BREAKING GROUND WITH BAMBOO

ROBOTIC ADDITIVE MANUFACTURING OF A SELF SUPPORTING WALL WITH BAMBOO

MSc Graduation Thesis Report

Jasmine Wong

TU Delft Faculty of Architecture and the Built Environment
MSc Architecture, Urbanism and Building Sciences | Building Technology track

breaking ground

To do something completely different from what has been done before.

Source: macmillandictionary.com

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Abstract

Keywords: bamboo, bio-based, additive manufacturing,
3D printing, building component

The construction industry and the existing building stock are significant contributors to greenhouse gas emissions. To address this environmental challenge, there is a growing interest in using bio-based materials, such as wood, in architecture. Yet, the availability of wood resources is limited.
Bamboo, a non-wood species, holds promise as a potential substitute due to its rapid growth rate. However, its adoption in the construction industry remains limited due to the challenges posed by its hollow tube anatomy and the lack of established building codes for its use.
To overcome these challenges, this study proposes the utilization of bamboo in a powdered and fiber form to create a more versatile and standardized building material.

Additive manufacturing techniques, which have seen significant advancements in the past three decades, have also made their way into the construction sector, traditionally slower in adopting innovations. These additive manufacturing technologies offer the potential to reduce labor costs, minimize material waste, and enable the fabrication of complex geometries that are challenging to achieve using conventional construction methods.
While 3D printing technologies for concrete and steel structures have made significant progress, the research and application of additive manufacturing with bamboo for construction purposes still lag behind.

The thesis aims to address this research gap by developing a building component made with bamboo using additive manufacturing technology. By leveraging the benefits of additive manufacturing and utilizing bamboo as a renewable and versatile material, this thesis seeks to promote sustainable practices in the field of architecture.

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Introduction

1.1 Scope

The main focus of this thesis titled "Additive Manufacturing with Bamboo" is on using Additive Manufacturing technology with a bio-based material, specifically bamboo. The thesis is mentored by Serdar Asut and Stijn Brancart, two professors in the TU Delft MSc Architecture program, Building Technology track, with a focus on Design Informatics and Structural Design respectively.
The research involves working with bamboo dust supplied by "Made in Bamboo" and bamboo fibers provided from "Bambooder", a company that specializes in extracting and producing high-performance bamboo thread.

The main overview of the thesis will be presented in the Introduction Chapter, starting with a comprehension of the Problem Statement and culminating with the formulation of a specific Research Question. The Design Assignment identifies the intended outcome of the thesis and it will conclude with the Research Methodology, explaining the four main phases of the thesis advancement.

1.2 Problem Statement

The building industry accounts for 40% of global greenhouse gas emissions and utilizes a considerable amount of the raw materials produced worldwide (IEA, 2022) . As the population is rapidly increasing, which impacts the need for affordable houses, the growing demand of non-renewable resources needs to be reduced. The aim to create more ecologically friendly and sustainable processes has boosted interest in the use of natural buildings and production materials. Bamboo, straw, reeds, and hemp are a few examples of natural, resurfacing materials that have been utilized in the past and have been discovered to be helpful once more. These materials merit further study to fully comprehend their potential for various applications.

Products made from bamboo have been promoted as having significant beneficial effects on the environment and specific economic and social advantages through promoting resource-efficient uses, eco-innovation, and the circular economy.
In many industrial applications, bamboo can be used instead of wood, helping to save and restore the world's forests.
Bamboo has been used in construction and the built environment for centuries in many parts of the world, particularly in Asia (Manandhar et al., 2019). However, it is not as commonly used in the Western world and other developed countries. This is largely due to a lack of knowledge and understanding about the material's properties and how to properly use it in construction. The material typically comes in different diameters, and it is difficult to make a selection and apply it in the built environment, bamboo characteristics vary as its anatomy varies. Since it is a natural material and due to its anisotropy, it shows a wide variety of mechanical properties, therefore it has limited application in complex geometries. Having bamboo dust and fibers will allow to have freedom in shapes and additive manufacturing is one of the solutions to manage complex geometries and reducing the amount of materials to a minimum.

Today, advanced technologies that are frequently utilized in manufacturing are exported for use in the building and architectural industries. Large challenges are being faced by the construction industry as digital technology sensor systems, intelligent machines, and smart materials are adopted. Construction-related additive manufacturing is a crucial enabling technology of this change, which has been called "Construction 4.0" (Craveiro et al., 2019). Even though Additive Manufacturing methods have been upgraded to adapt to construction requirements, there is still a need to design materials that can replace existing conventional materials on the market and that are compatible with the aforementioned processes.

One of the goals of Construction 4.0 is to increase the use of sustainable construction methods, and using Additive Manufacturing as a platform for materials design enables the use of natural and recycled materials (Craveiro et al., 2019).
Natural materials, particularly those derived from bamboo, are still not a common available feedstock for additive manufacturing. There are bamboo-composite filaments made of PLA and bamboo dust (Zhao et al., 2015) and chemically modified bamboo fibers mixed with ABS (Gama et al., 2021), but there is still no fully bio-based composite for additive manufacturing. Bamboo is a sustainable and environmentally friendly material that can be used in additive manufacturing. The fast-growing nature of bamboo means it can be harvested quickly, making it a more sustainable alternative to wood. Additionally, it is a renewable resource, easy to process and distribute, which could make it a cost-effective material for additive manufacturing.

However, few explorations have been pursued towards using bamboo in additive manufacturing regarding the consistency, quality control during the printing process and the use of natural additives and binders to enhance material properties.
More research is needed to better understand the properties and potential of bamboo as a material for additive manufacturing, as well as develop strategies for processing, designing, fabricating and post-processing objects made of bamboo.
This research project focuses on filling these gaps.

1.3 Design Objective

The objective of this study is to establish a connection between bamboo and the construction industry through the exploration of new raw materials and additive manufacturing methods. This investigation aims to address the increasing challenges posed by intricate geometries and designs.

Because natural materials reflect the changes brought about by innovative thinking, forward-thinking concepts and solutions, industrial evolution, and advances in technology, they have been proposed as the foundation for the economy of the future and the use of bamboo necessitates both of these (Borowski et al., 2022). Bamboo's unique combination of strength, growth rate, and sustainability make it an interesting and promising alternative for sustainable construction and manufacturing, especially in additive manufacturing.

A bottom-up approach is used in the research, which means that a building component is created using additive manufacturing by reassembling a bamboo dust base and fibers. As a result, the use of additive manufacturing and its material composition already places restrictions on the design of the construction component. By understanding the constraints and benefits of additive manufacturing with bamboo, their findings will aid and direct the design of the building component once several tests and trials have been conducted.
The tests and assessments can be carried out once the interview and literature review data have been compiled into tables. Additionally, when the recipe is printed, the boundary requirements will allow the design's final shape to be framed. The constraints and benefits of the acquired information will thus be used to determine the printed shape within a six-month period.

Since there is limited existing research on employing bamboo as a feedstock in additive manufacturing, the primary focus of this study is to develop a design for a construction industry building component.

1.4 Research Question

The main research question mentions the goals of looking into the material development, fabrication process and design intention:

What is the workflow to develop a building component made of bamboo with additive manufacturing?

Research sub-questions

The following sub-questions were also elaborated to support the research and as by-products of the work to be developed in order to address the main question.

Material
- What does make bamboo relevant for additive manufacturing?
- What is the state of the art of additive manufacturing with bio-based materials?
- What is the state of the art of additive manufacturing with bamboo?

Mixture
- What are the possible bio-binders that can be used with bamboo to create a printable mixture?
- How does the size of the fiber affect the mixture?

Fabrication
- What are the geometric limitations when printing with bamboo?

Design
- What are the design criteria in order to develop a building component with additive manufacturing?
- How to create a mechanically informed infill?

1.5 Process and methodology

Given the significance of design in generating new insights, knowledge, and practical-theoretical discourse that is accessible and endorsed by experts, this research adopts a research-by-design typology. The study capitalizes on existing digital design and fabrication technologies in architecture, particularly robotic printing, to explore the potential of bamboo as a feedstock.

The research process is structured into four distinct phases:
Phase 1: Literature Review
Phase 2: Material Research
Phase 3: Design and Prototyping
Phase 4: Conclusion and reflection

Phase 1: Literature Review
This phase involves an extensive examination of relevant literature sources, including books, reports, and online resources. It encompasses a comprehensive review of additive manufacturing, bamboo as a construction material, and the use of bio-based materials in additive manufacturing. Through keyword-based searches on platforms like Google Scholar, Scopus, Research Gate, and Springer Link, scientific papers, articles, and reports are selected to address the research question and sub-questions. The literature review informs the establishment of design criteria and generates initial design concepts.

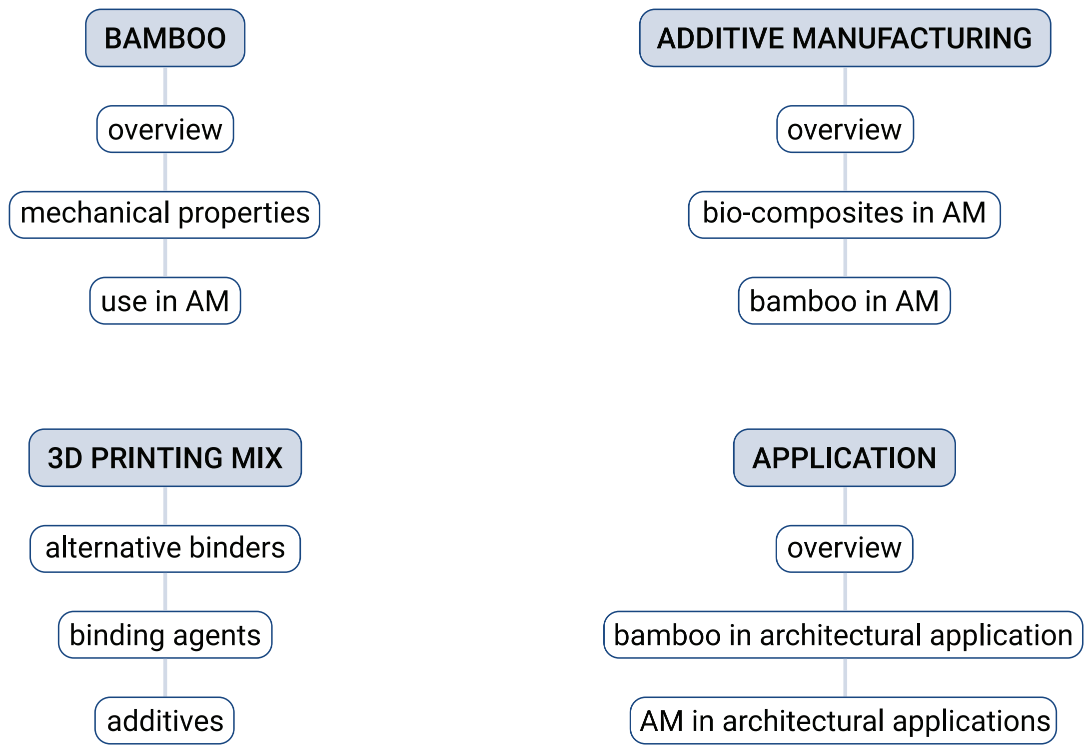


Figure 1: Literature review scheme.

Phase 2: Material Research
Once the literature review and interviews are completed, the material research phase commences. This involves exploring various material mixes, manually testing viscosity and homogeneity, and assessing printability using a syringe at room temperature. The results are documented for analysis and grading, which helps identify the most promising materials for subsequent mechanical testing. The chosen materials are then used to print samples using robotic arms and extruders, gathering data on their mechanical properties and evaluating their potential for structural applications in additive manufacturing.

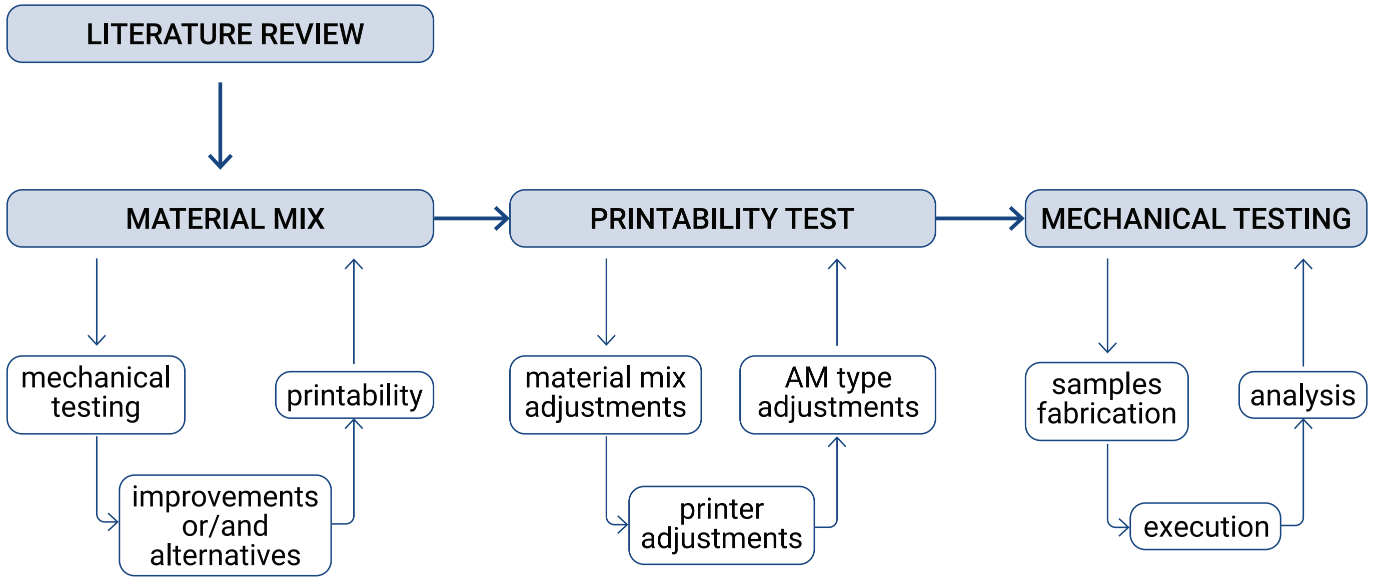


Figure 2: Material research scheme.

Phase 3: Design and Prototyping
In this phase, a specific building component is defined based on the findings of the previous phases. The selected material compositions and printing processes are refined to ensure optimal outcomes. Prototypes of the building component are fabricated, enabling the collection of relevant data on the material's performance. This data contributes to the final conclusions of the research.

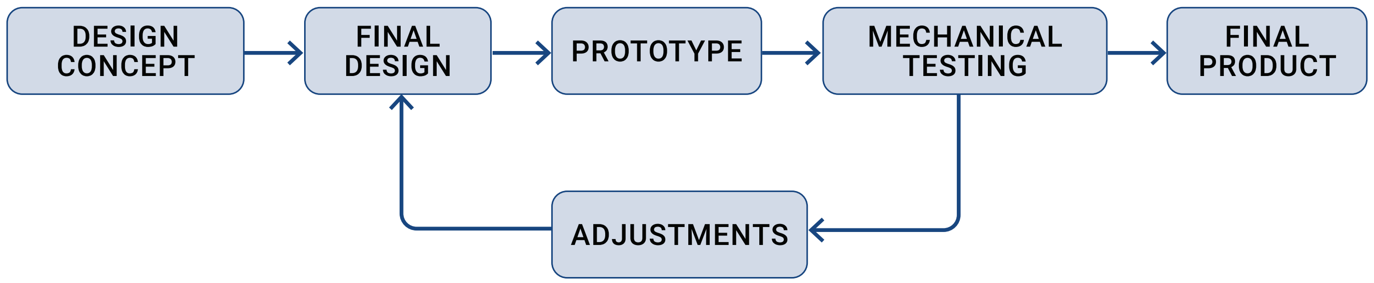


Figure 3: Design and Prototyping scheme.

Phase 4: Conclusion and Reflection
In the concluding phase, all the research findings are consolidated to offer a comprehensive response to the research question. The report thoroughly examines the material mix, including its constraints in the printing process, and assesses its potential and difficulties in fabricating a structurally optimized building component. Additionally, the report provides suggestions for future research, charting a course for future investigations.

