized structure)



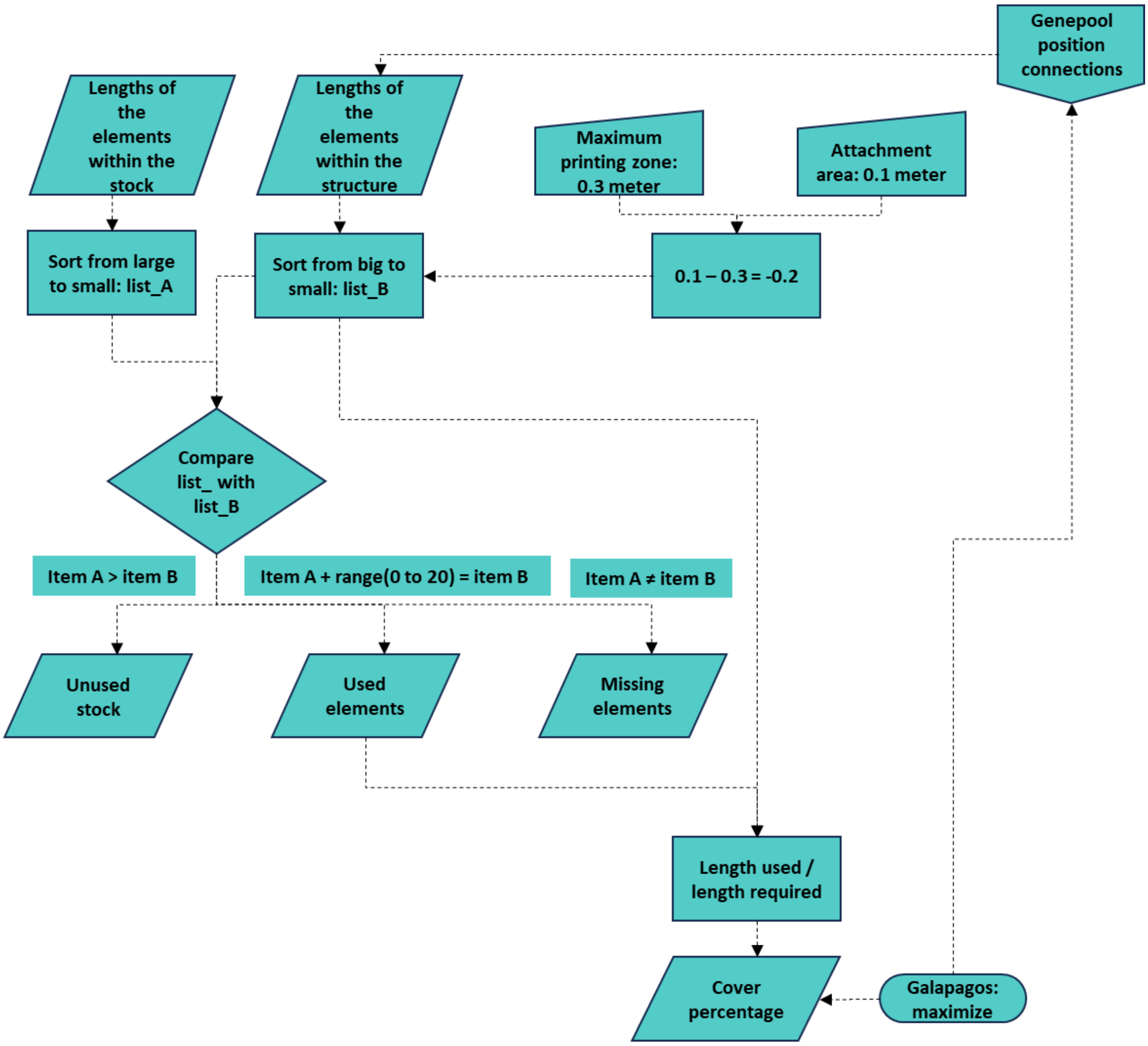

*Flowchart 7 Visualization of old stock-constrained design and optimization within Grasshopper, source: own work*

Scenario 4 simulates traditional stock-constrained design where the freedom of movement aims to increase the reuse rate and minimize total saw-off. For this research, saw-off is measured in meters. Although volumetric measurement offers better accuracy, it reduces calculation speed. Therefore, length-based measurement is used as an approximation.

Scenario 4 follows a similar process to Scenario 3, using list_A, B, and C to calculate saw-off loss. However, Scenario 4 incorporates a Galapagos component connected to saw-off loss (Fitness) in meters and the gene pools (Genome). By minimizing the fitness value, the Galapagos component iterates through different compositions to reduce saw-off losses as much as possible given the constraints.

- Sort stock and elements in the structure from small to large
- Use element in stock that are >= element in the structure
- Difference in total length is saw-off loss
- Minimize saw-off loss by adjusting the positions of the connections and altering the lengths of the elements within the structure

### The new method with printed connections (scenario 5 – 3D printed connections)




*Flowchart 8 Visualization of new stock-constrained design and optimization within Grasshopper, source: own work*

Scenario 5 is similar to Scenario 4 in that it alters the structure's composition to fit as many reusable elements as possible. However, Scenario 5 does not allow for saw-off losses. Instead, it adjusts the size of its connections to accommodate all unique elements within the structure.

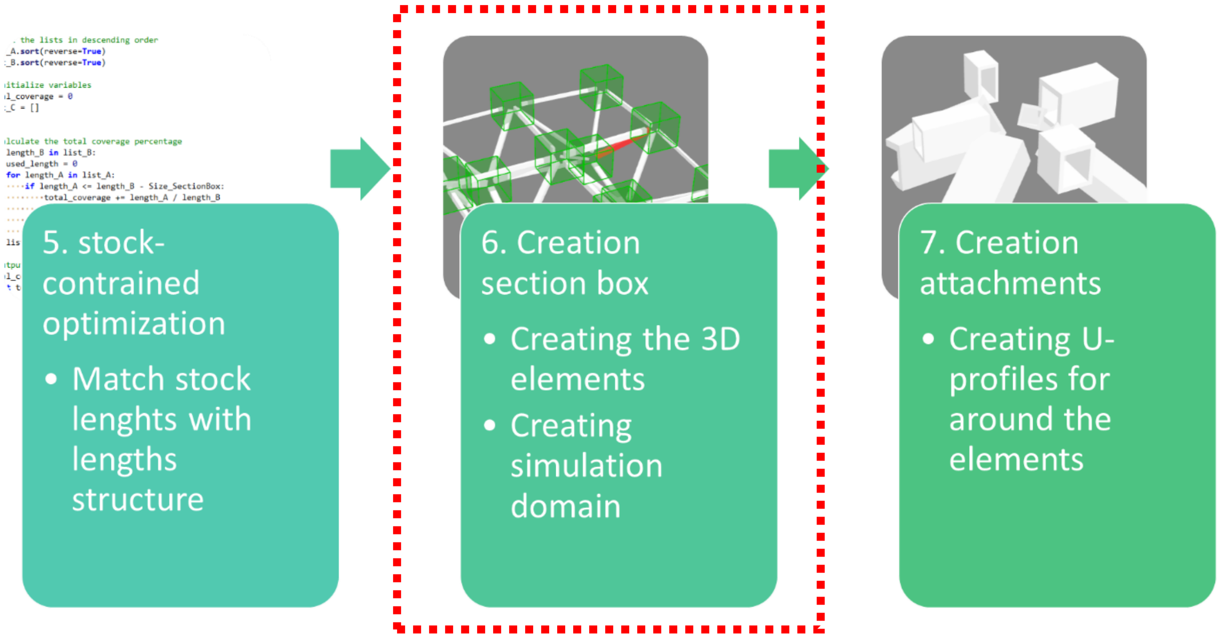
This approach introduces significant changes in its process. It starts by sorting the elements in the structure from large to small (instead of small to large). The Python command then selects the first element in list_A that is smaller than or equal to its corresponding element in list_B, within the maximum length the 3D printer can handle. The difference between the required and selected lengths becomes the length that needs to be printed. For fitness, a cover percentage is calculated: total length used divided by total length required, multiplied by 100. The Galapagos component maximizes this cover percentage.

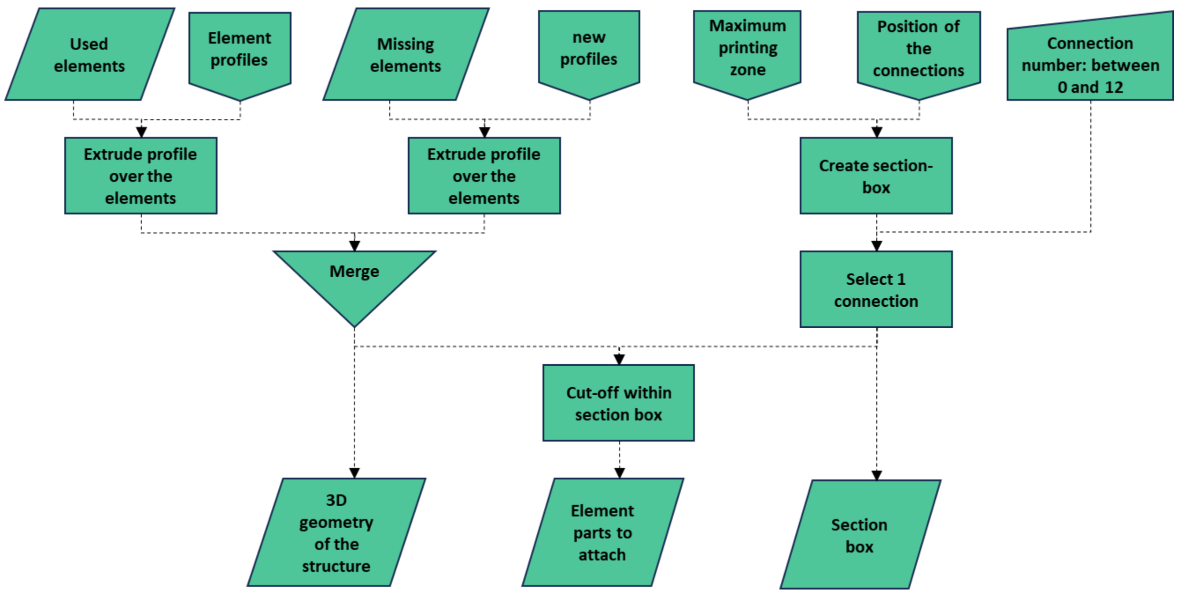
- Sort stock from small to big and elements within the structure from large to small
- Use element in stock that are <= element in the structure
- The difference in total length is the printing length for individual elements
- For the total structure, the length of elements needed divided by used is the cover percentage
- Maximizing the cover percentage by adjusting the position of the connections and altering the lengths of the elements within the structure

### Export: lengths used, lengths missing, position and orientation

The export for these three scenarios includes the composition of the structure, the placement of reused components, and the placement of any new elements. These details will be used in the next phase of transitioning from a line-based model to a 3D geometry.

## G. Section box creation




*Flowchart 9 Visualization of the creation of the section boxes, source: own work*

### Saw-off in to create original structure (scenario 3)

To determine the volumetric saw-off loss, a 3D geometry of the elements is required. First, new elements are created for the missing parts, simulating off-the-shelf profiles made from virgin wood. These elements are standardized with a profile of 12 x 6 cm. The lengths are used to construct a rectangular profile as a frame on the selected line, with the line itself becoming the centroid of the profile. This ensures all elements' centroids align at the connection point. By sweeping this profile and creating a Brep, the required 3D geometry is obtained.

For the reused elements, the process is similar, with the main difference being in profile creation. Since existing items are used, the matching profile must be recalled with the corresponding length. By using the same index for the lengths and profiles, the matching profile is obtained. The total saw-off loss is calculated by subtracting the absolute volume of the elements used from the absolute volume available. The export includes the volumes of virgin wood, reused wood, and waste wood (the saw-off), along with a 3D model of the structure with correct lengths and profiles. This process could later be used to replace line components with 3D components from a circular hub.

- Placing the new elements into the structure as a 3D geometry
- Placing the selected elements into the structure as a 3D geometry
- Determining the cut-off losses

### Shape optimization with saw-off (scenario 4)

Scenario 4 follows the same steps as Scenario 3.

- Creating new elements
- Placing the selected elements into the structure as a 3D geometry
- Determining the cut-off losses

### Export for scenario 3 and 4

Both scenarios share similar exports, including the orientation of the elements, the 3D geometry of the elements, and the saw-off losses that each scenario might create.

### The new method with printed joints (scenario 5)

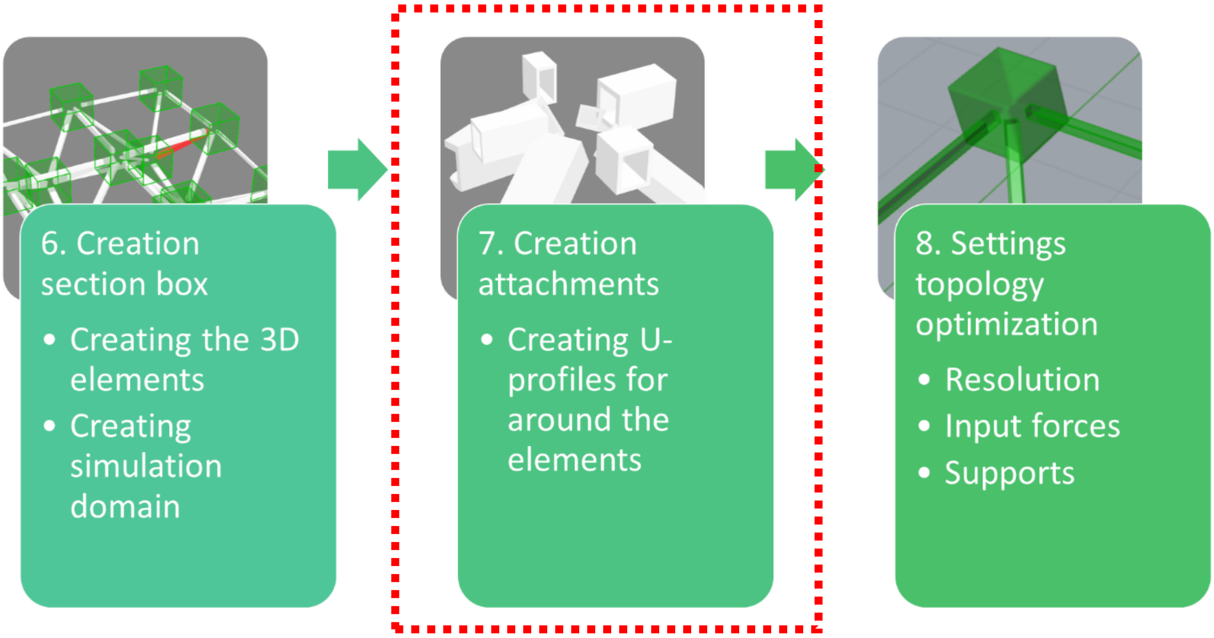
Scenario 5 starts similar to 3 and 4 by creating 3D geometries out of its selected elements and new elements but this time there are no saw-off losses. In addition, a section box is created that will in turn be used to create the area of attachment. Everything that is falls within the section box can be used by the topology optimization process to generate the connection.

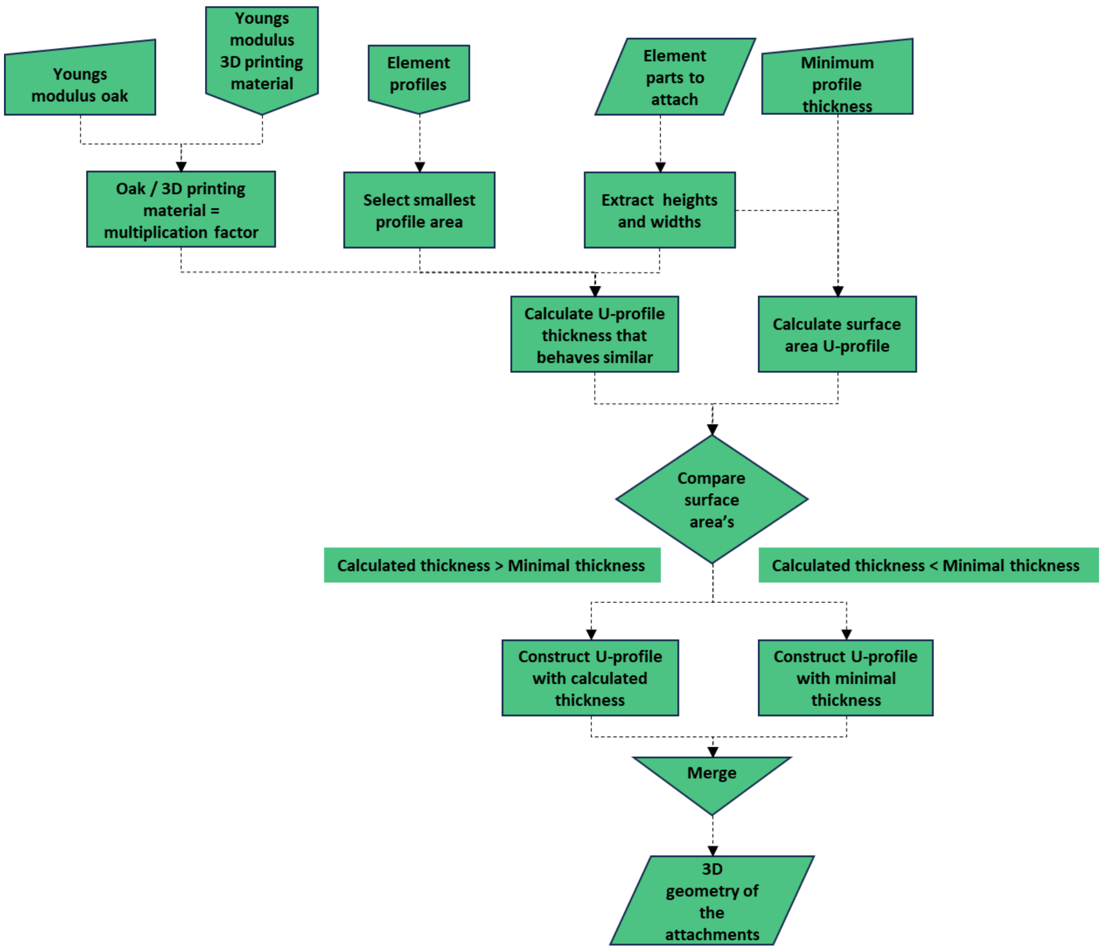
### The export of scenario 5

The export of this component is: the sectionbox, a 3D model of the structure with the correct lengths and profiles and the orientation of the elements (need that for divining some load vectors)

- Creation of the reused elements
- Creation of the new elements
- Creation of the sectionbox

## H. Creation attachments



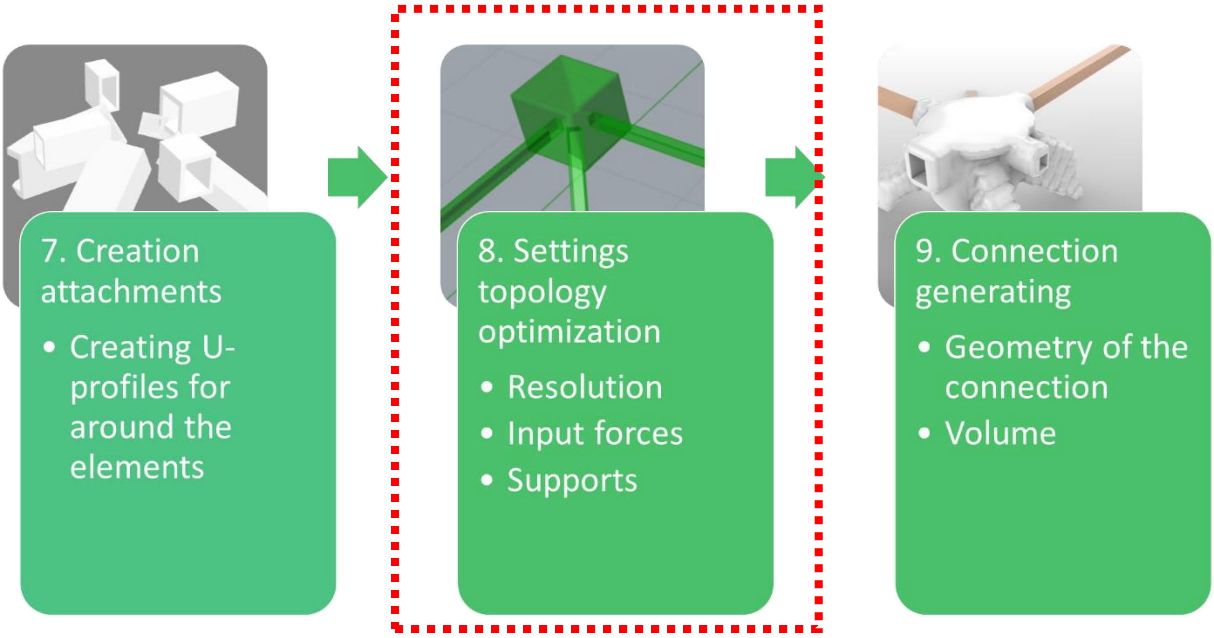



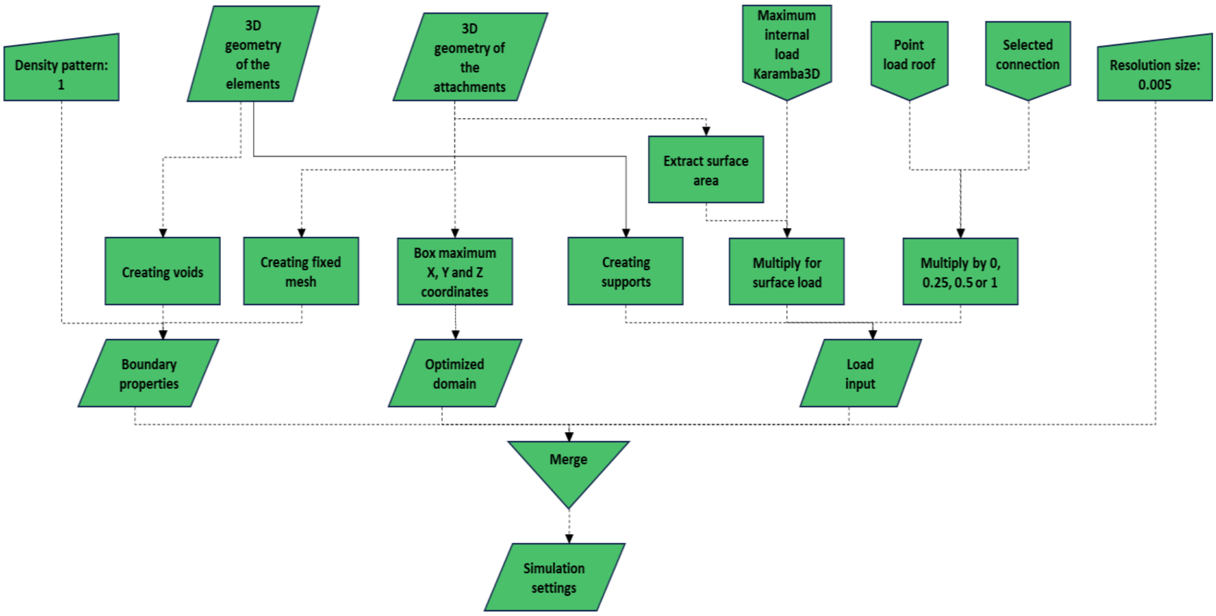

*Flowchart 10 Visualization of creating the attachments within Grasshopper, source: own work*

To safeguard the structural integrity the attachments are predefined. This guarantees that the simulation will add material to every component and allows the designer to specify a minimum thickness for the attachment. For this research, hollow rectangular profiles were used to simplify the study. The thickness of these profiles is automatically adjusted to the minimum area required in the design by ensuring they have the same surface area as the smallest timber element multiplied by the Youngs modulus difference. However, any type of attachment that meets the designer's needs can be created.

By predefining the attachment, the time required to complete the simulation is reduced. An attempt was made to incorporate U-profiles into the model. However, this became too complicated for the simulation, as these profiles regularly caused problems with the final results.

### I. Settings for 3D printed connections (scenario 5)






*Flowchart 11 Visualization settings 3D printed connections within Grasshopper, source: own work*

The next step for Scenario 5 involves preparing the settings and input data for generating connections. This begins with adjusting the domain. For most connections, it is possible to decrease the size of the previously created section box. For example, the joint at the corner of the structure does not need to extend beyond the boundary surface. By scaling down the section box, the task of calculating a topology-optimized connection requires less computational power and can be executed faster. The fixed attachments are used to determine the rescaled domain since these elements will be at the edges of the domain.

The loads are derived from the chapter on loads for the case study of roof panels. These loads are combined into the beforementioned load cases in a Python component, which outputs the largest load case for further structural analysis. After identifying the largest load, it can be multiplied by a self-created load factor. Since the edges and corners of the structure experience less weight from the panels, the load can be multiplied by either 1, 0.5, or 0.25. For the elements underneath the roof, the force can even be multiplied by 0, as these are not attached to the weight of the roof.

The second load type is the internal tension and compression resulting from the point load on the elements. To simulate this, the largest load was taken from the Karamba model and distributed over all surfaces of the elements entering the section box. This should force the simulation to distribute material around all the elements. The vector for the load was taken from the line model's position toward the midpoint of the section box.

Finally, the settings for the connection-building process include the properties of the printed material. These properties consist of density, Young's modulus, and Poisson's ratio. While numerous materials can be 3D printed, this research focuses on four materials due to their relevance and availability: PETG, PLA, steel, and carbon fiber. PETG and PLA were chosen for their availability at the LAMA lab at TU Delft, allowing for fabrication viability testing. Steel and carbon fiber were selected for their distinct material properties and carbon footprints compared to PETG and PLA. These materials will be tested in a digital environment due to limitations in time, cost, machinery, and materials. The properties of these materials were taken from the EduPack 2023 database, using average values for this research. Future designers can implement their own materials and values as needed.

| | Density ($g/cm^3$) | Young's modulus (GPa) | Poisson's ratio |
|---|---|---|---|
| **PETG** | 1,27 | 2,06 | 0,403 |
| **PLA natural Fiber filled** | 1,3 | 5,25 | 0,39 |
| **Steel** | 7,81 | 210 | 0.28 |
| **Carbon Fiber** | 1,82 | 380 | 0,1 |

*Table 1 Used materials and their properties, source: EduPack 2023*

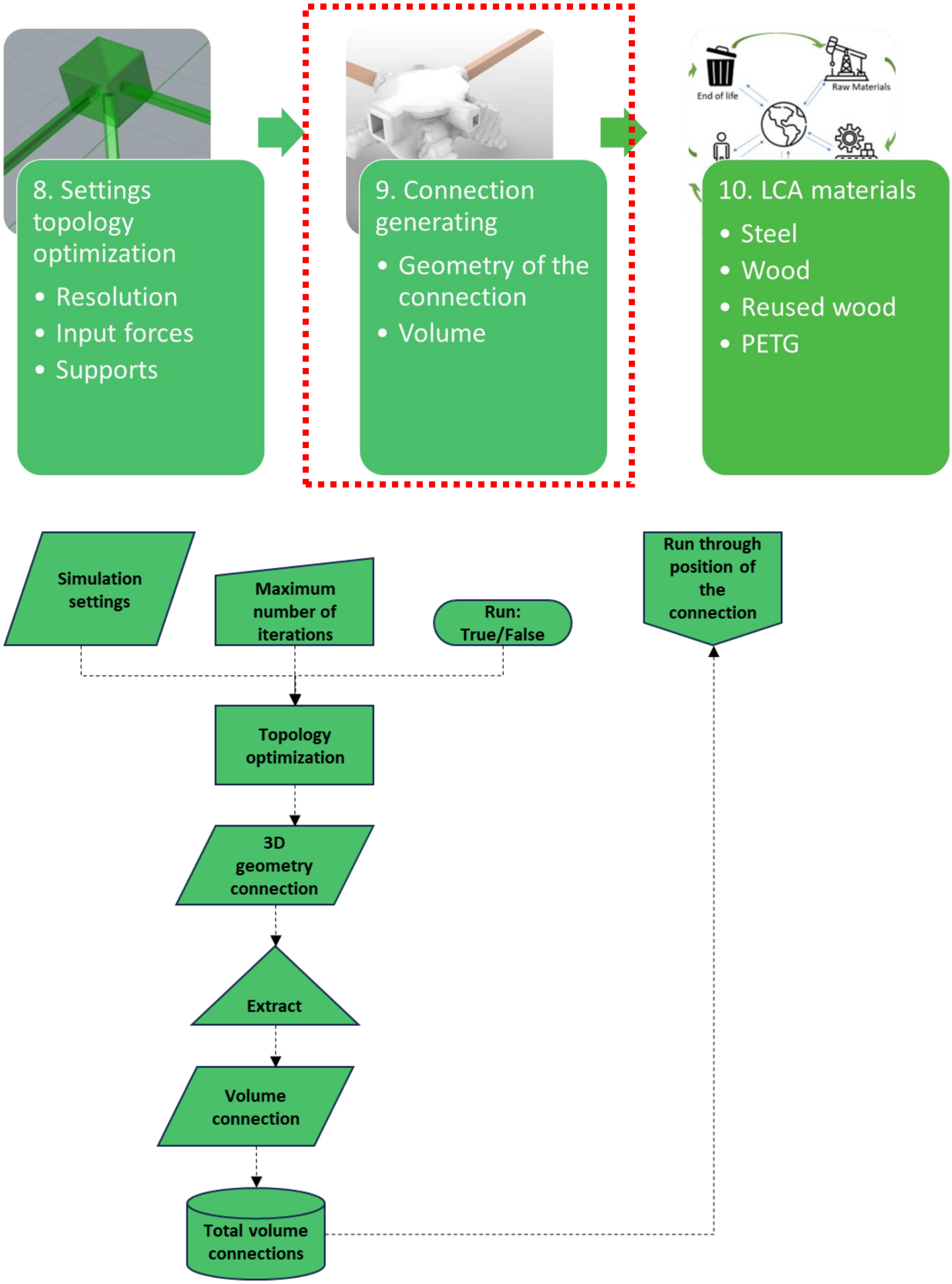
Besides material properties, boundary properties must also be defined. Here, fixed and void parts within the connection are predefined. As discussed earlier, the attachments are defined as fixed parts, while the elements themselves are considered voids. The density pattern is set to 1, meaning that the fixed and void parts must be included in the generating process and cannot be altered. This allows the designer to fully determine the appearance of the attachment and saves calculation time by reducing the number of possible variations.

Next, the boundary condition setup involves merging the point and surface loads into one input for the boundary condition setup. The parts of the elements within the section box are cut and selected as supports.

Finally, the resolution is determined before model building. The lower the resolution size, the more detail the final print will contain. The resolution size dictates the size of the pixels, and smaller pixels allow for more detail within the domain.

- Domain adjustment
- Point load from the roof
- Tension/compression in the elements
- Input
- Model building

## J. Creation of the 3D printed connections (scenario 5)




*Flowchart 12 Visualization of the topology optimization within Grasshopper, source: own work*

## Settings

Before the creation of the 3D printed joints, some final simulation settings need to be covered. After the model input, there are analyser parameters. The analyser parameters provide suggestions for the number of iterations and the amount of tolerance. While these parameters can be left at their default values, it is advisable for the designer to adjust them as needed.

The Optimus parameter gives control over the number of iterations, target volume, penalty, change, and sensitivity radius. The number of iterations allows the designer to experiment and verify if all settings are correct. By limiting the number of iterations in the early stages, it becomes apparent early on if everything is functioning correctly before conducting the full optimization, which takes longer.

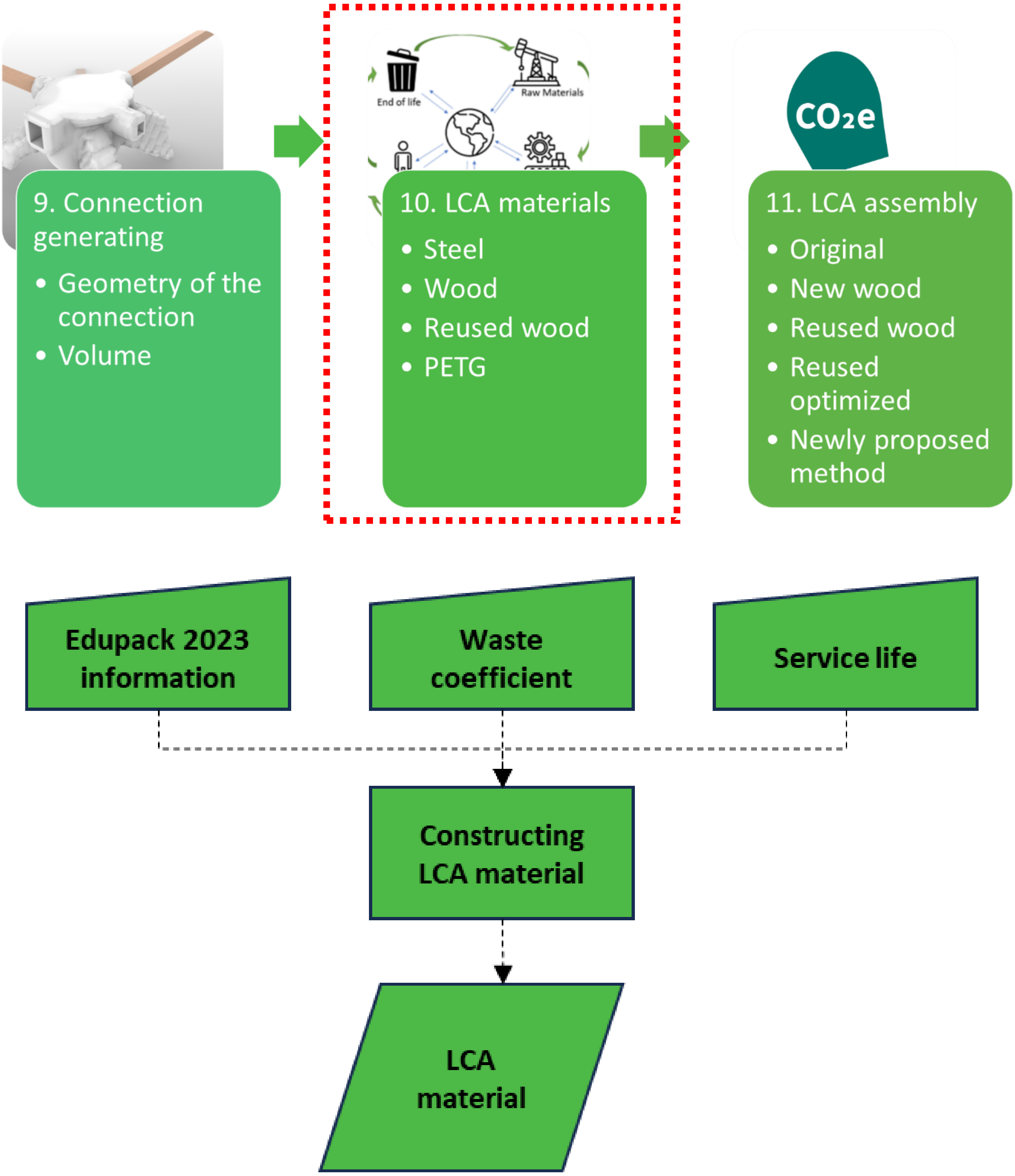
The volume fraction setting allows the designer to specify how much of the total volume should ideally be used. This can be useful for stopping the optimization once the set volume fraction is met. The standard value is 0.2, but this can be adjusted depending on the material used.

The change parameter can similarly be used to stop the simulation prematurely. The standard value for change is 0.005. This means that if the optimization process makes smaller steps than 0.005 of the total volume, the process stops. This prevents the optimization process from continuing for too long.

## Simulation

With all the aforementioned inputs, the simulation can start. After completion, the simulation provides the model, compliance, and performance data. The performance data includes information about the calculation time, the amount of data processed, and the memory used. Compliance is visualized in a graph showing the model's performance throughout the iterations. The model contains the final result, which will be used as the connection in a 3D model. This model can be "baked" (converted into a solid model), and its volume can be used for the next stage of the research.

## K. LCA materials




*Flowchart 13 Visualization of creating materials for the LCA within Grasshopper, source: own work*

The LCA is conducted using the EPiC plugin, which offers a parametric way to calculate the total footprint. While EPiC provides its own library, backed by the University of Melbourne, Australia, not all materials used in this research are included. Therefore, numerical values from EduPack 2023 were used to ensure a clear and consistent data source for all materials.