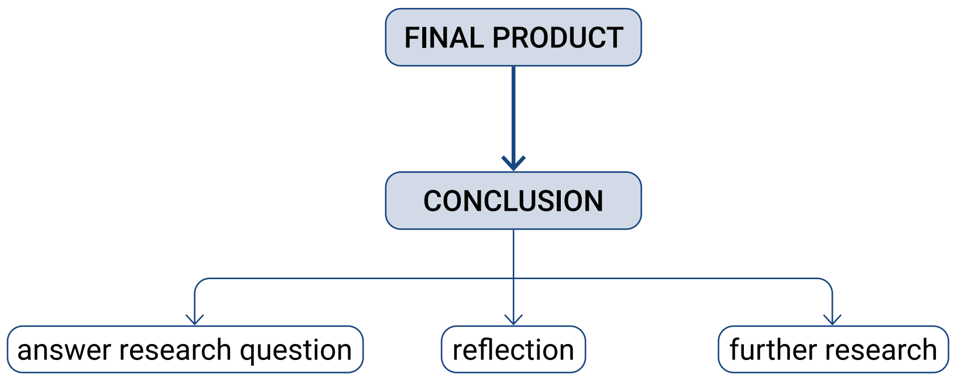


Figure 4: Conclusion and reflection scheme.

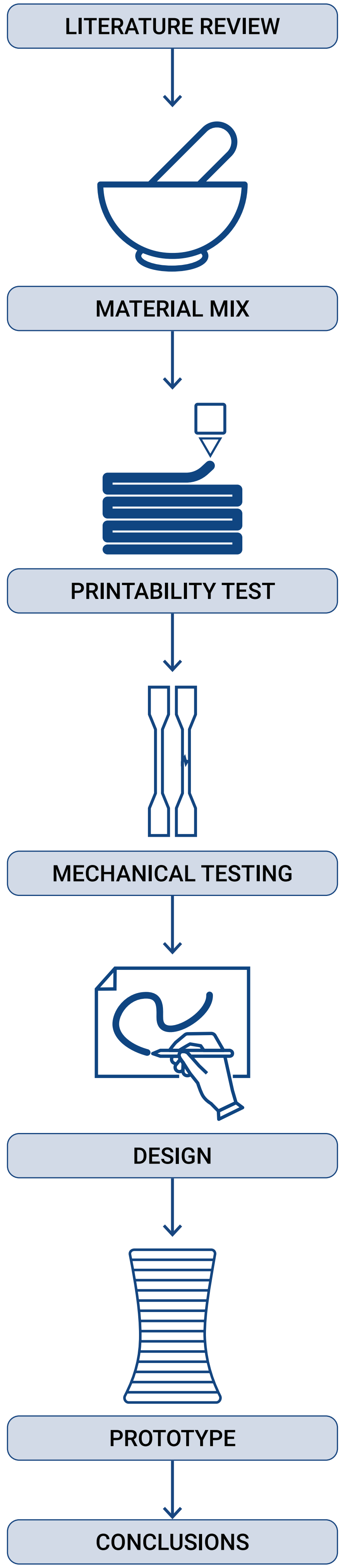
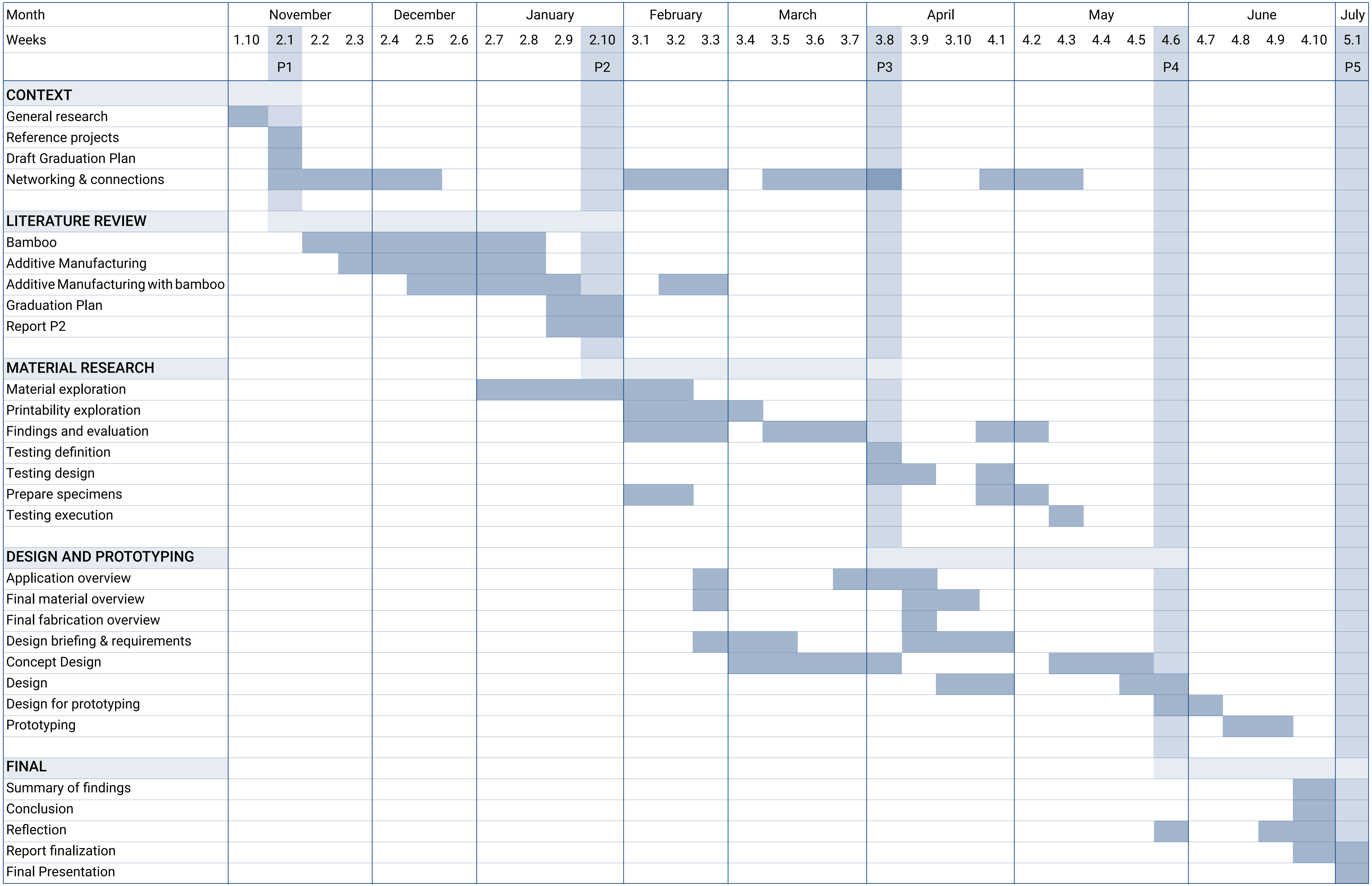


Figure 5: Methodology Overview.

1.6 Time planning



2

Literature Review

2.1 Material Scarcity

Due to the growing urban population and its 40% contribution to global greenhouse gas emissions, the construction industry is one of the fastest-growing emerging sectors in rapid urbanization (IEA, 2022). From 751 million in 1950 to 8 billion in 2022, the world's urban population has increased quickly. According to the United Nations' most recent estimate, the world's population might reach 8.5 billion in 2030, 9.7 billion in 2050, and 10.4 billion in 2100 (UN, 2022) The industry is the most astounding user of materials due to the wealth of this urbanization, the majority of which come from non-renewable resources that require replenishment.

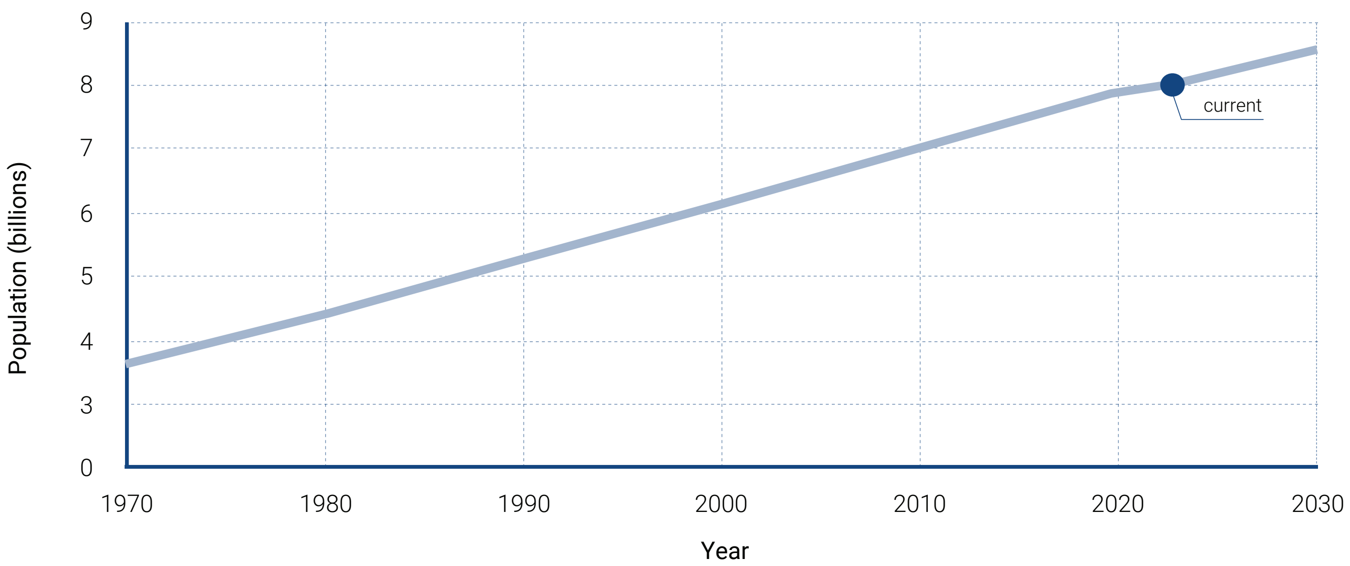


Figure 6: World's population growth. Source: IEA, 2022

In the past two centuries, since the Industrial Revolution, we have become dependent on fossil resources as a source of energy, while also using them for the production of high-tech non-renewable materials such as plastics, metals and minerals, that have largely replaced the dominant renewable materials.
The demand for materials (often non-renewable) and energy sources has significantly increased as a result of the expanding human population and rising consumption per person (often fossil-based). There are three main interconnected global environmental issues brought on by this unsustainable overconsumption: resource depletion, ecosystem degradation, and deterioration of human health. These issues also include related environmental effects like global warming, toxicity, acidification, eutrophication, ozone layer depletion, loss of biodiversity, excessive water use, waste production, etc (van der Lugt et al., 2017).

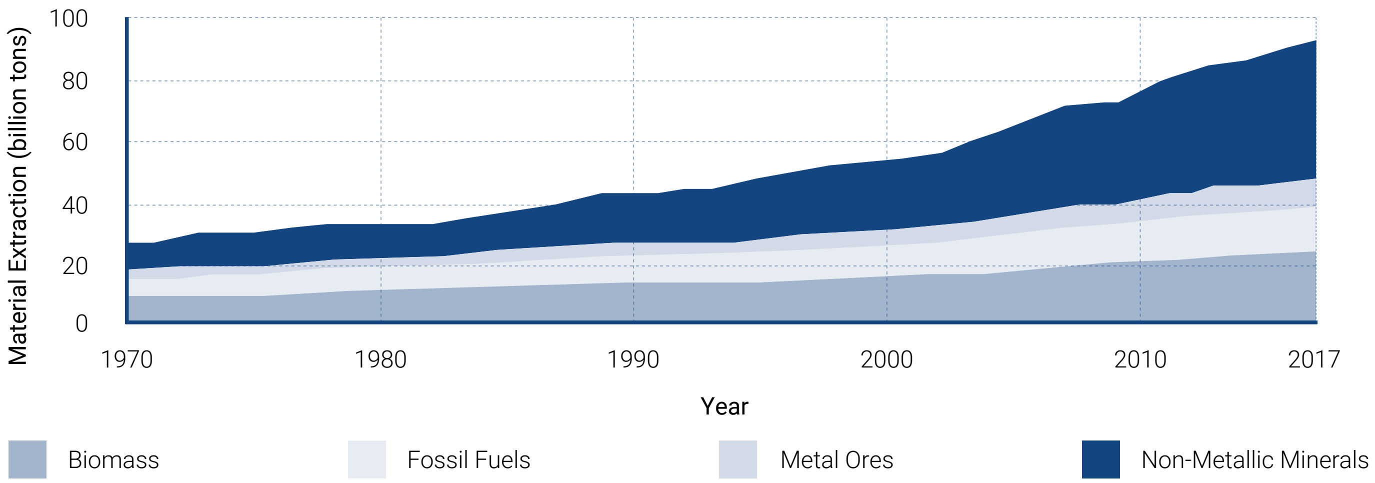


Figure 7: Material extraction. Source: EarthCharts

When it comes to building materials, sustainable development refers to a resource-use strategy that meets the needs and prerequisites of both present-day society and future generations while minimizing environmental damage. Hazards from conventional building materials that have an influence on the social and environmental spheres are a topic of concern and awareness on a global scale. Reduced building material characteristics like embodied energy, energy use, CO_2 emissions, and recyclability can have an impact on both the environment and human health. The building sector urgently needs innovative materials and technology to overcome these problems (Khoshnava et al., 2020).

2.2 Bio-based Materials

It is obvious that humanity is facing a serious resource dilemma as a result of global consumption and population growth as well as an addiction to fossil fuels. This has led to a rise in interest in bio-based materials as a means of creating ecologically friendly and more sustainable processes.
Bio-based materials and goods are made from renewable resources, which, in contrast to many mineral and fossil resources, regenerate more quickly than they are used up. A replacement of materials manufactured from renewable resources immediately lowers CO_2 emissions since most of bio-based materials are produced with far less energy than materials like aluminum, steel, and concrete and act as carbon sinks due to their use (Jones et al., 2017).

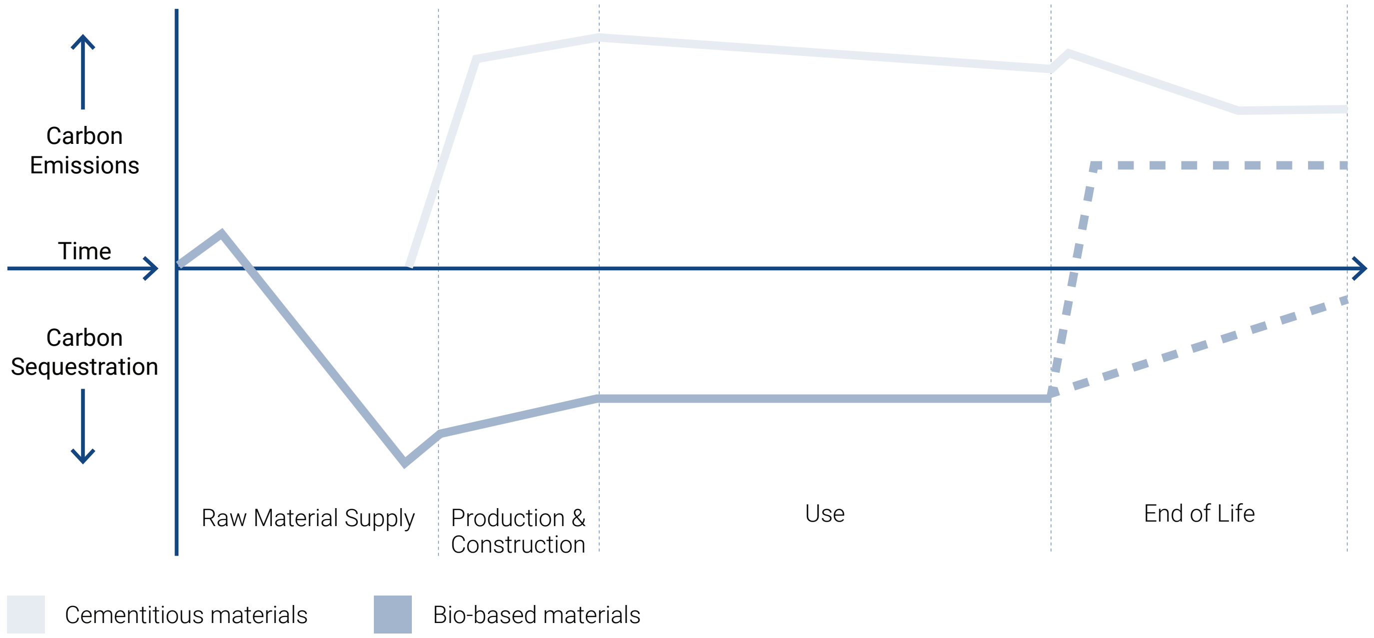


Figure 8: Carbon sequestration of cementitious and bio-based materials across lifecycle stages (J.H. Arehart, J. Hart, F. Pomponi et al. 2021).

Because of their availability, versatility, relative simplicity, and sustainability, the use of bio-based materials has been significant throughout human history. These bio-based materials have the following benefits: they are renewable, practically widely available in a variety of forms, easily obtainable, easily adaptable to needs and uses, hydroscopic, recyclable, adaptable, porous, and nonabrasive (Jones et al., 2017).

Figure 9: Nest We Grow, Kengo Kuma. Source: Archdaily

Figure 10: Centre Pompidou Metz, Shigeru Ban. Source: Archdaily

Figure 11: Timber House, KUHNLEIN Architektur. Source: Archdaily

2.2.1 Sustainable but not Unlimited

Although using bio-based products has many advantages, it also has some limitations. Depletion also results from overexploitation caused by demand that exceeds natural reproduction. This is especially true of hardwood, which is typically from tropical areas. Hardwood forests will continue to be vulnerable to deforestation due to their growth, lengthy rotation cycles, high demand, and superior technical performance. This is not the case for softwood from temperate locations. The northern hemisphere's net forest acreage is really growing, albeit slowly. However, the hardwood example demonstrates that even regenerative resources have their limits because to possible overexploitation and competition with other land uses (agricultural, grassland for cattle, infrastructure, etc.), particularly in tropical areas (Ramage et al., 2017).

According to Ashby, the demand for wood will be impacted by material consumption, which is anticipated to increase over the next 25 years at a 2.8% annual rate. Meanwhile, the growing emphasis on a bio-based economy is anticipated to further boost the demand for biomass for bio-chemistry and bio-energy. Large-scale reforestation initiatives are required to increase the production capacity of the wood sector in order to support this expansion and the effort to increasingly replace techno-cycle materials.

Figure 12: Deforestation. Source: qz.com

Alternative, preferably fast-growing plants like bamboo, hemp, flax, seaweed, miscanthus, and cork, as well as various types of algae and fungus like mycelium, may play a significant role in this booming bio-based economy (van der Lugt et al., 2017). As a result, it has become more important to look for alternatives to complement wood as a bio-based material rather than to replace it as a solution for the construction industry. A viable raw material should be affordable, quickly growing, easily accessible, and have similar physical and mechanical qualities like wood.Bamboo could be a suitable substitute (Chaowana, 2013).

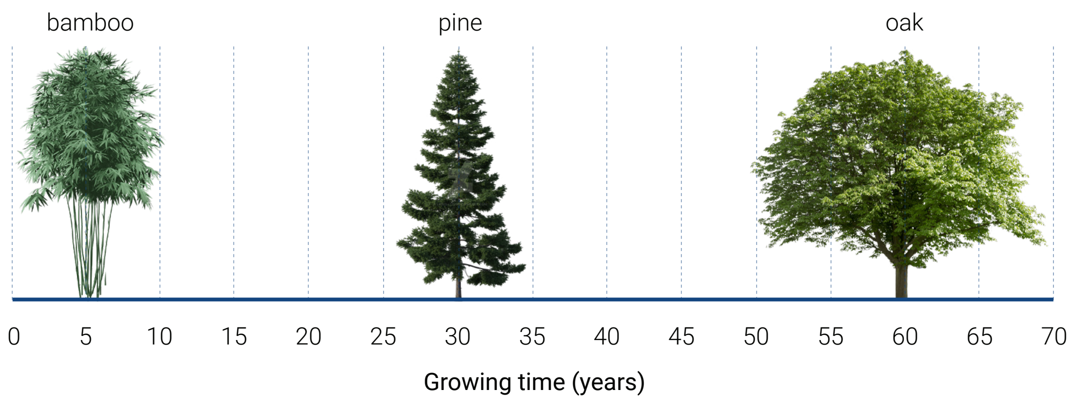


Figure 13: Bamboo, Pine tree and Oak tree growing time (Kampinga et al., 2015).

2.3 Bamboo

Bamboo is a massive perennial grass belonging to the monocotyledon order of the angiosperms, the biggest member of the grass family (Goh et al., 2020). Bamboo plants sprout from seeds or rhizomes in their native habitat. Bamboo depends heavily on its rhizome system. The latter acts as the basis because bamboo lacks the central trunk that trees have. Rhizomes of bamboo can be broadly divided into pachymorph (sympodial) and leptomorph (monopodial). In the pachymorph rhizome system, a rhizome's apex produces a shoot that develops into a culm, the bamboo plant's woody stem. Such culms cluster together in a clump as they expand. Each internode's lateral bud in the leptomoroh rhizome system matures into a culm or rhizome. The monopodial bamboo cluster spreads out as the rhizome's apex rises horizontal to the ground, with each culm growing apart from the others (Janssen et al., 1997).

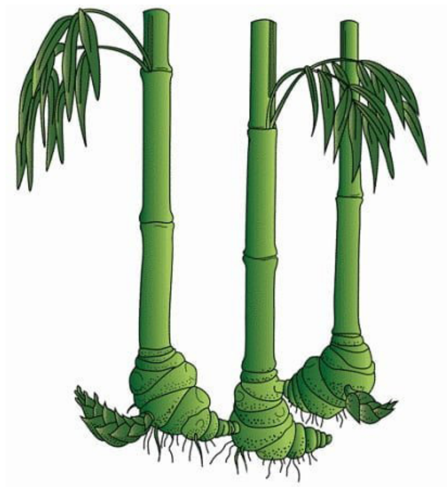


Figure 14: Pachymorph bamboo.

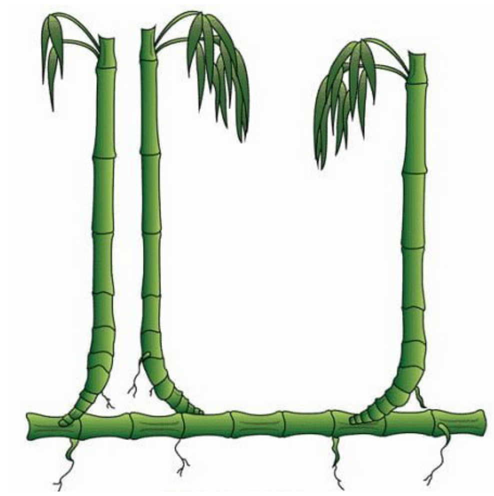


Figure 15: Leptomorph bamboo

Bamboo production is seen as an intriguing climate change mitigation technique due to its quick growth cycle. Bamboo has highly interesting development characteristics because, in its second and third weeks, it grows quickly longitudinally. Bamboo grows up to 6 cm every day during its first development phase, after which the growth dynamics pick up quickly and the bamboo grows 37 cm in the following 4 days. Bamboo can grow up to 80 cm each day in the third week. These characteristics allow bamboo to absorb a lot of CO2. According to simulations of bamboo farming, if 10 million additional hectares of bamboo were planted over the course of 30 years, the plants and products made from bamboo could prevent the emissions of more than 7 gigatons of CO2 (Borowski et al., 2022).

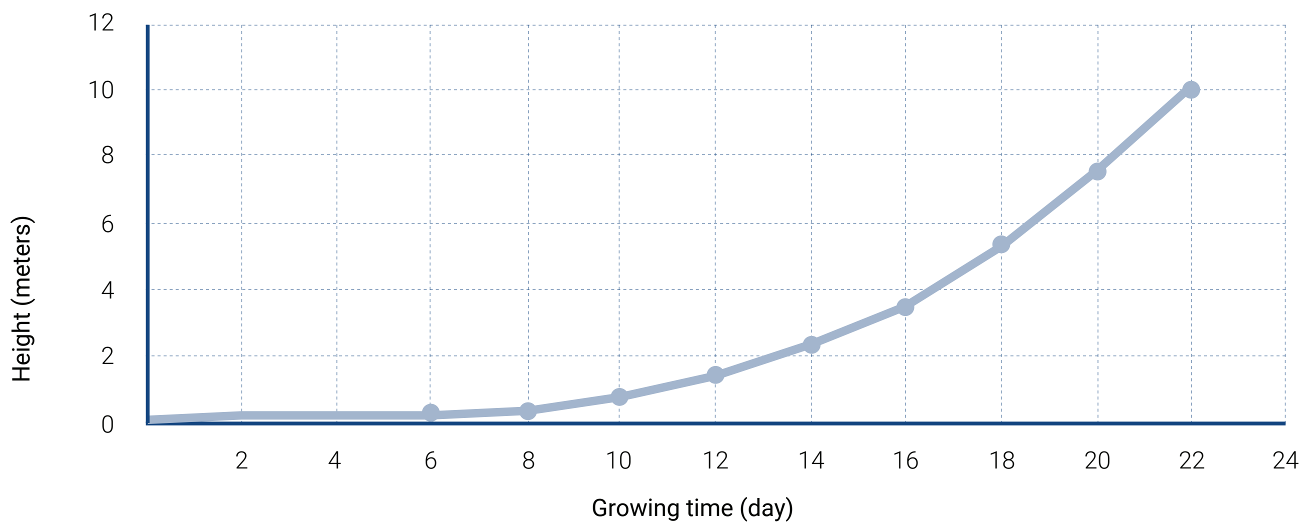


Figure 16: Dynamic of bamboo growth (Borowski et al., 2022).

Although it is a frequent misconception that bamboo only grows in Asia, bamboo actually has a very uniform global distribution. Giant bamboo species are typically found in subtropical regions, typically in developing nations or emerging economies, and have the greatest potential for industrial processing and economic development. The greatest bamboo forest stocks, totaling more than half of the 32 million ha of bamboo available globally, are found in China and India, with 7 million and 9 million hectares respectively (van der Lugt et al., 2017).

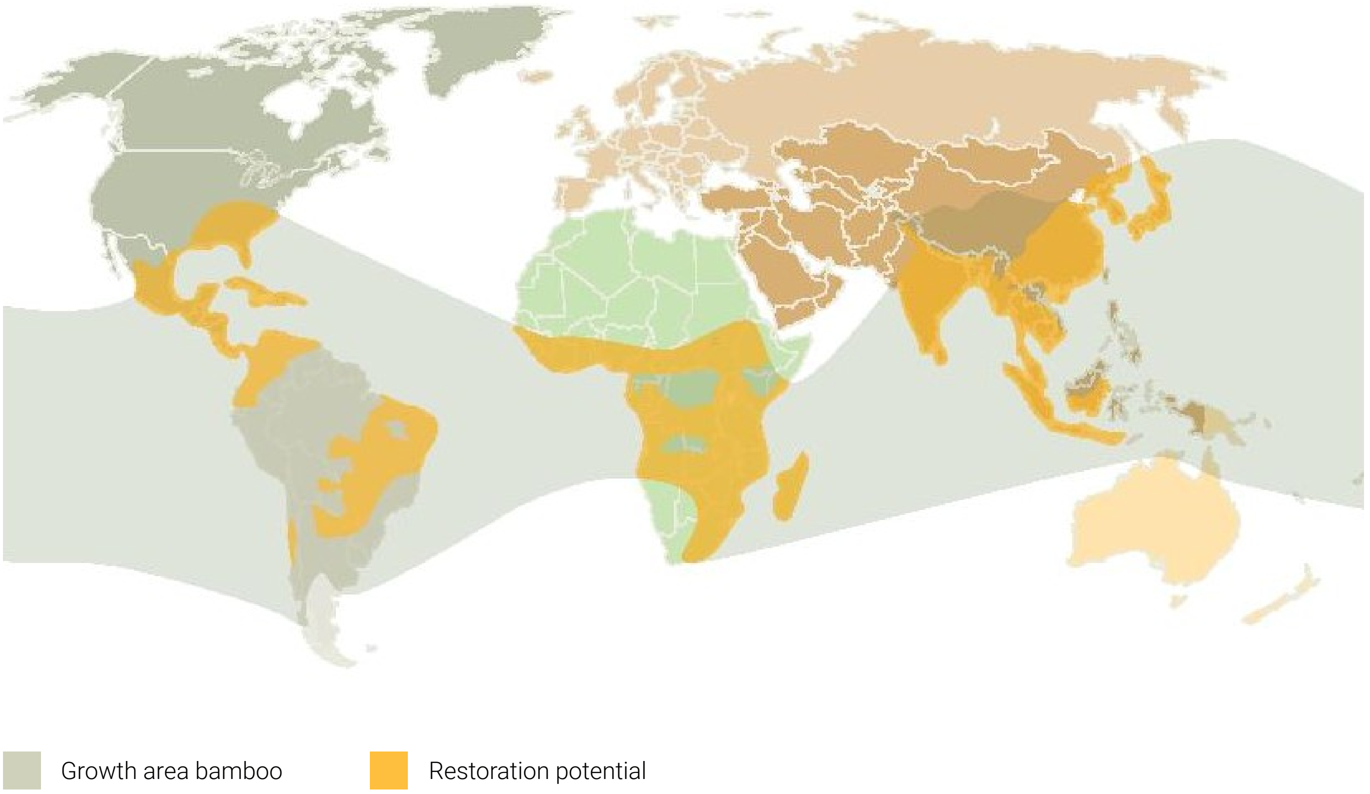


Figure 17: Overlap in natural growing area of bamboo with potential landscape restoration area (van der Lugt et al., 2017).

2.3.1 Bamboo Anatomy

Culms and rhizomes are the two primary anatomical components of bamboo. The sections of bamboo above ground are called culms. It is divided by nodes, which are solid transverse diaphragms that run along the culm of bamboos. Usually, internode length increases along the majority of the culm height and then reduces as it nears the apex of the culm (Amada et al., 1996). These nodes produce branches. An internode is the area that lies between the two nodes. Most bamboos have hollow internodes, which is the cavity (Janssen et al., 1997).

Figure 18 shows the culm wall's microstructure. The culm wall's outside is thin—about a quarter of a millimeter thick—and dense, as seen by the dark color. This layer is rich in silica, which is a suitable substance for shielding the plant. In the cross section, cellulose fibers and vessels are represented by the dark spots that decrease from right to left. Similar to steel bars in reinforced concrete or glass fiber in fiber-reinforced plastic, cellulose serves as reinforcement (Janssen et al., 1997). The distribution of fibers increases from the interior toward the exterior, where they are most needed to absorb moments of stress caused by mechanical loads. This is a great example of structural design from nature (van der Lugt et al., 2017). During the bamboo's lifetime, the vessels handle the transportation of liquids. The matrix in which the fibers are embedded is referred to as parenchyma, and it is found between the dark spots. A bamboo culm has roughly 40% fibers, 10% vessels, and 50% parenchyma (Janssen et al., 1997).

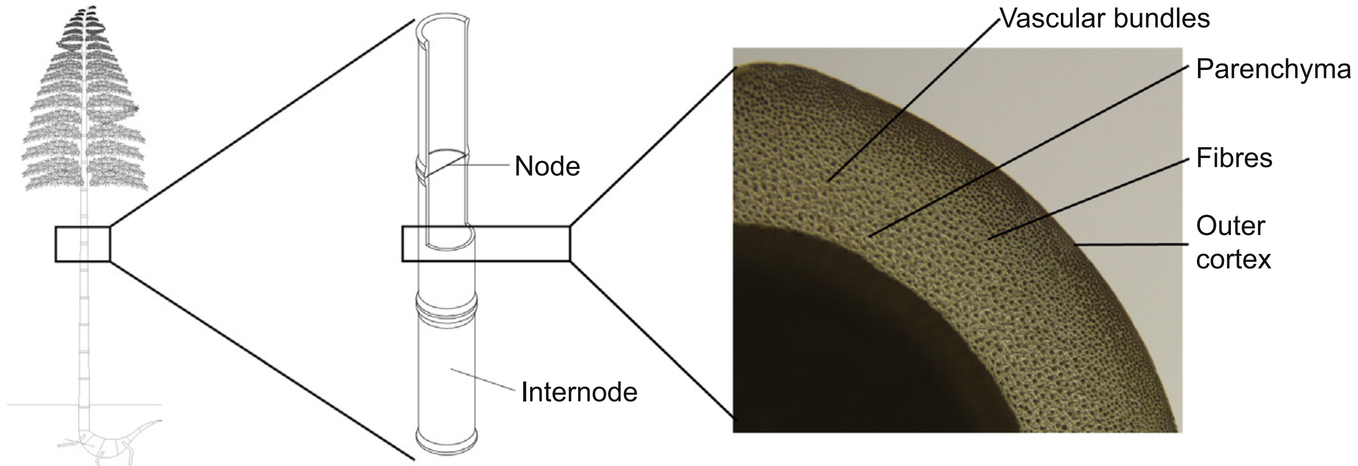


Figure 18: Structure of the bamboo culm (Correal et al., 2020).