**Steel pipes**

For the steel pipes, low carbon steel was chosen, a common material in steel frame structures. Combined with extrusion foil rolling, it provides an accurate indication of the current situation's footprint. The EduPack 2023 Built Environment library provided the following data for low carbon steel of typical grade, processed and recycled to material level:

| Low carbon steel | Energy (MJ/kg) | CO2 (kg/kg) | Water (L/kg) |
|---|---|---|---|
| Primary energy, CO2 and water | 15-17,5 | 1,05-1,2 | 44-49 |
| Processing energy, CO2 and water | 5,22-5,76 | 0,392-0,432 | - |
| Recycling and end of life | 6,96-7,48 | 0,547-0,588 | - |
| Summation | 27,18-30,74 | 1,989-2,22 | 44-49 |
| Used in the research | **29** | **2,1** | **47,5** |

*Table 2 Footprint of Low carbon steel (extruded), source: EduPack 2023*

Since waste coefficient and material service life are not provided in EduPack, EPiC's suggestions of 5% waste coefficient and a 50-year service life for steel pipes are used.

**Steel connections**

For steel connections, low carbon steel was again chosen, common in steel frame structures. Combined with casting, it provides an accurate footprint estimation. The EduPack 2023 Built Environment library provided the following data:

| Low carbon steel | Energy (MJ/kg) | CO2 (kg/kg) | Water (L/kg) |
|---|---|---|---|
| Primary energy, CO2 and water | 15-17,5 | 1,05-1,2 | 44-49 |
| Processing energy, CO2 and water | 11,1-12,2 | 0,832-0,917 | - |
| Recycling and end of life | 6,96-7,48 | 0,547-0,588 | - |
| Summation | 33,06-37,18 | 2,429-2,705 | 44-49 |
| Used in the research | **35** | **2,6** | **47,5** |

*Table 3 Footprint of Low carbon steel (Casted), source: EduPack 2023*

EPiC's suggestions of 5% waste coefficient and a 50-year service life for steel pipes are also used for steel connections.

**Wooden components**

As a wood type the hardwood oak was chosen due to its industrial use in structural functions. The results will change according to the wood type, but for the research it is important that it is a wood type that is used on an industrial scale in the build and environment within structural functions. That's why oak has been chosen for now, but can be replaced by any type the designer desires.

For oak the EduPack 2023 Build Environment library was used. The unit used for building the EPiC component was kg, since that's the most frequent used in the rest of the data. With a density of 850-1.03 kg/m$^3$ a density of 940 kg was used. Within that database the following data was retrieved for Oak of typical grade, processed and recycled to material level:

| Oak | Energy (MJ/kg) | CO2 (kg/kg) | Water (L/kg) |
|---|---|---|---|
| Primary energy, CO2 and water | 68,1-75,1 | 0,355-0,391 | 665-735 |
| Processing energy, CO2 and water | - | - | - |
| Recycling and end of life | 19,8-21,3 | 1,69-1,78 | - |
| Summation | 113,07-124,15 | 3,928-4,258 | 665-735 |
| Used in the research for new wood | 71,6 | 0,37 | 700 |
| Used in the research for reused wood | 0 | 0 | 0 |
| Used in the research for cut-off wood | 20,6 | 1,7 | 0 |

*Table 4 Footprint of Oak, source: EduPack 2023*

EPiC's suggestions of 5% waste coefficient and an endless service life for new oak are used. For reused and cut-off wood, 0% waste coefficient and an endless service life are assumed since cut-off is a one-time event and the footprint of reused wood has already been counted in its first service life.

**PETG**

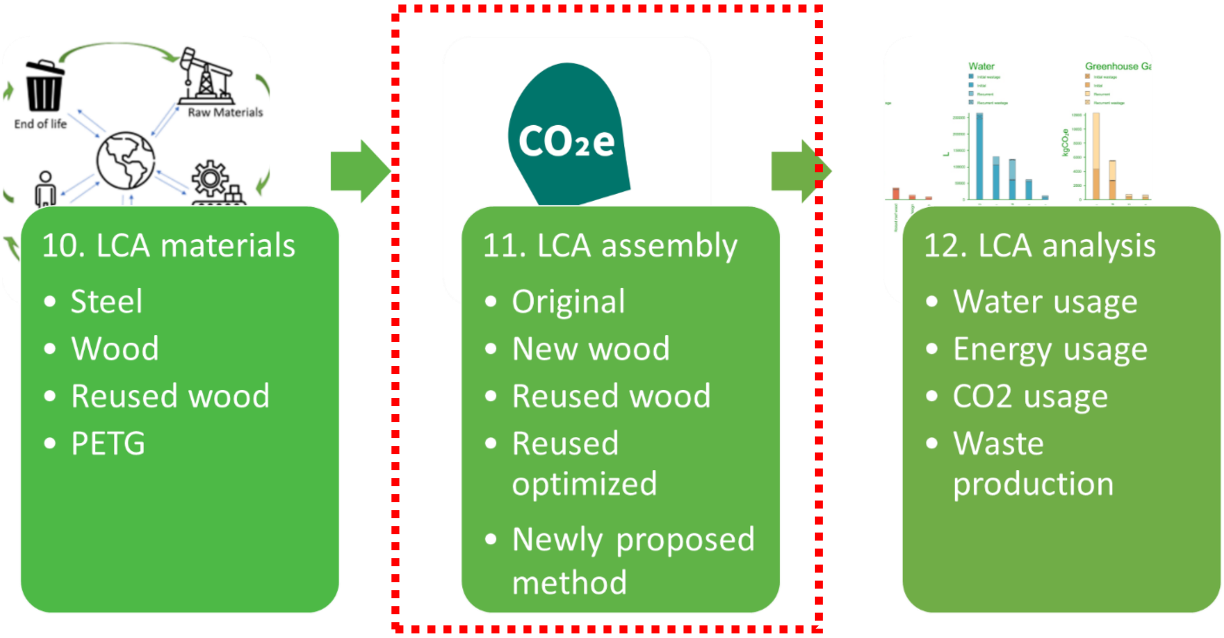
For PETG, the EduPack 2023 Level 3 Aerospace library provided the following data:

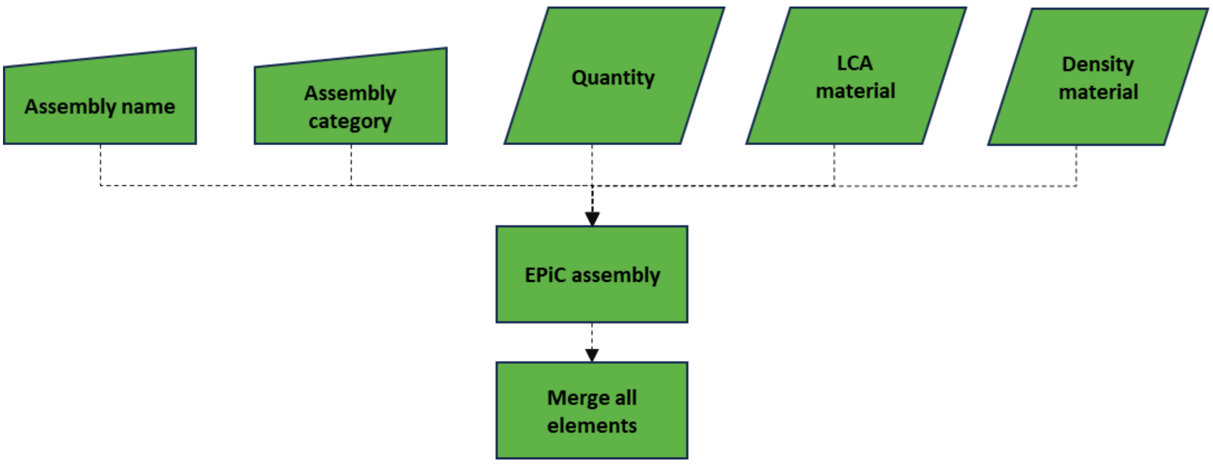
| PETG | Energy (MJ/kg) | CO2 (kg/kg) | Water (L/kg) |
|---|---|---|---|
| Primary energy, CO2 and water | 89-98,2 | 4,16-4,59 | 126-140 |
| Processing energy, CO2 and water | 5,92-6,54 | 0,444-0,491 | 4,87-7,3 |
| Recycling and end of life | 30,2-33,4 | 1,41-1,56 | - |
| Summation | 125,12-138,14 | 6-6,641 | 130,87-147,3 |
| Used in the research for first service life | **93,6** | **4,38** | **133** |
| Reused PETG | **38,4** | **1,95** | **6,1** |

*Table 5 Footprint of PETG (extruded), source: EduPack 2023*

EPiC's suggestions of 5% waste coefficient and a 15-year service life for plastic are used. Within the overall analysis the assumption is made that the extraction only happens once, after that the PETG will contain only reused material.

## L. Life Cycle Assessment (LCA) of structures




*Flowchart 14 Visualization of LCA assembly within grasshopper, source: own work*

## LCA of steel structure (scenario 1)

- **Steel pipes**

An estimated total volume of 0.06 $m^3$ was used for the steel pipes. This volume was measured from the 3D model described in the section on creating the original structure.

- **Steel connections**

Using the same technique, the estimated total volume for the steel connections was 0.006 $m^3$.

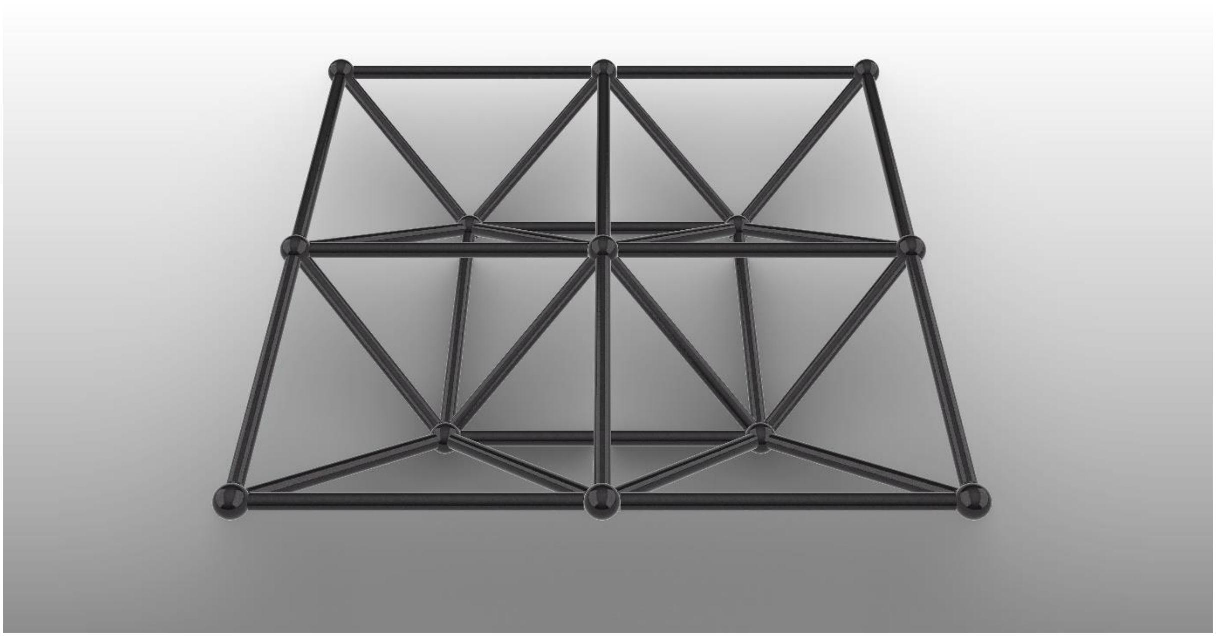


*Figure 9 Visualization of the steel structure, source: own work*

## LCA of new wooden structure (scenario 2)

- **New wooden elements**

The volume of new wooden elements was calculated to be 0.37 m³ by multiplying the profile by the total length within the structure.

- **Steel connections**

The estimated total volume for the steel connections was 0.006 m³, using the same technique as for the steel pipes.

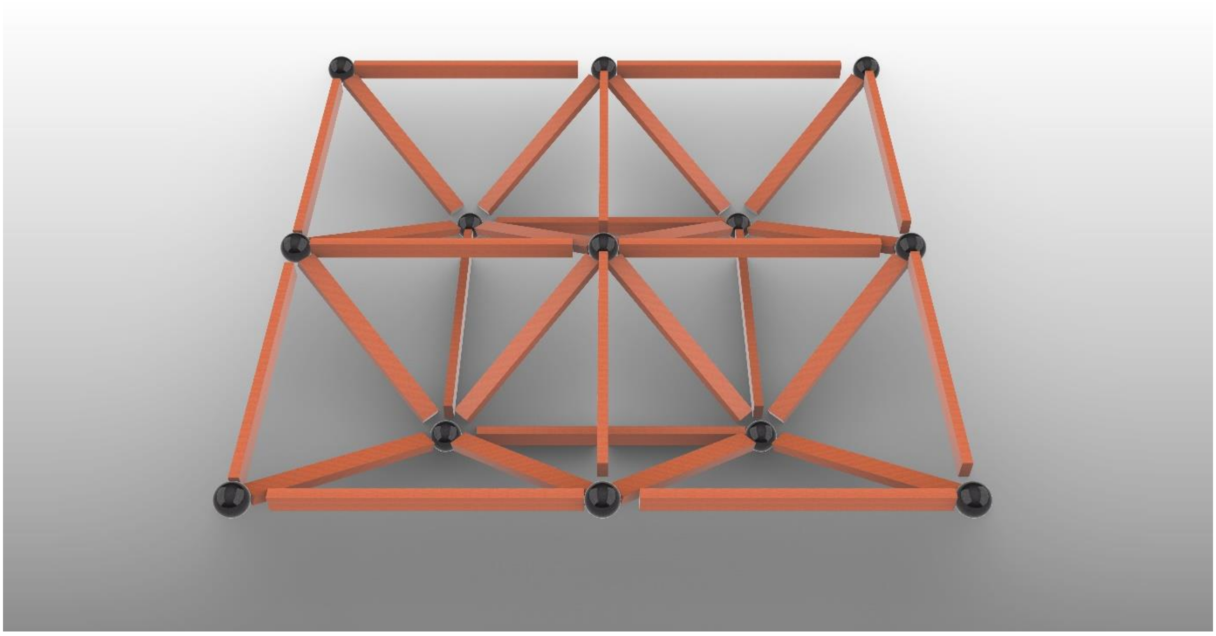


*Figure 10 Visualization of the new wooden structure, source: own work*

## LCA of reused wooden structure (scenario 3)

Due to the dependency on available stock, the results will vary with each seed of the random stock generator. The following results are based on seed number 10, containing 100 items.

- **New wooden elements:**

No new elements were required within the created stock.

- **Reused wooden elements:**

The total volume of reused wooden elements that is directly measured from the model is 0,28$m^3$.

- **Cut-off losses:**

The total cut-off losses measured from the model amounted to 0.08 $m^3$.

- **Steel connections:**

The estimated total volume for the steel connections remained at 0.006 $m^3$.

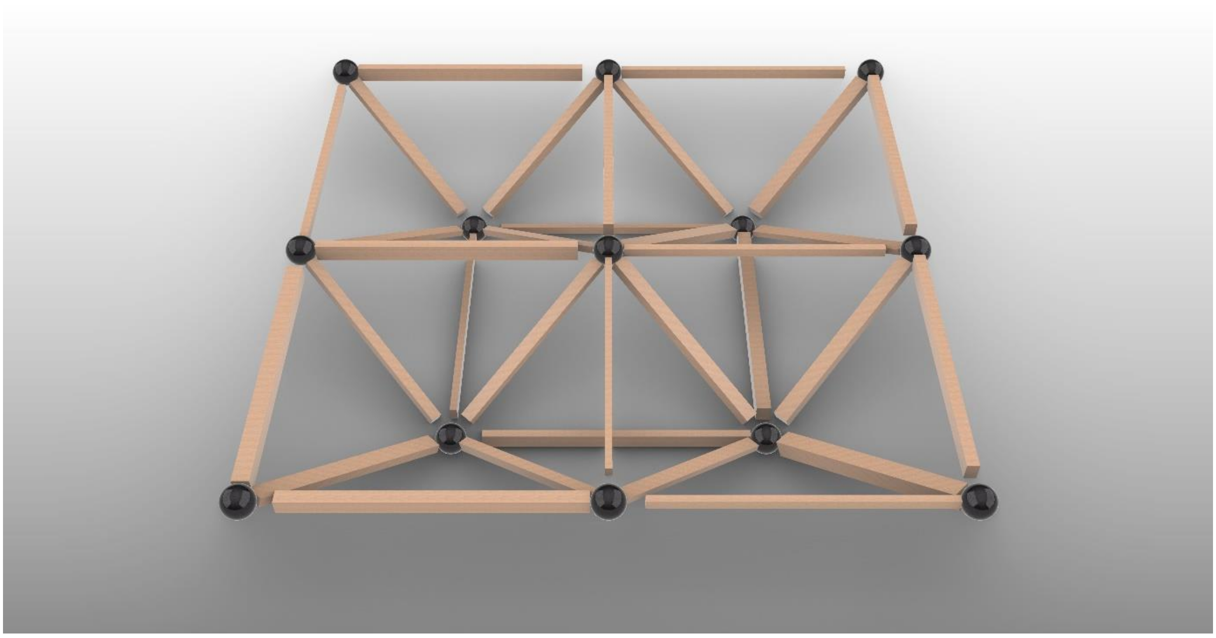


*Figure 11 Visualization of the reused wooden structure, source: own work*

## LCA of reused wooden optimized structure (scenario 4)

Due to the dependency of the stock available the result will differ in each of the chosen seeds of the random stock generator. For the following results number 10 was used containing 100 items.

- **New wooden elements:**

No new elements were required within the created stock.

- **Reused wooden elements:**

The total volume of reused wooden elements that is directly measured from the model is 0,26m3.

- **Cut-off losses:**

The total cut-off losses measured from the model amounted to 0.01 $m^3$.

- **Steel connections:**

The estimated total volume for the steel connections remained at 0.006 $m^3$.

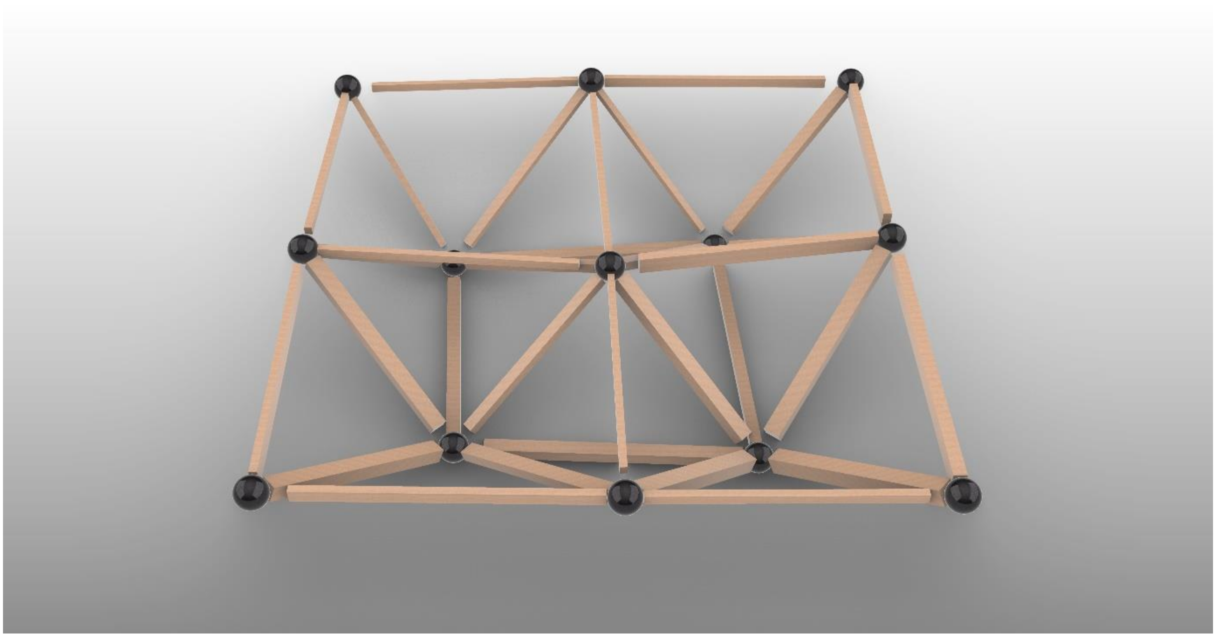


*Figure 12 Visualization of the optimized structure, source: own work*

### LCA of reused wooden optimized structure with 3D printed connections (scenario 5)

Due to the dependency on available stock, the results will vary with each seed of the random stock generator. The following results are based on seed number 10, containing 100 items.

- **New wooden elements:**

The total volume of new wooden elements that is directly measured from the model is 0,017$m^3$.

- **Reused wooden elements:**

The total volume of reused wooden elements measured directly from the model was 0.24 $m^3$.

- **PETG connections:**

The total volume of PETG measured directly from the model was 0.53 $m^3$.

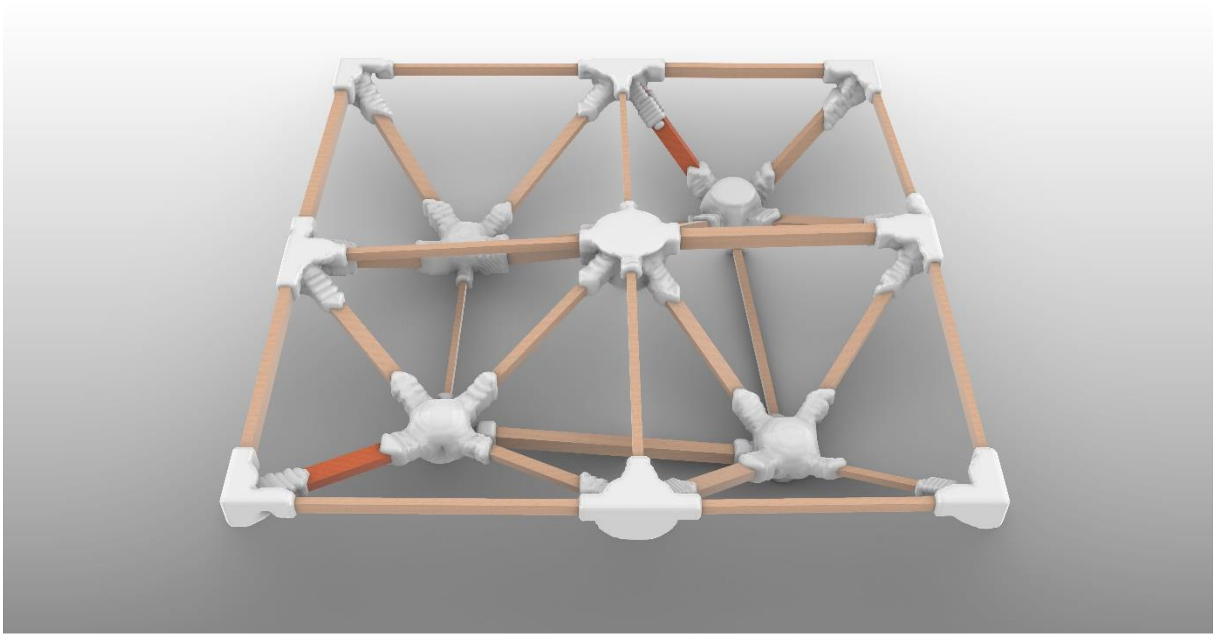
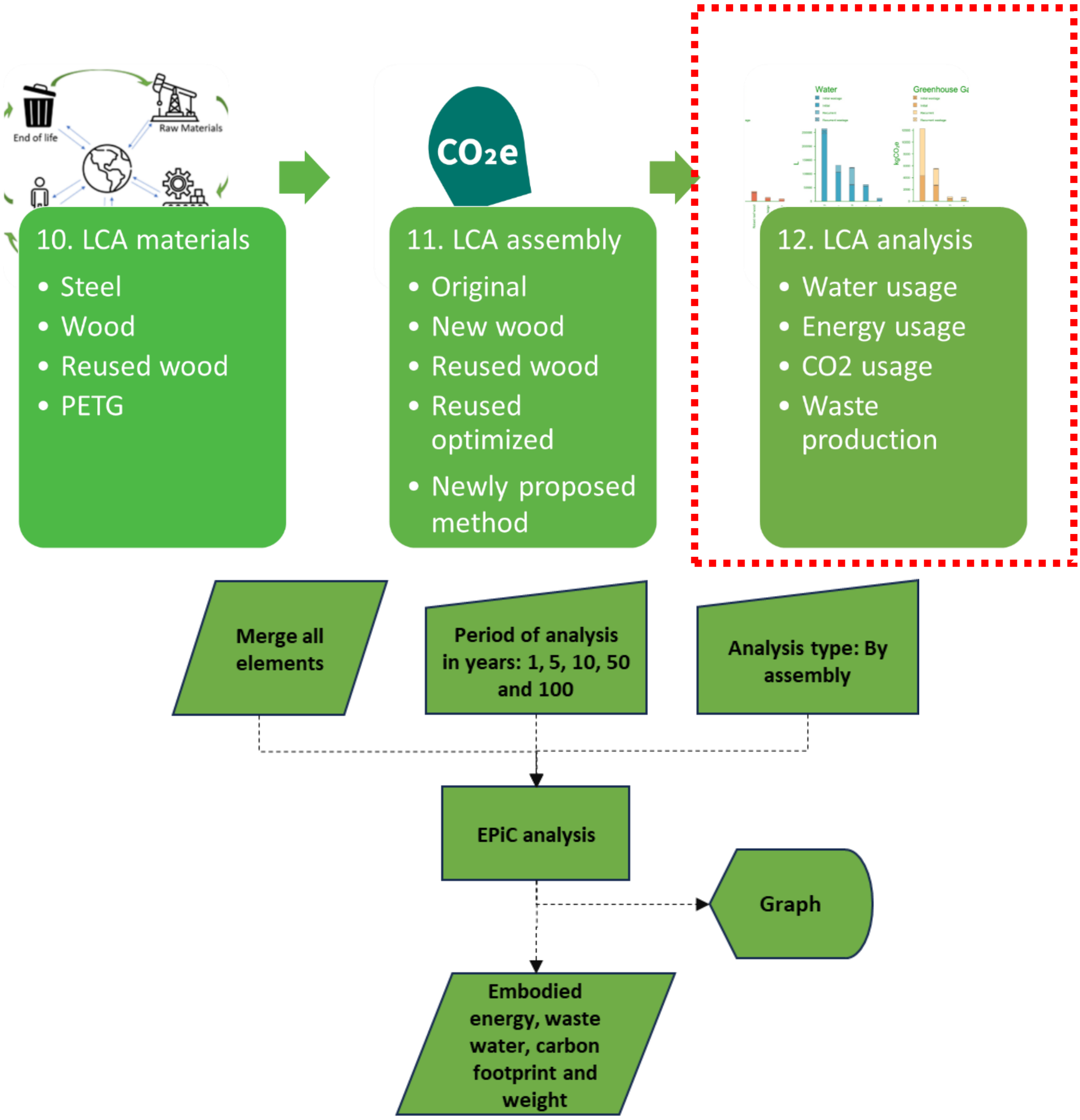


*Figure 13 Visualization of the optimized structure with 3D printed connections, source: own work*

## M. Life cycle assessment (LCA) of the scenarios



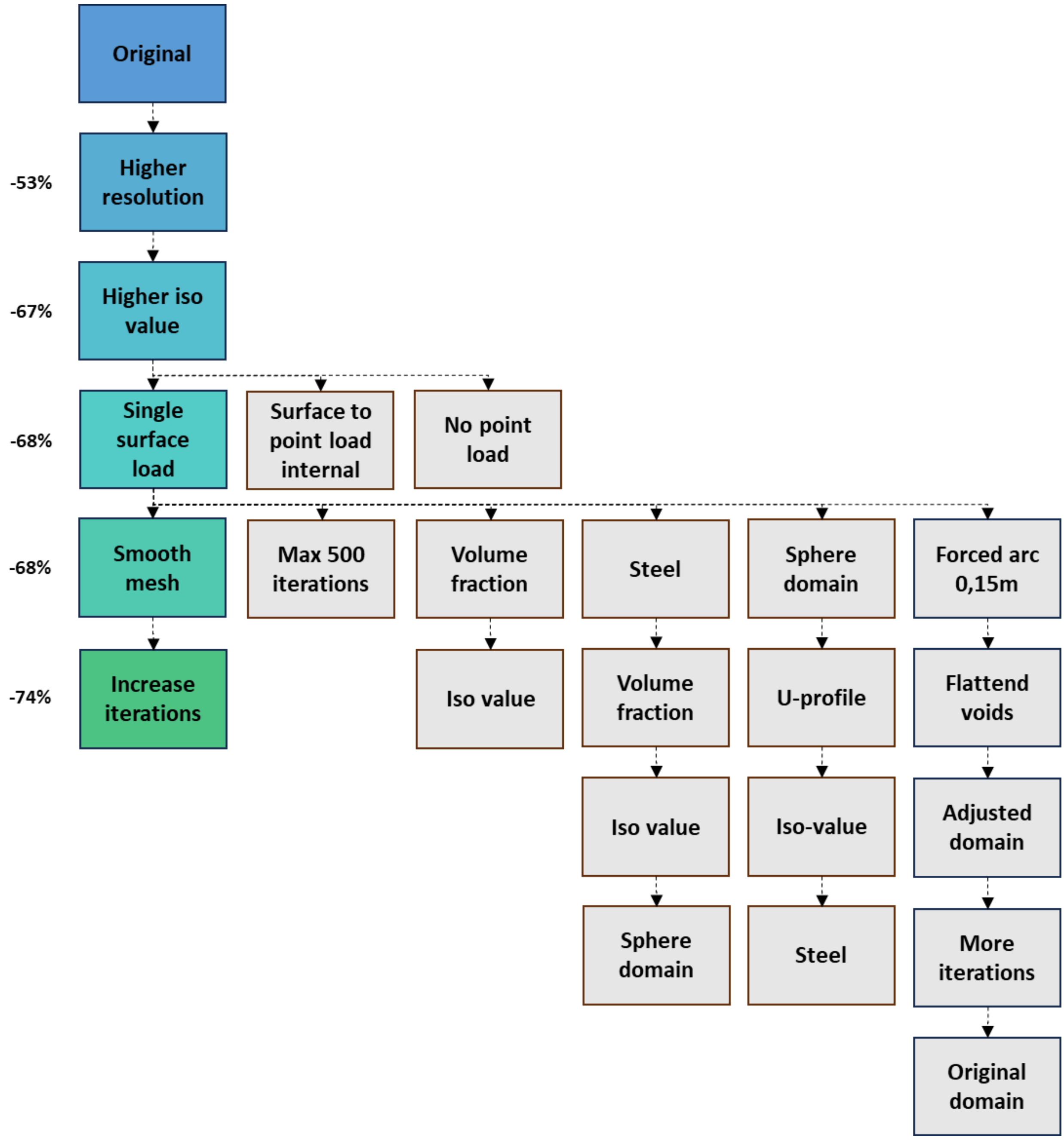

*Flowchart 15 Visualization of the LCA analysis within grasshopper, source: own work*

All materials used in the scenarios are combined and input into the EPiC analysis. The final input for the analysis component is the time horizon, with periods measured at 1, 5, 10, 50, and 100 years. The data can then be analysed per assembly (scenario), per material, or both. The total analysis is not relevant for this research and will be omitted. Similarly, analysis per material is not useful as it mixes the different scenarios. Analysing per assembly is beneficial for comparing the scenarios and determining if the LCA improves or worsens with each alteration. Additionally, analysing by assembly and material can help explain any differences observed.

# VI. Final products

## A. Generated connections

The workflow offers a variety of parameters for generating connections. By running the script with different settings, it is possible to further optimize the end result. The goal is to minimize the volume of the connection, without compromising structural integrity.




*Flowchart 16 further refinement of the generated connection, source: own work*

Over 50 connections were generated to find the best connection. The parameters used include resolution, iso-value, internal loads definition, number of iterations, volume fraction, 3D printing material, domain type, void definition, smoothening, and manually adding thickness.

**Original connection**

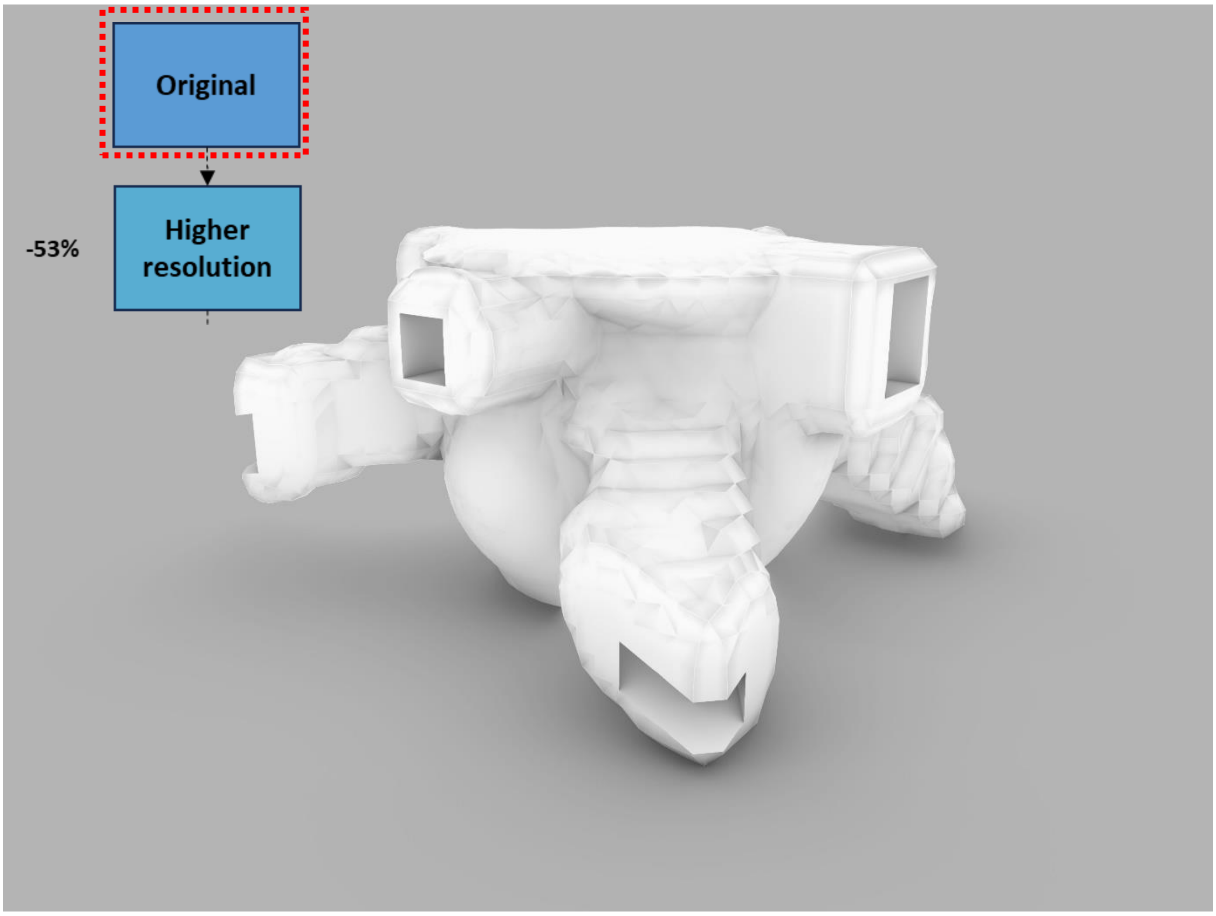



*Figure 14 Original generated connection, source: own work*

Using the steps described in the workflow, the connection above was generated with a volume of 0.065176 $m^3$. The current workflow prioritizes calculation speed over precision, and the resolution was set at 0.01.