Despite having nearly equal chemical compositions, bamboo and wood have very different anatomical composition. For instance, bamboo lacks rays, which are areas for the storage and transportation of food, primarily sugar, and which render the material weak. Furthermore, compared to the solid stem of trees, the stem of bamboo is hollow (van der Lugt et al., 2017).
Since bamboo is an extremely adaptable plant, all of its components can be used to their utmost potential, as seen in figure 19. (Goh et al., 2020).

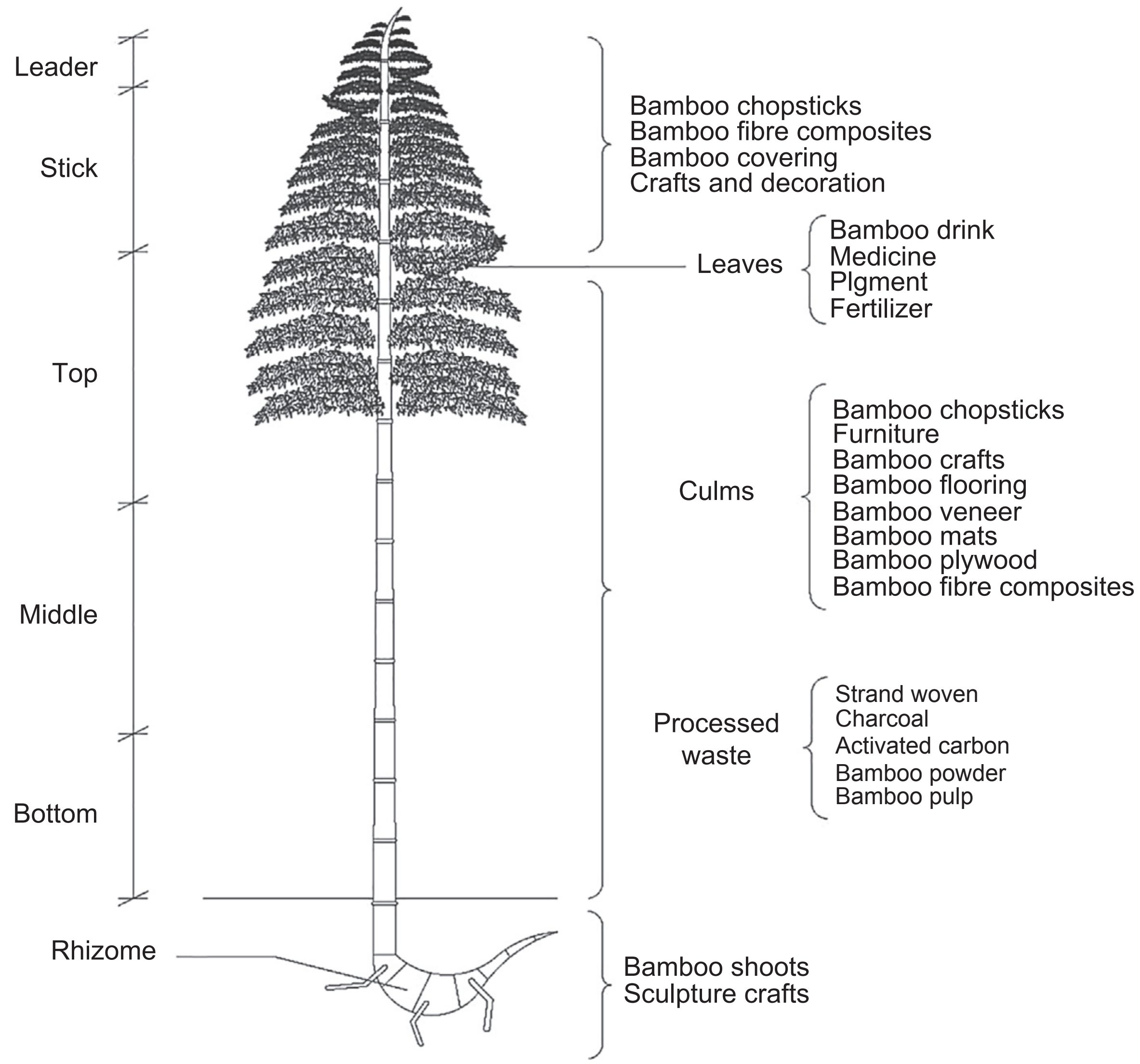


Figure 19: Parts of bamboo and its utilization. (Correal et al., 2020).

2.3.2 Bamboo Environmental Sustainability

Bamboo is a very adaptable plant that can grow well in a variety of climates and elevations, which enables it to contribute to the expansion of forest resource volumes and the alleviation of pressure from the use of wood substitutes as a source of raw materials. Bamboo forests have a great potential for sequestering carbon, making them the type of forest that is most likely to join the market for emission reduction. The involvement of bamboo forests in the world carbon cycle and its effective use in absorbing wastewater from industry, agriculture, and pollution have both been reported by a number of research. As a good material for carbon sequestration, bamboo is particularly beneficial in terms of air protection (Borowski et al., 2022).

The ability of bamboo to absorb CO2 has been researched in the past, mostly in regions where bamboo grows naturally to produce wild forests. Bamboo forests are an important carbon sink and contributor to regional and global carbon cycles. In addition to maintaining the atmosphere's gas concentration and releasing 30% more oxygen than other plants, bamboo may absorb up to 12 tons of CO2 per hectare each year. As a result, bamboo can be seen as having a positive impact on lessening the negative consequences of climate change because it is a significant natural carbon sink that helps human ecosystems adapt (Borowski et al., 2022).

2.3.3 Bamboo as a Construction Material

The use of bamboo as a structural material has recently attracted a lot of interest. Cost is one of the primary factors used in the building business when choosing materials. Compared to other naturally growing resources, bamboo has a high productivity rate and a quick harvest cycle, making it a suitable building material. Researchers argued that if structural bamboo plants were planted today, mature clusters of bamboo plants would be accessible in about three to four years, and within eight years, there would be enough mature materials to build a sturdy, low-cost structure (Richard et al., 2013). In addition, bamboo's great weight to strength ratio and high tensile strength are its standout qualities that make it a promising building material. It can be utilized as a highly resilient material against dynamic stresses produced by earthquakes and high-velocity winds thanks to the good weight to strength ratio.

Figure 20: Bamboo Stalactite, VTN Architects. Source: Archdaily

The natural durability of bamboo should be the first consideration when using it as a building material in real life. Bamboos typically have a short lifespan (1-3 years) due to their susceptibility to fungus and insect assault. Because their outer and, to a lesser extent, inner membranes are impervious to liquids, they are particularly difficult to treat with conventional preservation techniques in dry conditions (Liese et al., 1985). However, if bamboo was well treated for and industrially processed, it can often have a long lifespan of 30 to 40 years (Goh et al., 2020).

In recent years, one of the most environmentally friendly and productive construction methods has been the use of bamboo as a raw material for both structural and non-structural operations. Bamboo can be utilized in place of traditional building materials for a number of building components, including trusses/ roof structure, walls, flooring, foundation, and scaffolding (Yadav & Mathur, 2021).

Figure 21: Bamboo roof. Source: Dezeen

Figure 22: Bamboo flooring. Source: Archdaily

Figure 23: Bamboo foundation. Source: Archdaily

Figure 24: Bamboo scaffolding Source: Archdaily

2.3.4 Bamboo Mechanical Properties

Bamboo is well-known for its exceptional mechanical properties due to the high content of cellulose, which is its primary constituent. It has been demonstrated that bamboo can perform well in buckling because of the high energy absorption at the joints, resulting in much lower stresses compared to steel (Correal et al., 2020). Bamboo is stronger than concrete and steel by weight, owing to its microfiber structures that contain lignin and hemicellulose (van der Lugt et al., 2017).

Experimentally, certain bamboo species have been found to have an ultimate tensile strength in the range of 140-280 MPa, which is comparable to mild steel (Patil and Mutkekar et al., 2014). The strength of the lignin matrix is the primary factor limiting the strength of bamboo. In construction applications, bamboo's shear strength and longitudinal splitting are critical factors to consider.

Bamboo is a viscoelastic and anisotropic material that exhibits differences in physical and mechanical properties along its three orthogonal axes, with variations being more significant along the length of the culm due to the tapered shape and increasing density with height. Furthermore, bamboo's physical and mechanical qualities are affected by moisture content, age, and the location on the stem (Correal et al., 2020).

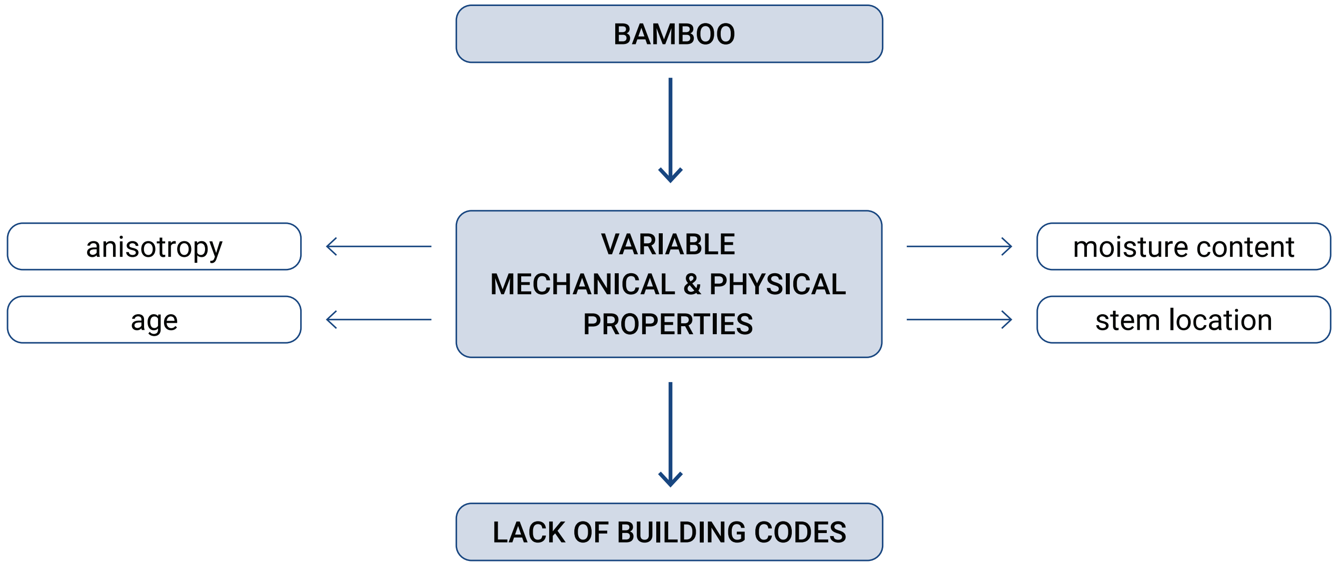


Figure 25: Bamboo variale properties scheme.

According to van der Lugt (2017), the outer half of the stem wall is stronger due to the uneven distribution of vascular bundles, resulting in density, dry shrinkage, and strength changes occurring in close proximity to one another. The wall thickness and strength increase in the same direction from the bottom section of the bamboo stem due to density.
Additionally, moisture content has a negative impact on bamboo's compressive strength, which can fluctuate by 35% depending on moisture content, ranging from 12% to 6% and 20%, respectively. The mechanical properties of node parts and internode parts also vary, with nodes having lower tensile strength than internodes.
The structural and mechanical characteristics of bamboo stem also vary with age, with 2-year-old bamboo being softer and weaker, while 4-6 years old bamboo is robust and strong. However, bamboo aged 7 years or older has very low strength and is fragile (Correal et al., 2020; van der Lugt et al., 2017).

Bamboo, like wood, is a heterogeneous and anisotropic material whose mechanical properties are unstable due to various factors, making them more unstable than wood in some respects (Rogerson et al., 2016).

2.4 Construction 4.0

There is a demand for inexpensive homes, public transportation, and utility infrastructure due to the rapidly growing urban population. However, the building industry is seen as being primarily low-tech and still dependent on craft-based processes, with a poor reputation for quality and performance.
Today, advanced technologies that are frequently utilized in manufacturing are exported for use in the building and architectural industries. Contrary to other industries, construction has not seen a significant disruptive revolution and has been slow to incorporate new technologies.
In order to increase quality and productivity, other industrial sectors, like automotive, aeronautics, and aerospace, experienced major process changes. The embedded system production technologies and smart production processes are connected by this digital transformation, which is frequently referred to as "Industry 4.0," which is fundamentally altering industry and production value chains and business models.

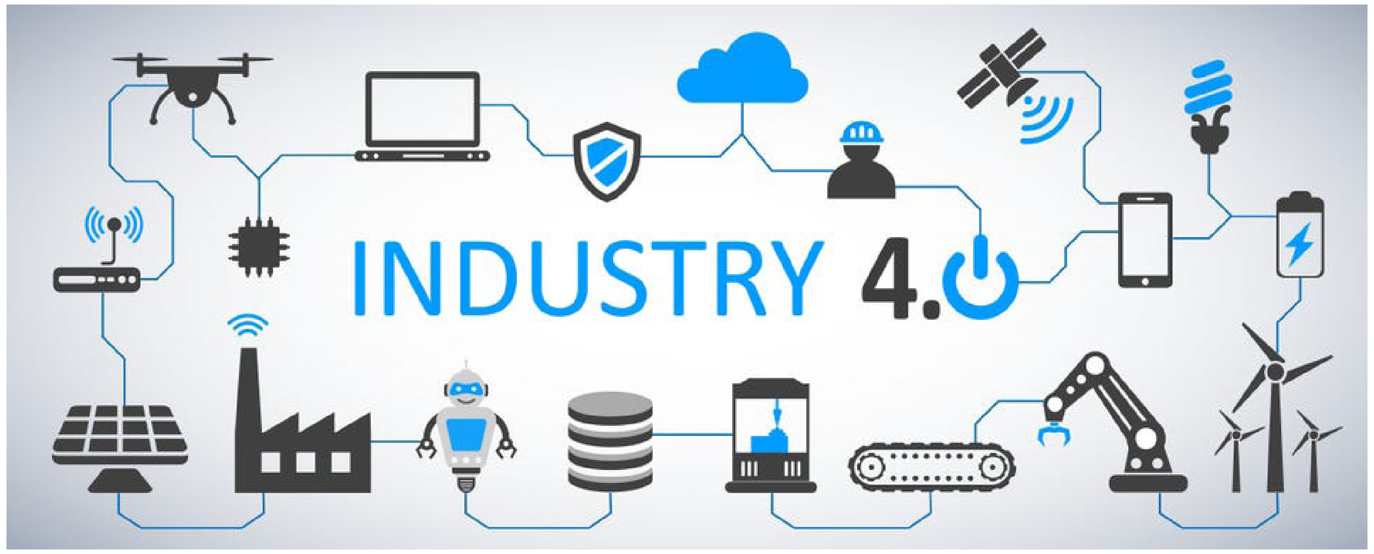


Figure 26: Industry 4.0. Source: Adobe Stock

Among other technologies, the utilization of sensors and controls, augmented reality systems, cognitive and high performance computing additive manufacturing, sophisticated materials, autonomous robotics, and digital design and simulation systems is what is driving this industrial transformation.
Due to the widespread use of digital technology, sensor systems, intelligent machinery, and smart materials, the construction industry is currently experiencing significant challenges. Construction organizations will be able to increase productivity, decrease project delays and cost overruns, manage complexity, and improve safety, quality, and resource efficiency thanks to this change, which has been called "Construction 4.0" by analogy with the manufacturing industry (Craveiro et al., 2019).

The construction industry will need to change in order to embrace the fourth industrial revolution, moving from automated production to a higher level of digitilization, through the use of a BIM (Building Information Modelling) system that connects virtual and real buildings. BIM and augmented reality improve decision-making since they enable one to see how the design fits on the site before building begins, manage disagreements, check for structural safety issues, support automated construction, and more. By enabling building performance simulation, energy efficiency, and the use of sensor technologies like thermography, as well as by encouraging collaborative design development, it can result in the building's performance being improved.
Construction will be driven toward the adoption of automated modeling and manufacturing processes as the industry transforms into a digital and innovation-based sector. Additionally, the new digital construction environment will encourage stakeholder engagement, creativity, supply chain strengthening, and on-demand supply (Craveiro et al., 2019).