**Connection at higher resolution**

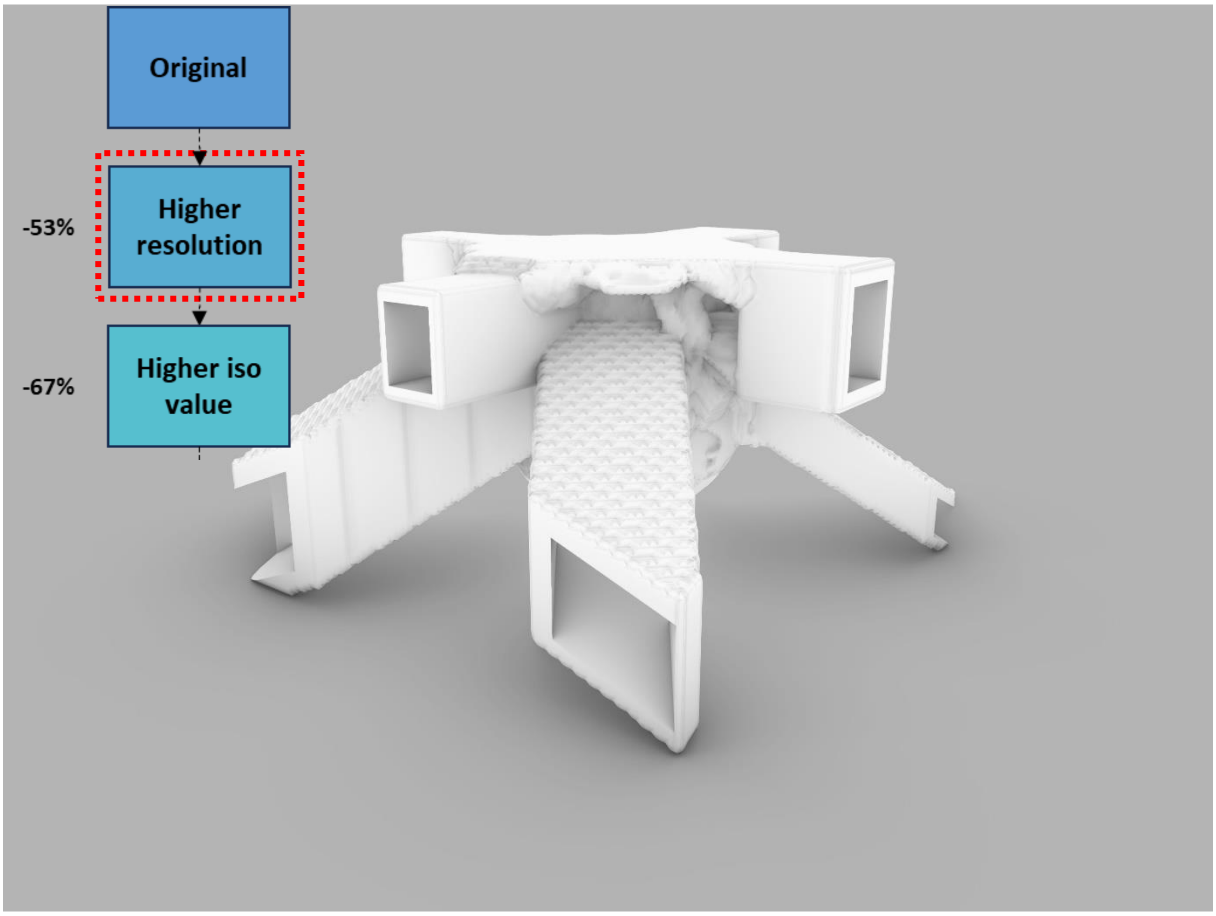



*Figure 15 Connection at higher resolution, source: own work*

Running the same simulation at a higher resolution (0.005) made the topology optimization clearer. Utilizing the computers at the VR lab at TU Delft BK faculty, the pixels were divided into smaller units, creating a more accurate profile thickness and reducing material usage. The new measured volume was 0.029781 $m^3$, a 54% reduction from the original volume.

**Higher iso value**

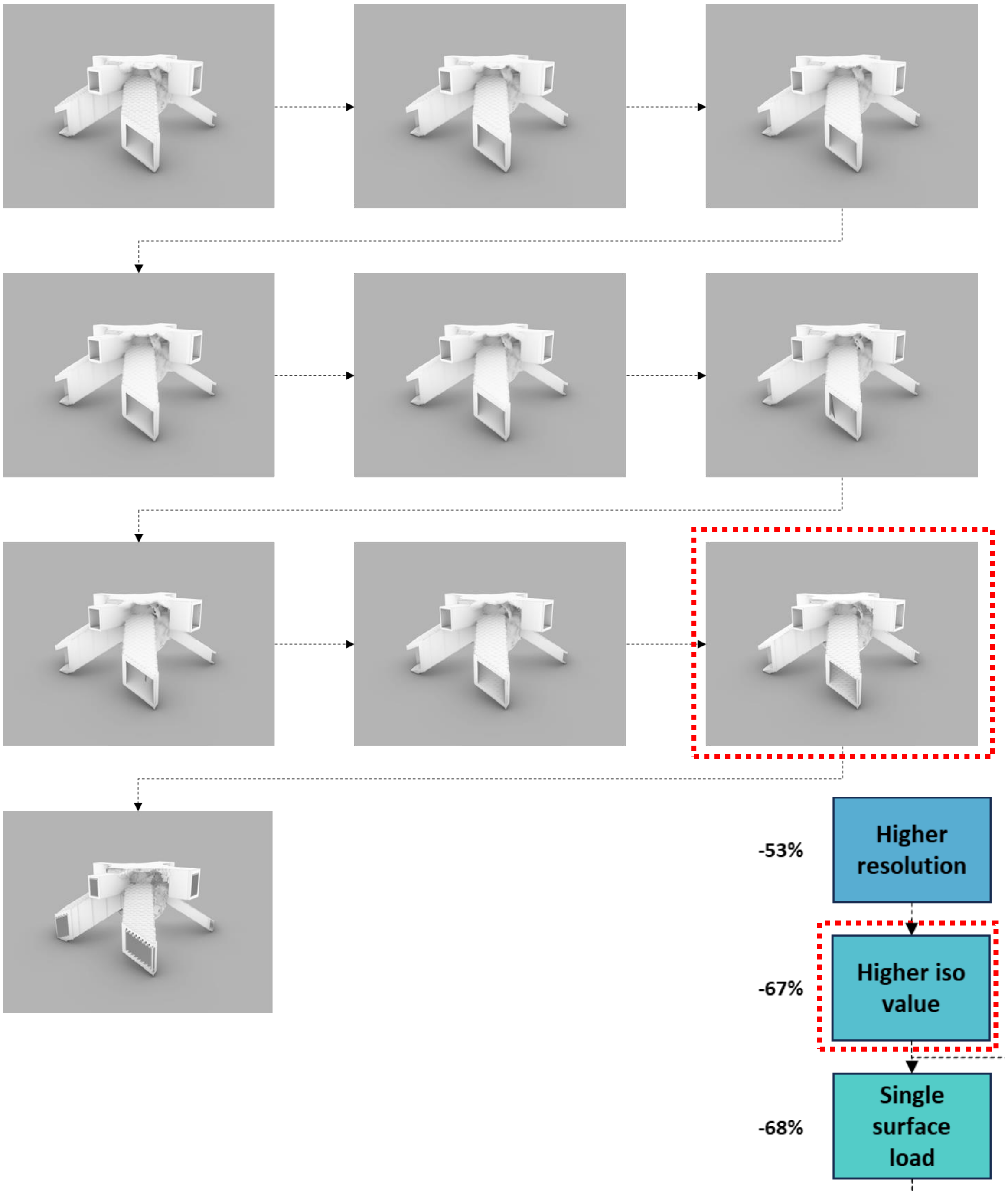



*Figure 16 Changes to the connection with different iso values ranging from 0.1 to 1, source own work*

The higher resolution allowed for altering the iso-value while maintaining the attachments. However, with an iso-value of 1, certain interconnections became invalid. Therefore, an iso-value of 0.9 was standardized, reducing the new volume to 0.021438 m³, a 67% reduction compared to the original connection.

| Iso value | Volume in $m^3$ | % volume reduction compared to original |
|---|---|---|
| **Iso value 0.1 (original)** | 0.029781 | -53% |
| **Iso value 0.2** | 0.028507 | -56% |
| **Iso value 0.3** | 0.027437 | -58% |
| **Iso value 0.4** | 0.026486 | -59% |
| **Iso value 0.5** | 0.025565 | -61% |
| **Iso value 0.6** | 0.024608 | -62% |
| **Iso value 0.7** | 0.023680 | -64% |
| **Iso value 0.8** | 0.022669 | -65% |
| **Iso value 0.9** | 0.021438 | -67% |
| **Iso value 1** | 0.019810 | -70% |

*Table 6 Volume reduction due to increase iso value, source: own work*

**From internal point load to single surface load**

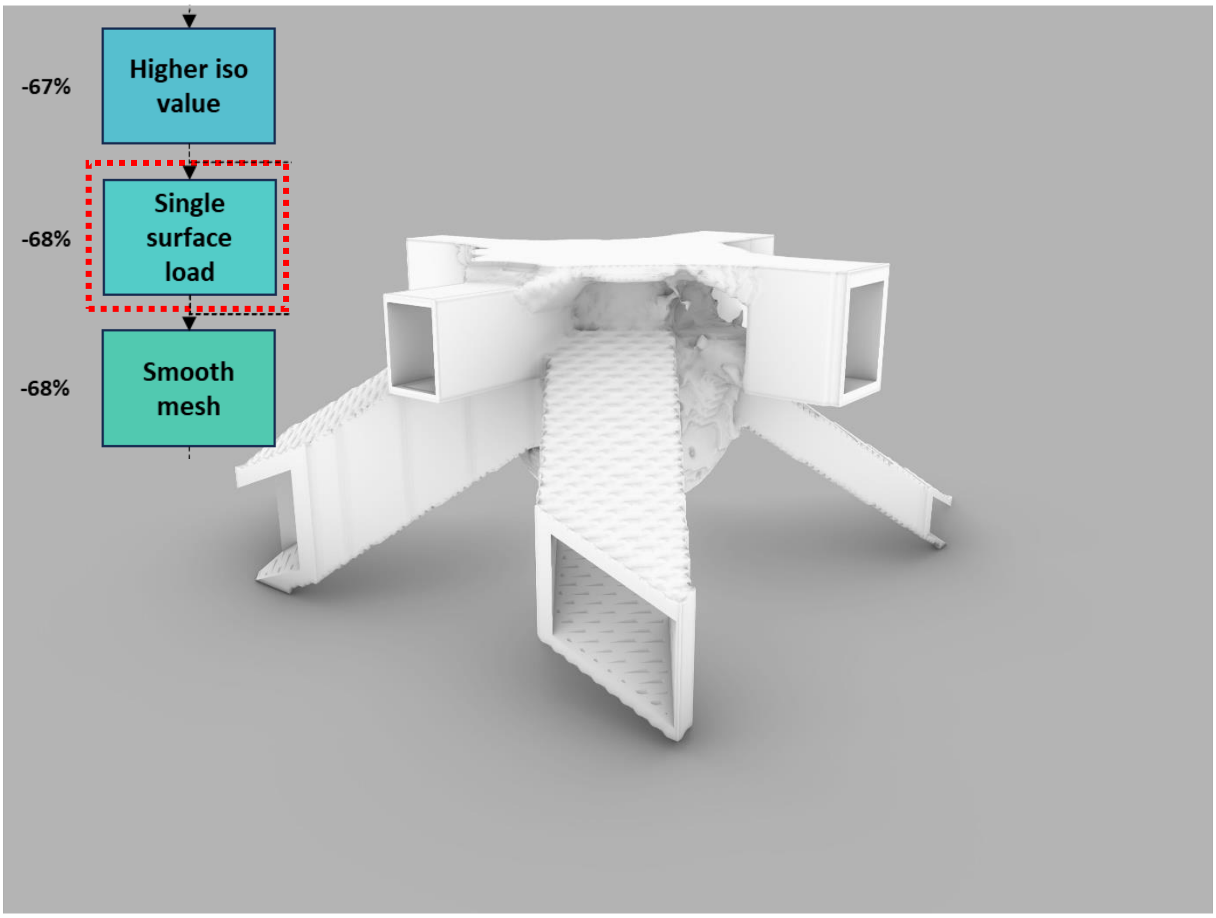



*Figure 17 Generated connection with the internal loads as singular surface loads, source: own work*

Changing the internal load type alters the volume and shape of the connection, emphasizing the importance of realistic load simulations. The previous surface loads were divided among five sides incoming into the connection, then changed to the end of the element as a single surface load for a more realistic simulation. The new volume was 0.021098 $m^3$, a 68% reduction compared to the original case.

**Smoothening the surface**

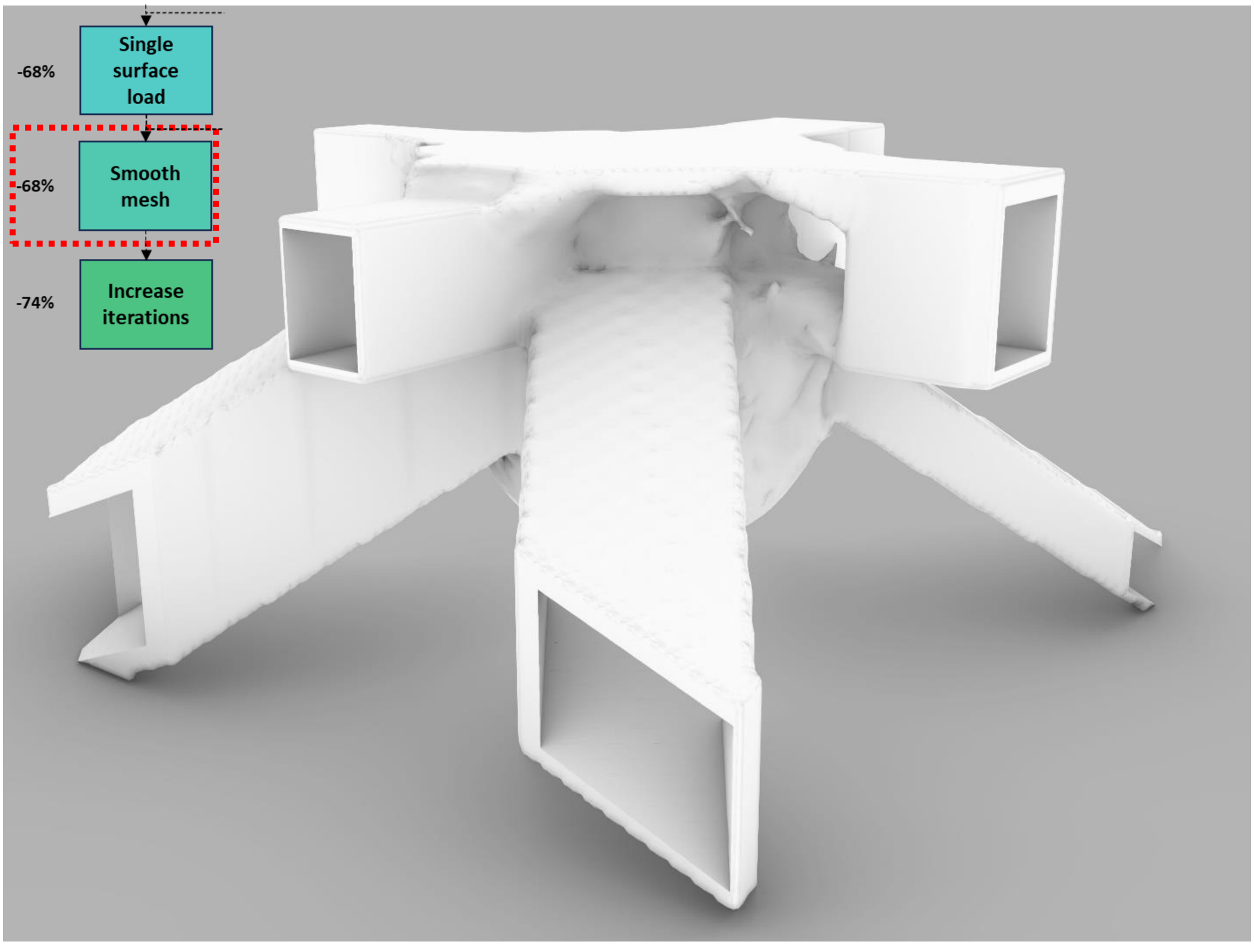
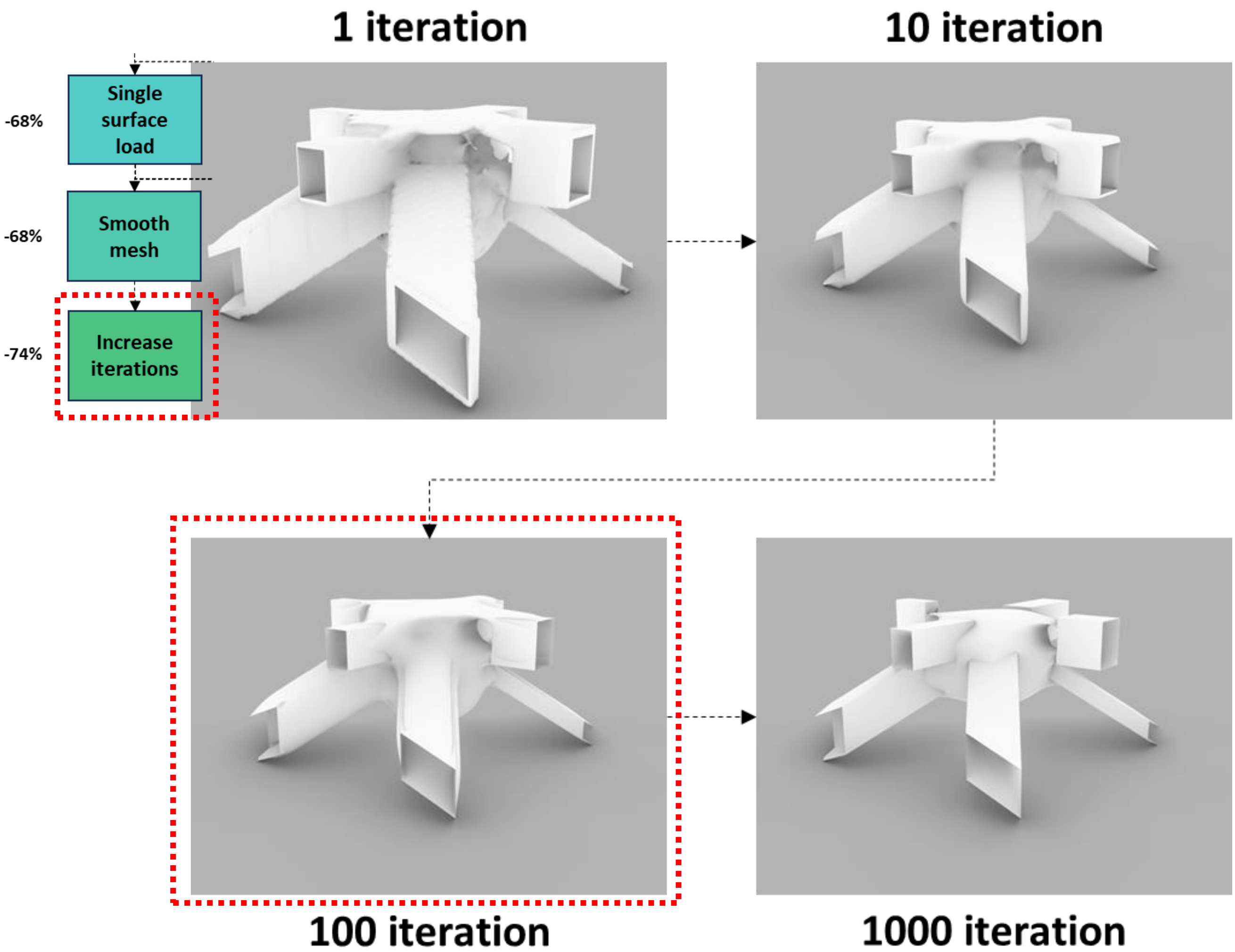



*Figure 18 Generated connection with smoothening strength at 1.0, source: own work*

Changing the internal load type alters the volume and shape of the connection, emphasizing the importance of realistic load simulations. The previous surface loads were divided among five sides incoming into the connection, then changed to the end of the element for a more realistic simulation. The new volume was 0.021098 $m^3$, a 68% reduction compared to the original case.

**Increasing the number of iterations for smoothening the surface**




| Number of iterations | Volume in $m^3$ | % volume reduction compared to original |
|---|---|---|
| 1 | 0.021106 | -67% |
| 10 | 0.020609 | -68% |
| 100 | 0.016673 | -74% |
| 1000 | 0.004358 | -93% |

By increasing the number of iterations, the pixelated surface transforms into a flowing geometry. This also connects components not fully attached yet. However, excessive smoothening (e.g., 1,000 iterations) resulted in unusable shapes for construction. The connection generated after 100 iterations had a workable shape and was used for the rest of the research.

**Double check through Simplify3D**

o ensure accuracy, the volume calculated in Grasshopper was double-checked using Simplify3D. The volume and weight of 19 kilograms matched the calculations in Grasshopper, confirming the amount of material used.

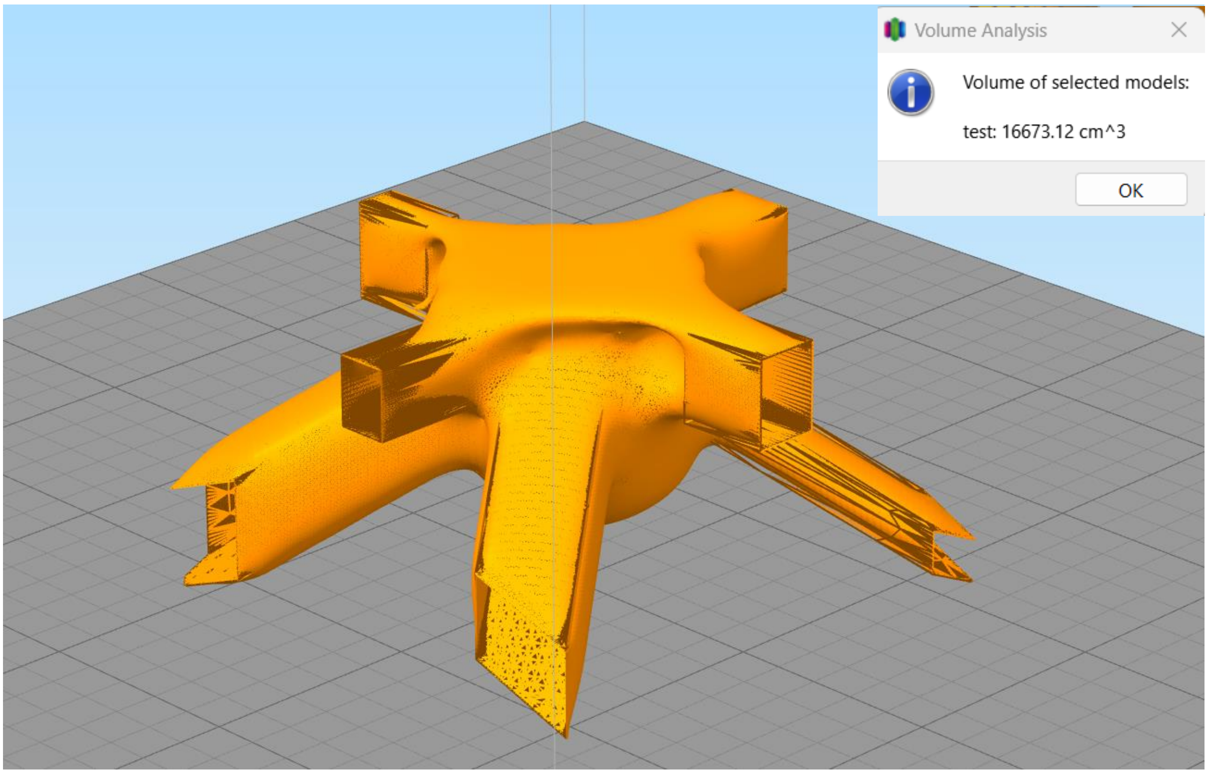



*Figure 19 Visualization in Simplify3D, source: own work*

## B. LCA results

The LCA results show the total water and energy usage, as well as carbon emissions over specified periods. The time periods used in this research are 1, 5, 10, 50, and 100 years. The results are as follows:

**Scenarios 1, 5, and 10 years**

| Scenario 1 – 1, 5 and 10 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| **Steel pipes** | 14586 | 23891 | 1056 | 479 |
| **Steel connectors** | 1800 | 2443 | 134 | 49 |
| **Total** | 16386 | 26334 | 1190 | 528 |

*Table 7 LCA scenario 1 over 1, 5 and 10 years, source: own work*

| Scenario 2 – 1, 5 and 10 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| New wooden elements | 25872 | 252940 | 134 | 344 |
| Steel connectors | 1800 | 2443 | 134 | 49 |
| Total | 27672 | 255383 | 267 | 393 |

*Table 8 LCA scenario 2 over 1, 5 and 10 years, source: own work*

| Scenario 3 - 1, 5 and 10 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| New wooden elements | 0 | 0 | 0 | 0 |
| Reused wooden elements | 0 | 0 | 0 | 267 |
| Cut-off loses | 5071 | 49580 | 26 | 71 |
| Steel connectors | 1800 | 2443 | 134 | 49 |
| Total | 6871 | 52023 | 160 | 387 |

*Table 9 LCA scenario 3 over 1, 5 and 10 years, source: own work*

| Scenario 4 – 1, 5 and 10 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| New wooden elements | 0 | 0 | 0 | 0 |
| Reused wooden elements | 0 | 0 | 0 | 248 |
| Cut-off loses | 61 | 597 | 0,3 | 0,85 |
| Steel connectors | 1800 | 2443 | 134 | 49 |
| Total | 1861 | 3040 | 134 | 298 |

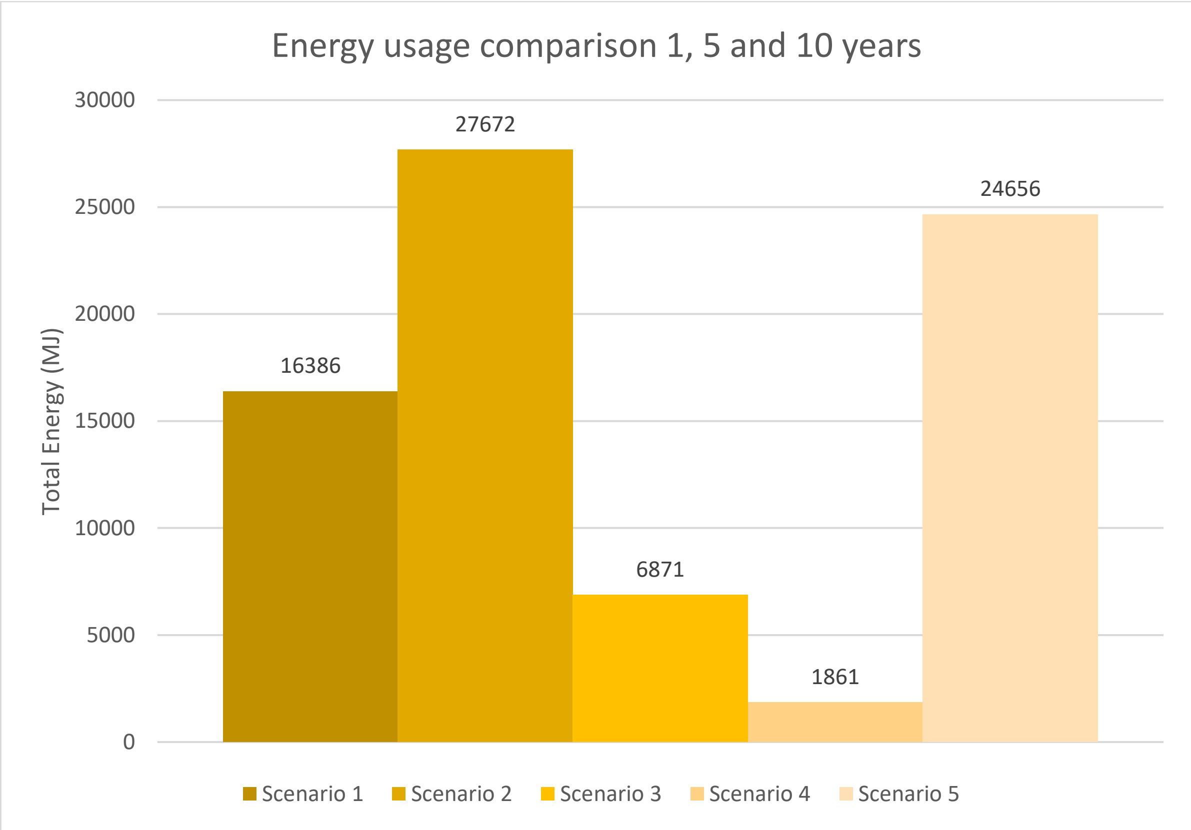
*Table 10 LCA scenario 4 over 1, 5 and 10 years, source: own work*

| Scenario 5 – 1, 5 and 10 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| New wooden elements | 1173 | 11464 | 6 | 16 |
| Reused wooden elements | 0 | 0 | 0 | 223 |
| 3D printed connectors | 23484 | 24672 | 1123 | 177 |
| Total | 24656 | 36136 | 1129 | 416 |

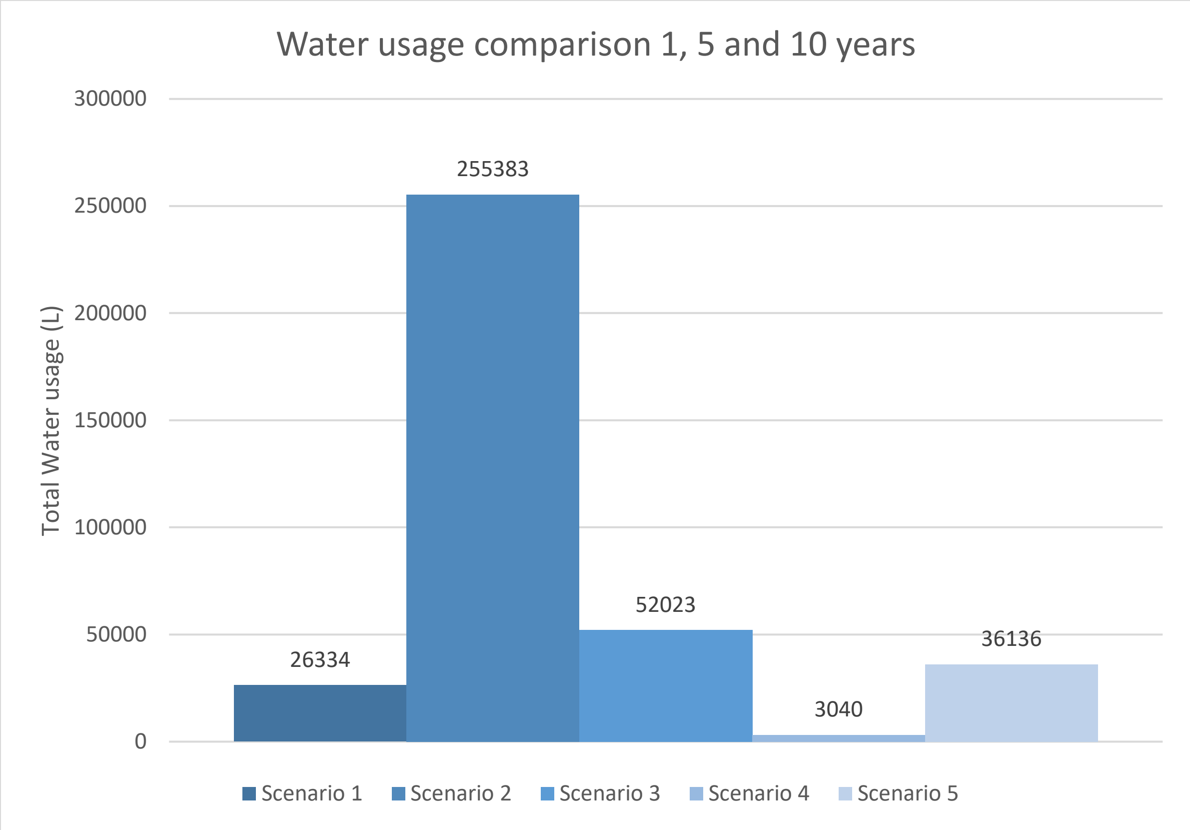
*Table 11 LCA scenario 5 over 1, 5 and 10 years, source: own work*

| Scenarios 1, 5 and 10 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| Scenario 1 | 16386 | 26334 | 1190 | 528 |
| Scenario 2 | 27672 | 255383 | 267 | 393 |
| Scenario 3 | 6871 | 52023 | 160 | 387 |
| Scenario 4 | 1861 | 3040 | 134 | 298 |
| Scenario 5 | 24656 | 36136 | 1129 | 416 |

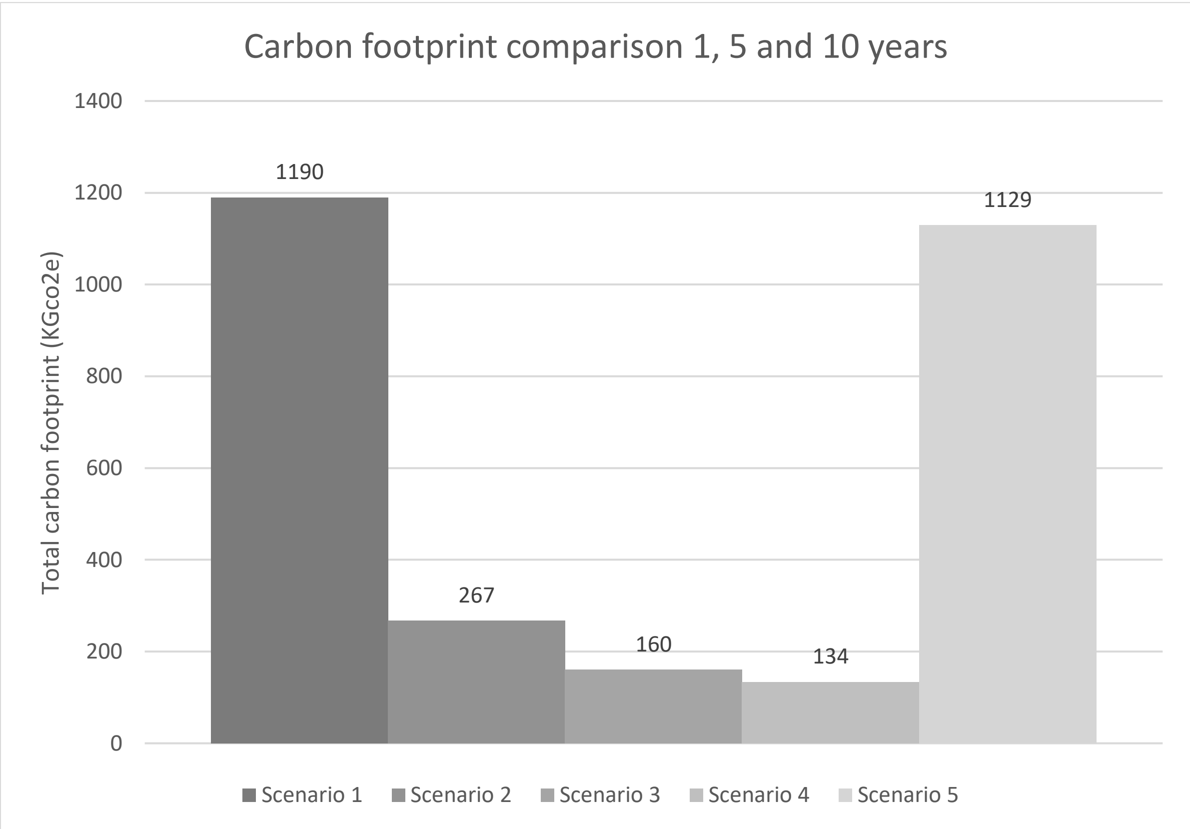
*Table 12 Overview of the LCA scenarios over 1, 5 and 10 years, source: own work*




*Column chart 1 Energy consumption of the 5 scenarios for the first 10 years, source: own work*




*Column chart 2 Water consumption of the 5 scenarios for the first 10 years, source: own work*




*Column chart 3 Carbon footprint of the 5 scenarios for the first 10 years, source: own work*

**Scenarios 50 years**

| Scenario 1 - 50 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| Steel pipes | 14586 | 23891 | 1056 | 479 |
| Steel connectors | 1800 | 2443 | 134 | 49 |
| Total | 16386 | 26334 | 1190 | 528 |

*Table 13 LCA scenario 1 over 50 years, source: own work*

| Scenario 2 - 50 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| New wooden elements | 25872 | 252940 | 134 | 344 |
| Steel connectors | 1800 | 2443 | 134 | 49 |
| Total | 27672 | 255383 | 267 | 393 |

*Table 14 LCA scenario 2 over 50 years, source: own work*

| Scenario 3 - 50 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| New wooden elements | 0 | 0 | 0 | 0 |
| Reused wooden elements | 0 | 0 | 0 | 267 |
| Cut-off loses | 5071 | 49580 | 26 | 71 |
| Steel connectors | 1800 | 2443 | 134 | 49 |
| Total | 6871 | 52023 | 160 | 387 |

*Table 15 LCA scenario 3 over 50 years, source: own work*

| Scenario 4 - 50 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| New wooden elements | 0 | 0 | 0 | 0 |
| Reused wooden elements | 0 | 0 | 0 | 248 |
| Cut-off loses | 61 | 596 | 0,3 | 0,85 |
| Steel connectors | 1800 | 2443 | 134 | 49 |
| Total | 1861 | 3039 | 134 | 298 |

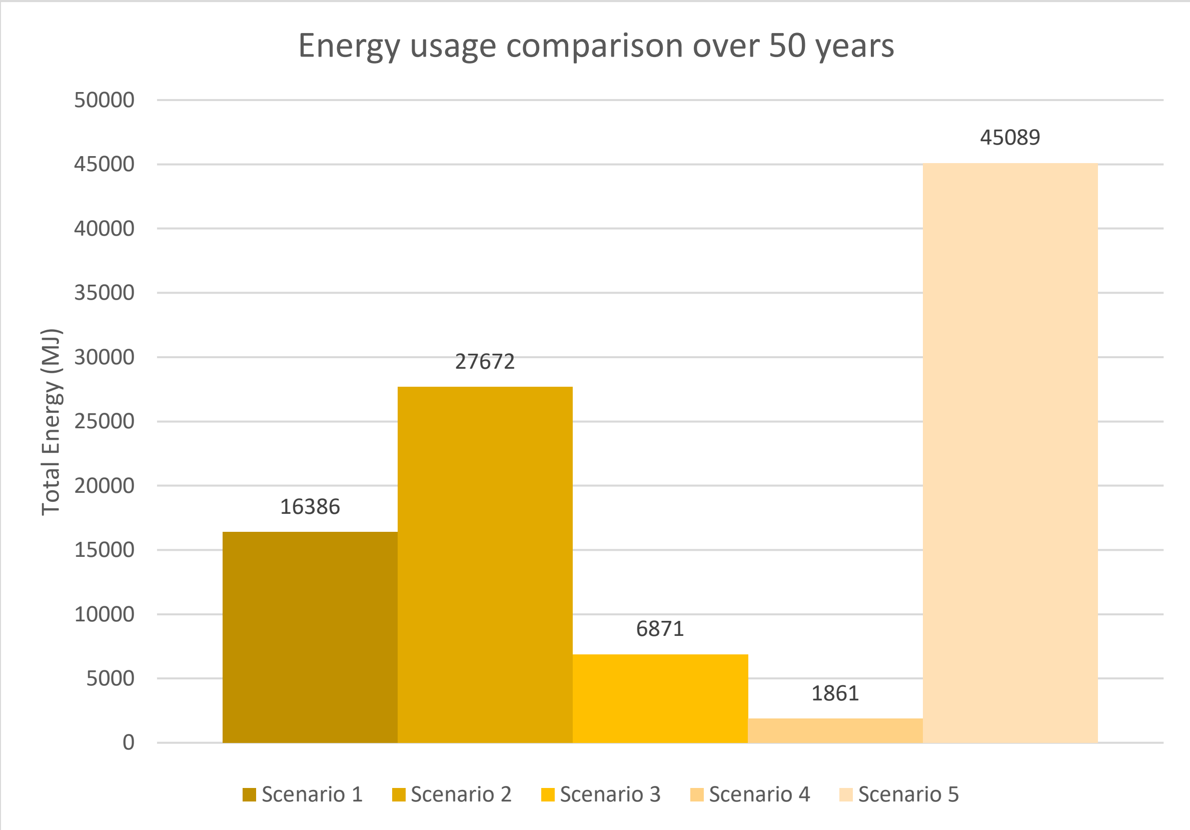
*Table 16 LCA scenario 4 over 50 years, source: own work*

| Scenario 5 - 50 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| New wooden elements | 1173 | 11464 | 6 | 16 |
| Reused wooden elements | 0 | 0 | 0 | 223 |
| 3D printed connectors | 43917 | 27918 | 2160 | 177 |
| Total | 45089 | 39382 | 2166 | 416 |

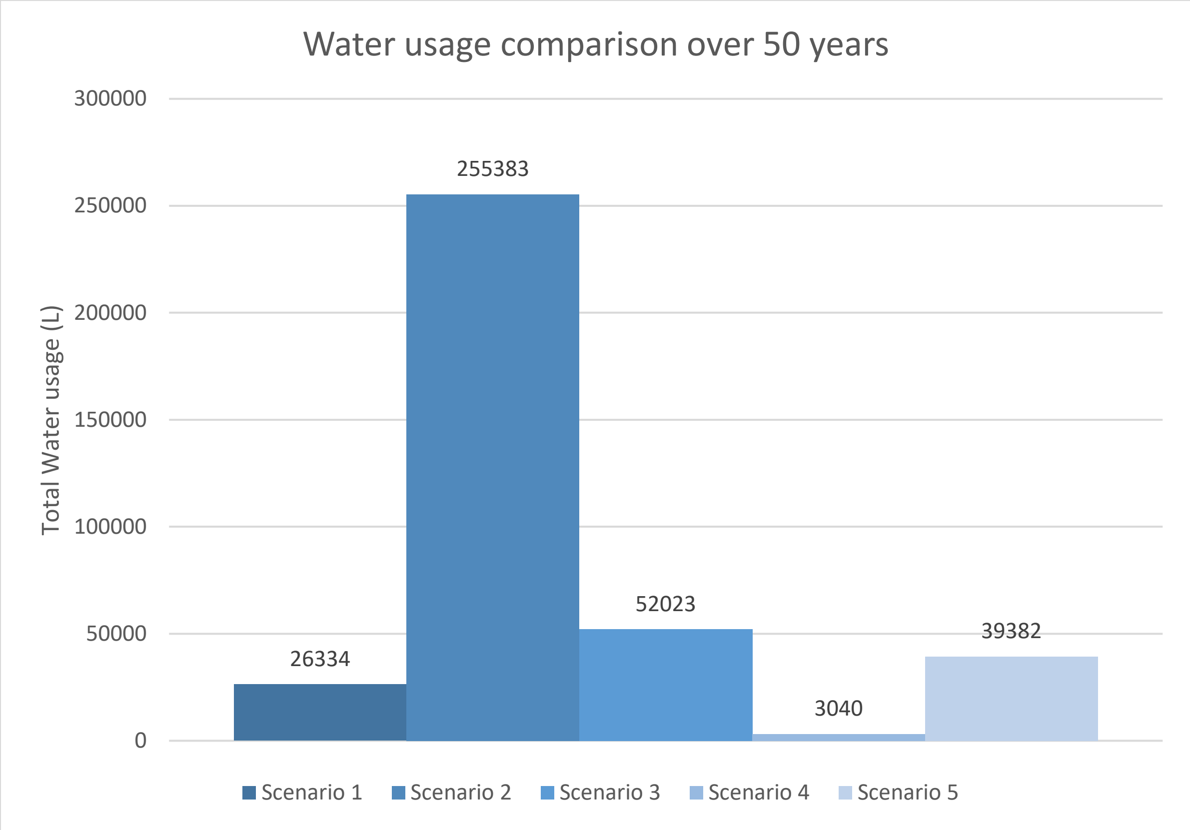
*Table 17 LCA scenario 5 over 50 years, source: own work*

| Scenarios 50 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| Scenario 1 | 16386 | 26334 | 1190 | 528 |
| Scenario 2 | 27672 | 255383 | 267 | 393 |
| Scenario 3 | 6871 | 52023 | 160 | 387 |
| Scenario 4 | 1861 | 3039 | 134 | 298 |
| Scenario 5 | 45089 | 39382 | 2166 | 416 |

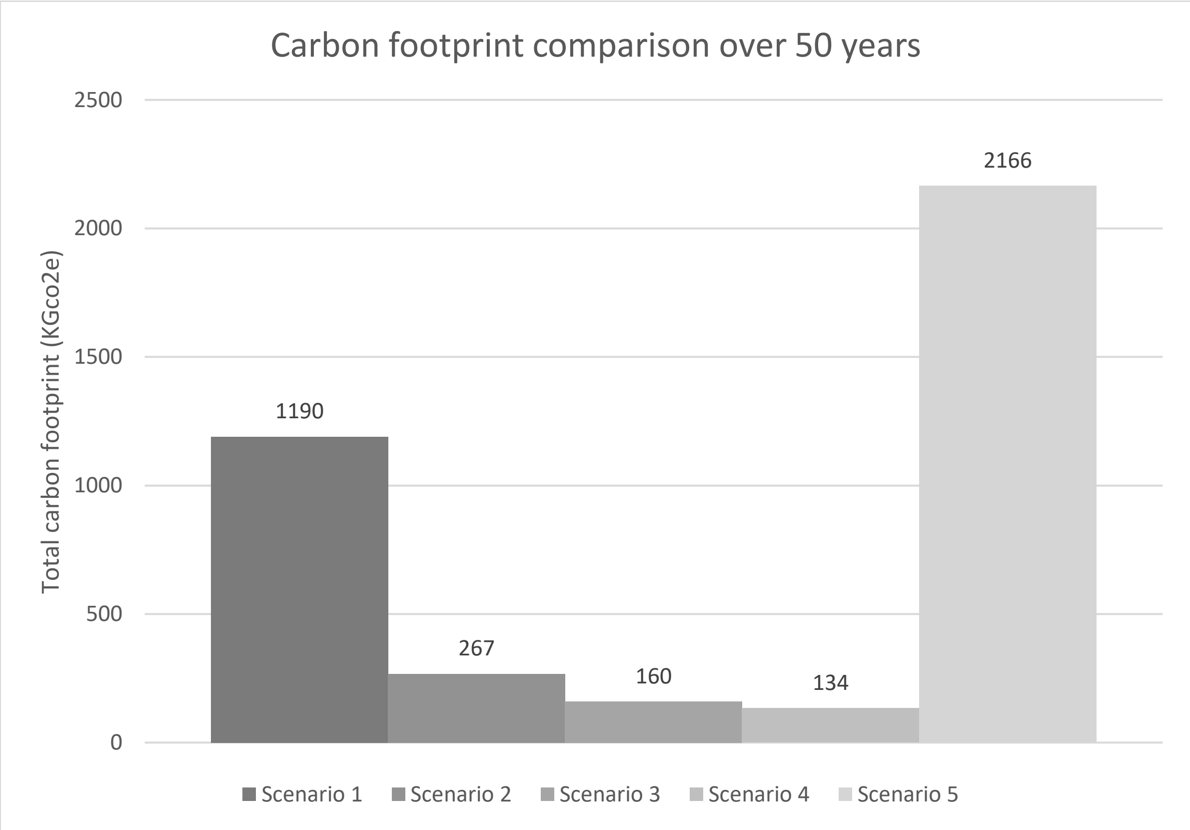
*Table 18 LCA overview over 50 years, source: own work*




*Column chart 4 Energy consumption of the 5 scenarios over 50 years, source: own work*




*Column chart 5 Water consumption of the 5 scenarios over 50 years, source: own work*




*Column chart 6 Carbon footprint of the 5 scenarios 50 years, source: own work*

**Scenarios 100 years**

| Scenario 1 - 100 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| Steel pipes | 29172 | 47781 | 2112 | 479 |
| Steel connectors | 3600 | 4886 | 267 | 49 |
| Total | 32772 | 52667 | 2380 | 528 |

*Table 19 LCA scenario 1 over 100 years, source: own work*

| Scenario 2 - 100 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| New wooden elements | 51744 | 505880 | 267 | 357 |
| Steel connectors | 3600 | 4886 | 267 | 49 |
| Total | 55344 | 510766 | 535 | 406 |

*Table 20 LCA scenario 2 over 100 years, source: own work*

| Scenario 3 - 100 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| New wooden elements | 0 | 0 | 0 | 0 |
| Reused wooden elements | 0 | 0 | 0 | 267 |
| Cut-off loses | 10143 | 99159 | 52 | 71 |
| Steel connectors | 3600 | 4886 | 267 | 49 |
| Total | 13743 | 104045 | 320 | 387 |

*Table 21 LCA scenario 3 over 100 years, source: own work*

| Scenario 4 - 100 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| New wooden elements | 0 | 0 | 0 | 0 |
| Reused wooden elements | 0 | 0 | 0 | 248 |
| Cut-off loses | 122 | 1192 | 0,6 | 0,85 |
| Steel connectors | 3600 | 4886 | 267 | 49 |
| Total | 3722 | 6078 | 268 | 298 |

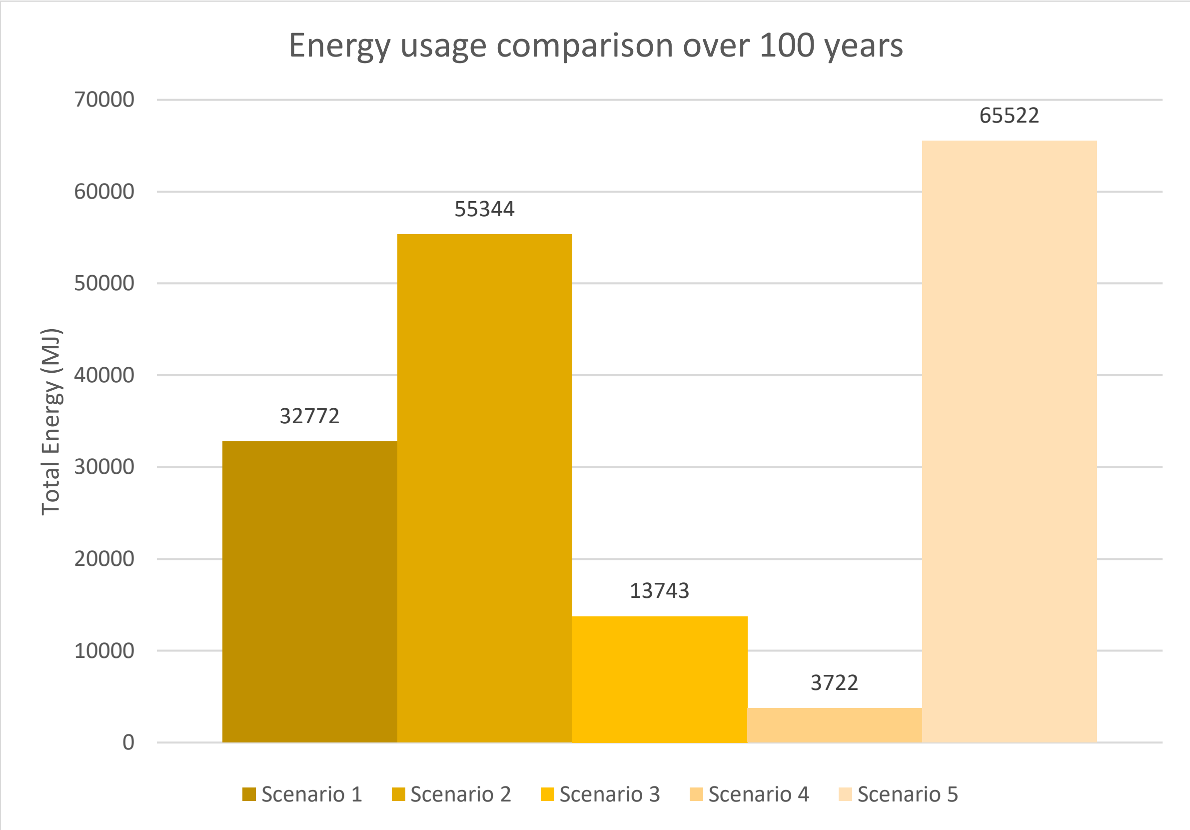
*Table 22 LCA scenario 4 over 100 years, source: own work*

| Scenario 5 - 100 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| New wooden elements | 1173 | 11464 | 6 | 16 |
| Reused wooden elements | 0 | 0 | 0 | 223,4 |
| 3D printed connectors | 64349 | 31164 | 3198 | 177 |
| Total | 65522 | 42628 | 3204 | 416 |

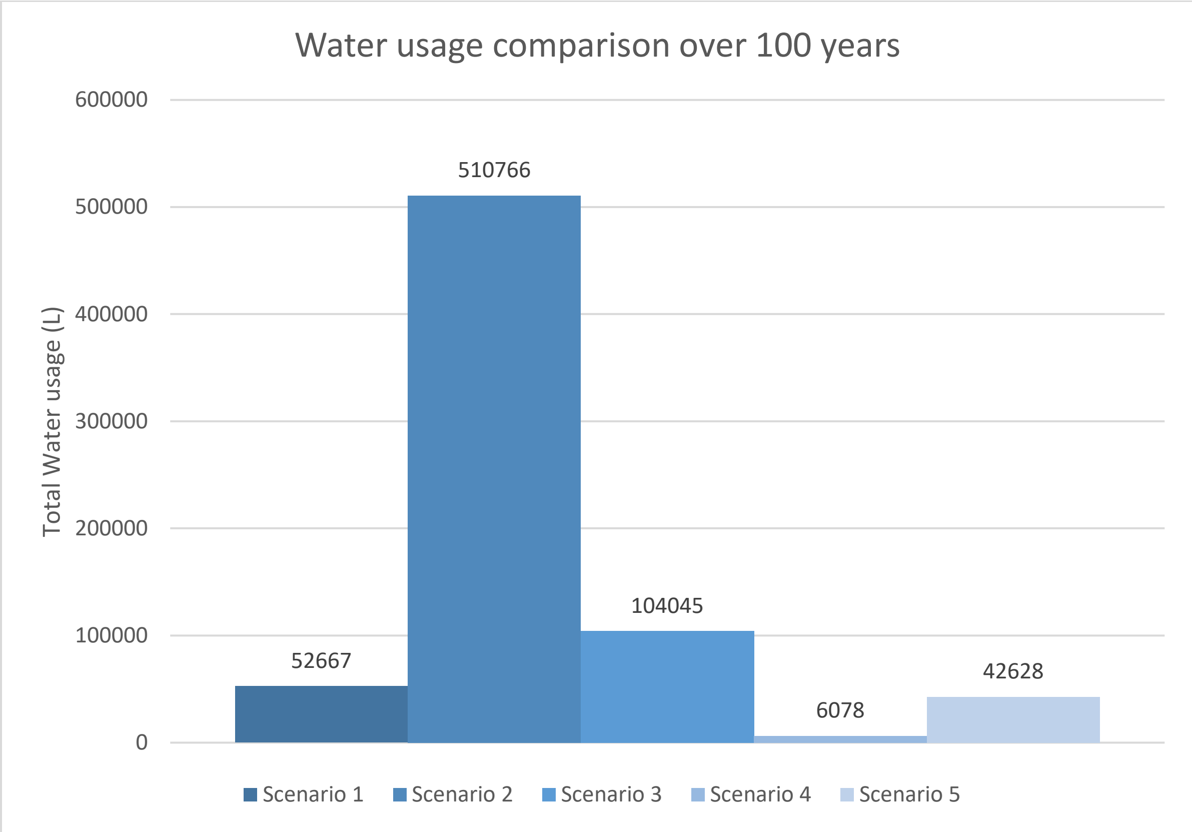
*Table 23 LCA scenario 5 over 100 years, source: own work*

| Scenarios 100 years | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| Scenario 1 | 32772 | 52667 | 2380 | 528 |
| Scenario 2 | 55344 | 510766 | 535 | 406 |
| Scenario 3 | 13743 | 104045 | 320 | 387 |
| Scenario 4 | 3722 | 6078 | 268 | 298 |
| Scenario 5 | 65522 | 42628 | 3198 | 416 |

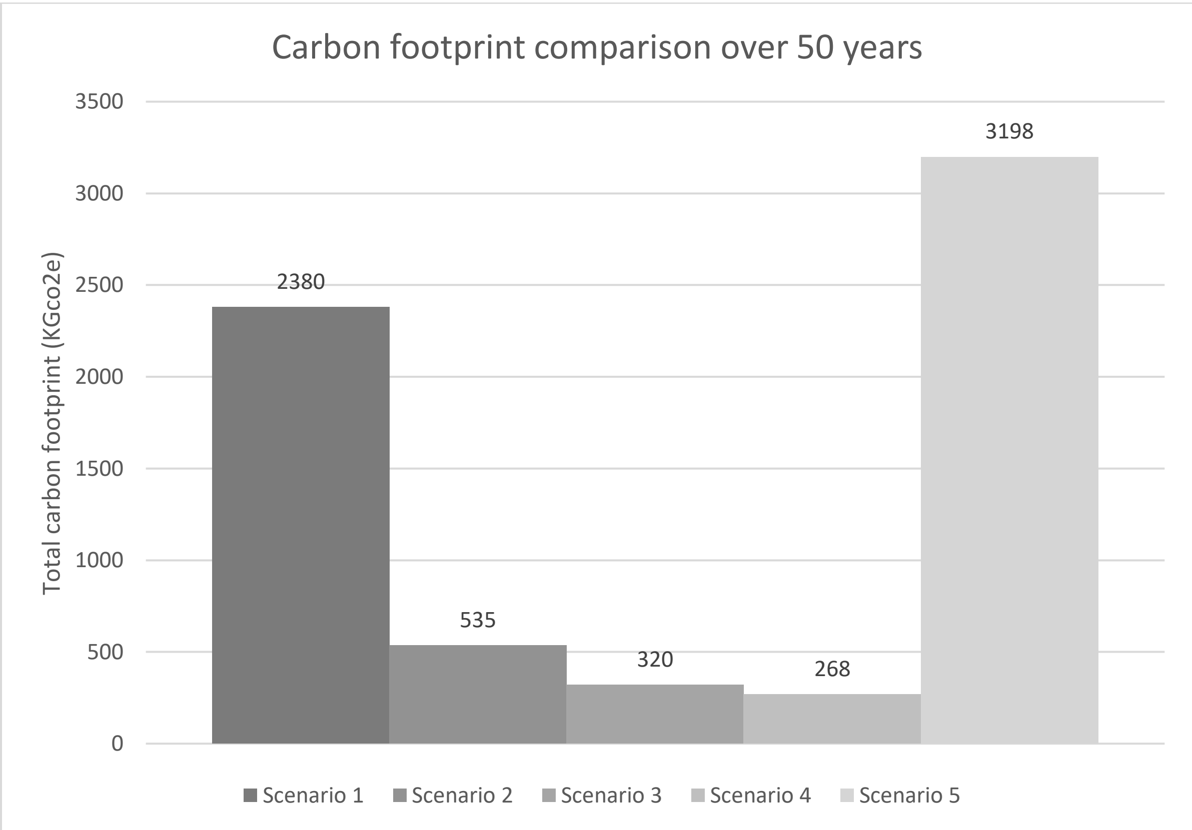
*Table 24 LCA overview over 100 years, source: own work*




*Column chart 7 Energy consumption of the 5 scenarios over 100 years, source: own work*




*Column chart 8 Water consumption of the 5 scenarios over 100 years, source: own work*




*Column chart 9 Carbon footprint of the 5 scenarios 100 years, source: own work*

The results indicate that the first proposed changes continuously lower the total carbon footprint (scenarios 1 to 4). However, in Scenario 5 (the new proposal), the carbon footprint goes up again. Depending on the time horizon will determine if it can compete with the original steel structure.

## C. Waste production results

As mentioned before: *a circulair economy aims to keep manufactured goods as long as possible in circulation through closed loops.* With the scenarios in the research the following waste flow was measured in kg. In the first service life that includes cut-off loses, the assumption was made that this is not the case for new elements. Since scenario 1 and 2 are simulating are simulating the current situation where landfill is the common end of life, the entire weight is seen as waste.

**Waste production 1st service life**

| Scenarios | Waste (kg) |
|---|---|
| Scenario 1 | 0 |
| Scenario 2 | 0 |
| Scenario 3 | 70,8 |
| Scenario 4 | 0,85 |
| Scenario 5 | 0 |

*Table 25 Waste production 1st service life, source: own work*

**Waste production 2th service life**

| Scenarios | Waste (kg) |
|---|---|
| Scenario 1 | 528 |
| Scenario 2 | 406 |
| Scenario 3 | 141,6 |
| Scenario 4 | 1,7 |
| Scenario 5 | 0 |

*Table 26 Waste production 2th service life, source: own work*

For the second service life, a decline in waste is observed with each alteration from Scenario 1 to Scenario 5. This result was expected as the steps progress from reducing waste to refusing waste.

## D. Connection generation results

All 13 connections were generated within the research structure. The composition of the elements coming into the connection was designed using the stock-constrained design tool, while the resulting connections were designed through topology optimization. To further explore the fabrication of these connections, several 3D prints were made.

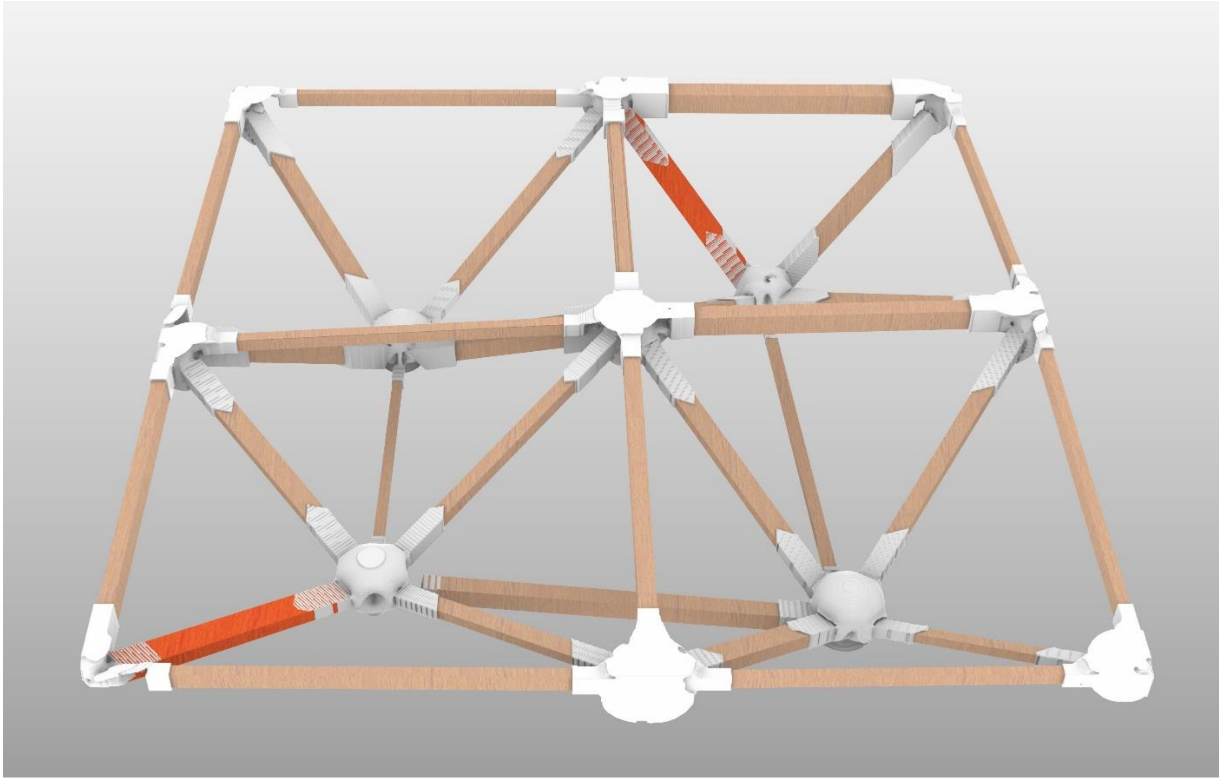


*Figure 20 Top view structure created, source: own work*

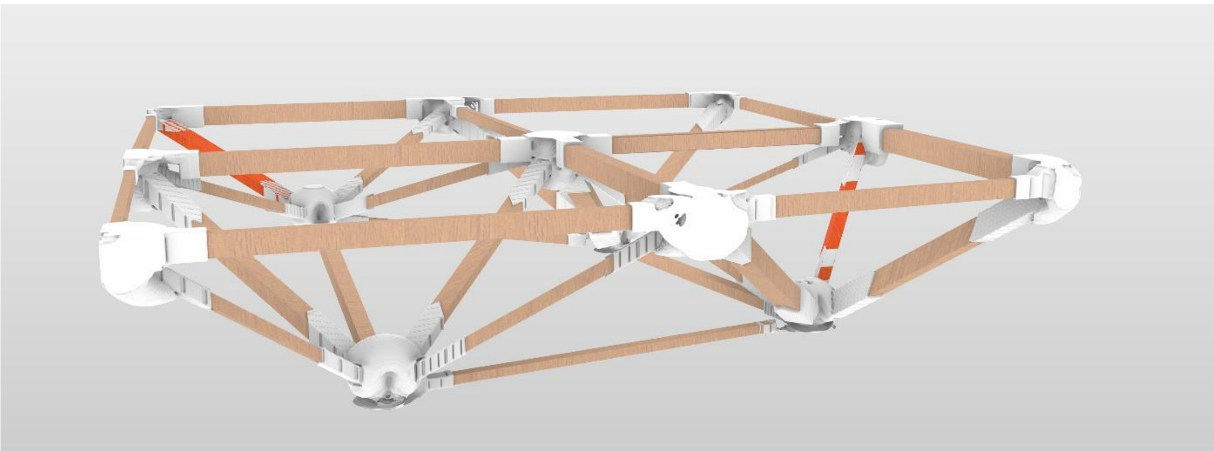


*Figure 21 Side view created structure, source: own work*

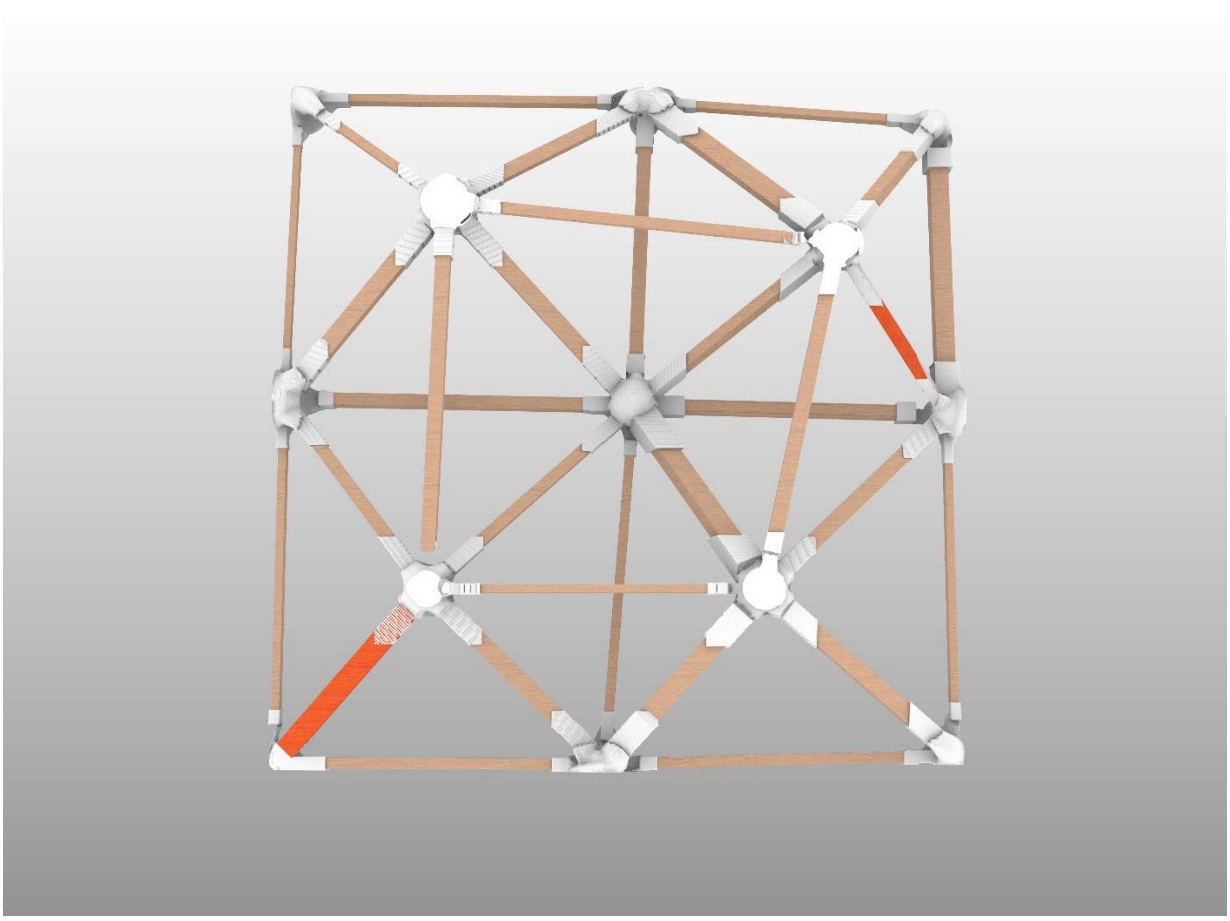
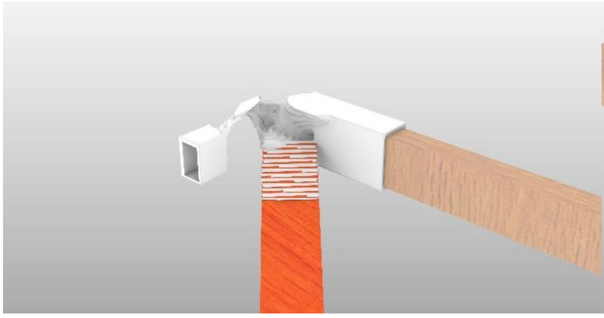


*Figure 22 View underneath created structure, source: own work*



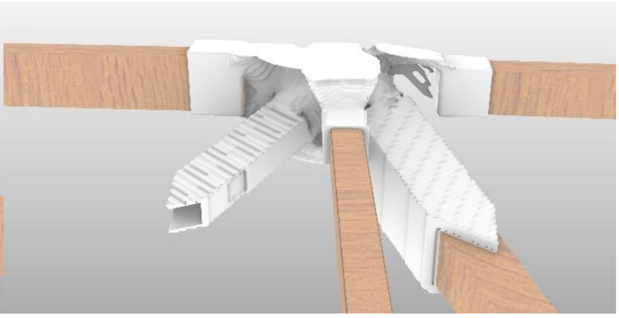
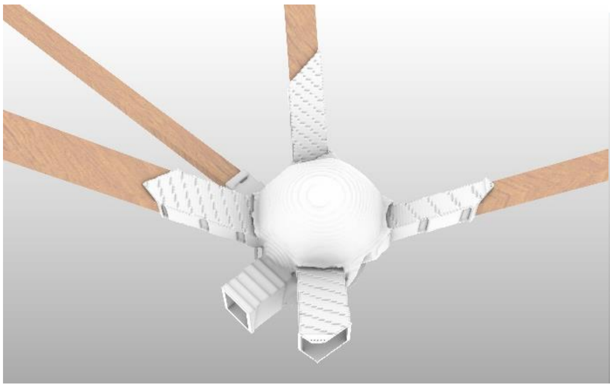


*Figure 23 Created corner connection, source: own work*

*Figure 24 Created side connection, source: own work*



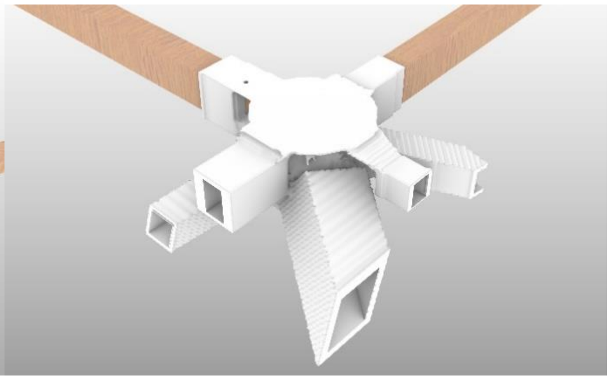


*Figure 25 Created lower support connection, source: own work*

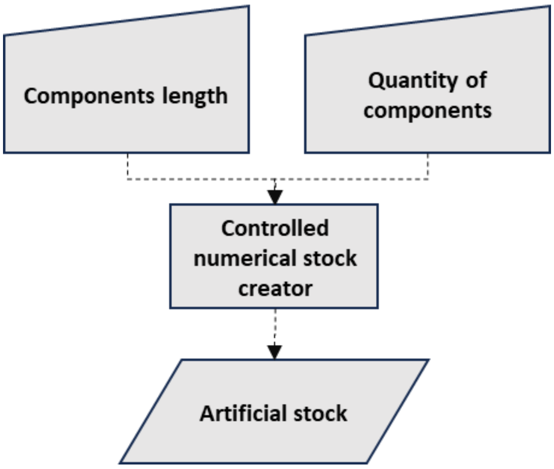
*Figure 26 Central created connection, source: own work*

# VII. Testing workflow

## A. Artificial stock

As mentioned previously, a circular material database that can be used does not yet exist. The assumption is that such a database will be available in the future. For now, an artificial stock will be created to simulate a real-life scenario. Three methods of stock creation were considered: controlled numerical, controlled drawn, and a random generator. Ultimately, the random generator was chosen. The decision-making process is described below:

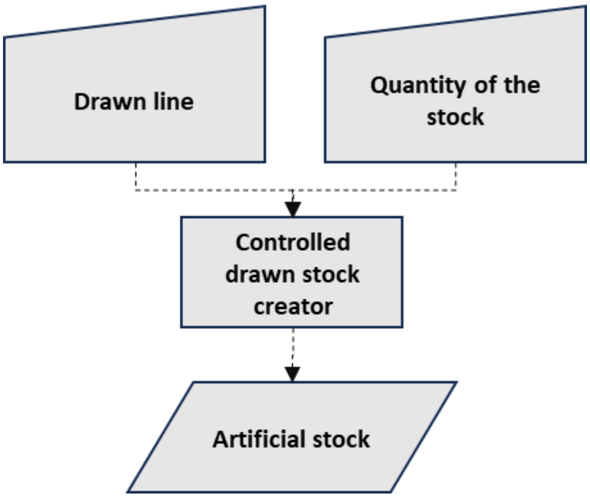
### Controlled numerical




*Flowchart 17 Controlled numerical artificial stock in Grasshopper, source: own work*

The controlled numerical stock creator allows manual control of the lengths and quantities of the elements. This method is very useful when the stock lengths are known by the designer. It also provides the option for a controlled input of lengths, which can be used to verify if the tool works as expected. For example, if the lengths within the structure are known and the stock is set to the same values, the reuse should be 100%. However, testing multiple scenarios (different stock combinations) requires more manual effort to alter everything. Additionally, the number of unique elements is limited for stock made up of wooden elements from multiple sources or potentially damaged. The main advantage of computational power over manual stock-constrained design is its ability to iterate through multiple combinations every second, regardless of the number of variations.