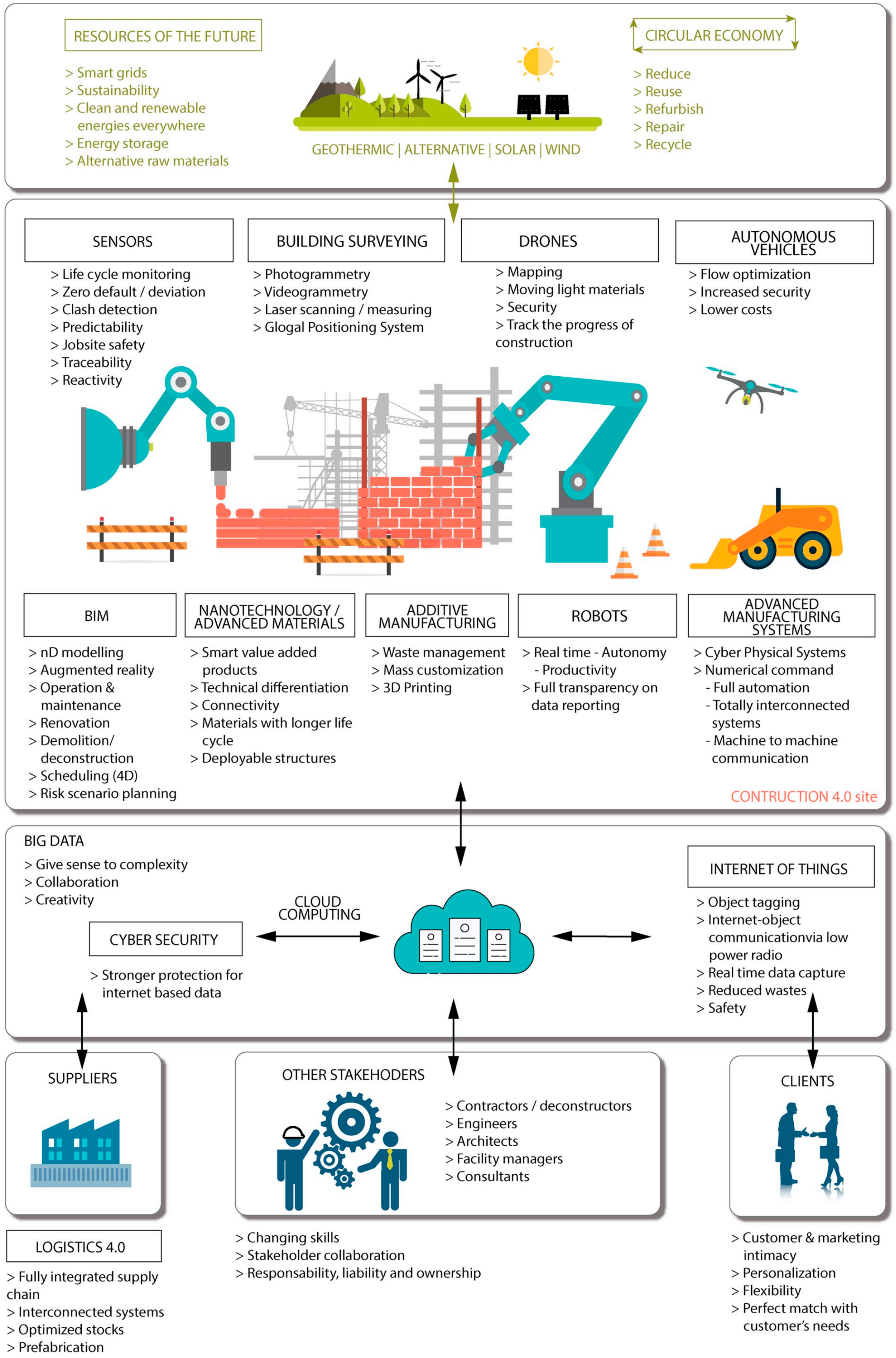


Figure 27: Construction 4.0 (Craveiro et al., 2019)

2.5 Additive Manufacturing

Innovations in the way construction are required to change the current state of industry practice. Work in harsh environments, a shrinking qualified labor, safety during construction, the generation of significant amounts of waste, and the delivery of supplies to the site are just a few of the difficulties faced by the construction industry. There is a lot of fragmentation in the building business. Because there are so many specialized small and medium-sized construction companies, many of them are reluctant to share helpful information or technology with others, further impeding potential innovation in the sector. These obstacles to innovation and challenges are considered as chances for additive manufacturing.

Figure 28: Current state of industry practice.

Additive manufacturing is distinct from conventional manufacturing techniques like subtractive procedures that generate a lot of waste material as a solid piece of material is cut into the desired shape or formative processes that need to create a mold to produce a product in large quantities. Filling a need created by traditional manufacturing techniques, additive manufacturing can advantageously fabricate complicated geometries with no part-specific tooling and significantly less waste material (Delgado Camacho et al., 2018).

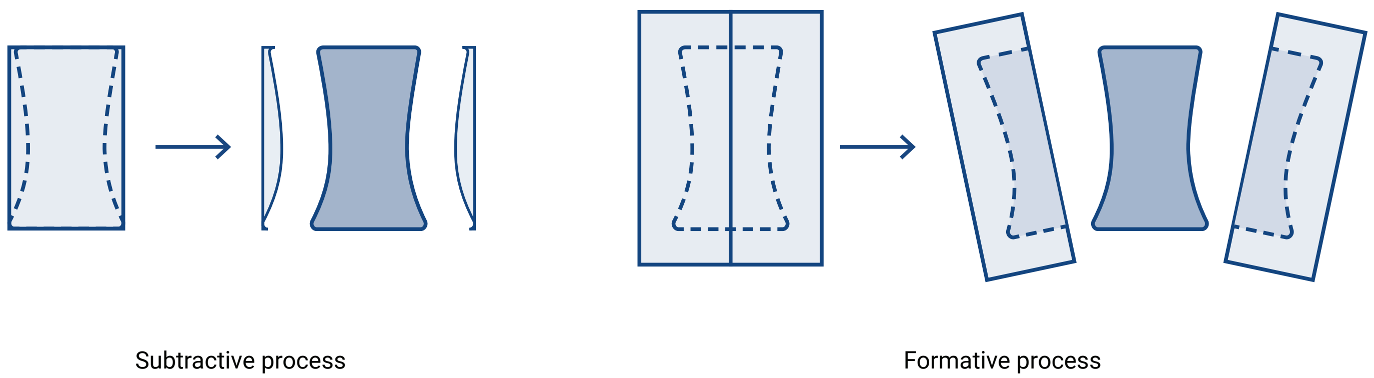


Figure 29: Conventional manufacturing techniques.

2.5.1 What is Additive Manufacturing

Additive Manufacturing (AM), also known as 3D printing, is the process of printing materials layer by layer on top of each other (Bhatia & Sehgal, 2021).
This technology is expanding quickly in several industry fields, including aerospace, automotive, medical, architectural, arts and design, food, and construction. Additional design options become available as the process of visualizing and prototyping gives way to functional and actual part replacement (Al Rashid et al., 2020).

Because it provides affordable goods, durable and lightweight components, adaptable designs, reducing material wastage, ease of access, quick design and manufactures, and many other benefits, additive manufacturing is not just utilized for prototypes but also for small-scale manufacturing. A move from “Rapid prototyping” to “Rapid manufacturing”, which means a full part can be built with the aid of a rapid prototyping device, is a result of additive manufacturing technology being perfected day by day, which increases its accuracy and versatility (Bhatia & Sehgal, 2021).

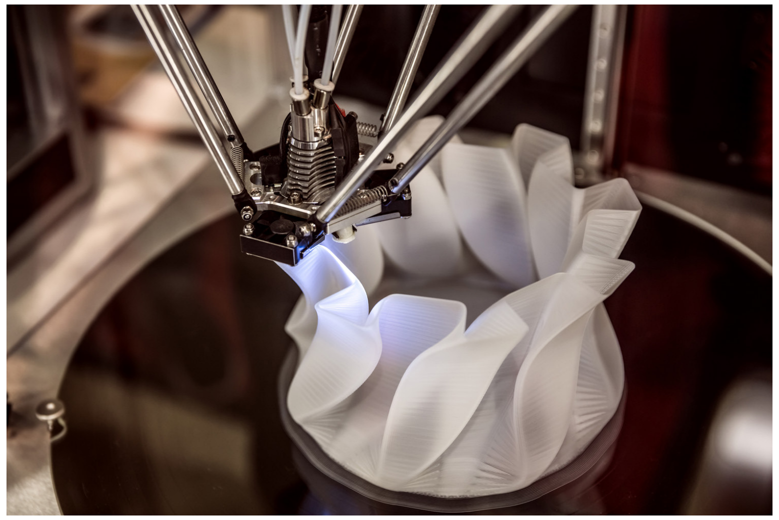


Figure 30: Additive Manufacturing. Source: Archdaily

2.5.2 Additive Manufacturing Processes

By adding layers of material, additive manufacturing methods create complicated geometries and 3D components. CAD models are frequently used in AM technology. These CAD models are used to specify the cross-sections of the geometries, and material is then added to each layer to create a solid and detailed item. Based on the technique and materials, AM processes can be broadly divided into seven categories (Al Rashid et al., 2020):

Vat Photopolymerization (VP)
Photosensitive materials are used as the main building blocks in the photopolymerization technique, also known as stereolithography, to create solid parts. When exposed to radiation, these materials go through chemical processes and solidify. Depending on the material’s chemical makeup, a variety of radiation sources can be employed. In the context of vector scans, mask projection, and two-photon procedures, respectively, a single laser source, a digital micrometer device, and two laser sources are potential radiation sources for curing the photo-sensitive materials. These procedures can only be used on materials that go through photopolymerization.

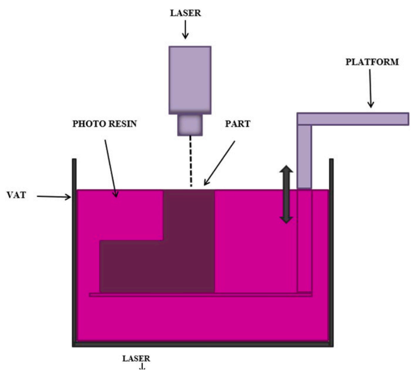


Figure 31: Vat Photopolymerization (Al Rashid et al., 2020).

Powder bed fusion processes (PBF)
When using a powder bed fusion technique, the powder material is placed in a bed and heated to cause the powder particles to fuse together. A new powder layer is added to the bed of the following layer after the fusing of one complete layer in the bed. These processes can be divided into four categories, depending on the heat source: direct metal laser sintering (DMLS) or selective laser melting (SLM), which use lasers to melt the target material for the fusion of molecules; selective laser sintering (SLS), which is similar to SLM but doesn’t involve full melting; electron beam melting, which uses an electron beam as an energy source to melt the powder material in a vacuum; and selective heat sintering, which uses heat to melt the target material.

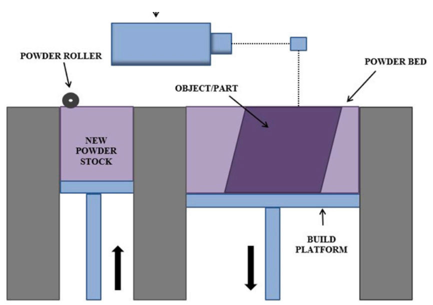


Figure 32: Powder bed fusion (Al Rashid et al., 2020).

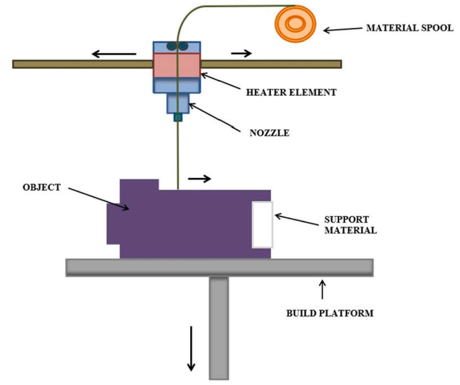


Figure 33: Material extrusion (Al Rashid et al., 2020).

Material extrusion based systems (ME)
Extrusion-based systems use nozzles to push semi-solid material from a reservoir into the desired shape, where it solidifies and bonds to previously extruded material. Fused deposition modeling (FDM), which uses a polymer material fed into the system in the form of filaments to liquify the polymer in a heating chamber, and contour crafting (CC), which uses a scraping tool to smooth the exterior profile and thereby improve the surface finish of the object being extruded, are the two most popular methods using extrusion-based AM technology.

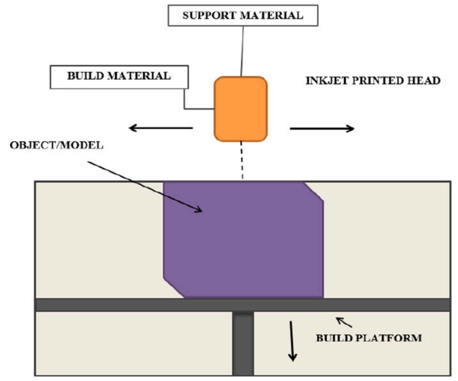


Figure 34: Material jetting (Al Rashid et al., 2020).

Material jetting (MJ)
Similar to how inkjet printers operate, material jetting disperses liquid radiation-sensitive material from a printhead. One layer of material can be dispensed at a time by several printheads, which is then subjected to radiation to solidify the layers as they are being deposited.

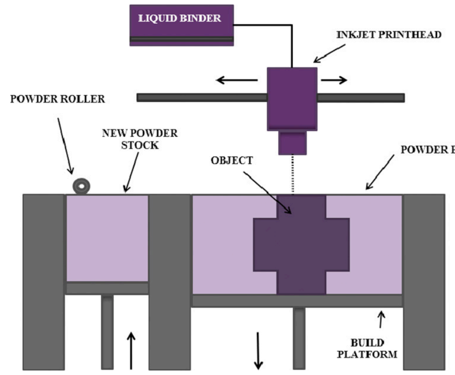


Figure 35: Binder jetting (Al Rashid et al., 2020).

Binder jetting (BJ)
Although they don’t use a heat source, binder jetting procedures are quite similar to powder bed fusion processes. A binder is delivered by a print head to the location where the material needs to be fused. A fresh coating of powder material is applied for the next layer when the first layer is finished.

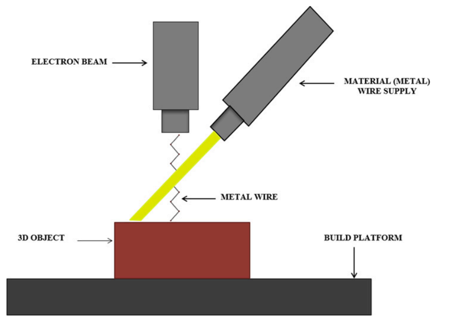


Figure 36: Directed energy deposition (Al Rashid et al., 2020).

Directed energy deposition processes (DED)
A material is melted during a directed energy deposition method using a small, focused beam of energy. Since the material is not already set out in a powder bed, these methods are different from powder bed fusion techniques.

Sheet lamination processes (SL)
Sheet lamination processes involve the shaping and bonding of material sheets. Laminated object manufacturing is conducted by trimming the material sheets into the required dimensions and gluing them together to produce an object. Ultrasonic additive manufacturing produces metal objects by making use of ultrasonic welding.

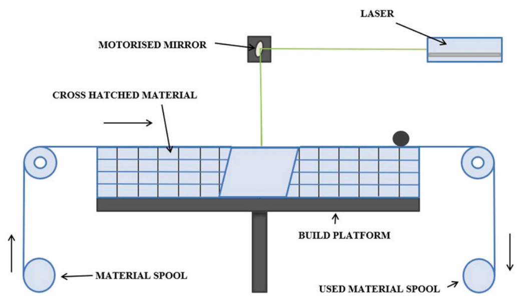


Figure 37: Sheet lamination (Al Rashid et al., 2020).

2.5.3 Additive Manufacturing in the Built Environment

Since 1997, the building industry has embraced additive manufacturing techniques. Even if this technology is preferable than conventional procedures due to decreased dangers on job sites, quick production, lower emissions, and less material waste, its integration into the construction industry has been seen to go slowly. To date, complex structures, curved surfaces, wall structures, beams, architectural models, bridge structures and home were adopted by additive manufacturing techniques (Al Rashid et al., 2020).

Figure 38: MX3D Bridge, Joris Laarman Lab, Amsterdam. Source: Dezeen

Due to their numerous advantages over traditional methods, such as quick production, personalized products, lower labor and waste costs, precision, and accuracy, additive manufacturing technologies have been sees as having the potential to play a large role in the design and construction of built environments. Architectural firms can now create more complex interior and exterior geometries that would be challenging and expensive to create using traditional construction methods thanks to large-scale additive manufacturing (AM) of end-use building materials. AM gives architects more flexibility to rethink their designs and forms without compromising complexity or productivity during construction. Architects and designers have the possibility to focus more on functionality and less on whether or not each component can be built (Delgado Camacho et al., 2018).