### Controlled drawn

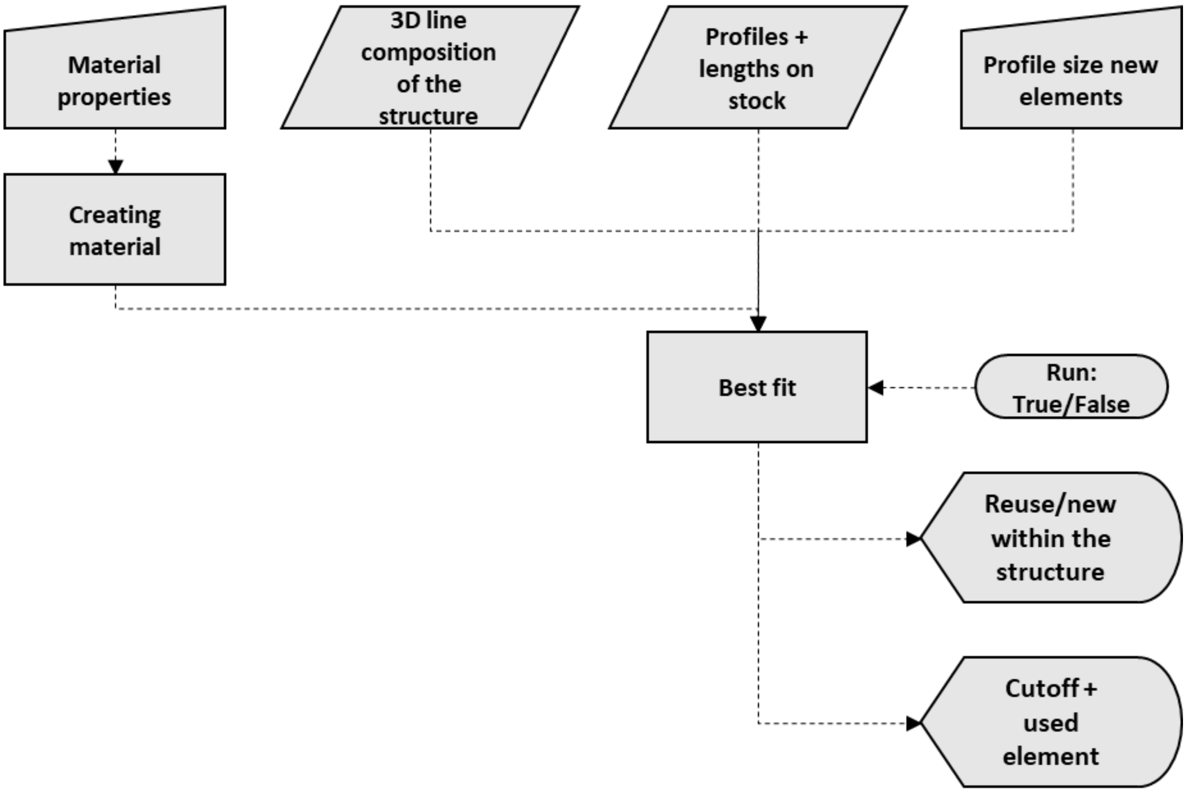



*Flowchart 18 Controlled drawn artificial stock in Grasshopper, source: own work*

The controlled drawn method converts drawn lines into lengths, allowing the quantity to be increased in Grasshopper itself. This could be useful if the database consists of drawn lines. The benefits and disadvantages are similar to the controlled numerical method, offering significant control but requiring more manual labour when testing multiple scenarios and unique lengths.

Due to the beforementioned advantages and disadvantages of these techniques, a combination of controlled numerical and random generator methods was used. The controlled numerical method offers better control and oversight in the early stages to validate the process of creating a stock-constrained design tool. Once the results are consistent with expectations, the switch is made to the random generator to obtain results closer to reality due to the unique elements.

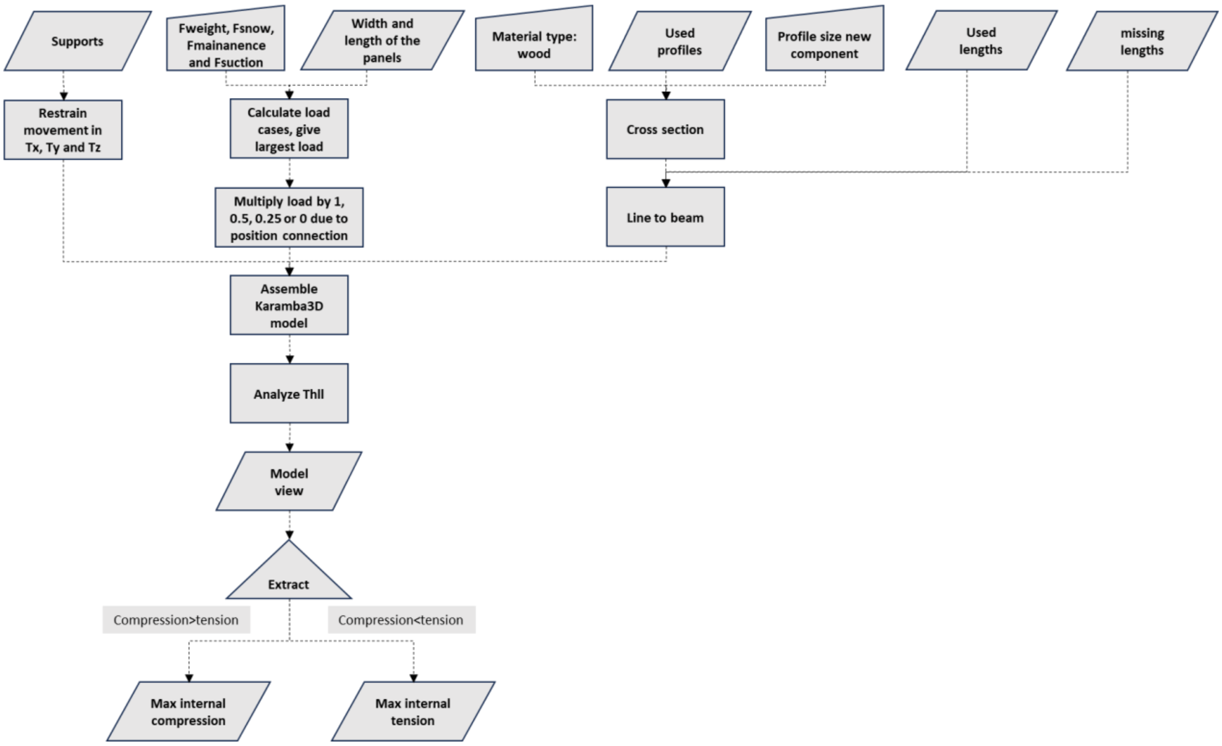
## B. Phoenix 3D




*Flowchart 19 Visualization of Phoenix 3D within Grasshopper, source: own work*

Initially, Phoenix 3D was used for the second and third scenarios. However, this did not yield the required results for this research. The output made it impossible to retrieve the elements used within the structure, preventing the calculation of saw-off losses. As a result, the stock-constrained design performed by Phoenix 3D became a black box where crucial data was lost. Therefore, a stock-constrained design tool was built in Python to proceed with the research.

## C. Karamba 3D




*Flowchart 20 Visualization of Karamba3D within Grasshopper, source: own work*

The connectors at the bottom are selected as supports. In a larger structure, only a limited number of these connections are actual supports. However, for the purpose of this research, the structure in the workflow is a sample size to determine if everything works, so it can be scaled up in future research. The timber elements in use are assigned their profiles to check if the proposed structure derived from the stock-constrained design is workable. Ideally, this should be integrated into an automated process where the stock-constrained design receives a penalty from the Karamba simulation if the structure is invalid. However, this drastically decreases the calculation time of the shape-finding process. Therefore, for this research, it was decided to ensure the structure would always work with the given profiles, performing structural validation beforehand. By testing the worst-case scenario, it can be certain that the generated composition works. Manual testing revealed that buckling is normative, and minimum sizes for the stock were adjusted accordingly. However, in future work with improved computational power, the two should be combined to optimize utilization.

## D. Connection generating

With only the point load of the roof added to the model, the first simulation was performed. This initial test revealed two immediate problems: not all elements were used as support in creating a connection, and it did not provide a surface that allowed for a connection with the roof.

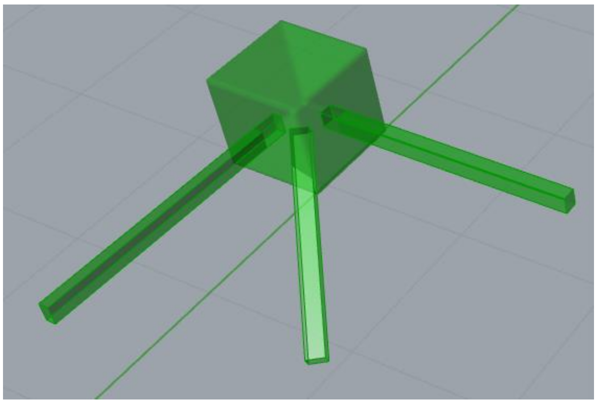


*Figure 28 Section box with selected elements Grasshopper, source: own work*

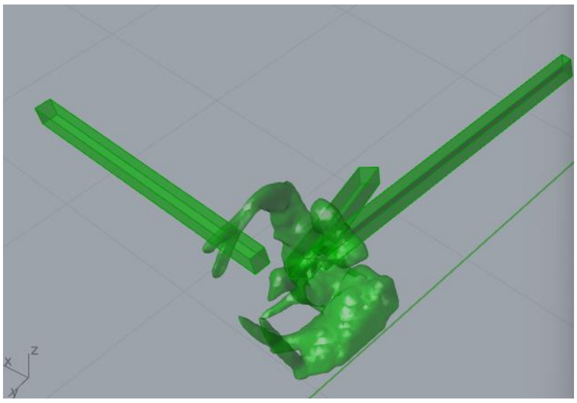


*Figure 27 First generated connection trial Grasshopper, source: own work*

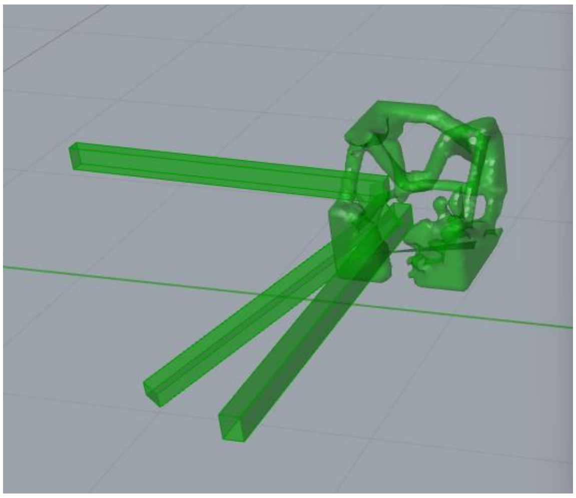


*Figure 29 Second generated connection trial Grasshopper, source: own work*

First, the connection to the roof was addressed by changing the point load to a surface load. Assuming a similar connection to the modelling hall's steel pipe, a circular surface was created. Since the vector is multiplied by the surface in square meters, a multiplier was added to ensure the vector becomes the total load.

This still did not yield the desired attachments needed for a functional connection. The internal loads expected within the model were then added. The idea is that the simulation must place material around the timber elements to neutralize their movement. The tension/compression experienced can differ per element and position. For this research, it was simplified by taking the largest value within the structure and designing for that. The assumption is that since the profiles are similar in sizes, optimizing the attachment for each profile individually is negligible. Future research should verify if this assumption is correct. Another benefit is that it provides an extra safety factor, which is recommended for reused wood that can be unpredictable. The largest compression or tension value is selected and spread over the surfaces of the elements entering the section box. This way, every element will experience maximum tension/compression in the simulation to generate connections.

This addition made a positive change and brought the connection closer to what was expected for performance.

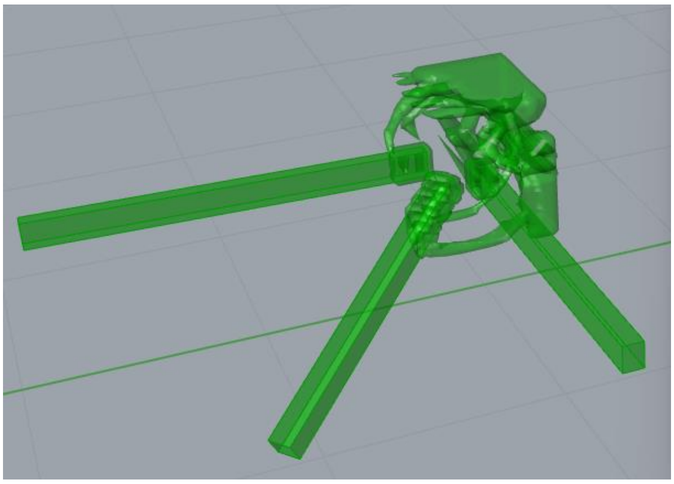


*Figure 30 Third generated connection trial Grasshopper, source: own work*

From the third attempt, it was detected that the simulation tried to attach material to the edges of the domain. To combat this problem, an attempt was made to exclude any material from the edges of the section box by creating a small offset into the original box. This edge was marked as a void for the input.

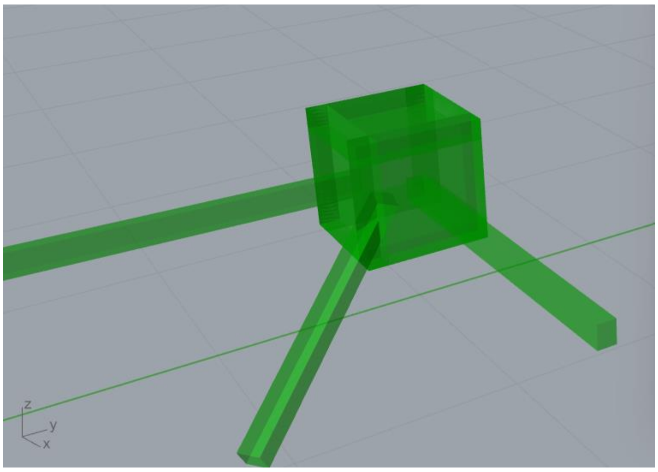


*Figure 31 Offset in sectionbox Grasshopper, source: own work*

Manually inputting predetermined voids also requires a fixed input of parts that must be solid in the simulation. To speed up the process of generating the connections and safeguard their structural integrity, part of the connection is predetermined. This is done by creating a hollow profile around the receiving element with the surface area of the smallest element in use, multiplied by the difference in Young's modulus. This ensures similar behaviour in tension and compression as the elements themselves. These parts are fixed within the joint generator so the generator does not have to iterate to find the attachment to the element but can focus on connecting the attachment into a joint.

This improved the simulation, reducing the total simulation time from 30 minutes to less than 2 minutes.

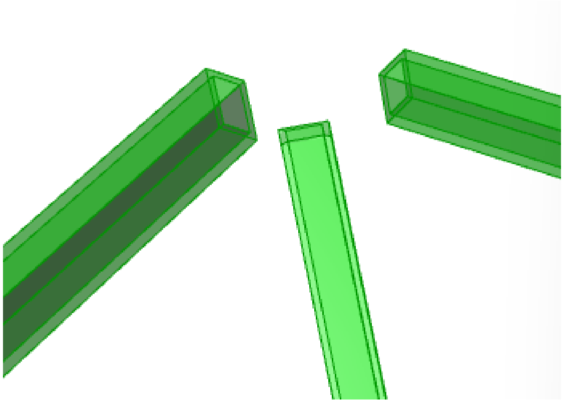


*Figure 32 Hollow predetermined profiles Grasshopper, source: own work*

The hollow profiles also posed a potential problem for assembly. The lack of tolerances or room to manoeuvre the elements during assembly or disassembly made it impossible to build the complete structure. For this reason, the hollow profiles were converted from hollow rectangular to U-profiles. By closing these off later, there is enough room for the elements to manoeuvre into position. Unfortunately, the simulation actively closed these U-profiles, even with the use of voids. Therefore, for now, the openings will have to be made manually after generating the connection. Due to time constraints and the limited scope of the research, it was not possible to address this problem or optimize the attachment itself.

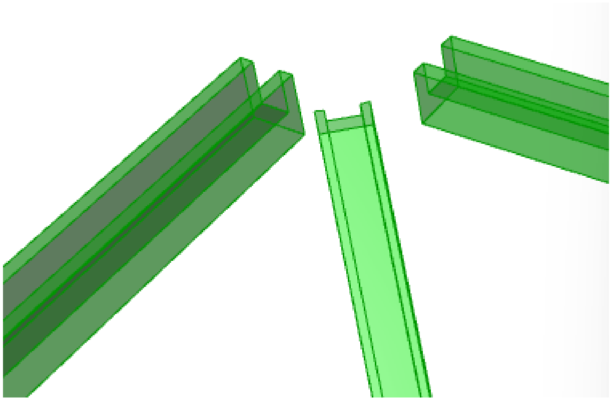


*Figure 33 U-profiles Grasshopper, source: own work*

## E. Millipede

Between the third and fourth trials, a different technique was explored using a different program: Millipede. Millipede, like tOpos, is a topology optimization program. However, it did not yield usable results, struggling to take in the necessary information to describe the constraints. The only available version of Millipede was an older version. After carefully rethinking the problem and resolving it in tOpos, further attempts to use Millipede were deemed not worthwhile. In the future, a second attempt could be made to compare the two programs in solving this specific problem.

*Figure 34 Millipede plugin for grasshopper, source: (*Millipede Plugin Grasshopper 3D*, z.d.)*

# VIII. Conclusion

## A. Research questions

This graduation project aims to answer the following primary research question:

*"Can stock-constrained digital design combined with 3D printing support the reuse of wooden structural elements without saw-off losses in a sustainable way?"*

To address this, several sub-questions were developed and are discussed below before answering the main question:

1. **What are the primary obstacles faced by designers in the process of reusing wooden structural elements?**

    - Multiple obstacles exist, such as the lack of constant availability of standardized elements, making it difficult to rely on reclaimed wood. The mixed quality of reclaimed elements, varying profiles, lengths, structural properties, types of damage, and other irregularities make the design process more time-consuming and resource-intensive compared to using new, off-the-shelf components. In short, it leads to a more complicated and resource-demanding design process.

2. **What prevents stock-constrained design tools from improving the reuse of wooden structural elements in the current environment?**

    - Stock-constrained design traditionally results in saw-off losses, causing material loss in each service life, thus not achieving full circularity. Additionally, design optimization often leads to complex compositions with unique connections, requiring customized connections that are resource-intensive to design, validate, and produce.

3. **Can a rationalized connection between stock-constrained design and additive manufacturing of the structural connections streamline the development of projects?**

- Additive manufacturing can streamline the process from the design of unique connections to manufacturing without altering the fabrication process. In order to prevent the manual design of all unique connections, automation is key. So yes, a rationalized between design and the additive manufacturing process can streamline the entire process as long as the process is responsive to the input.

**4. How should this connection work in order to produce functional joints?**

- The connection should encompass the entire process from design inputs to fabrication. This means that every input will automatically alter the end result, including automating the design of the total structure and the connections.

***Can stock-constrained digital design combined with 3D printing support the reuse of wooden structural elements without saw-off losses in a sustainable way?***

- To make stock-constrained design sustainable, saw-off losses must be avoided. 3D printed connections can compensate for missing lengths, allowing necessary adjustments within each unique connection without altering the fabrication technique. The grasshopper script described in this research enables the creation of structures where the wood does not need to be altered, thereby preventing saw-off waste. Consequently, the structural elements retain their value throughout their lifecycle, promoting sustainability. However, the overall technique with 3D printed connections currently results in a higher carbon footprint when compared with other techniques to reuse. This research shows that while saw-off losses can be avoided, achieving immediate sustainability is challenging. Further research is needed to determine if there is a breakeven or net gain in certain scenarios.

## B. Future research

The Grasshopper script presented in Chapter V was developed specifically for this research. Due to the scope and time limitations, there is room for further development. Future research could improve the tool's accuracy, provide more information, or apply it for multiple user ends. The following directions are suggested for future research:

- **Compatibility with different 3D printing techniques:**
  - The generated connection should be producible. Depending on the 3D printer type, settings, and material, the design needs alterations to perform and survive production. Ideally, this step would be automated within the workflow, reducing the user's need for 3D printing expertise.
- **Structural validation of the connections:**
  - Physical testing has not been conducted so far. Such tests would provide insights into the influence of 3D printer settings and the translation of a topology-optimized connection into a physical object. These tests could also provide information on the service life of 3D printed connections.
- **Attachment optimization:**
  - U-profiles were attempted as attachments to enable assembly while adjusting the surface area to the largest load within the structure. Due to the simulation only working with hollow profiles, this remains to be done successfully. However, this could be optimized to save material or simplify assembly.
- **Including different loads:**
  - Currently, only compression and tension forces are considered. Including bending and analysing the structure's behaviour when a component fails would bring the design closer to a final working product suitable for practical use.
- **Economics:**
  - Creating structures without waste and fully reusable components requires a new economic system. Research could explore viewing structures as temporary material banks that can be rented. Future studies should investigate which economic systems are most suitable for such structures.
- **Scaling up the structure and adding different structural typologies:**
  - The structure size was kept minimal during this research, so scaling effects have not been observed. Future research could explore scaling up and incorporating different structural typologies and materials.
- **More in-depth LCA**
  - Adding more data about the carbon footprint sources could help make the results more sustainable. Understanding energy sources could aid in estimating the feasibility of using sustainable energy in the future. The LCA is also location-

dependent, and transportation, currently excluded from the analysis, could influence design choices.

- **Creating a real stock:**
    - This research relies on the existence of 3D models of reclaimed timber from circular hubs. Research into creating such a system would bring the tool closer to practical application.
- **Optimizing printing techniques:**
    - Various parameters in the printing process affect total energy usage, including plate and nozzle temperature, printing time, speed, infill, and ventilation. Optimizing these parameters could reduce the total footprint and improve the final product's strength.
- **Post-treatment**
    - In this research, some post-treatment of the connections was explored. Smoothening the surface can enhance the overall structure by ensuring that forces do not concentrate in individual corners, but are instead evenly spread out over the entire surface. However, as the research has also shown, post-treatment can be overdone. Future research should explore the effects of post-treatment on structural functionality to find the right balance.
- **Utilizing AI**
    - As demonstrated during the research, obtaining an accurate volume for every connection requires a powerful computer and significant time. For early-stage design, where a quick estimation of material usage is crucial, AI could be beneficial. By predicting volume or even shapes, AI could help direct the design strategy more efficiently.

# IX. Discussion

By combining stock-constrained design with 3D printed connections, generated out of a typology optimization it is possible to reuse timber without saw-off losses. However, results from the LCA have also shown that this might come at a high cost. Whereas total waste production over multiple life cycles went down, the carbon footprint went up. Besides, it still demanded the usage of some new elements.

However, the high carbon footprint could change over time. Since all of the materials remain within the circularity cycle it means only energy goes into the cycle. If this energy could come from a clean energy source the outcome might be different. Besides energy, changing material could also have a large impact on the carbon footprint. A different material can provide the structure with a lower footprint due to being more sustainable, having a longer lifespan, lower energy usage for fabrication or by requiring a lower volume than the tested PETG. This research already explores ways on how to further reduce the volume, showing potential gains for further research.

Besides, the connections should also become fire proof, something that has so far been left outside of the scope of this research. Combined with the simplifications made in the structural value of the final product this process still has some steps to go before it can be used in a structure.

It does offer potential for elements that otherwise wouldn't be reused to become part of a structure. The created tool/workflow does save design time and is capable of using all kinds of profiles and lengths into one structure. Compared to current reuse of timber elements it can tap into a large pool of reclaimed timber that other reuse techniques do not offer. With an increase in scarcity, it can offer an interesting alternative. It could improve self-sufficiency of local economies and keep value in the economy.

It will be import to find the right balance of finding out which technique suits a project the best.

# X. Reflection

## A. Thesis process

My thesis focuses on implementing the ideals of the circular economy. It aims to achieve this goal through problem-solving by integrating multiple fields of expertise. This interdisciplinary approach is central to the Building Technology Graduation Studio, where balancing knowledge from different domains is crucial for finding creative solutions with a positive impact. In this case, the positive impact is transitioning from a linear economy to a fully circular economy without any waste. The goal was to combine structural knowledge from the SD-department with computational power and fabrication techniques from the DI-department. Together, they were used to bridge the knowledge gap from designing with reuse to designing with reused materials and without waste.

To conduct this research, I employed a combination of literature review and research by design. The literature review highlighted the major obstacles the current industry faces in reusing wood and the inefficiencies in current practices. It also revealed existing solutions and their limitations. Using Grasshopper and its plug-ins as the design tool turned out to be a good choice. Its environment allowed for integrating topology optimization, stock-constrained design, structural analysis, and LCA analysis into one script with visual representation in Rhino. By baking the connections, they could be extracted for 3D printing. This integration enabled all processes to be linked into one workflow, making it possible to oversee the consequences of each alteration. Although more steps are required before this workflow can be used in an actual structure, it offers important insights at an early design stage. This information can help determine which sustainability strategy best suits a project and poses potential for future research to develop new sustainable methods. By informing designers early about potential alternatives, we can take a step closer to a circular economy.

Although this research appears technical, it also involves design research. Developing such a workflow is an iterative process, much like any other design process. Theoretical knowledge on how to design connections was required. A better understanding of the problems and tools aided the designing phase of the research. While constructing the workflow, numerous tests were conducted, helping reshape the overall design until it worked. Designing and testing led to new findings, and further research helped explain these findings, making the final workflow possible.

Circularity has many definitions and adaptations within the building industry. This study measures different sustainable alternatives against each other, providing a clearer overview of the true costs. Each solution could be presented as "circular." It is important for research like this to be transparent about the different pros and cons. The newly proposed method ensures no loss of material and offers the same technical value at the end of its service life. However, as the research has shown, it comes with a larger carbon footprint. It does provide the option to become more self-sufficient. After obtaining the materials, only energy goes into the cycle. With the growing scarcity of building materials, this strategy might help mitigate some shortages while reducing dependence on global trade.

## B. Sustainability impact

The workflow developed during this research can help move closer to a fully circular economy. It began by analysing the current problems within the building industry to identify obstacles and potential areas for improvement. The analysis revealed that wood currently fails to meet the demands of the building industry and rarely gets a second service life. By increasing the duration timber can remain in the economy, materials like concrete and steel can be phased out, thereby lowering the building industry's total footprint. The current obstacles for reusing timber elements are primarily related to design and fabrication complexity when a project is constrained by available stock. To simplify the process, timber elements are often remanufactured to fit pre-existing designs. Removing these obstacles can improve wood reuse and prevent saw-off losses.

The workflow aims to address these problems by first altering the composition of components to better fit the structure. It then automatically designs connections that compensate for any missing lengths. By preventing saw-off losses and making the design process more accessible, timber elements can theoretically remain in the economy indefinitely. However, the added carbon cost of the 3D printed connections must be considered. This tool provides a workflow where all alternatives to the original structure can be compared quickly in the early design stage.

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# Appendix A – Generated connections

In this part of the appendix the connections that were generated but didn't lead to the desired changes will be discussed.

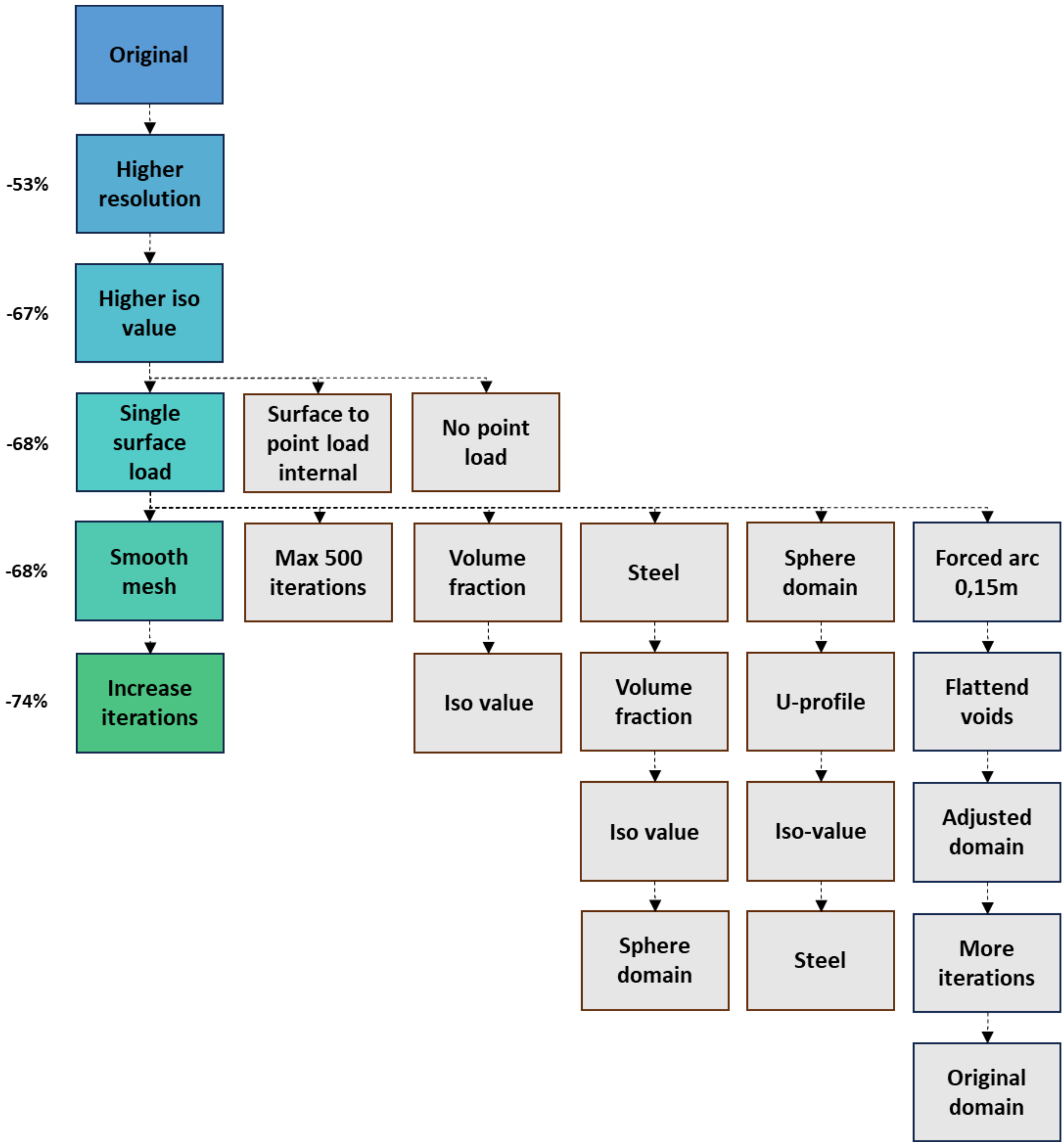



*Figure 35 further refinement of the generated connection, source: own work*

**No point load test**

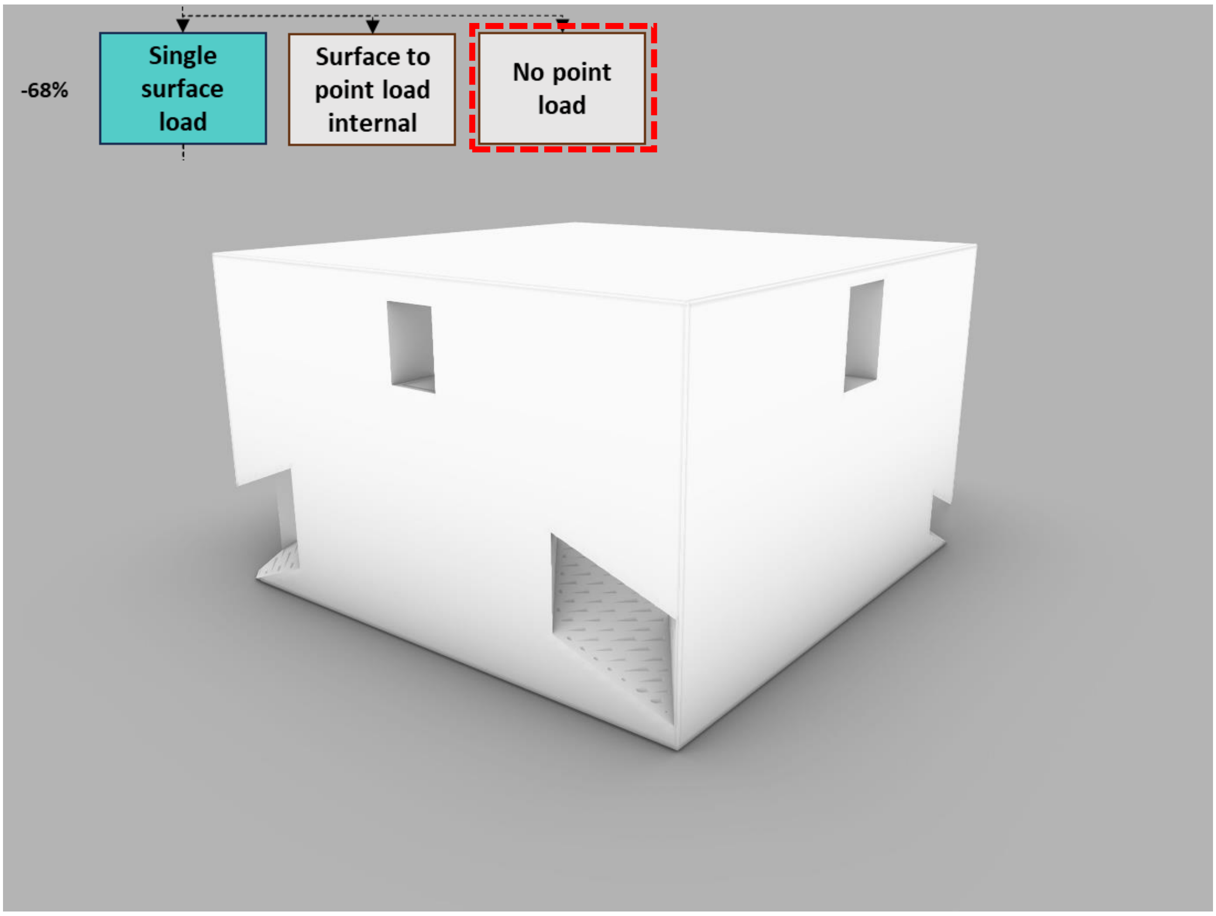



*Figure 36 Generated connection whit iso value turned off, source: own work*

The expectations for the connection that would be generated were that arcs between the incoming elements would be generated. However, in the previous generated connections in consistently generates a sphere in the centre of the connection. A speculation is that this is due to the nature of the topology optimization. Perhaps it starts by adding as much material as possible underneath the largest load (which will be the point load of the roof) and during the optimization it keeps subtracting material (making the sphere smaller) until it hits its optimal shape. In order to test this hypothesis, the point load was turned off to see the result with only the internal loads. However, the simulation seems to fail with the final shape being a solid domain except for the predetermined voids. Further testing will show if the internal loads have an effect on the final shape at all.