Figure 39: Digital Grotesque II, Michael Hansmeyer and Benjamin Dillenburger. Source: Designboom

The majority of additive manufacturing processes utilized in the construction industry are extrusion-based and binder jetting methods for off-site and on-site applications, including the fabrication of new construction parts/houses or repairing applications. This is due to the specialized nature of each technology as well as the type of materials and size of building elements (Craveiro et al., 2019).

Figure 40: Deep Facade, ETH Zurich. Source: Dezeen

Figure 41: Concrete Choreography, ETH Zurich. Source: Archdaily

Figure 42: Smart Slab, ETH Zurich. Source: Dfabhouse

Figure 43: Strctural joint, ARUP. Source: Dezeen

Figure 44: Radiolaria, Shiro Studio. Source: Dezeen

Figure 45: Tecla house, Mario Cucinella. Source: Archdaily

2.6 Additive Manufacturing with Bio-based Materials

Although additive manufacturing processes and technologies have recently advanced, there are still urgent research needs to create new, sustainable materials for construction applications, determine the optimal process parameters and conditions, create computational modeling methods, add reinforcements and improvements to additive manufacturing structures, and create new technologies. While other researchers have employed innovative materials including geopolymer concrete, natural fiber-reinforced materials, waste-reinforced construction materials, and recycled materials, some researchers have attempted to use traditional construction materials to print structures using additive manufacturing techniques. Even though additive manufacturing technologies have been enhanced to better suit construction needs, there is still a need to create materials that can displace currently available conventional materials that are not sustainable since they have negative environmental impacts. Therefore, creating sustainable materials that work with advanced manufacturing techniques is currently important (Al Rashid et al., 2020).

The most popular additive manufacturing processes for bio-based materials are extrusion-based techniques. To create a bio composite filament for FDM, short natural fibers are often combined with polymer pellets and extruded. FDM can also be used to manufacture thermoplastic composites with long natural fibers using additive manufacturing. Since they have been shown to enhance the mechanical qualities of the printed products, micro nanocellulose fibers have been routinely used as reinforcement in FDM. Printing gels and inks is the primary application for LDM, an extrusion-based 3D printing technique also known as liquid deposition modeling, direct paste writing, or paste extrusion (Gauss et al., 2021).
For this project, LDM chosen. This is done because of the conclusion drawn from the literature research and the resources available at TU Delft.

2.6.1 Printing with pastes

The printing technique employed in this project is extrusion-based 3D printing, more precisely paste-extrusion printing. Although there are many different kinds of pastes, they may all be thought of as viscous liquids that are created by combining one or more solid elements with a liquid. The primary focus of this study is composite pastes. Binders and fillers are the minimum number of constituent kinds required to create composite paste materials (Bremmer, 2020).

Fillers
Solid components known as fillers are added to a binder mixture to enhance the mechanical qualities. Fillers come in the form of particles or fibers; fibers are employed, for instance, to increase tensile strength (Bremmer, 2020).
The primary goal of using natural fibers in polymer matrix composites is to reduce the cost of the feed stock material and to achieve higher stiffness-to-weight ratios, recyclability, biodegradability, thermal insulation, and CO2 neutrality compared to their conventional counterparts, which include glass fibers and carbon fibers (Balla et al., 2019).

An innovative replacement for traditional non-renewable synthetic fibers like glass and carbon reinforced composites has been sought for due to the growing environmental and sustainability concern. Due to the growing need for the use of nonrenewable resources, eco-friendly products, recycling, and reusing are generally acknowledged by both the scientific and industrial worlds. From this perspective, biocomposites made of biofiber and biopolymers are very appealing since they can provide necessary qualities and functions at an affordable price. In contrast to composites made from synthetic materials, these bio-composite materials can be easily recycled or disposed of after their service life without harming the environment.
It is essential to understand the processing methods and characteristics of fibers, matrices, and their interfaces in order to use bio-composites in novel applications. Based on the source, biodegradable polymers can be broadly divided into two categories: synthetic and biodegradable polymers (Andrew & Dhakal et al., 2022).


Figure 46: Bamboo fibers with cork from Bamboode r.


Figure 47: Compressed sheet of bamboo fibers from Bamboode r.


Figure 48: Compressed sheet of bamboo fibers and long fibers from Bamboode r.


Figure 49: Flakes made with pressed bamboo fibers and resin from Bamboode r.

Binders
Binders are viscous liquids or solids that are combined with liquids to create viscous liquids that can solidify as a result of a chemical or physical reaction. The filler materials (fibers or powder) that are put to the binder, for instance, are bound by binders. Glue is a common instance of a binder (Bremmer, 2020).

The four main synthetic thermosetting resins phenol formaldehyde, urea formaldehyde, melamine-formaldehyde, and polymeric diphenylmethane diisocyanate resin form the basis of conventional adhesives for wood composites. These resins have been made using non-renewable petroleum resources. Consequently, there has been an increase in interest in the creation of renewable resource-based eco-friendly wood adhesives.
As a sustainable feedstock, a variety of biomass resources, including lignin, starch, plant proteins, tannin, bark, and vegetable oils, have been used to create bio-based adhesives. Kraft lignin as a phenol replacement. Because it is readily available, simple to process, inexpensive, and has strong adhesion and film forming capabilities, starch is a viable feedstock for the creation of bio-adhesives.
Another natural resource used to make environmentally friendly wood adhesives is plant protein (Ferdosian et al., 2017).

Binders serve almost the same purpose as adhesives, which is to create a matrix to bind with fillers. However, limited research was available on bio-based binders, so a thorough literature review was conducted on bio-adhesives and bio-composites to gain a stronger understanding of the topic. This review led to the discovery of the most commonly used bio-adhesives as renewable feedstocks, and provided a basis for an informed selection of binders for the initial material experimentation that is discussed in the next chapter.

Materiom

Materiom is a pioneering organization that provides open source recipes and data on materials made from abundant sources of natural ingredients. The platform gathers the world of regenerative material solutions to optimize and match them to real-world needs. With open data and AI, Materiom empowers scientists, material developers, and brands to accelerate research and development and drive massive market entry.
In the materials library the "3D printing" filter was selected to see the existent research done and took them as reference for the material exploration.

Figure 50: Materiom logo. Source: Materiom

Mica

Mica powder	7 gr
Water	10 gr

Figure 51: Mica. Source: Materiom

Olive pomace

Olive pomace	58 gr
Sodium alginate	133 gr
Water	2.7 gr

Figure 52: Olive pomace. Source: Materiom

Eggshell

Eggshell	120 gr
Water	100 ml
Xanthan	4 gr

Figure 53: Eggshell. Source: Materiom

Oyster shell

Honey	4 %
Oyster shells	68 %
Sodium alginate	0.7 %
Water	27.3 %

Figure 54: Oyster shell. Source: Materiom

Mussel shell

Mussel shell powder	70 %
Sugar	15 %
Water	15 %

Figure 55: Mussel shell. Source: Materiom

Mussel shell

Mussel shell powder	70 %
Alginate	0.6 %
Water	29.4 %

Figure 56: Mussel shell. Source: Materiom

Mussel shell

Mussel shell powder	6.1 gr
Sodium alginate	0.3 gr
Water	3.6 gr

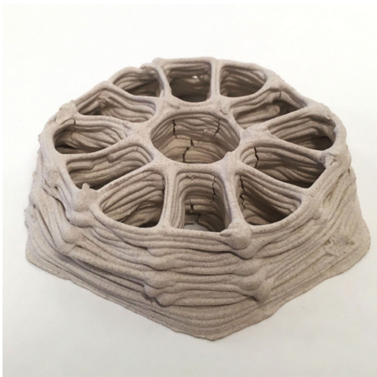


Figure 57: Mussel shell. Source: Materiom

Tree Column - Blast Studio

Blast Studio, a London-based architectural firm, has devised an innovative approach to 3D printing using living mycelium. Their method involves creating a column that serves both as a source of mushrooms and a structural building component.
Dubbed the Tree Column, this two-meter-tall structure features a textured and undulating design reminiscent of a tree trunk. The column's shape is algorithmically generated to optimize its structural capacity and provide an ideal environment for mycelium growth—the network of fungal roots. To construct it, mycelium is combined with a mixture of waste coffee cups collected from various locations in London. This blend is then fed into a specialized cold extruder, which shapes the column. Once the column is formed as explained by the autor: "The mycelium consumes the pulped paper cups and spreads throughout the entire structure, yielding edible mushrooms that can be harvested. Subsequently, the mycelium is dried, resulting in a load-bearing architectural element that possesses natural insulating and fire-retardant properties.

Figure 58: Mushroom growth on the surface of the structure. Source: Dezeen

The production process for the Tree Column begins by shredding paper coffee cups and boiling them in water to create sterilized paper pulp. This pulp is then mixed with mycelium, along with natural pigments for color, if desired. The resulting biomass paste is extruded through a 3D printer, layer by layer, to construct ten separate modules. These modules are then stacked and fused together using additional mycelium, resulting in a final column measuring 2.1 meters in height.
The intricate folds and crevices in the column's design are purposefully created to support the self-supporting capabilities during the additive manufacturing process. Additionally, these features facilitate the growth of mycelium by creating sheltered "microclimate pockets" that retain moisture along the length of the column."

Figure 59: Mycelium columns. Source: Dezeen

Kusudama Wall - University of Minho

The author describes Kusudama Wall as “a computational model and additive manufacturing prototype that proposes a modular, self-supporting wall structure using cellulose-based architectural components.

The design approach involves creating regular hexagonal blocks through additive manufacturing techniques, using natural materials such as cellulose pulp, starch, sawdust, and ceramic paste.”

Figure 60: Kusadama Wall. Source: be-am

These blocks are produced in two variations: one with a triangular interior opening and another with a pentagonal interior opening. By exploring different combinations of these natural materials, various parameters related to their behavior, including shrinkage, cracking, deformation, delamination, curing time, color change, flexibility, and more, can be studied and analyzed.

Figure 61: Kusadama Wall. Source: be-am

The main objective is to develop a range of natural mixtures and design a modular wall system. The overall aim of this project is to identify abundant, natural biopolymers as potential materials and investigate their compatibility for application in additive manufacturing. The ultimate goal is to create more intricate, sustainable, and biodegradable architectural building systems using these materials.

Figure 62: Kusadama Wall. Source: be-am

BioTILES - University of Minho

Motivated by the need to find a new strategy to reduce the continuous accumulation of seafood waste in the fishing industry. The University of Minho developed a set of natural, non-toxic, low-cost, renewable, sustainable and biodegradable mixtures, creating the BioTILES.

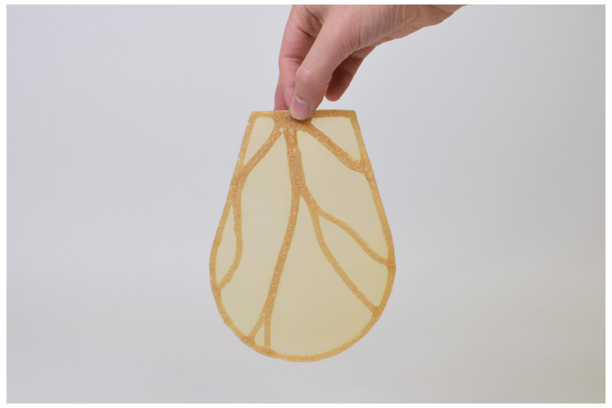


Figure 63: BioTILES. Source: be-am

The alteration of the proportions of the different mixtures produced confer different mechanical, physical and aesthetic behaviors. The function of the cellulose is to increase the strength, rigidity and durability of the final product. The addition of glycerin is intended to give flexibility to the material, the higher the proportion, more flexible is the product. The chitosan and then the addition of acetic acid aims to transform the water-based hydrogel into a fully viscous and homogeneous pulp. The production of the components resulted in the combination of two AM techniques: molding and PEM. First the fixing was placed on the edge of the previously made mold. Then, the fluid mixture was introduced inside the mold until the empty space was filled, holding on to the open geometry grid (fixing soaked in the mixture). Finally, the developed pattern was printed on the previously filled mixture.

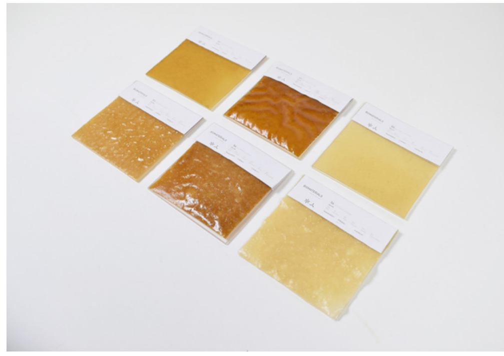


Figure 64: Different ratios samples. Source: be-am

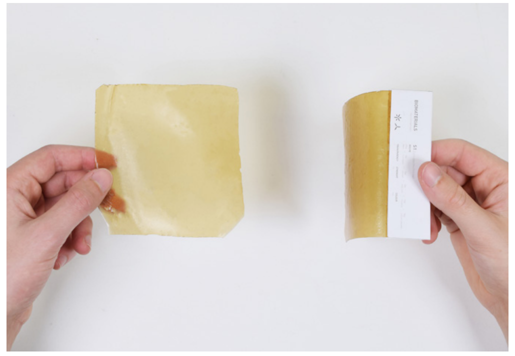


Figure 65: Flexibility of different samples Source: be-am

For the manufacture of the components, two types of mixture were used. The one that was introduced into the mold, is a fluid mixture with a high level of flexibility made of water, starch, glycerin and chitosan. Whereas the one that was printed on the mold is a fluid mixture with a high level of resistance and contains water, starch, cellulose and chitosan. The combination of these two mixtures allows the module to assume different shapes, with a degree of resistance to possible breaks or tears.

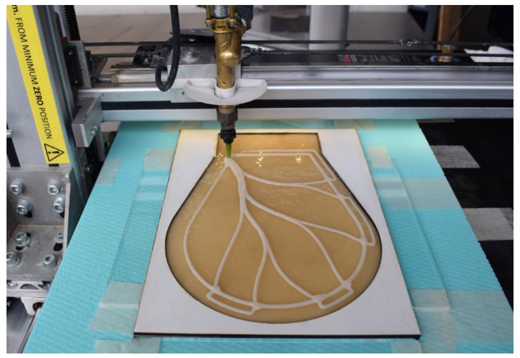


Figure 66: Printing process. Source: be-am

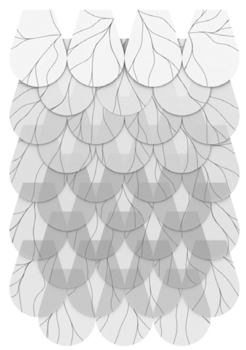


Figure 67: Design visualization. Source: be-am

Buildmatterial 0.8 - Omlab

Omlab has developed Buildmatterial 0.8, a super-circular cement-free building material waste. With Buildmatterial, the studio 3D printed examples of emission-free construction products and explores co-operation with the industry.

Figure 68: Buildmatterial 0.8. Source: Omlab

The material has the strength of C8 concrete, prevents CO2 emissions (less waste incineration and transport) and is biodegradable. End-of-life it can be re-printed. A building element weighs about half of 3D printed concrete.

Figure 69: Use of the component Source: Omlab

The mixture consists of 98% circular and circular biobased raw materials from sewage and drinking water treatment: calcite, cellulose (Recell), Kaumera in addition with alginate and water.
The 3D-printed elements can be used (multi)functional, modular and movable in renovation buildings, for example as an interior wall.

Figure 70: Samples. Source: Omlab

Figure 71: Material. Source: Omlab

Emerging Objects

Star Lounge

Emerging Objects fabricated a PLA-based 3D printed freestanding, doubly curved dome. It is composed of 2073 hexagonal blocks printed in 28 translucent colors; each color corresponds to one particular block type.
The design of each individual component maximizes the efficiency of the printer and the print volume. This process opens the door to creating 3D printed bricks, walls, celings, partitions and cladding for a sustainable architecture of the futures.

Figure 72: Star Lounge. Source: Emerging Objects

Picoro Wall

The wall is constructed using the Picoroco Block, a 3D printed building block for modular wall fabrication printed in translucent orange PLA. Three different blocks, with two, three, or four holes, are used in the construction of the wall. Each block can be rotated randomly to create the variable pattern found in the wall. The blocks are held in place with 3D-printed orange PLA clips, which have four prongs that connect the blocks at the corners.

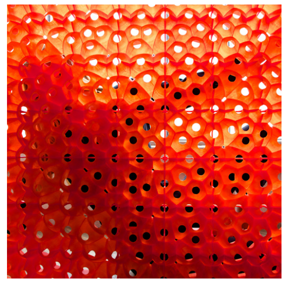


Figure 73: Picoroco Wall. Source: Emerging Objects

Saltygloo

The Saltygloo is an experiment in 3D printing using locally harvested salt from the San Francisco Bay to produce a large-scale, lightweight structure. 336 translucent panels were 3D printed using this unique material invention. The panels are connected together to form a rigid shell that is further supported with lightweight aluminum rods flexed in tension, making the structure extremely lightweight and able to be easily transported assembled in only a few hours.

Figure 74: Saltygloo. Source: Emerging Objects

GEOtube

This is a scale model for a Vertical Salt Deposit Growth. Gravity-sprayed with adjacent Persion Gulf waters, its building skin is entirely grown rather than constructed; is in continual formation rather than fully completed; and is created locally rather than imported. As the water evaporates and salt deposits aggregate over time, the tower transforms from a transparent skin to a highly visible white solid plane. The result is a habitat for wildlife and an accessible surface for the harvesting of crystal salt.

Figure 75: GEOtube. Source: Emerging Objects

Wood block

This is an example of 3D printed wood as a possible building material that can be mass-customized. The additive layer manufacturing of the Wood Block creates a grain similar to natural wood. The wood material is composed of recycled agricultural waste. The texture and subtle translucency of the 3D printed wood material gives the material a warmth, texture and luminosity under certain lighting conditions. The Wood Block can be used as a curtain wall or as a customized masonry unit.

Figure 76: Woodblock. Source: Emerging Objects

Poroso

Poroso is an experiment in block aggregation using a specially formulated walnut shell material combined with sawdust. The blocks are double sided, with a hollow interior. There is no front or back: each face of the Poroso assembly is unique, allowing for a rich, layered effect when one looks through the wall. The pattern are designed in way in which the pattern of each tile connects to that in every adjacent tile, creating an uninterrupted motif across the surface with continuous variation.

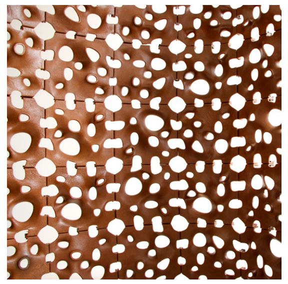


Figure 77: Poroso. Source: Emerging Objects

2.7 State of the art of Additive Manufacturing with Bamboo

There is no commercial additive manufacturing process that uses only bamboo as feedstock but there are few examples of additive manufacturing with bamboo fibers.

Gama et al. (2021) chemically modified via a two-step reaction bamboo fiber that were mixed (5% wt/wt) with ABS to improve the 3-dimensional printed quality of bio-based composites. As the paper states: "The initial phase involved grafting NCO groups from a diisocyanate onto the surface of the fibers, which was then followed by a polyol reaction. By using spectroscopic analysis, the chemical change was verified. The hydrophobicity, density, and thermal degradation of the fibers were also assessed. After then, these fibers were used to create 3D-printed things. First, the melting flow index (MFI) and glass transition temperature (Tg) values of these composite materials were examined in order to gauge their printability. The morphology of the 3D-printed specimens was then studied to corroborate the improvement in 3D printing quality. The benefit of employing treated fibers was evident in the enhanced mechanical performance of the 3D specimens that were produced."

Figure 78: Images of the 3D printed species (left to right): ABS, ABS-bamboo, ABS-bamboo modified (Gama et al., 2021).

Soh et al. (2020) developed an extrudable paste made of bamboo fiber, chitosan and mycelium. This study's combination of chitosan and mycelium-enriched bamboo shows promise for the construction of mycelium-bound composites with intricate 3D forms. The compositions that combine workability, extrudability, and buildability the best used 500 micrometer mycelium-enriched bamboo fibers blended at a 60:40 or 70:30 ratio with chitosan and a 3 weight percent chitosan solution made at pH 6. Furthermore, the mycelium's growth was unaffected by the use of chitosan. After 20 days of mycelium growth, the mixture was compressed and the results showed that it had a compression modulus of 40 kPa as opposed to 240 kPa without chitosan.

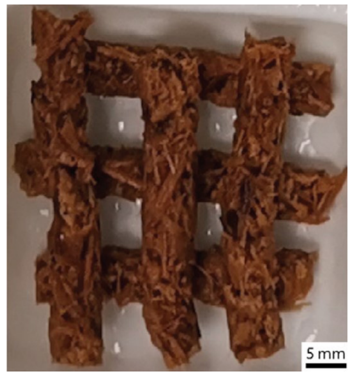


Figure 79: Extrusion of mycelium-enriched bamboo fibres-chitoan pastes (Soh et al.,2020).

Zhao et al. (2015) studied on the right ratio of bamboo powder and poly lactic acid (PLA) to produce the 3D printing wire. The research on a newly developed, ecologically friendly BPC material that satisfies 3D printing specifications is summarized in this publication. The research team printed more than 300 meters using the testing material from this paper. The printing process runs smoothly without any blocking, and the finished items have a wood-like texture, a consistent texture, and are non-toxic. When the extrusion temperature is 180 C, the ideal BPC ratio is 5:2 with 2% plasticizer and 2% lubricant.

Figure 80: Premixing bamboo powder with PLA and comparison of different adding proportion (Zhao et al.,2015).

Additionally, the company Bambooder collaborated with another company to develop a bamboo-based filament, which was used to 3D print a vase.

Figure 81: Bambooder 3D printed vase with bamboo short fibers and PLA. Nozzle 0.18 mm. Source: Bambooder

2.8 Conclusion

The preliminary stage of this research involved a thorough review of existing literature on additive manufacturing and bamboo. The information gathered from various sources, including interviews with experts in the field, provided a comprehensive background knowledge for proceeding with the next steps of the research.

As a result of this investigation, the upcoming chapters of the research paper were structured to guide the subsequent phases of the research. Given the scarcity of research in the area of additive manufacturing with bamboo, this study is considered an exploratory research on a relatively new material in the field. It is important to note that this research represents only the initial phase of a larger project, and is intended to serve as a starting point for future development and further exploration.

3

Material Exploration

3.1 Overview

The initial phase of material exploration was informed by the insights gained from the literature review. With the goal of formulating a bio-based recipe, a series of experiments were conducted to study the behavior of various binders, both individually and in combination at different ratios. This exploration was carried out in two phases.

During the first phase, a set of binders were identified through the literature research and expert interviews. Manual extrusion was used to test whether the mixture could be extruded, and the resulting material was evaluated after drying. Unfortunately, this initial experimentation did not yield a large number of promising binder options. It became apparent that additional binders needed to be investigated, including the use of a different type of dust and the incorporation of fibers as a filler. Furthermore, a different evaluation process would have provided a more accurate assessment of the results.

To this end, a set of criteria was established based on visual analysis and manual testing, to evaluate the outcomes. The selected mixture is subsequently manufactured in large quantities to fill the cartridge utilized by the extruder. This promising recipe will be further investigated in the printability exploration and consequently in the design phase. This will form the basis for the next phase of the research, which will focus on creating an extrudable and printable paste for the additive manufacturing of a self supporting wall made from bamboo dust and fibers.

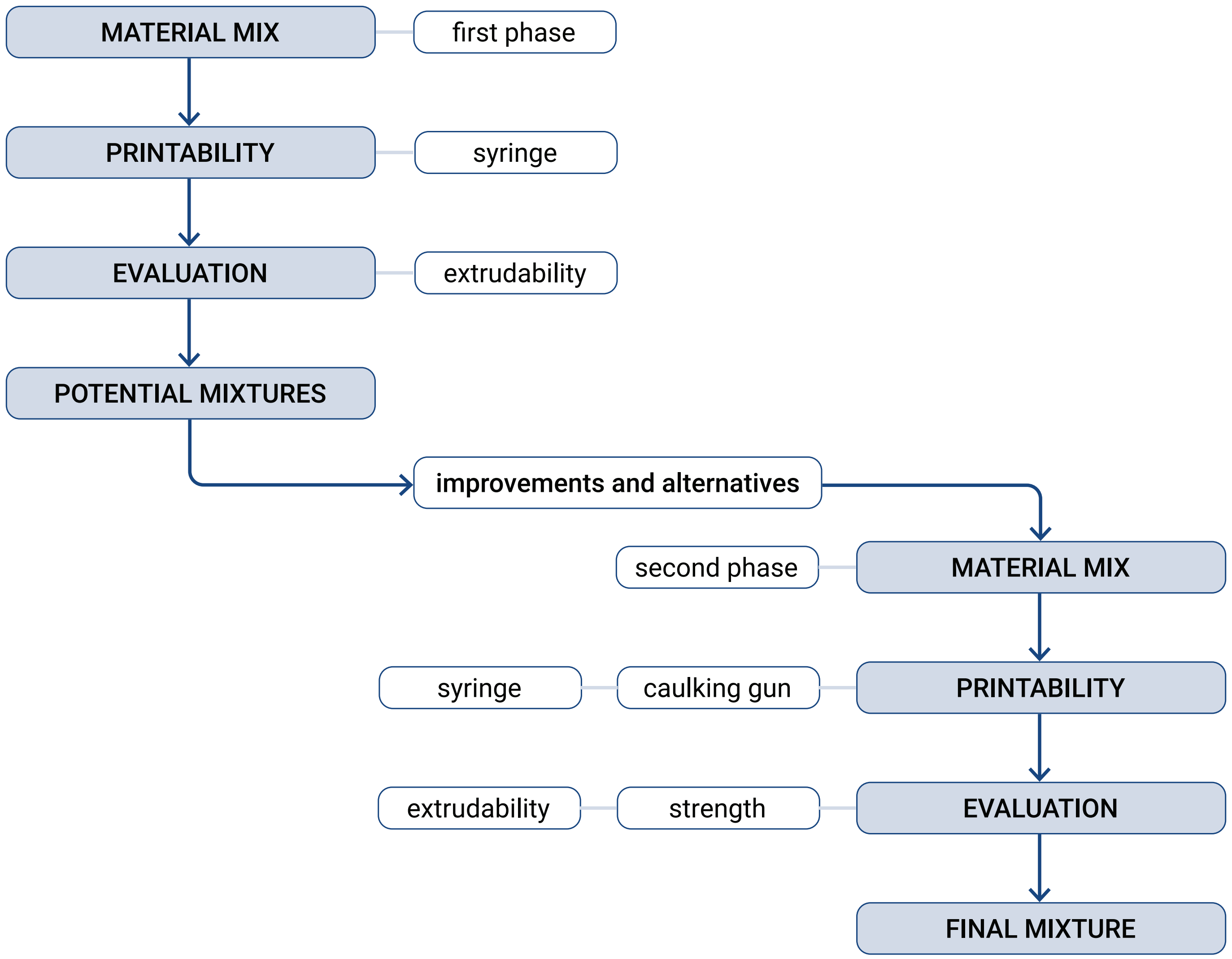


Figure 82: Material Exploration scheme.

3.2 Experiment Design

The material experiments were conducted in two separate stages, investigating the binding agents and selecting the most favorable options. Each stage involved incrementally refining the precision and improving the analysis of the results, incorporating additional parameters to evaluate each iteration of the material mix. The material discovery phase aimed to comprehend the behaviour of bamboo dust and fibers when combined with various binders and solvents, with the objective of creating a stable bio-based mixture with optimum viscosity and bonding properties suitable for extrusion via LDM technique.

To initiate the material discovery, an individual experiment was conducted by mixing bamboo dust with water to determine if it could be developed into a paste. Unfortunately, the mixture could not be extruded from the syringe, leading to the selection of several binding agents to identify the most effective one. The uniformity of each experiment with the binding agent was initially evaluated before mixing it with bamboo dust.

Ratios were calculated based on eye observations made throughout the material mixing procedure. Then, in order to compare and evaluate the recipes, material qualities were examined. The most potential recipes were improved upon and classified for comparison. By implementing these experiments, a better understanding of the behaviour of bamboo dust and fibers with different binding agents and solvents was achieved, ultimately leading to the development of more effective and efficient recipes for extrusion.

3.3 Workspace Setup

During the initial stages of the research process, the first two experiments were carried out in a home setting where temperature and relative humidity were not controlled.
In order to conduct these experiments, the following tools were utilized:

Measuring	Mixing	Extruding	Storing

Measuring	Mixing	Extruding	Storing
Scale Glass bowls Plastic beaker Coffee cups	Spatula Handmixer Spoon Saucepan	Syringe Caulking gun	Plastic container Plastic bag

Figure 83: Tools used for material exploration.

3.4 Materials

The raw materials employed in this research were primarily bamboo fibers and dust.
These materials were generously provided by Bambooder, a Netherlands-based company with expertise in

the extraction of long bamboo fibers and production of an endless bamboo thread for high-performance composite applications.

Additionally, a second type of bamboo dust that will be called “green bamboo dust”, obtained from the stem and leaves of *Sasa tsuboiana*, was utilized and was kindly supplied by Made in Bamboo, an Italian business network comprising of bamboo user companies, giant bamboo growers, and professionals united by a common interest in the valorization of bamboo and its diverse products.

BAMBOODER® BIOBASED FIBER

madeinbamboo

Figure 89: Bambooder and Made in Bamboo logos.

fraction	length	diameter
0100	powder	0-100 µm
100200 SF	powder	100-200 µm
100200 LF	1-3 mm	100-200 µm
100200 XLF	3-15 mm	100-200 µm
200400 SF	1-3 mm	200-400 µm
200400 LF	3-6 mm	200-400 µm
200400 XLF	6-20 mm	200-400 µm
4001000	6-25 mm	400-1000 µm

Figure 84: Types of fibers from Bambooder.

Figure 85: T Bamboo dust from Made in Bamboo.

Figure 86: Fiber 0100 from Bambooder.

Figure 87: Fiber 200400 SF from Bambooder.

Figure 88: Fiber 4001000 from Bambooder.

Binders

Local stores were sourced for the remaining materials, specifically the binders.

Regarding the binders, it is preferred to use bio-based ones since the filler is bio-based as well but not necessarily. The focus of this phase is to understand how the bamboo behaves when combined with specific binders, so it is useful also to take into consideration non bio-based binders to be able to make comparison.

BINDERS
- bio-based
- non bio-based

Figure 90: Bio-based binders.

Figure 91: Non bio-based binders.

3.5 First Material Experimentation

In the first phase of the material experiments, the focus was on exploring the binding agents that could be used to develop an extrudable paste. Initially, water was used as a binder to test the extrudability of bamboo dust. However, it was found that the mixture could not be extruded from the syringe. Therefore, different bio-based and non bio-based binders were explored as potential alternatives.

The proportions of the binders were determined through a trial and error approach. The binder was first mixed until it reached a glue-like consistency, and then the bamboo dust was gradually added until it formed a paste. The paste was then introduced into the syringe and pressure was applied to extrude the material. This process was repeated for each binder, with the uniformity of each experiment being assessed before the bamboo dust was added.

The objective of this phase was to understand the extrudability of the different binders and to determine the most promising ones for further investigation in the second phase of the material experiments.

3.6 Evaluation First Material Experimentation

Alexsander Coelho and Christopher Bierach's research employed a comprehensive evaluation system for the material mixes and the resulting samples, which consisted of nine parameters. The first phase of the assessment was based on manual evaluation and visual observations.
The parameters included in the evaluation system were homogeneity, viscosity, adhesion, extrudability, bio-based content, shrinkage, brittleness, curing time, and aesthetics (Coelho, 2022). Each parameter was assigned a grade of -1, 0, or 1, indicating poor, neutral, or good performance, respectively. The grading system allowed for a quick and thorough comparison of the samples.

evaluation parameters	negative	indifferent	positive
	-1	0	1

Figure 92: Evaluation method first material experimentation.

- **Homogeneity:** evaluated how smoothly the paste was extruded. A homogeneous paste was devoid of lumps, agglomerated threads, and had a consistent color and texture.
- **Viscosity:** determined how easy it was to extrude the material. The ideal material had a medium to high viscosity that was neither too dry nor too crumbly.
- **Adhesion:** assessed the strength of the bond between layers and the overall structural integrity of the print. The optimal material for additive manufacturing had a moderate to high adhesion, was sticky without hindering movable parts, and did not interfere with equipment operation.
- **Extrudability**: Extrudability was a combination of adhesion and viscosity and was tested using a manually driven syringe.
- **Bio-based:** referred to the proportion of natural components in the material. The grade was 1 if the material was entirely bio-based.
- **Shrinkage:** evaluated the deformation of the samples after curing. The amount of shrinkage increased with the mixture's water content, and it affected the shape fidelity and geometrical stability of the printed part.
- **Brittleness:** referred to the ease with which the material sample could be broken with little pressure.
- **Curing time:** determined the length of time it took for the printed part to dry out. Short curing times resulted in greater efficiency, enabling the production of taller, multi-layered structures and more extrusions in a shorter amount of time.
- **Aesthetics:** evaluated the overall appearance of the substance.