**Internal surface to point load**

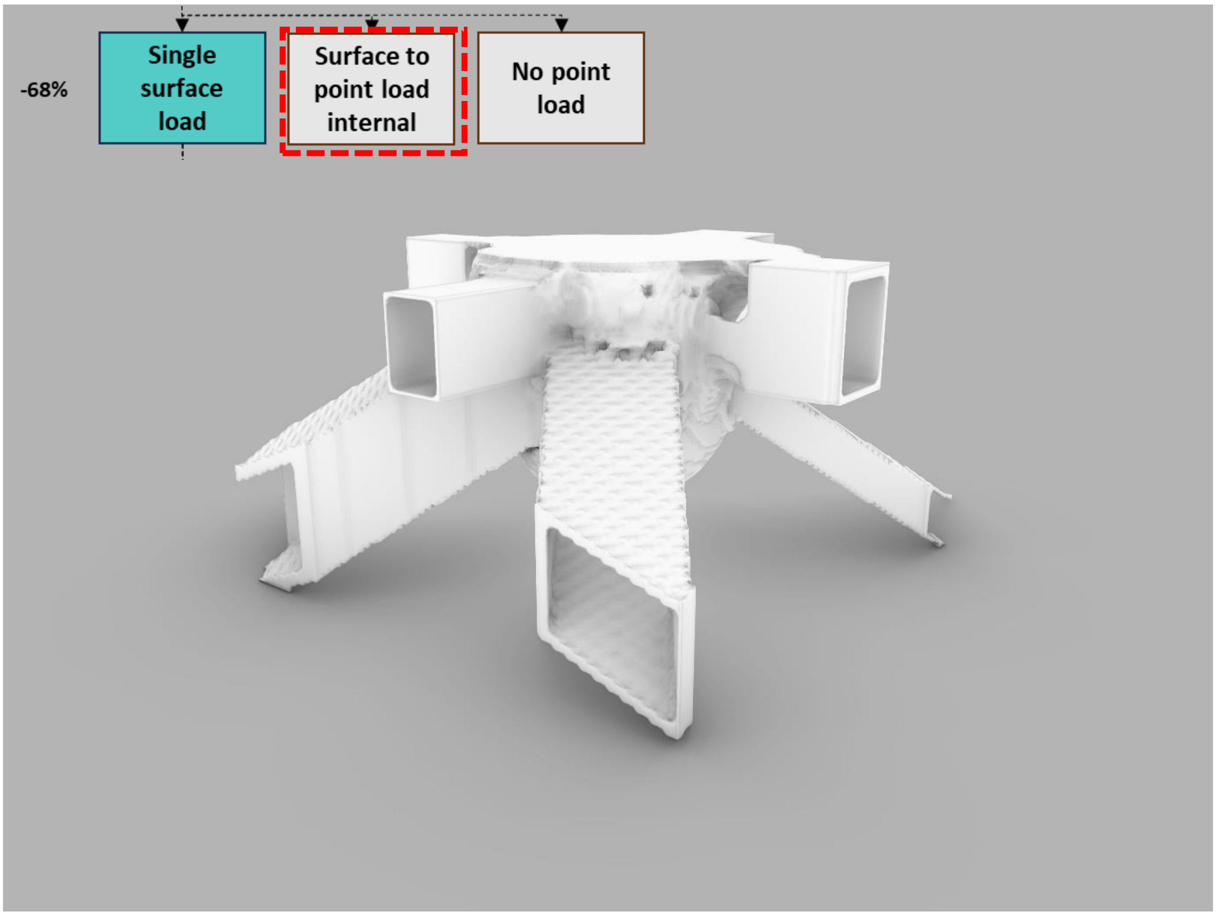



*Figure 37 Generated connection with internal surface loads replaced by point loads, source own work*

By changing the internal loads from a surface load around the incoming elements to a simplified point load a different connection occurs. This could indicate that either the previous internal loads weren't properly defined or that the internal loads alone aren't big enough to start the simulation. After a second test with the new internal loads shows the same generated connection as the one before with no point load. Nevertheless, it shows that the way how to define the internal load can affect the new volume. This new connection has a volume of 0.020024 $m^3$, lower than the previous case. It also shows that if the predefined profile is properly defined as a fixed mesh the internal loads don't need to be spread-out over-all surfaces.

**Putting the maximum iterations to 500**

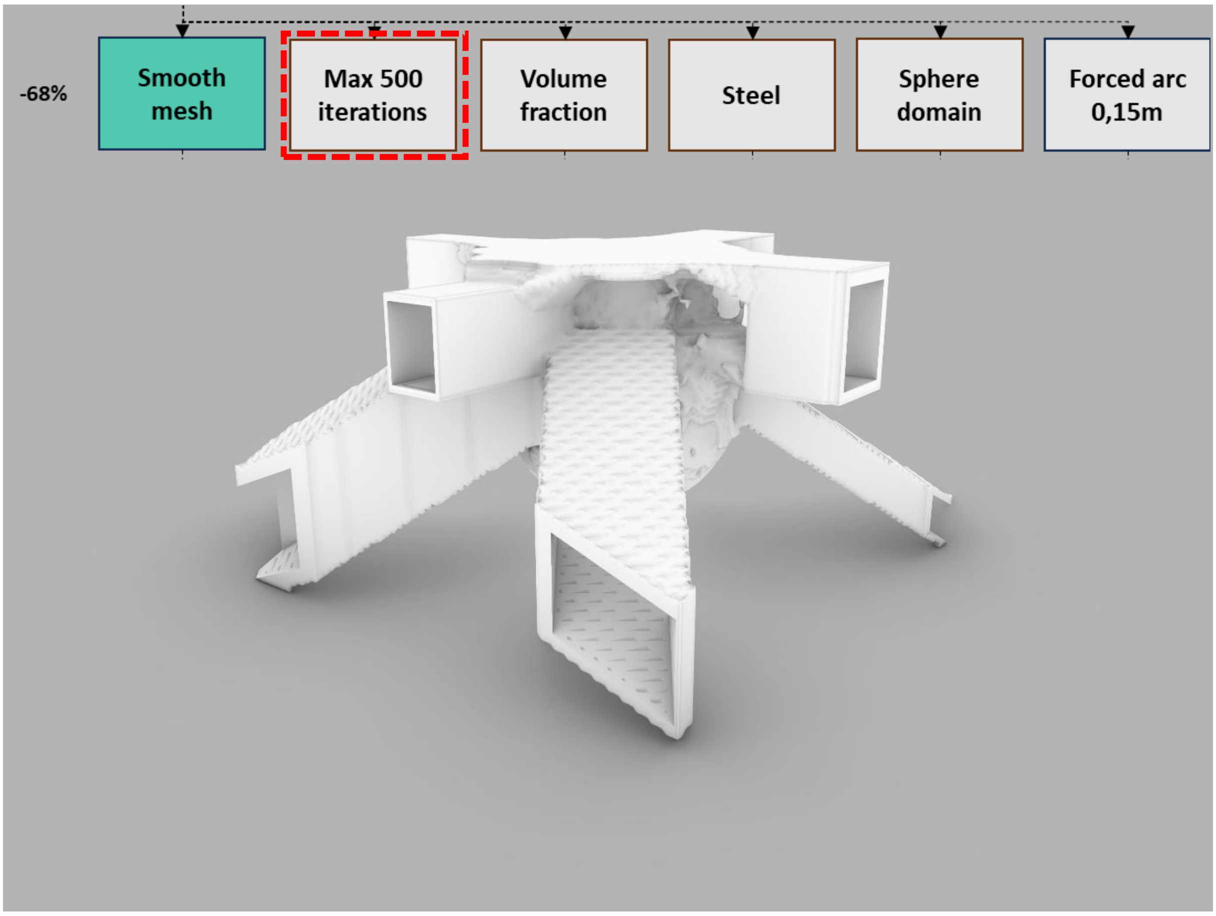



*Figure 38 Generated connection with iteration limit set at 500, source: own work*

In order to attempt to gain a further optimized connection the maximum number of iterations was set to 500. Previous simulations have shown that often it finds the optimum solution at iteration 19-27 with a maximum of 100 iterations (that is put in place to prevent false results taking too long). However, the simulation still stopped within the beforementioned range with the same shape as before. The volume didn't change much and increase slightly to 0.021113, most likely due to some randomness within the simulation type.

The maximum number of iterations will be set back to 100 due to the lack of improvement.

**Volume fraction**

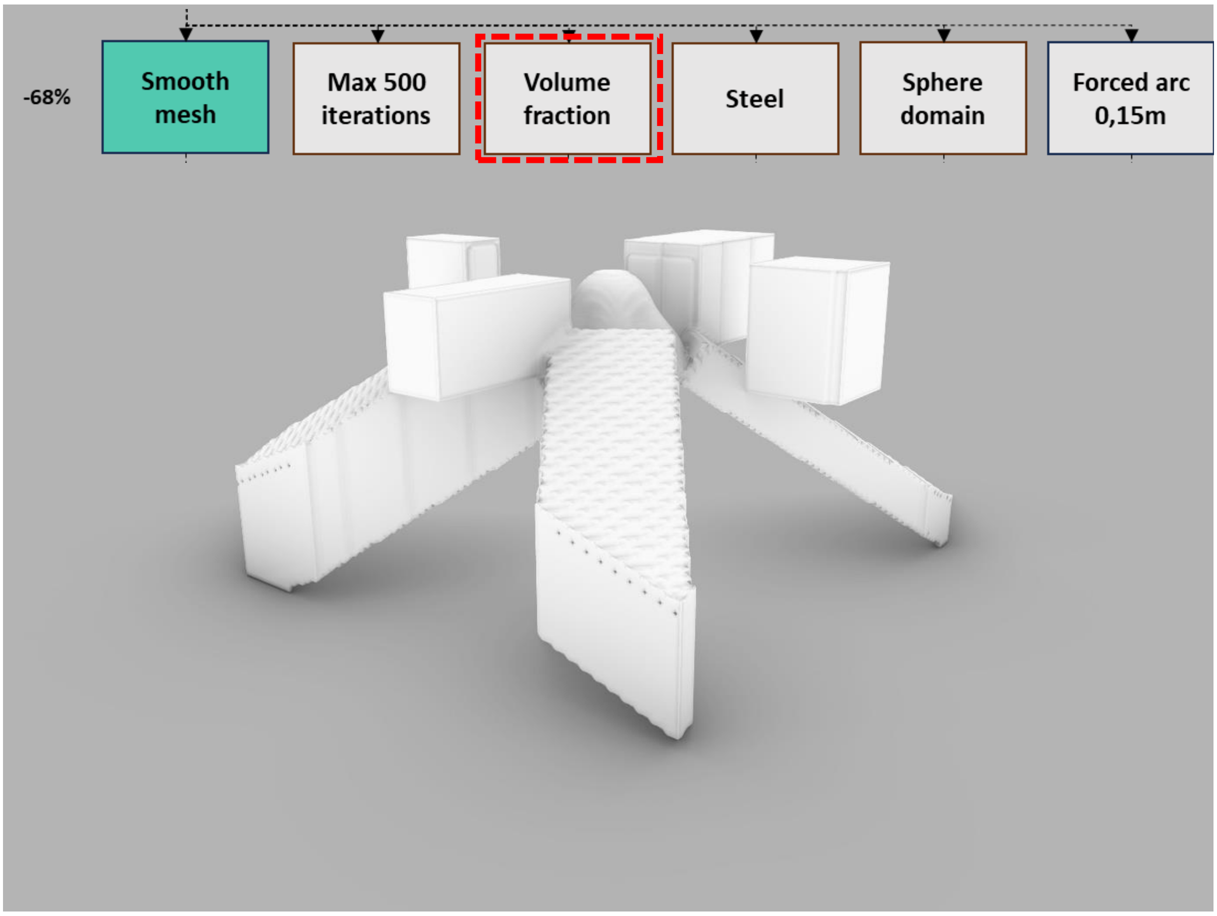



*Figure 39 Generated connection with volume fraction set to 0.1, source: own work*

In order to attempt to gain a further optimized connection the volume fraction was changed from 0.2 to 0.1. As can be seen in the generated connection: the connection has been segmented into separate parts. However, it did lower the generated volume. By trying out different combinations of volume reduction and iso value a potential solution could be found.

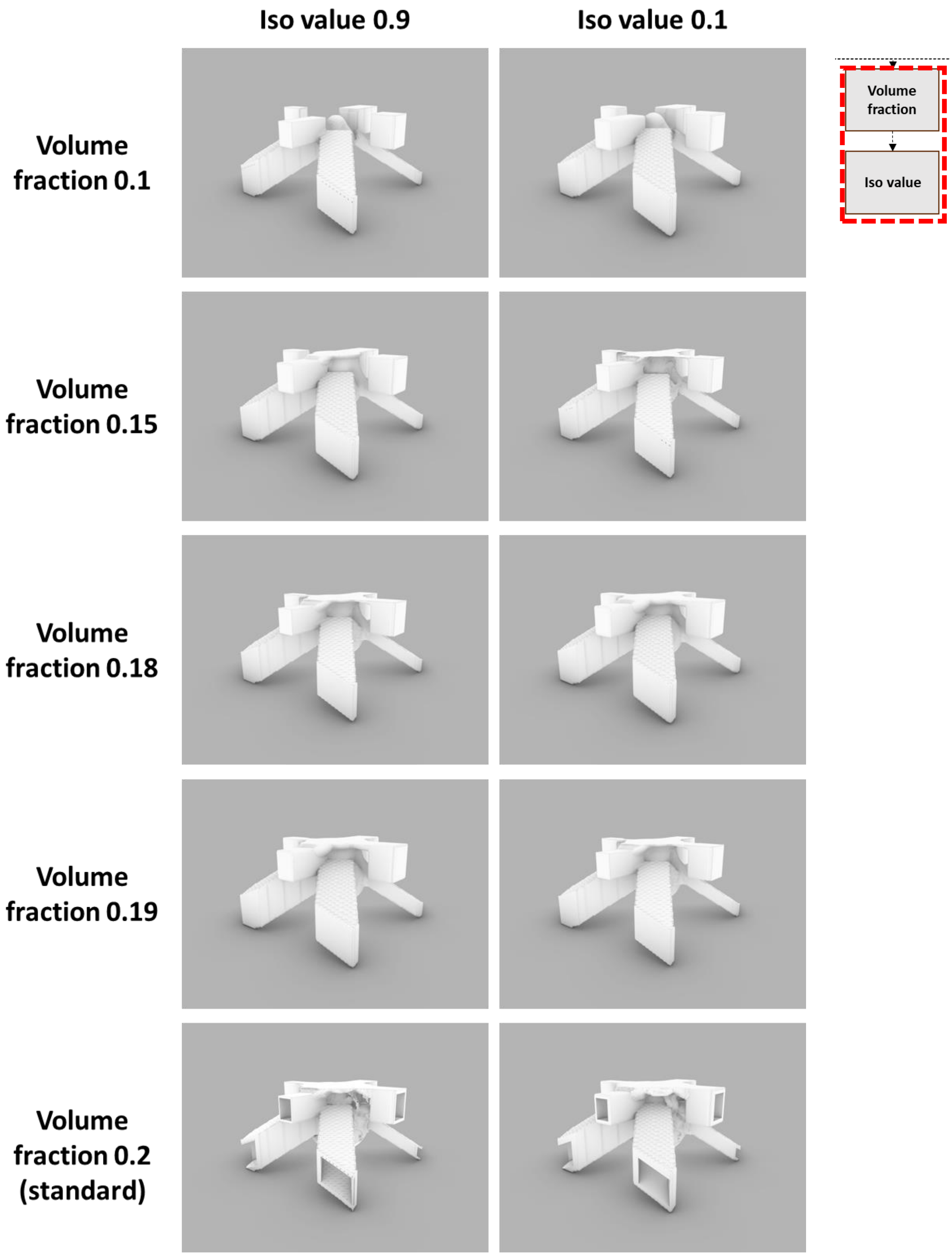



*Figure 40 Generated connections with different volume fractions and iso values, source: own work*

As can be seen in the overview, the volume reduction works best with the standard 0.2 volume fraction. Every generated connection with a lower value creates gaps in the final connection.

With the knowledge gained, the volume fraction will be set back to 0.2.

**Changing the 3D printing material to steel**

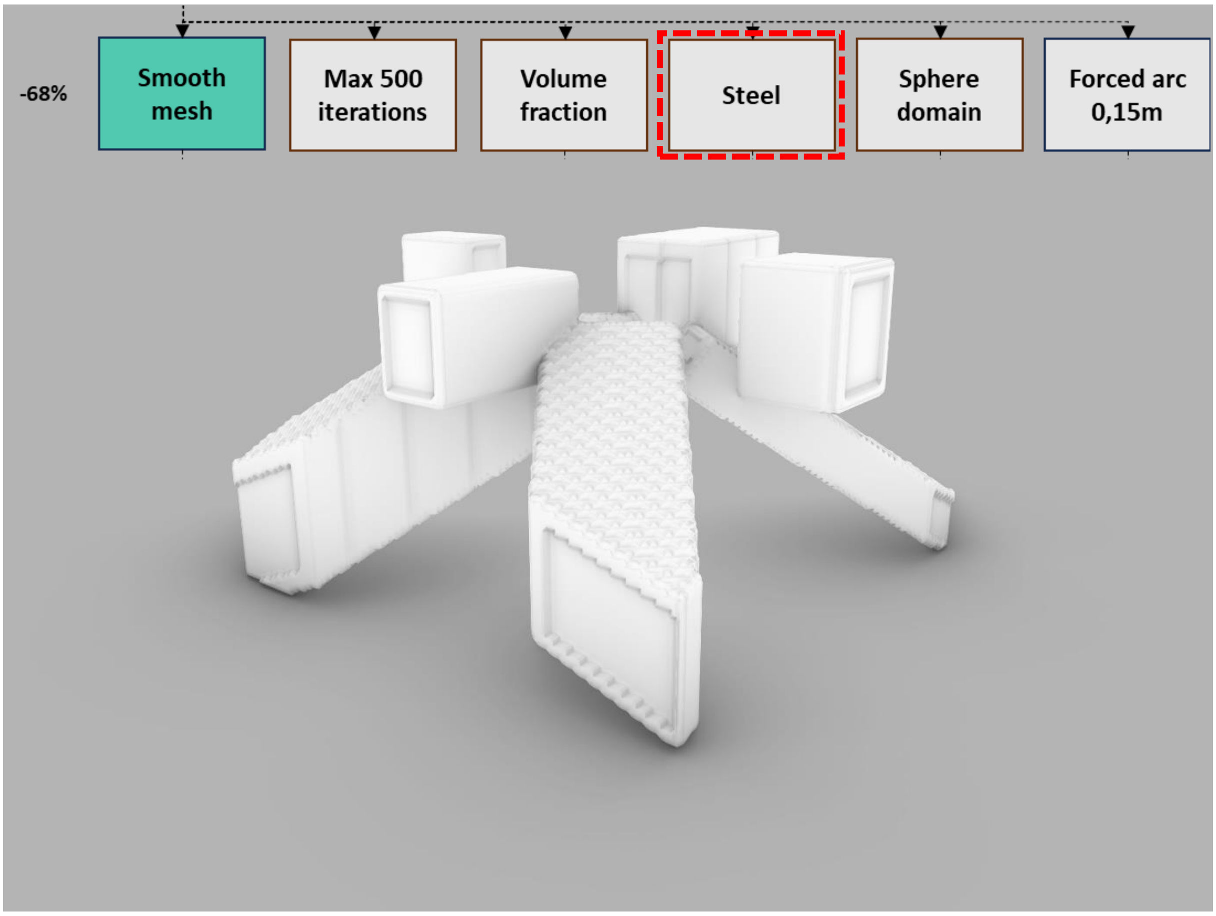



*Figure 41 Generated connection with steel as 3D printing material, source: own work*

So far, the properties of PETG have been used to generate connections. By changing the material properties to a material with different properties a new shape can be generated that uses less material and potentially a lower carbon footprint. The first test shows a disconnect in the segments. To fix this the volume fraction and iso values are altered in a series of test to find a new connection shape. In order to speed the process up the number of iterations was limited to 50 iteration and the resolution to 0.008 due to the heavy simulation.

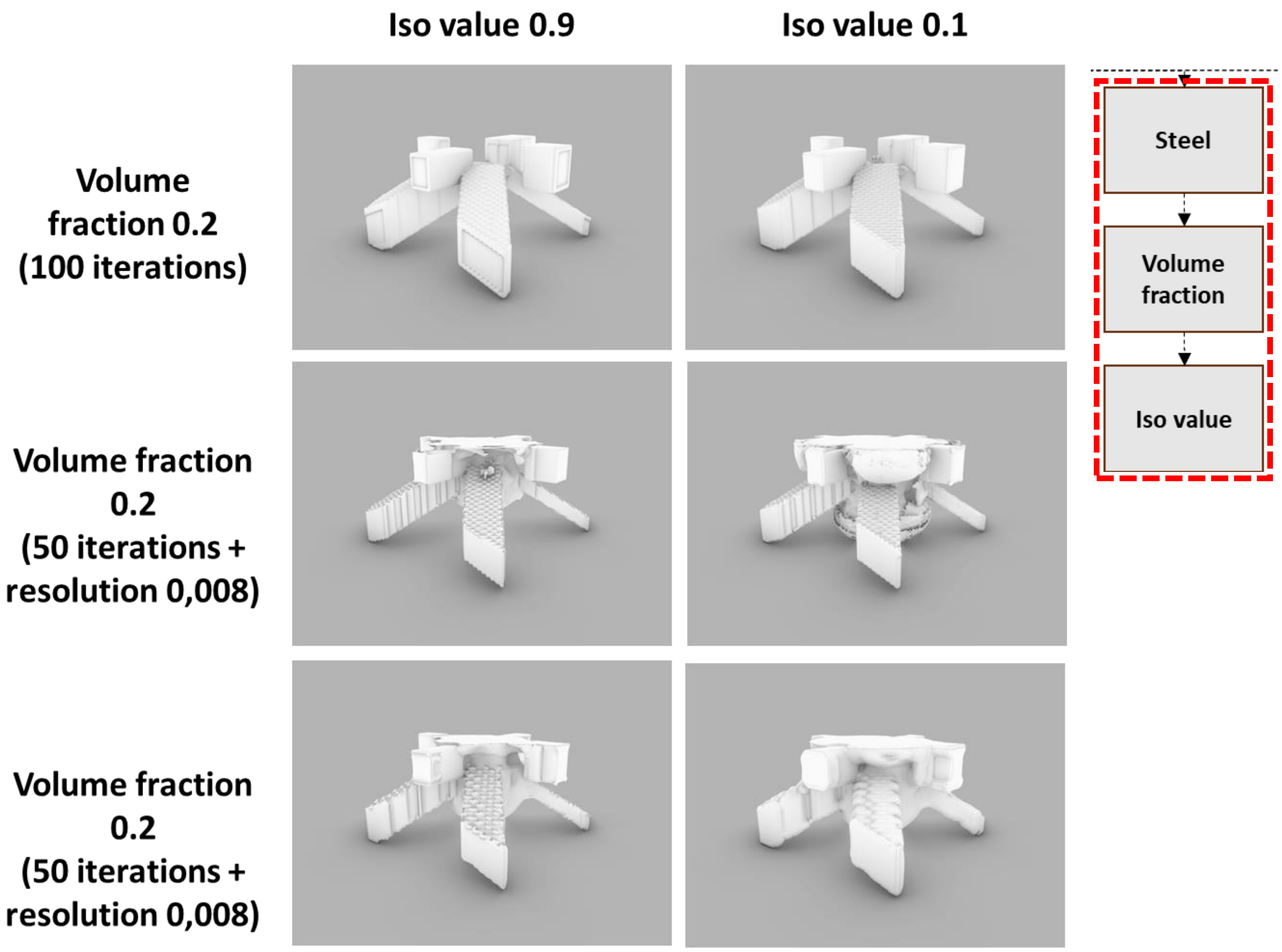



*Figure 42 Overview of generated connections out of steel with different settings, source: own work*

The results are inconsistent and still contain a lot of material for a material that should offer a smaller connection. In combination with the increase in calculation time it's expected that the higher performance in material offers a larger variability in the shape finding process. It's expected that the maximum resolution that can be achieved in TOpos (0.002) is too large for a steel connection.

With the gained knowledge the simulation was set back to PETG and was only experimented with in research that was executed parallel to this one.

**Domain adjustment**

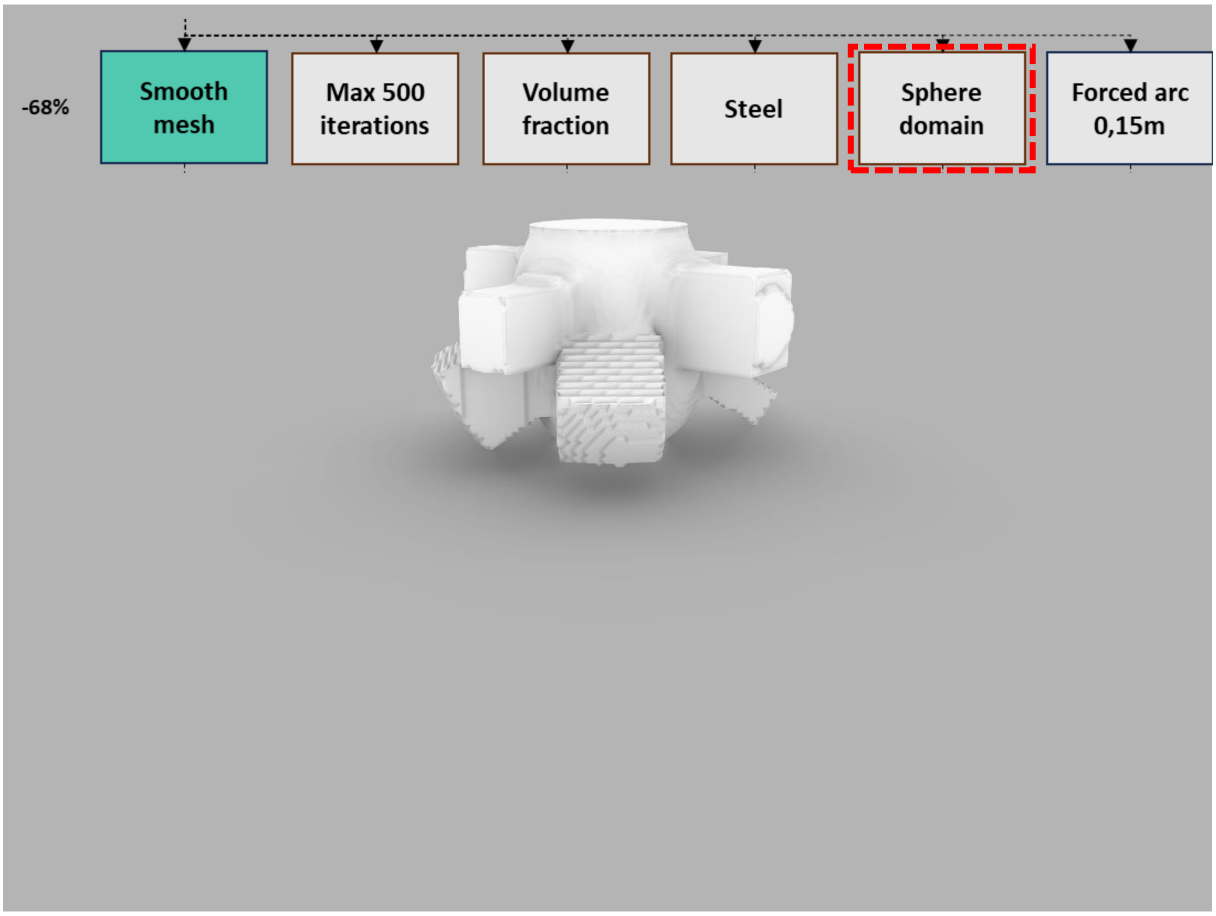



*Figure 43 Generated connection with resized smaller box domain, source: own work*

In order to attempt to gain a further optimized connection the domain was altered to minimize the length of the attachments. Within the current workflow the section box is always the maximum 3D printing size, even when this size is not required. In order to save more material, the domain where the connection will be generated within will be resized in such a way that the attachments reach their minimal required length. The smaller domain should also positively influence the calculation time for the total structure.

The generated connection doesn't make the expected profiles anymore that were predefined. However, it does show a compacter connection with a smaller volume. The next steps will try to alter the attachments.

**Changing the material to steel and resizing the domain**

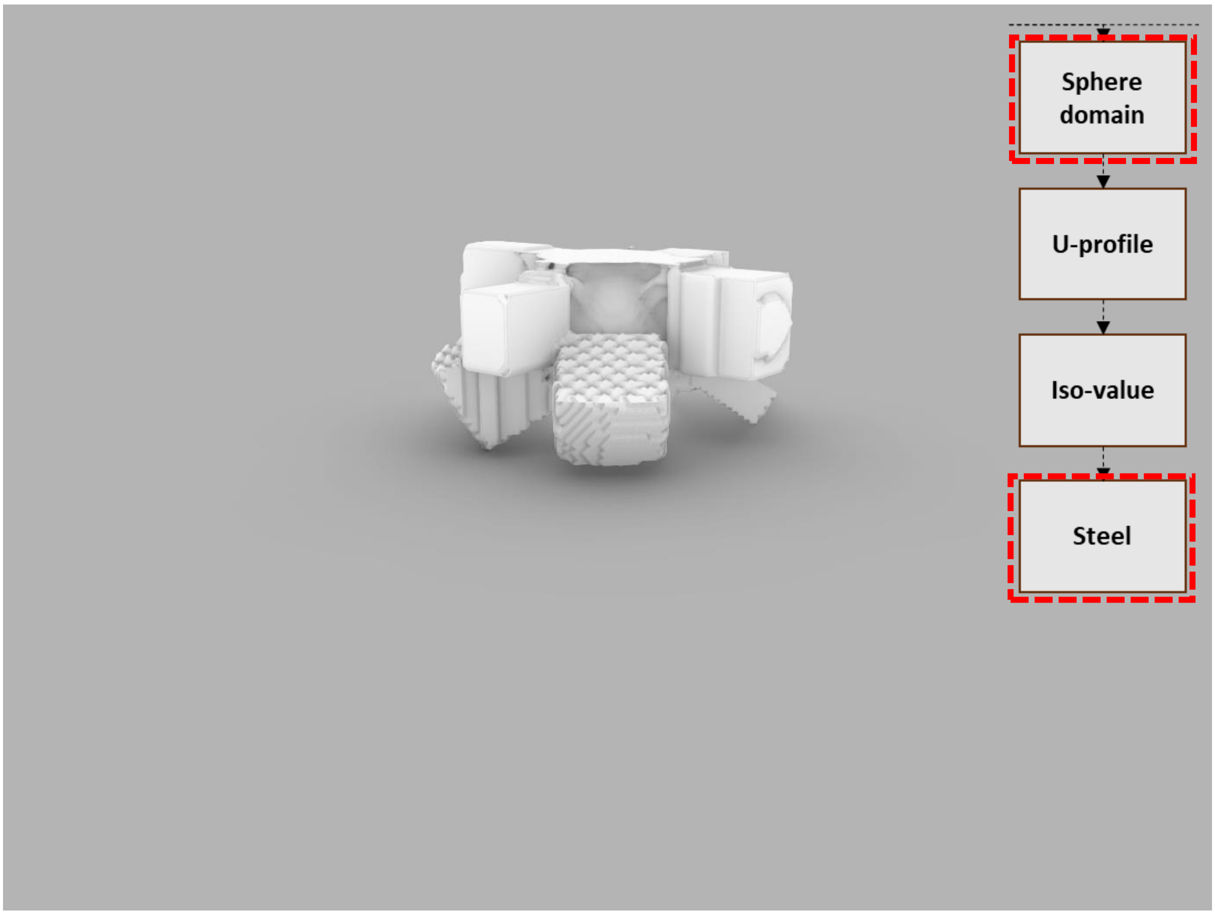



*Figure 44 Generated connection with adjusted domain box, source: own work*

In the previous generated connection, it became visible that the domain could become even smaller since some material was sticking out on top. This must be prevented since this could clash with the roof. Therefor the domain was adjusted to become even smaller. The material change to steel was chosen to see if this would generate the required attachments. Although the steel connection looks interesting and closer to what would be expected, it still doesn't give the required attachments. As mentioned before, due to the increase in computational power to simulate these connections and lack of detail that can be offered for steel the follow-up research was conducted in PETG again. This makes it possible to get more results in the same amount of time, strengthening the research.

**PETG, adjusted sphere domain and U-profiles**

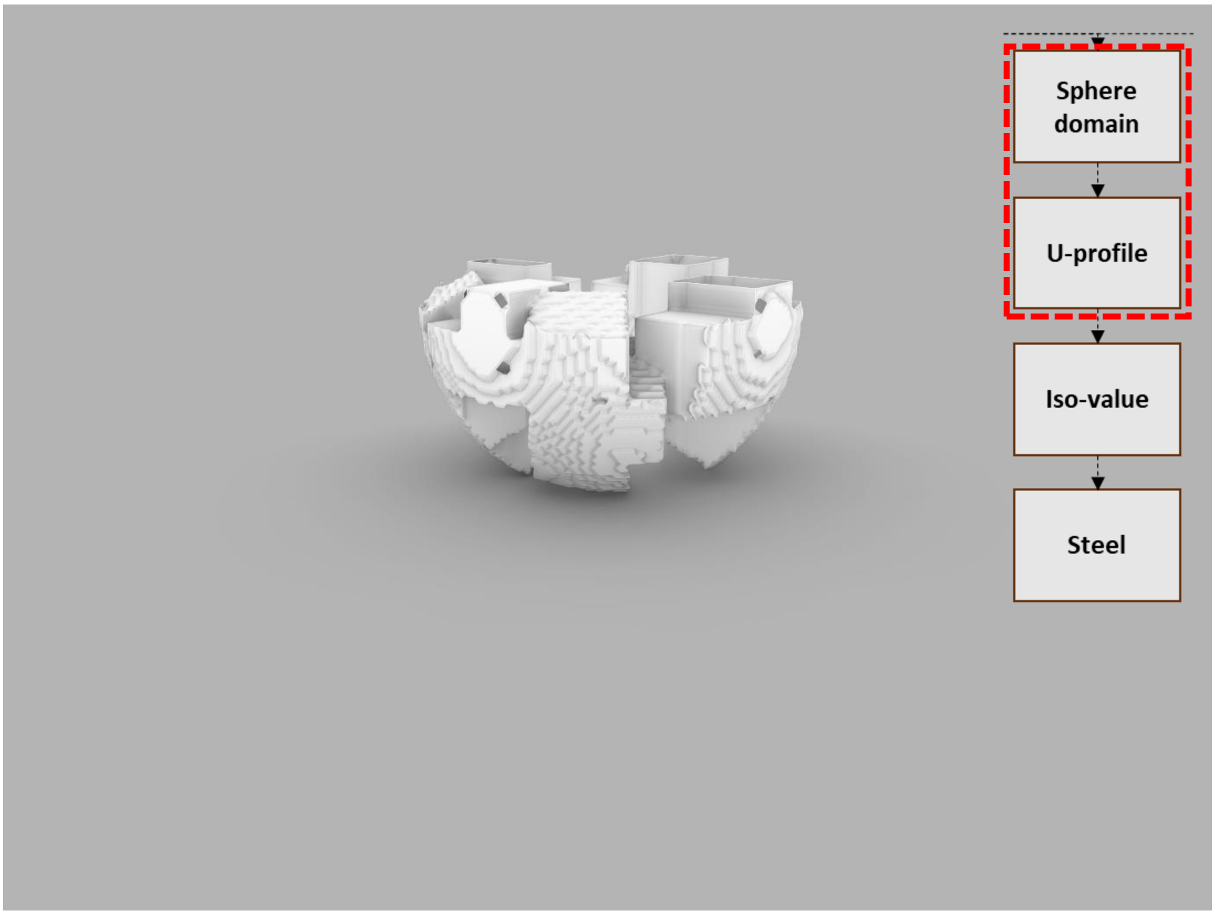



*Figure 45 Generated connection with U-profiles, source: own work*

To address the missing attachments an attempt was made where the profile was redefined to this U-shaped profile. This would simultaneously solve the assembly problem. However, this attempt led to a disconnected geometry.

**PETG, adjusted sphere domain and U-profiles + iso value to 0.1**

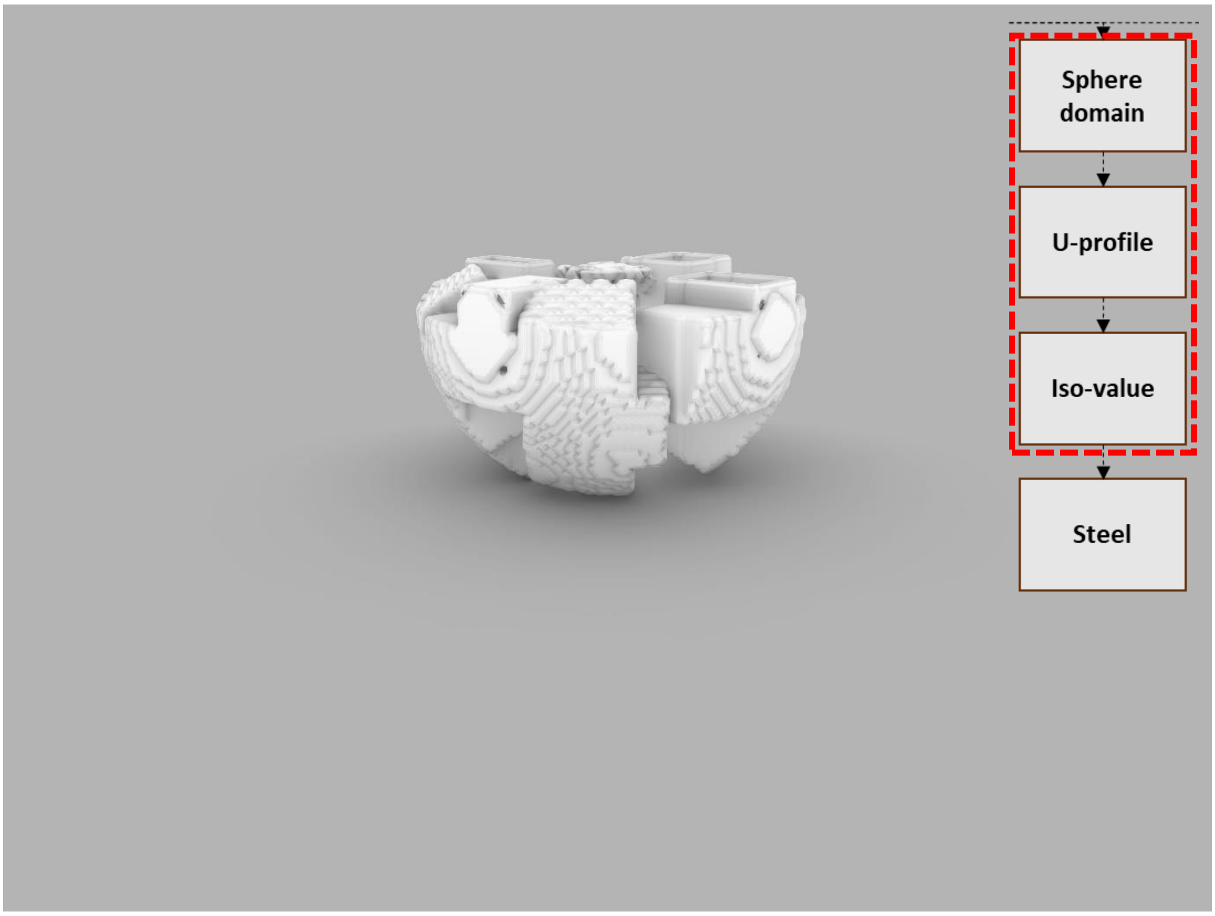



*Figure 46 Generated connection with a lower iso value, source: own work*

To see if the elements are indeed not interconnected the iso value was lowered in order to see any hidden parts. This did reveal a small part in the middle that prompted the interest to continue testing with U-profiles.

**PETG, adjusted sphere domain and U-profiles + iso value to 0.1 + 25 iterations**

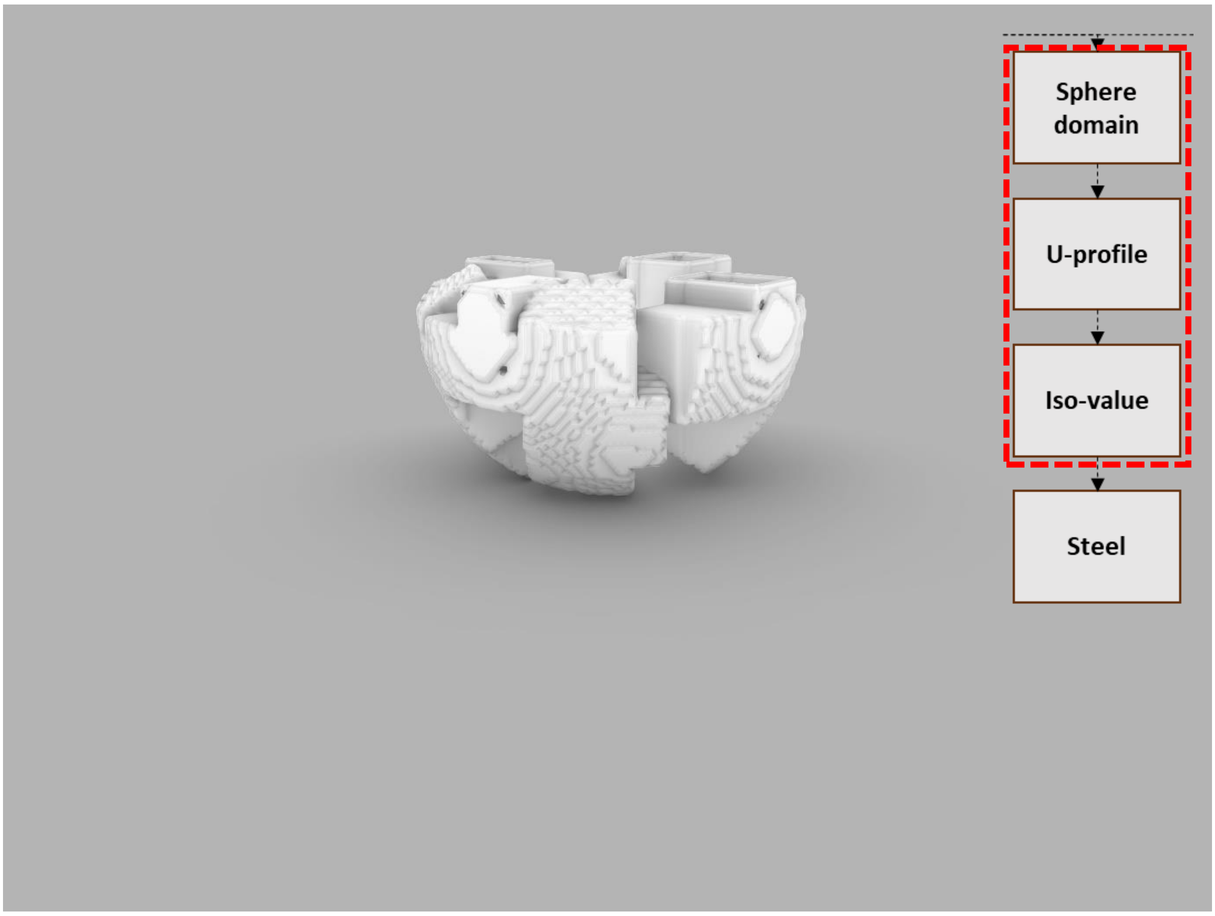



*Figure 47 generated connection with iteration limit of 25, source: own work*

By observing the simulation live it became apparent that the simulation doesn't create a coherent connection. This could be due to the domain being relatively small compared to the predefined attachments. Combined with a volume fraction of 0.2 and a density pattern of 1 the possibilities within the simulation are limited.

**PETG, adjusted sphere domain and U-profiles + iso value to 0.9 + 25 iterations**

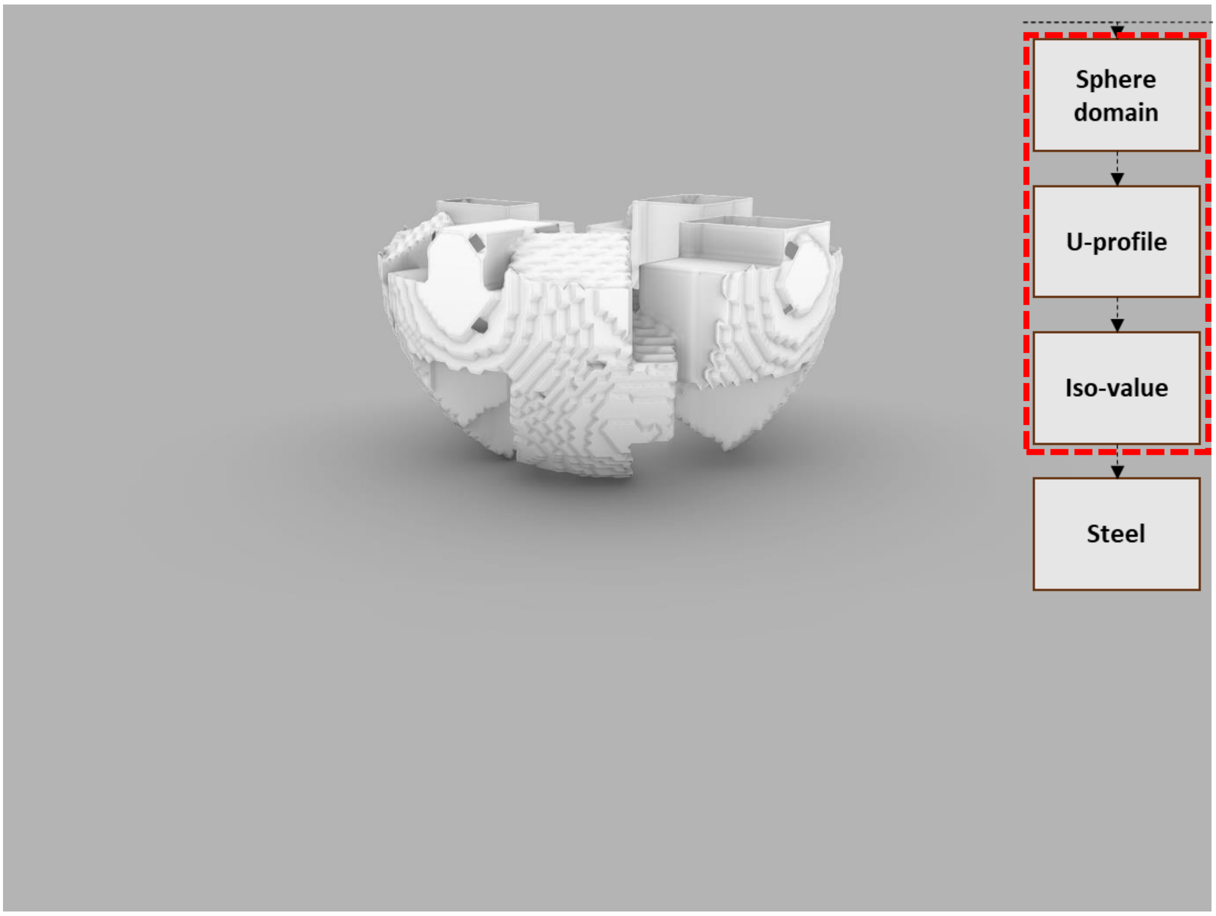



*Figure 48 generated connection with a higher iso value, source: own work*

To doublecheck the previous stated hypotheses it was double checked with a different iso value. Since this barely altered the resulting shape, the hypotheses still stand.

**Steel, adjusted sphere domain and U-profiles + iso value to 0.9 + 50 iterations**

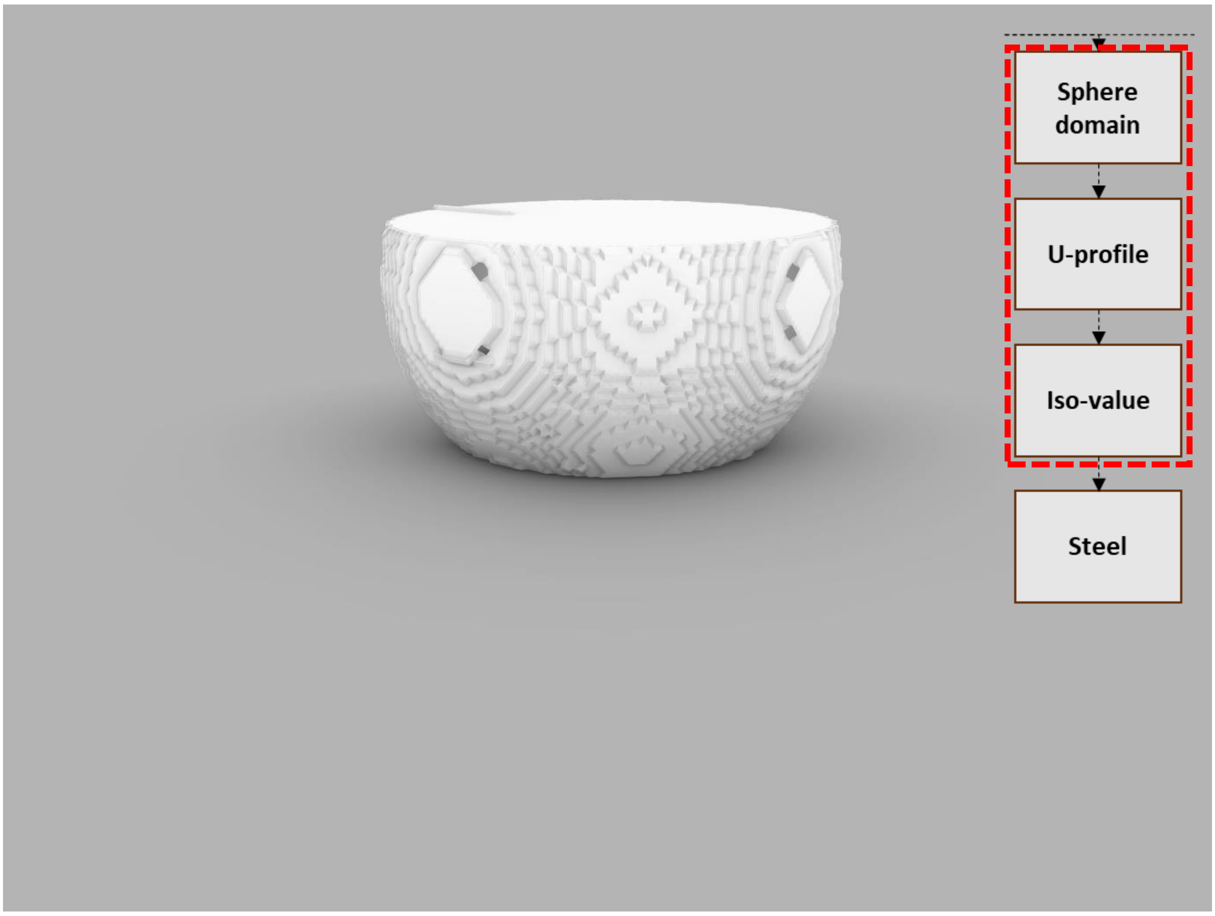



*Figure 49 Generated connection with iteration limit of 50 and out of steel, source: own work*

By switching from PETG to steel as a 3D printing material the predefined profiles will decrease and more design freedom for within the simulation. However, as the generated image shows, this hypothesis didn't become true.

**Steel, adjusted sphere domain and hollow-profiles + iso value to 0.9 + 50 iterations**

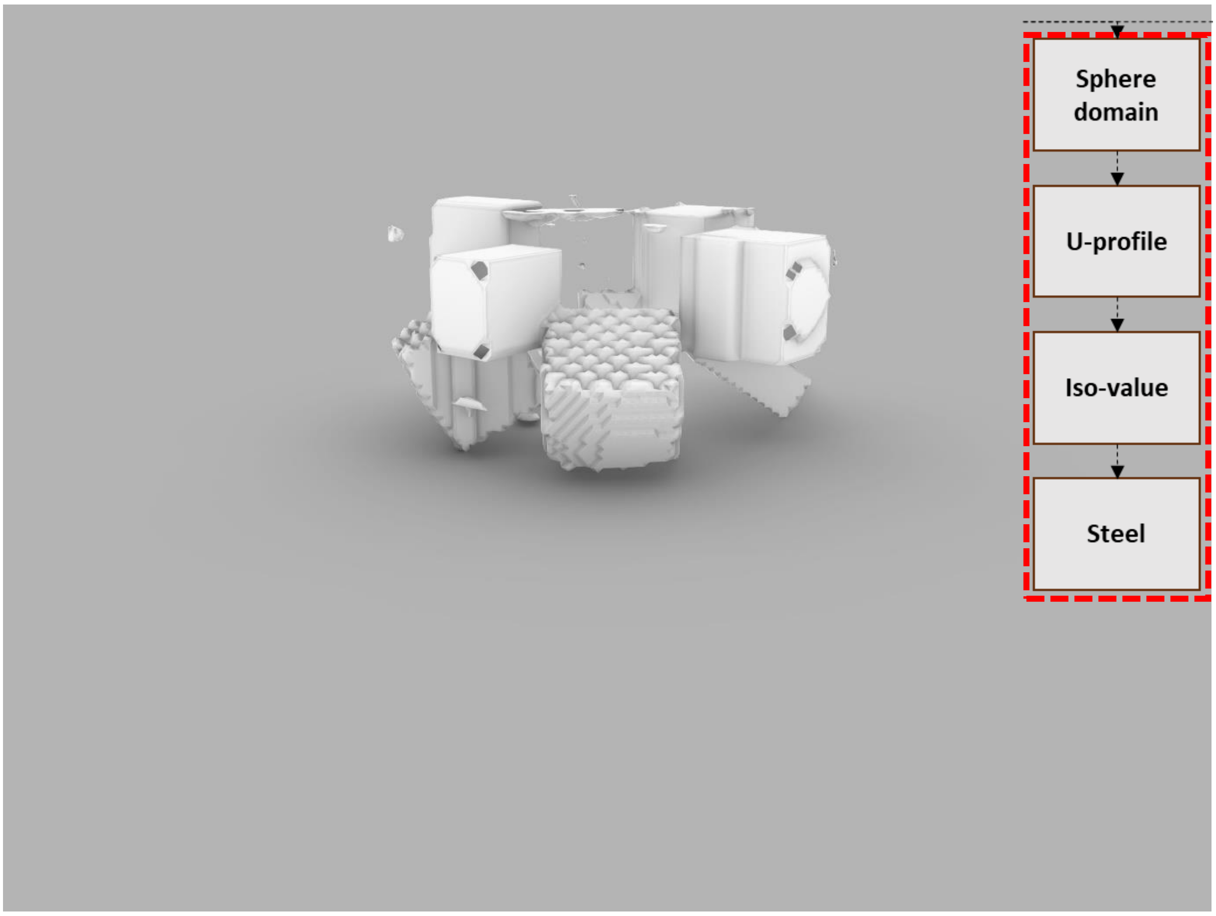



*Figure 50 Generated connections with hollow profiles, source: own work*

To test if the steel option would work with hollow profiles another simulation was conducted. This however shows a lot of disconnected parts within the generated connection, making the generated connection unusable.

**Steel, adjusted sphere domain and hollow-profiles + iso value to 0.1 + 50 iterations**

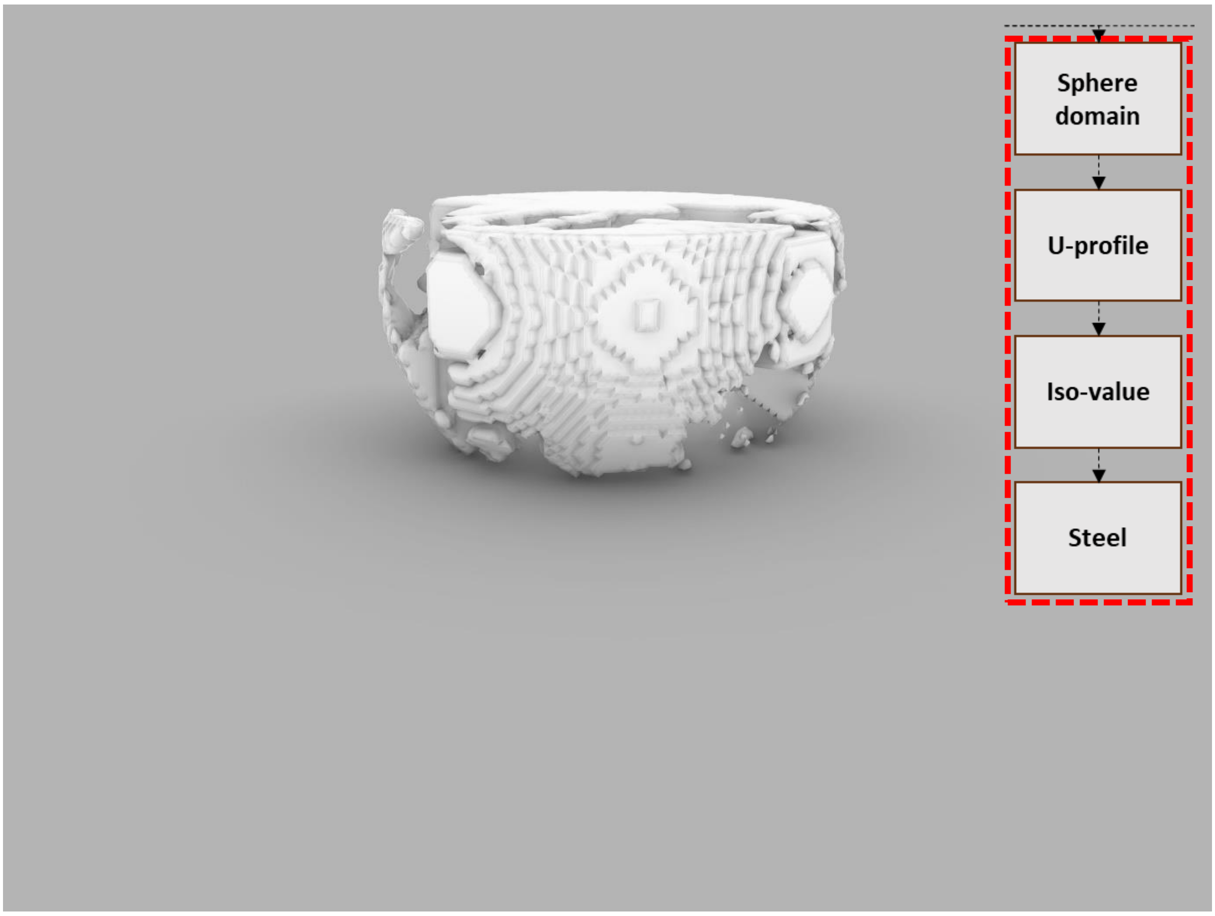



*Figure 51 Generated connection with low iso value, source: own work*

To double check the generated connection the iso-value was lowered to see if the separated parts weren't connected in a way that got filtered out of the simulation. This however led to a shape that didn't construct itself in a way that would be expected. It seems like the structure didn't iterate long enough for the connection to form.

**Steel, adjusted sphere domain and hollow-profiles + iso value to 0.9 + 100 iterations**

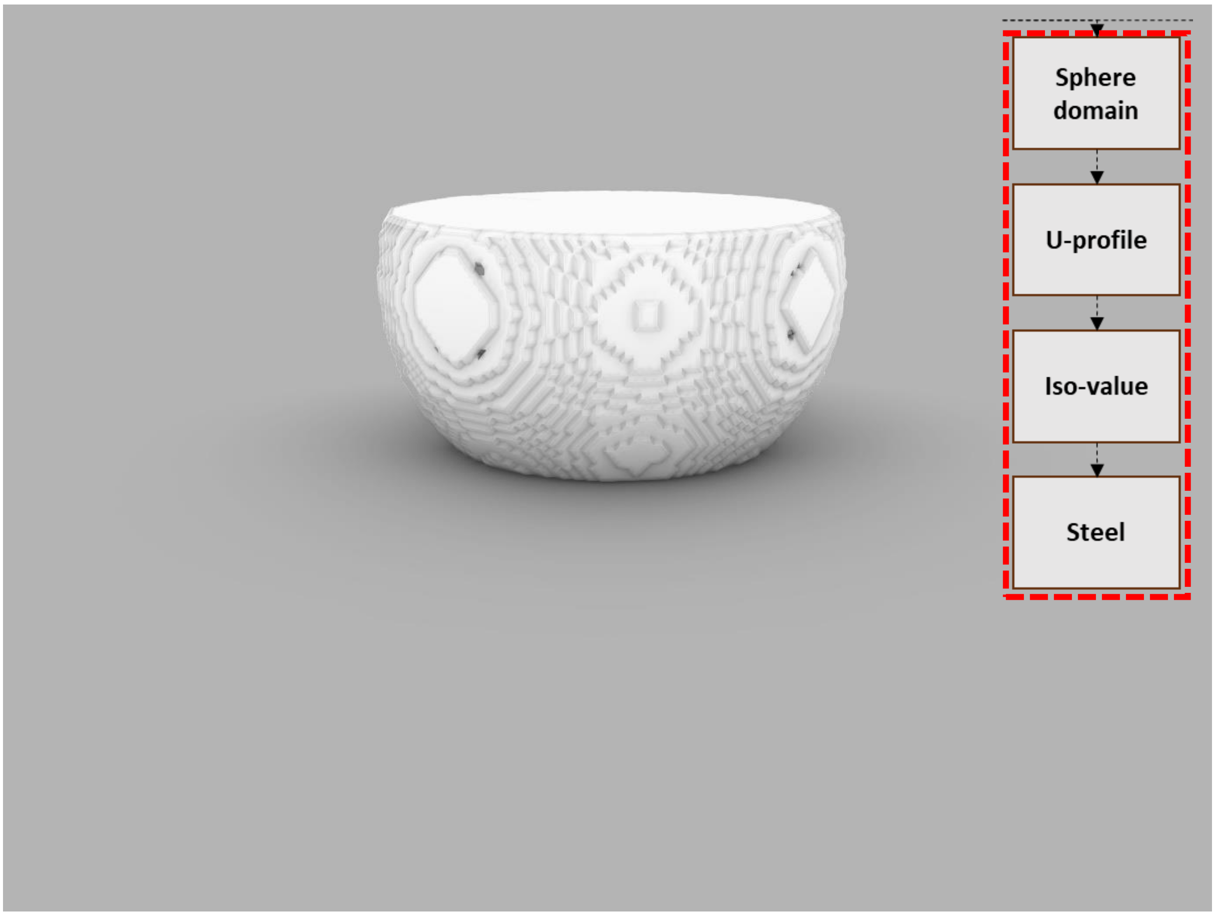



*Figure 52 Generated connection after 100 iterations, source: own work*

To see if it was indeed due to a lack of iterations the number of iterations was increased. However, increasing the number of iterations didn't improve the final connection and showed that for now making the domain smaller doesn't improve the overall connection yet.

After this the testing returned to its settings before the domain was altered.

**Forced arc of 15 centimetre**

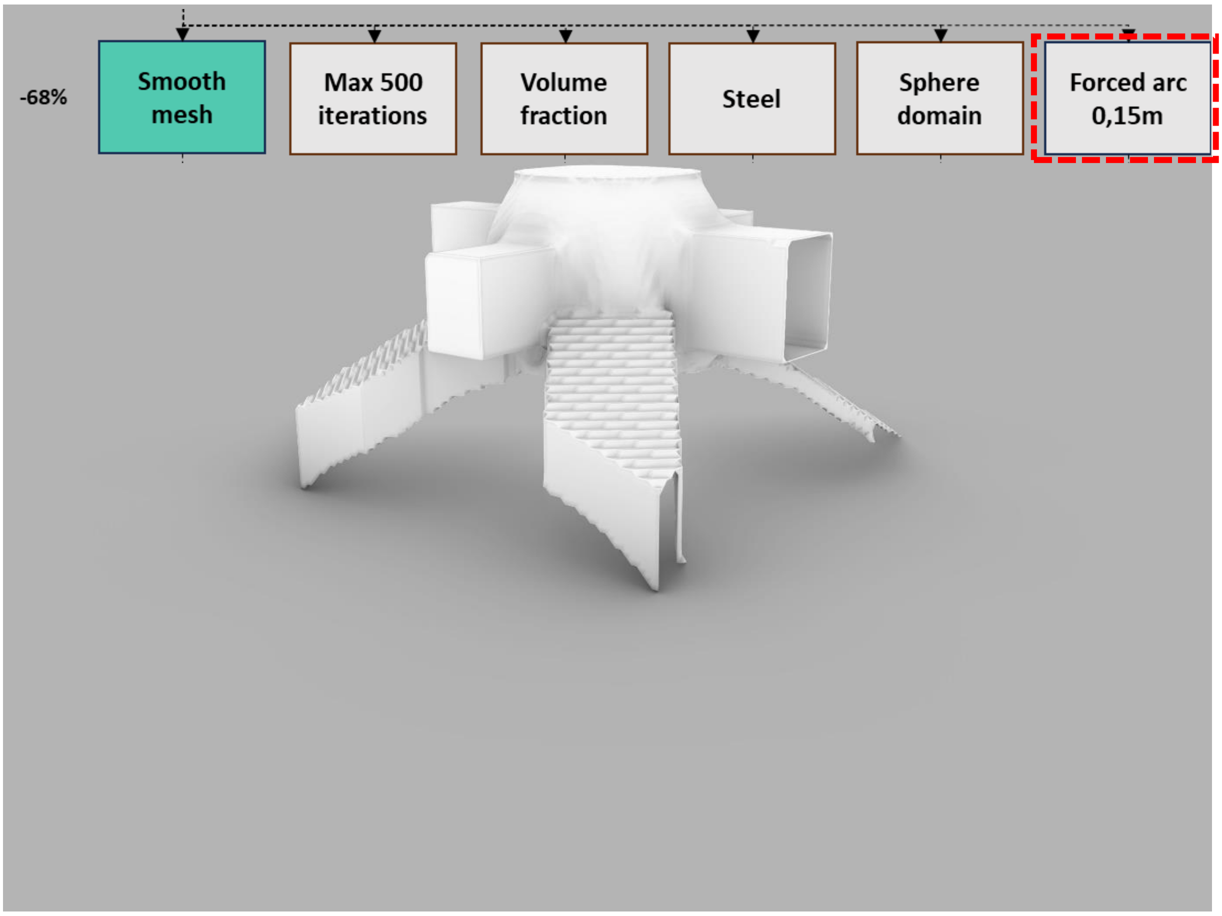



*Figure 53 Generated connection with a forced arc of 15-centimetre, source: own work*

The expected shape of the connection beforehand would be that it starts forming arcs between the elements. Instead, in the generated connections a sphere always appears. This sphere might be formed due to the way the simulation starts extracting material. To try if an arc can be formed a dome will change the domain of the simulation. This seems to have an effect on the final shape but in this case the profile is partly being destroyed as well and the profiles aren't hollow anymore.

**Forced arc of 15-centimetre, flattened voids**

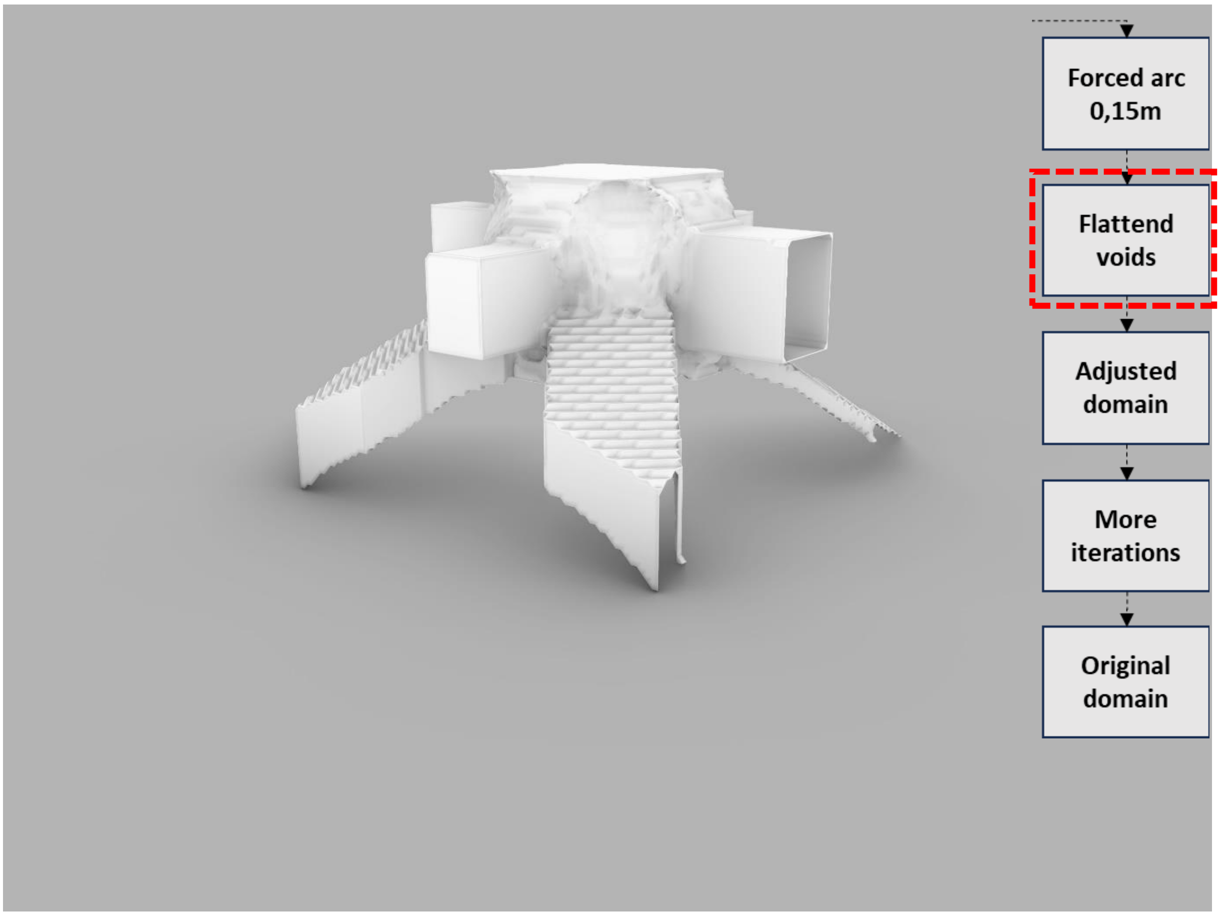



*Figure 54 Generated connection with voids flattened, source: own work*

In order to address the missing attachments/voids the voids were flattened to test if it makes a difference to make the profiles hollow again. This alteration however didn't provide the expected change.

**Forced arc of 7-centimetre, smaller domain, 50 iterations**

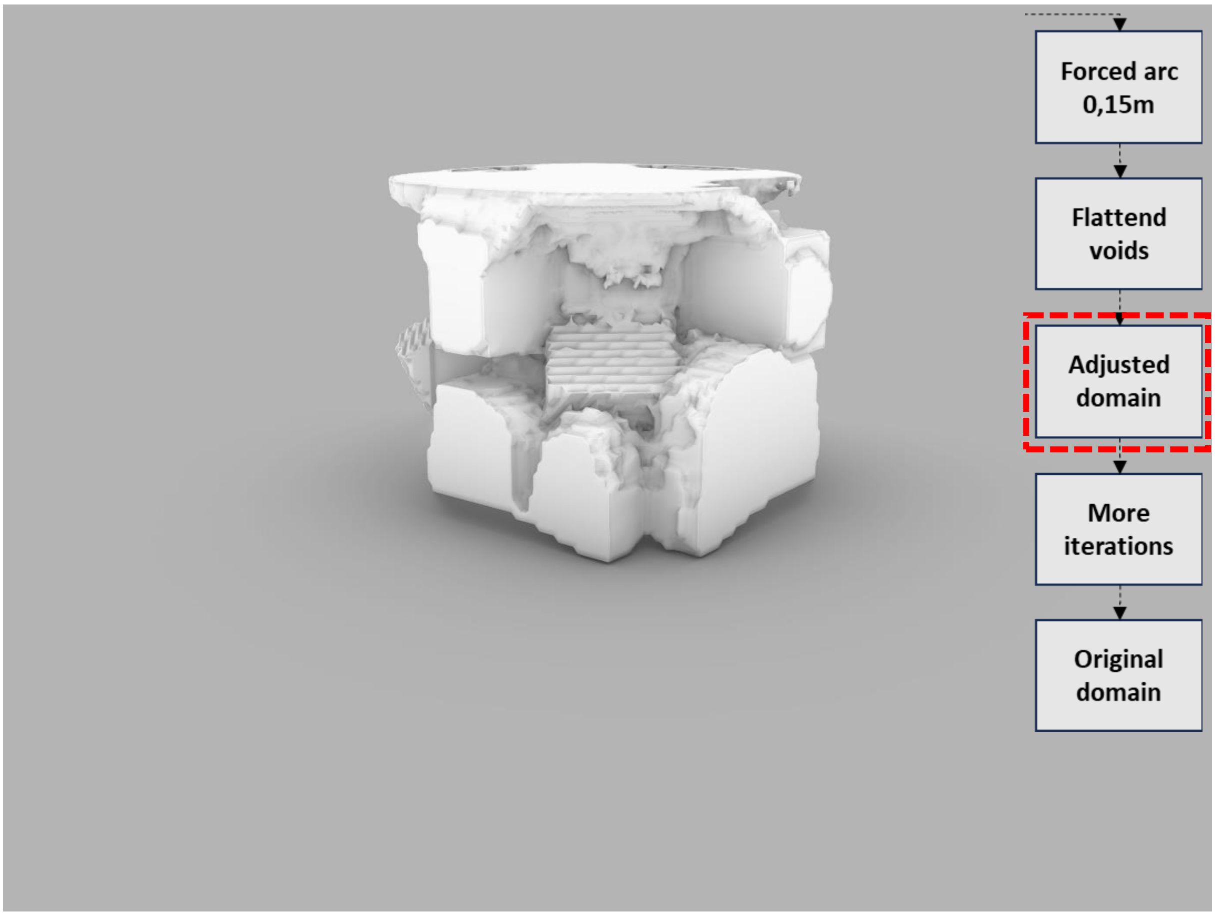
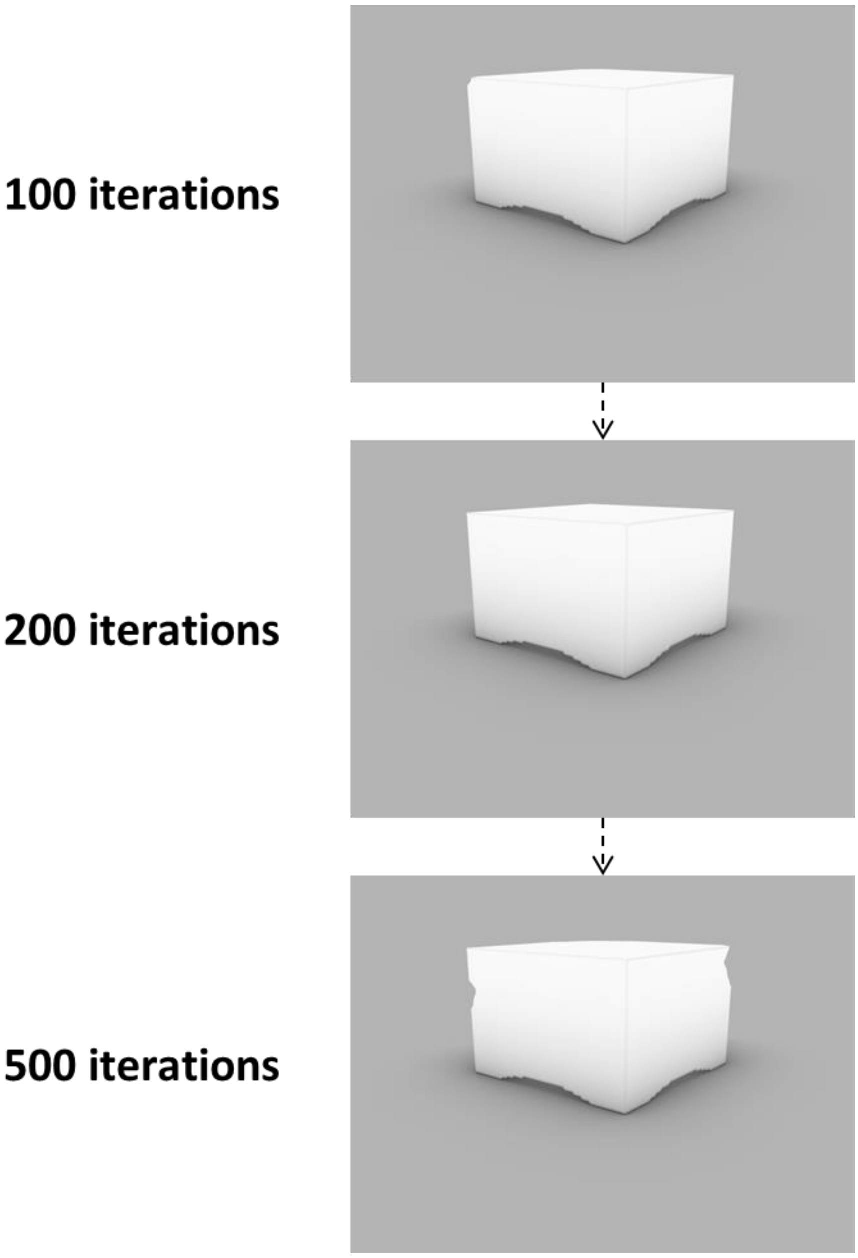



*Figure 55 Generated connection with smaller domain and 50 iterations, source: own work*

By readjusting the arc to a smaller size, together with the domain, the arc shouldn't interfere anymore with the attachments as before. The outcoming generated connection looked like it wasn't able to finish, since it finished at the last iteration round and has some volume that doesn't seem essential to its function. In order to learn more, a larger number of iterations are required.

**Forced arc of 7-centimetre, more iterations**



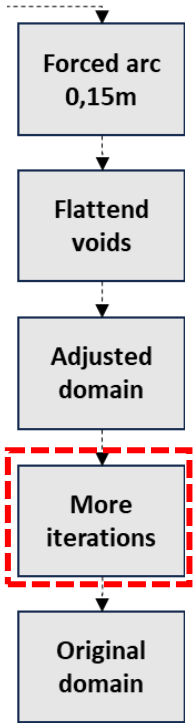




*Figure 56 Generated connections with more iterations, source: own work*

The increase in iterations seem to lead to no improvement to the generated connection. The domain was made solid with very little differences between the tests. Due to the lack of improvements to the generated connections no further attempts with a forced arc were made.

**Forced arc 7 centimetre**

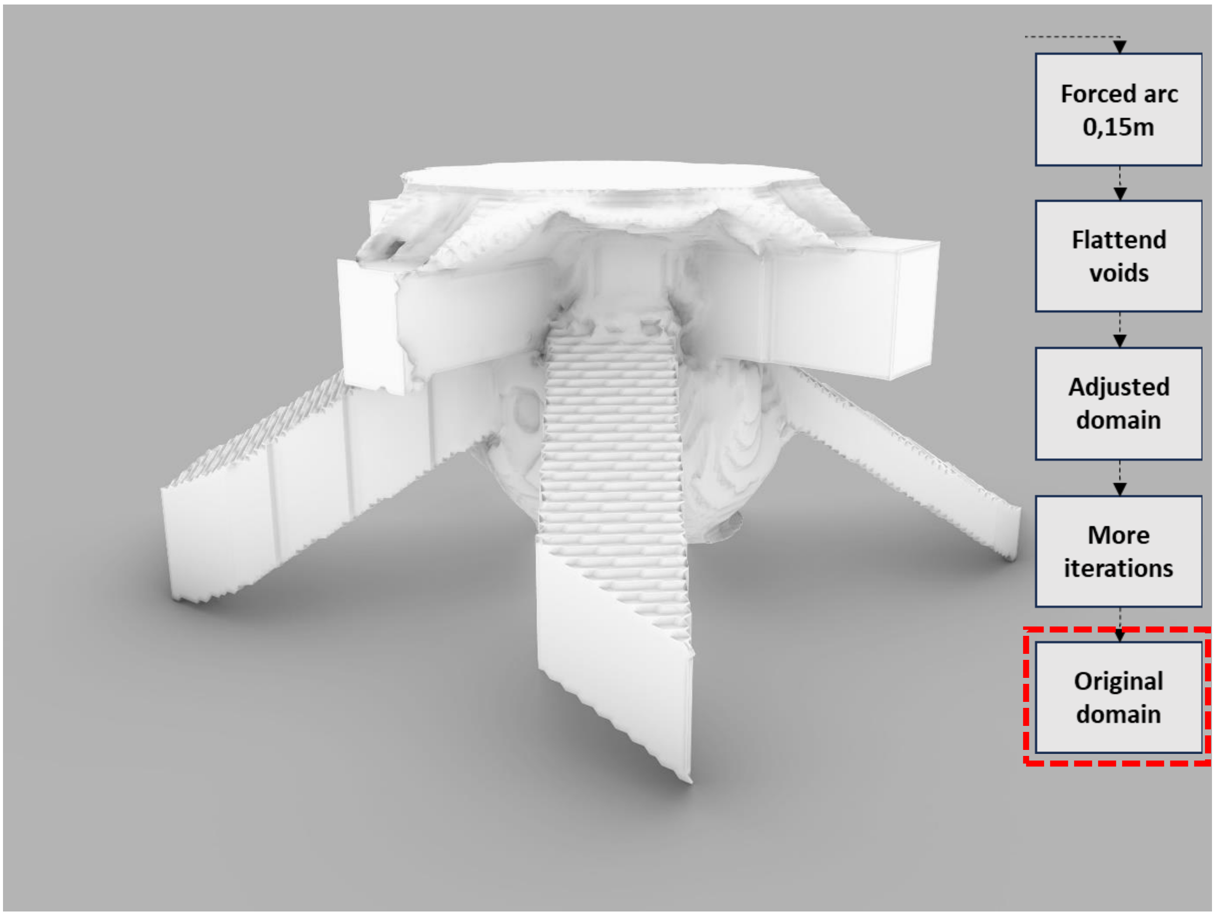



*Figure 57 Generated connection with forced connection of 7-centimetre, source: own work*

Lowering the arc to 7 centimetres prevents it from clashing with the attachments. This however doesn't change much compared with the original state. The sphere almost seems to rest on the arch that has been forced upon it, while placing more material at the top. Simultaneously it continues to make the attachments closed and not the correct size.

**Forced arc 7 centimetre with original loads**

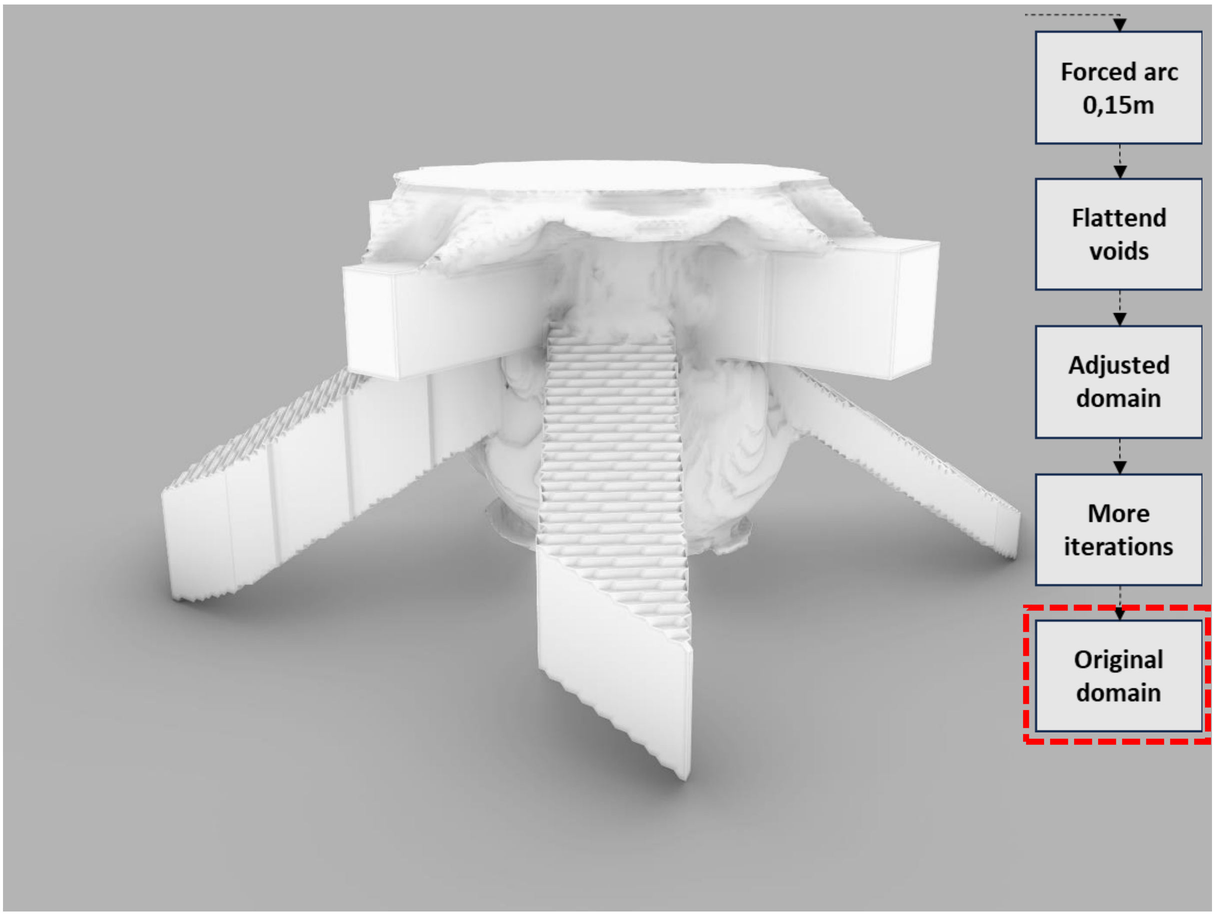



*Figure 58 Generated connection with forced connection of 7-centimetre with original loads, source: own work*

By changing the internal loads, the attachments might open up again. However, as is visible in the generated connection above, this is not the case. The result is similar to the previous one, with only some small differences visible once laid over each other.

## Appendix B- LCA results original connection

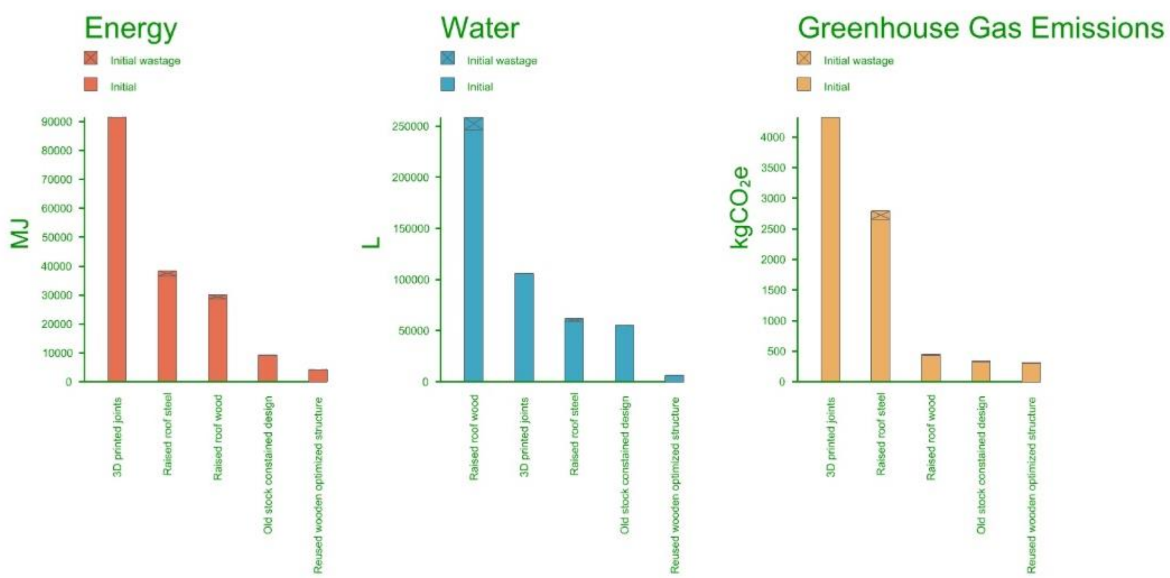
For the first generated connection a set of LCA results was generated as well. These results later got replaced by the once presented in the research itself. However, they do form the base for the results since the reduction in volume was used to reduce the matching footprint.

The LCA results show the total water and energy usage, as well as carbon emissions over specified periods. The time periods used in this research are 1, 5, 10, 50, and 100 years. The results are as follows:

**Scenarios 1, 5, and 10 years**

| Scenarios | Total Energy (MJ) | Total Water (L) | Total GHG (kg CO2e) | Qty (kg) |
|---|---|---|---|---|
| Scenario 1 | 38426 | 61749 | 2790 | 1238 |
| Scenario 2 | 30108 | 258688 | 448 | 459 |
| Scenario 3 | 9307 | 55328 | 341 | 453 |
| Scenario 4 | 4297 | 6345 | 315 | 365 |
| Scenario 5 | 91494 | 106356 | 4324 | 921 |

*Table 27 Scenarios LCA over 1, 5 and 10 years, source: own work*

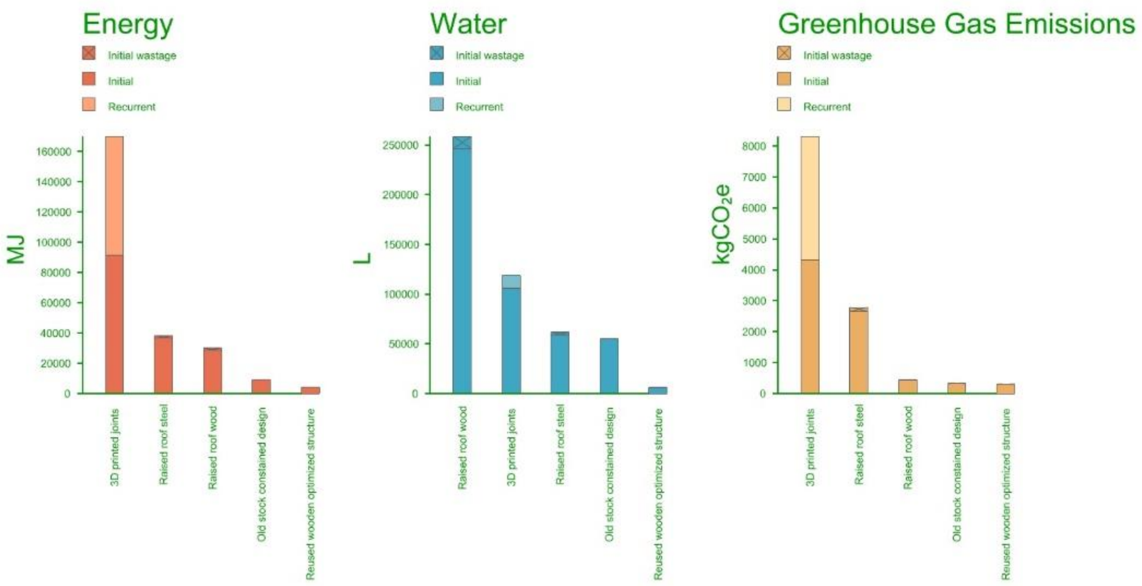



*Graph 1 LCA over 1, 5 and 10 years, source: own work*

**Scenarios 50 years**

| Scenarios | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| Scenario 1 | 38426 | 61749 | 2790 | 1238 |
| Scenario 2 | 30108 | 258688 | 448 | 459 |
| Scenario 3 | 9307 | 55328 | 341 | 453 |
| Scenario 4 | 4297 | 6344 | 315 | 365 |
| Scenario 5 | 170082 | 118841 | 8315 | 921 |

*Table 28 Scenarios LCA over 50 years, source: own work*

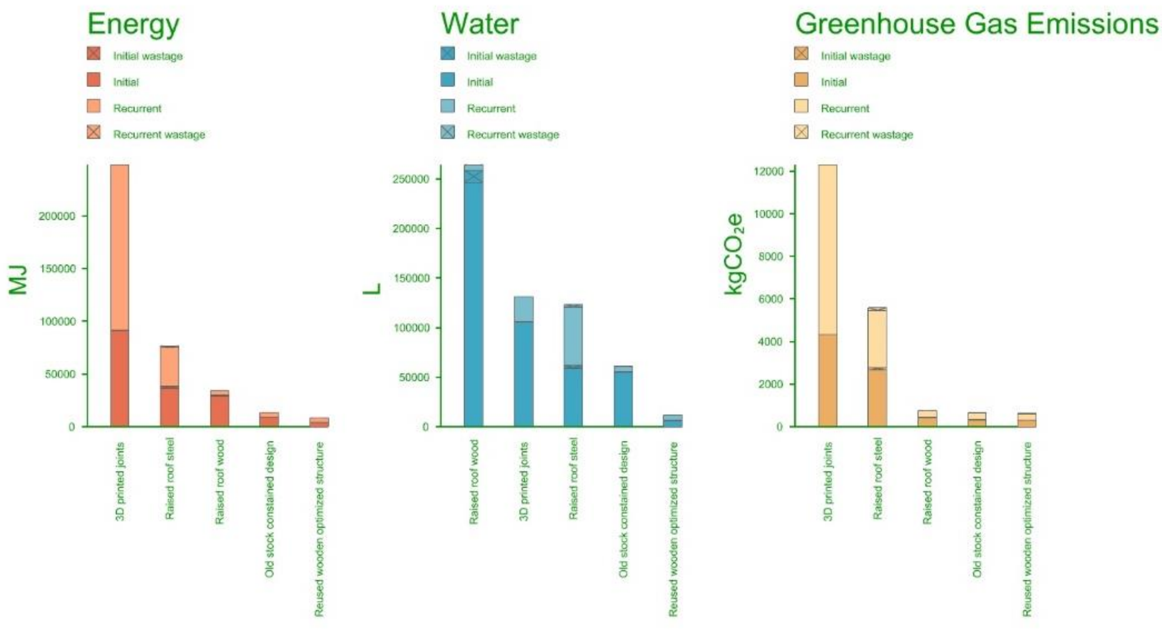



*Graph 2 LCA over 50 years, source: own work*

**Scenarios 100 years**

| Scenarios | Total Energy (MJ) | Total Water (L) | Total GHG (kgCO2e) | Qty (kg) |
|---|---|---|---|---|
| Scenario 1 | 76851 | 123499 | 5581 | 1238 |
| Scenario 2 | 60215 | 517376 | 897 | 472 |
| Scenario 3 | 18614 | 110656 | 682 | 453 |
| Scenario 4 | 8593 | 12688 | 630 | 365 |
| Scenario 5 | 248670 | 131324 | 12300 | 921 |

*Table 29 Scenarios LCA over 100 years, source: own work*




*Graph 3 LCA over 100 years, source: own work*

The results indicate that the first proposed changes continuously lower the total carbon footprint (scenarios 1 to 4). However, in Scenario 5 (the new proposal), the carbon footprint is higher than the original structure (Scenario 1).

# Appendix C- Connection generation results

All 13 connections were generated within the research structure. The composition of the elements coming into the connection was designed using the stock-constrained design tool, while the resulting connections were designed through topology optimization. The connection here are the once from the workflow, before further refinement was applied.

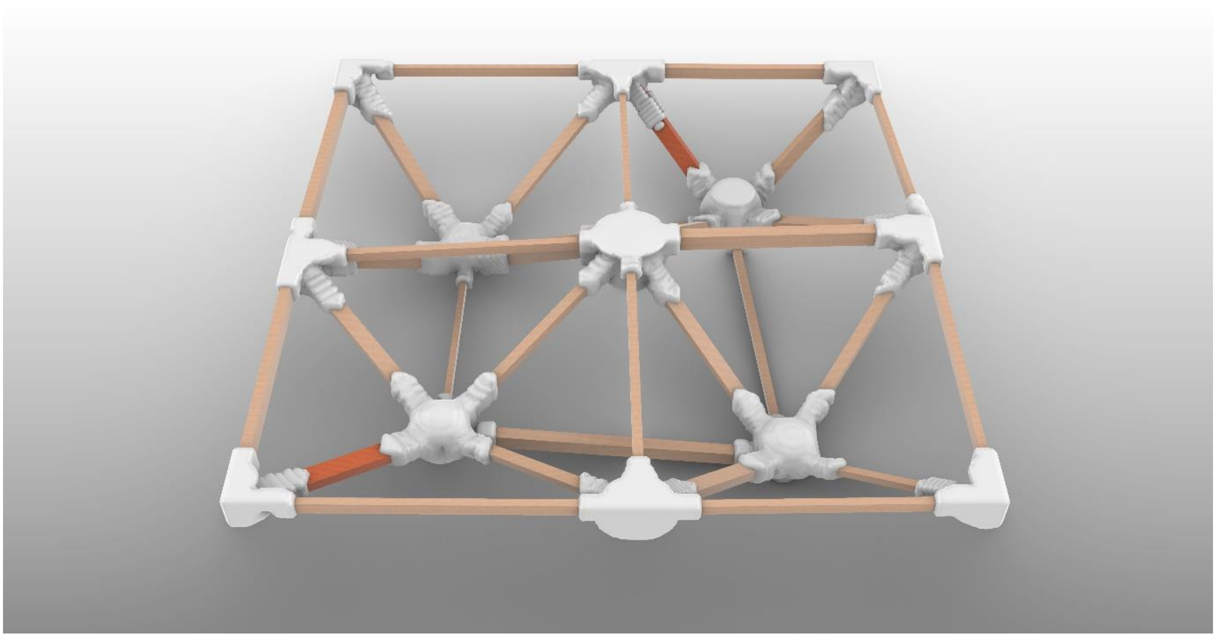


*Figure 59 Top view structure created, source: own work*

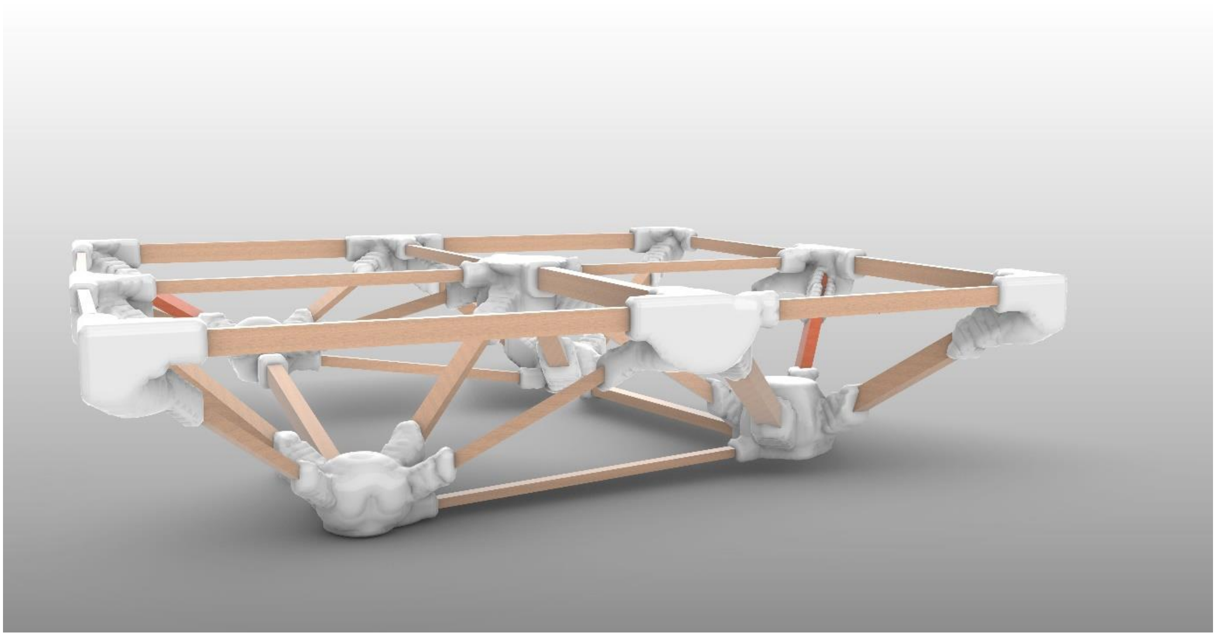


*Figure 60 Side view created structure, source: own work*

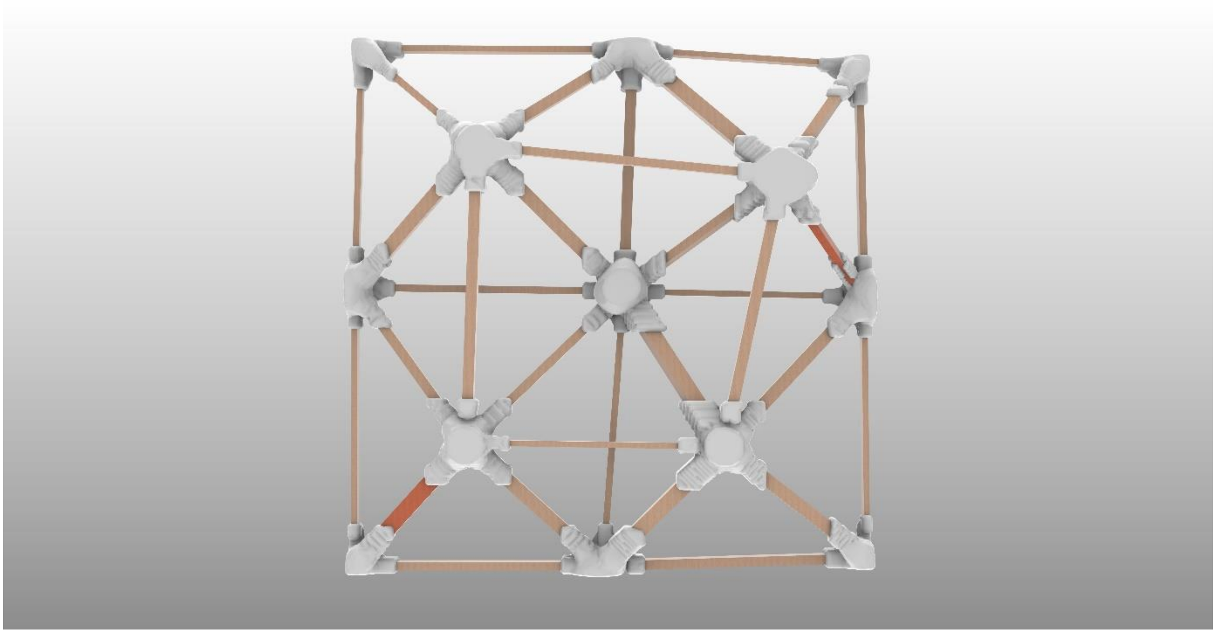


*Figure 61 View underneath created structure, source: own work*

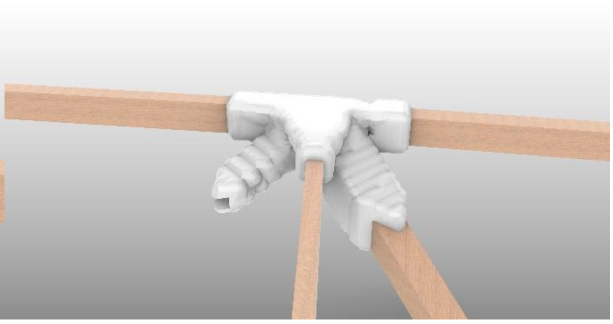
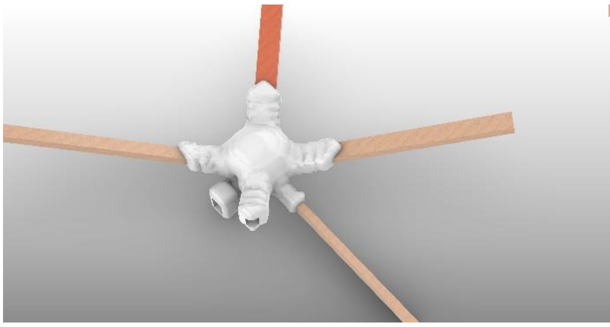


Figure 62 Created corner connection, source: own work

Figure 63 Created side connection, source: own work



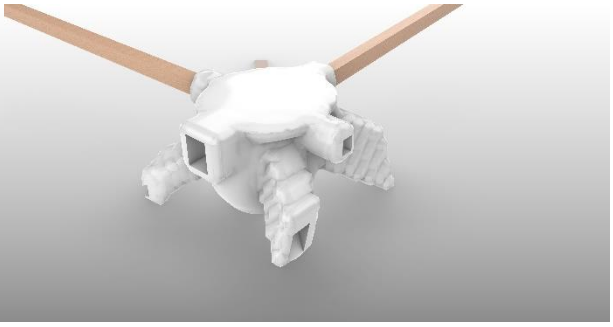
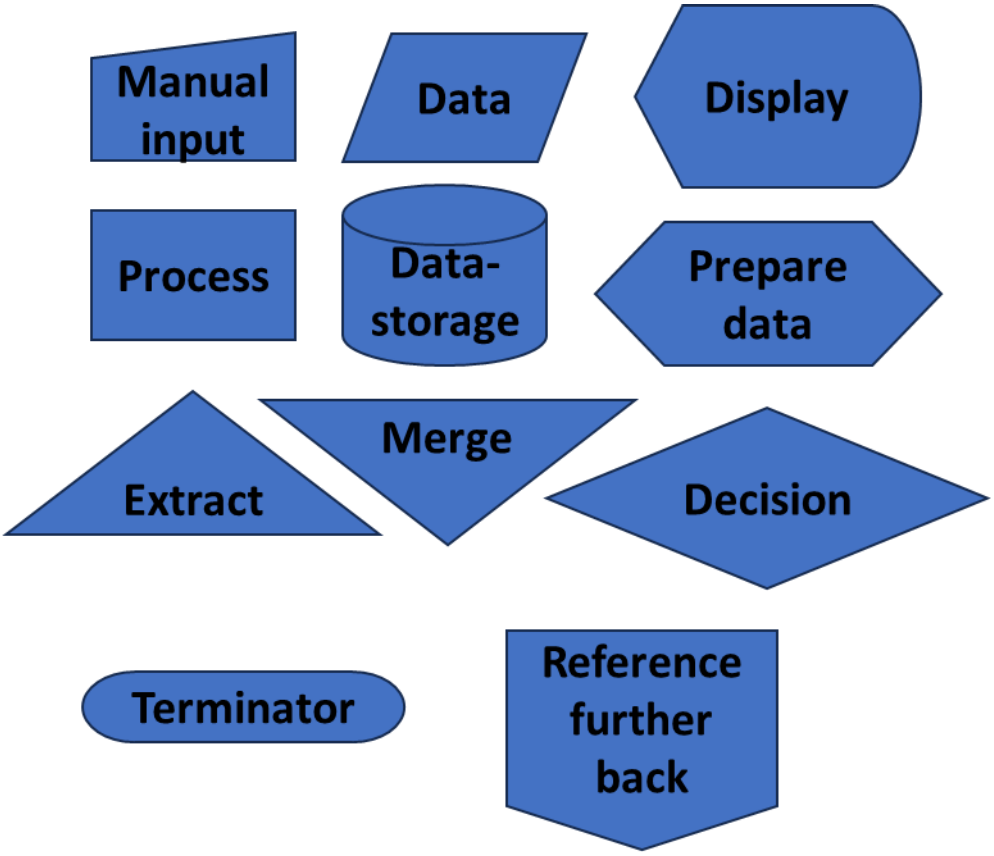


Figure 64 Created lower support connection, source: own work

Figure 65 Central created connection, source: own work

## Appendix D – Workflow legend



# Appendix E – Impression image

# Appendix F – High resolution grasshopper overview