3.7 Results

Mix 1_Water

Figure 93: Mixture result with water

Figure 94: Process with water

Mix_1 Water	Homogeneity	Viscosity	Adhesion	Extrudability	Bio-based	Shrinkage	Brittleness	Curing time	Aesthetics	Total
	0	-1	-1	-1	1	0	-1	-1	-1	-5

Process
The bamboo dust was added into the bowl. Water was then poured and mixed with the dust.

Outcome
The mixture was not homogeneous, and couldn't become an extrudable paste. Its consistency was like wet sand. It was impossible to extrude it with the syringe, with the pressure just the water would come out from the syringe.

Mix 2_Ethyl Alcohol

Figure 95: Mixture result with ethyl alcohol

Figure 96: Process with ethyl alcohol

Mix_2 Ethyl alcohol	Homogeneity	Viscosity	Adhesion	Extrudability	Bio-based	Shrinkage	Brittleness	Curing time	Aesthetics	Total
	0	-1	-1	-1	-1	0	-1	1	-1	-5

Process
The bamboo dust was added into the bowl. Alcohol was then poured and mixed with the dust.

Outcome
The mixture was not homogeneous, and couldn't become an extrudable paste. Its consistency was like wet sand. It was impossible to extrude it with the syringe, with the pressure just the alcohol would come out from the syringe.

Mix 3_Universal glue

Figure 97: Mixture result with universl glue

Figure 98: Process with universal glue

Mix_3 Universal glue	Homogeneity	Viscosity	Adhesion	Extrudability	Bio-based	Shrinkage	Brittleness	Curing time	Aesthetics	Total
	1	1	1	1	-1	1	1	0	1	6

Process
The bamboo dust was added into the bowl. Glue was then poured and mixed with the dust.

Outcome
The paste resulted homogeneous with a doughy consistency. It was possible to create an extrudable paste although it was quite hard to extrude it from the syringe.

Mix 4_Paper glue

Figure 99: Mixture result with paper glue

Figure 100: Process with paper glue

Mix_4 Paper glue	Homogeneity	Viscosity	Adhesion	Extrudability	Bio-based	Shrinkage	Brittleness	Curing time	Aesthetics	Total
	1	1	1	1	-1	1	1	0	1	6

Process
The bamboo dust was added into the bowl. Glue was then poured and mixed with the dust.

Outcome
The paste resulted homogeneous with a doughy consistency. It was possible to create an extrudable paste although it was quite hard to extrude it from the syringe.

Mix 5_Potato starch

Figure 101: Mixture result with potato starch

Figure 102: Process with potato starch

Mix_5 Potato starch	Homogeneity	Viscosity	Adhesion	Extrudability	Bio-based	Shrinkage	Brittleness	Curing time	Aesthetics	Total
	0	0	0	-1	1	0	-1	0	-1	-2

Process
Potato starch was first mixed with water to create a viscous and thick liquid. Bamboo powder was then added to create a paste.

Outcome
The paste looked homogeneous and at first it seemed that it could be extruded, but it was the same case as the Mix 1: only water was coming out of the syringe.

Mix 6_Tapioca starch

Figure 103: Mixture result with tapioca starch

Figure 104: Process with tapioca starch

Mix_6	Homogeneity	Viscosity	Adhesion	Extrudability	Bio-based	Shrinkage	Brittleness	Curing time	Aesthetics	Total
Tapioca starch	1	0	1	1	1	-1	1	0	0	4

Process
Tapioca starch was mixed with bamboo dust in a bowl. Boiling water was poured in the dry mixture until it became a dough.

Outcome
The dough had a rubbery consistency. It was easily extrudable but the extruded paste won't hold it's shape after a while.

Mix 7_Corn starch

Figure 105: Mixture result with corn starch

Figure 106: Process with corn starch

Mix_7	Homogeneity	Viscosity	Adhesion	Extrudability	Bio-based	Shrinkage	Brittleness	Curing time	Aesthetics	Total
Corn starch	1	1	0	0	1	0	-1	0	-1	1

Process
Potato starch was first mixed with water and then boiled in a pot until it became a thick paste. Bamboo dust was then added until it created a dough.

Outcome
Even though it was possible to create the dough, it was crumbly and not elastic. During extrusion it was difficult to create a continuous filament without breaking it.

Mix 8_Corn starch

Figure 107: Mixture result with corn starch

Figure 108: Process with corn starch

Mix_8 Corn starch	Homogeneity	Viscosity	Adhesion	Extrudability	Bio-based	Shrinkage	Brittleness	Curing time	Aesthetics	Total
	1	0	1	1	1	0	1	0	-1	4

Process

Potato starch was first mixed with water and then boiled in a pot until the reached a viscous consistency. Bamboo dust was then added until a dough was created.

Outcome

The outcome of this paste was different from the Mix 7, by changing the ratio, the dough was elastic enough to be extruded and create a continuous filament.

Mix 9_Agar agar

Figure 109: Mixture result with agar agar

Figure 110: Process with agar agar

Mix_9 Agar agar	Homogeneity	Viscosity	Adhesion	Extrudability	Bio-based	Shrinkage	Brittleness	Curing time	Aesthetics	Total
	0	0	0	-1	1	0	-1	-1	-1	-3

Process

Water was mixed with agar agar and then boiled until the liquid reached a thick consistency. Bamboo dust was then added

Outcome

The paste looked homogeneous and at first it seemed that it could be extruded, but it was the same case as the Mix 1: only water was coming out of the syringe.

Mix 10_Collagen peptides

Figure 111: Mixture result with collagen peptides

Figure 112: Process with collagen peptides

Mix_10 Collagen peptides	Homogeneity	Viscosity	Adhesion	Extrudability	Bio-based	Shrinkage	Brittleness	Curing time	Aesthetics	Total
	1	1	1	1	1	1	1	0	1	8

Process
Collagen peptides were first mixed with water to create a viscous and thick liquid. Bamboo dust was then added to create a paste.

Outcome
The paste was extremely thick and it had a doughy consistency. It was easily extrudable and it would hold its shape.

3.8 Summary of Findings First Material Experimentation

The initial mix using water as a binding agent proved ineffective, as pressure applied to the mixture in a syringe resulted in only water being extruded. Further attempts with ethyl alcohol, potato starch, and agar agar yielded similar results. While some of the subsequent binders did enable extrusion of the paste, tapioca starch and corn starch resulted in extreme brittleness.

The most promising binders were found to be universal glue, paper glue, and collagen peptides, with the latter being the only bio-based option. The table provide a summary of all experiments, along with the observations described above, provides a comprehensive background for identifying the most promising binding agents.

	Homogeneity	Viscosity	Adhesion	Extrudability	Bio-based	Shrinkage	Brittleness	Curing time	Aesthetics	Total
Mix_1 Water	0	-1	-1	-1	1	0	-1	-1	-1	-5
Mix_2 Ethyl alcohol	0	-1	-1	-1	-1	0	-1	1	-1	-5
Mix_3 Universal glue	1	1	1	1	-1	1	1	0	1	6
Mix_4 Paper glue	1	1	1	1	-1	1	1	0	1	6
Mix_5 Potato starch	0	0	0	-1	1	0	-1	0	-1	-2
Mix_6 Tapioca starch	1	0	1	1	1	-1	1	0	0	4
Mix_7 Corn starch	1	1	0	0	1	0	-1	0	-1	1
Mix_8 Corn starch	1	0	1	1	1	0	1	0	-1	4
Mix_9 Agar agar	0	0	0	-1	1	0	-1	-1	-1	-3
Mix_10 Collagen peptides	1	1	1	1	1	1	1	0	1	8

Figure 113: Table summary of findings.

Universal Glue **Paper Glue** **Collagen Peptides**

Figure 114: Potential Mixtures

3.9 Second Material Experimentation

After the initial phase of material experimentation, it was determined that a second phase was necessary in order to achieve a more comprehensive evaluation of the mix and to refine key parameters for optimal printability using the robotic arm. Insights gained from the initial experimentation phase highlighted areas for further investigation and refinement, leading to the decision for a second phase. This iterative approach ultimately results in more accurate and effective results in the printability testing phase.

3.10 Evaluation second material experimentation

The second phase of material exploration involved a different evaluation method than the first phase. Rather than grading materials with -1, 0, or 1, a binary positive or negative evaluation was used, along with a hierarchy of different parameters.
While aesthetics were not a factor in the evaluation, functionality was prioritized. Smoothness and homogeneity were found to be less important than functional and mechanical qualities, as seen in the comparison of a paste with only dust versus one with fibers. Extrudability was not considered as a variable, as all the mixtures were designed to be extruded.
The ratio of binder to filler was also taken into consideration, with a lower proportion of binder being preferred to highlight the importance of the bamboo filler. Due to time constraints, finding the optimal ratio for all mixtures was not possible, but as long as a mixture was printable, it was considered suitable. The preference for bio-based materials was noted, but it was not a variable used to exclude any mixtures.

Strength was not tested in the laboratory as the paste was extruded manually, making mechanical testing unreliable. Instead, the mixtures were evaluated based on printability, resistance to breakage and bending, and whether they were bio-based or not. The three most promising mixtures were evaluated using a mechanical test with a 350g weight, which demonstrated that mixtures containing fibers were the most resistant.

Figure 115: Mechanical testing

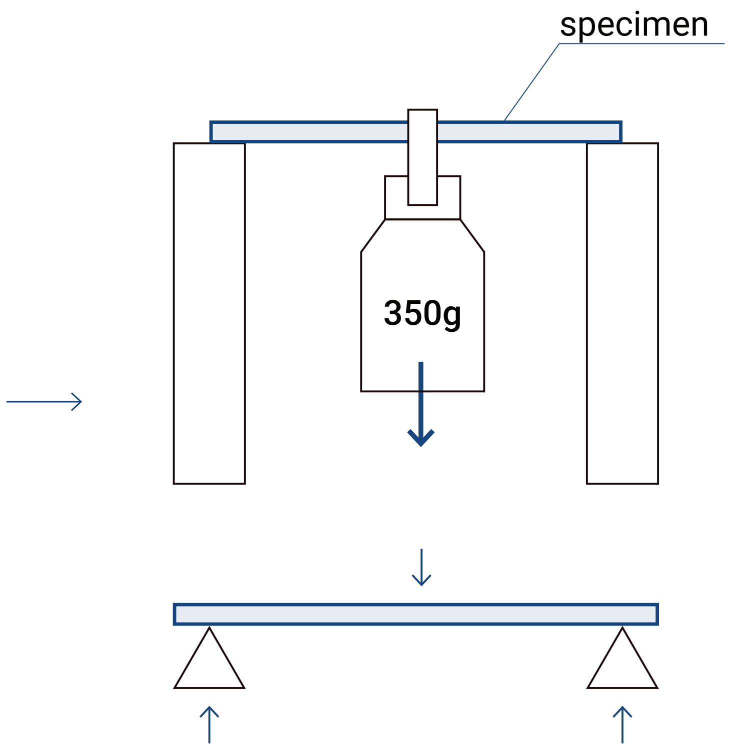


Figure 116: Mechanical testing

Mix 1A_Corn starch

Corn starch	10g
Water	50g
Dust 0100	10g

Ratio binder: filler = 6:1

Figure 117: Process with corn starch

Figure 118: Mixture result with corn starch before and after drying

Mix 1B_Corn starch

Corn starch	10g
Water	50g
Green Bambo Dust	10g

Ratio binder: filler = 6:1

Figure 119: Process with corn starch

Figure 120: Mixture result with corn starch before and after drying

Mix 1C_Corn starch

Corn starch	10g
Water	50g
Dust 0100	3g
Fibers 200400 SF	5g

Ratio binder: filler = 7,5:1

Figure 121: Process with corn starch

Figure 122: Mixture result with corn starch before and after drying

Mix 1D_Corn starch

Corn starch	10g
Water	50g
Green Bamboo Dust	10g
Fibers 200400 SF	3g

Ratio binder: filler = 4,5:1

Figure 123: Process with corn starch

Figure 124: Mixture result with corn starch before and after drying

Mix 1E_Corn starch

Corn starch	10g
Water	50g
Fibers 200400 SF	5g

Ratio binder: filler = 12:1

Figure 125: Process with corn starch

Figure 126: Mixture result with corn starch before and after drying

Mix 1F_Corn starch

Corn starch	10g
Water	50g
Fibers 4001000	4g

Ratio binder: filler = 15:1

Figure 127: Process with corn starch

Figure 128: Mixture result with corn starch before and after drying

Mix 2A_Potato starch

Potato starch	5g
Water	25g
Dust 0100	5g

Ratio binder: filler = 6:1

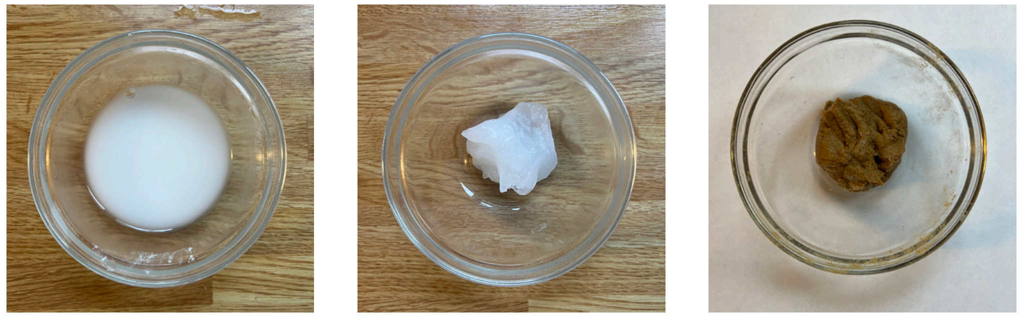


Figure 129: Process with potato starch

Figure 130: Mixture result with potato starch before and after drying

Mix 2B_Potato starch

Potato starch	5g
Water	25g
Green Bamboo dust	5g

Ratio binder: filler = 6:1

Figure 131: Process with potato starch

Figure 132: Mixture result with potato starch before and after drying

Mix 2C_Potato starch

Potato starch	5g
Water	25g
Dust 0100	3g
Fibers 200400 SF	2g

Ratio binder: filler = 6:1

Figure 133: Process with potato starch

Figure 134: Mixture result with potato starch before and after drying

Mix 2D_Potato starch

Potato starch	5g
Water	25g
Green Bamboo dust	2g
Fibers 200400 SF	3g

Ratio binder: filler = 6:1

Figure 135: Process with potato starch

Figure 136: Mixture result with potato starch before and after drying

Mix 3A_Tapioca starch

Tapioca starch	10g
Water	10g
Dust 0100	5g

Ratio binder: filler = 4:1

Figure 137: Process with tapioca starch

Figure 138: Mixture result with tapioca starch before and after drying

Mix 3B_Tapioca starch

Tapioca starch	10g
Water	10g
Green Bamboo dust	5g

Ratio binder: filler = 4:1

Figure 139: Process with tapioca starch

Figure 140: Mixture result with tapioca starch before and after drying

Mix 3C_Tapioca starch

Tapioca starch	10g
Water	10g
Dust 0100	3g
Fibers 200400 SF	2g

Ratio binder: filler = 4:1

Figure 141: Process with tapioca starch

Figure 142: Mixture result with tapioca starch before and after drying

Mix 4A_Gelatin

Gelatin paste	20g
Dust 0100	5g

Ratio binder: filler = 4:1

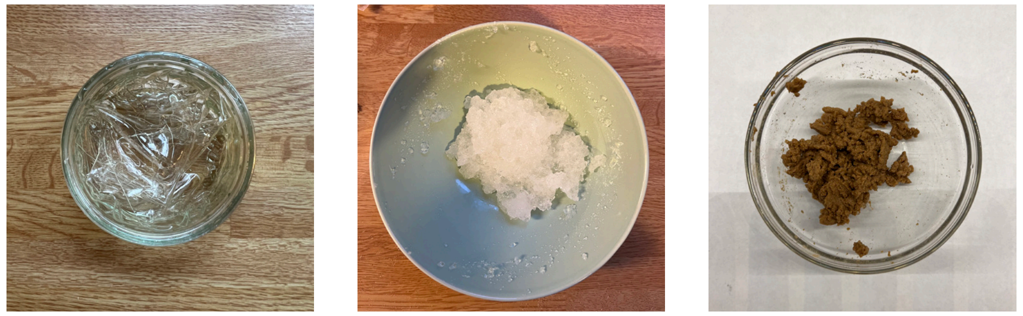


Figure 143: Process with gelatin

Figure 144: Mixture result with gelatin before and after drying

Mix 4B_Gelatin

Gelatin paste 20g
Green Bamboo dust 5g

Ratio binder: filler = 4:1

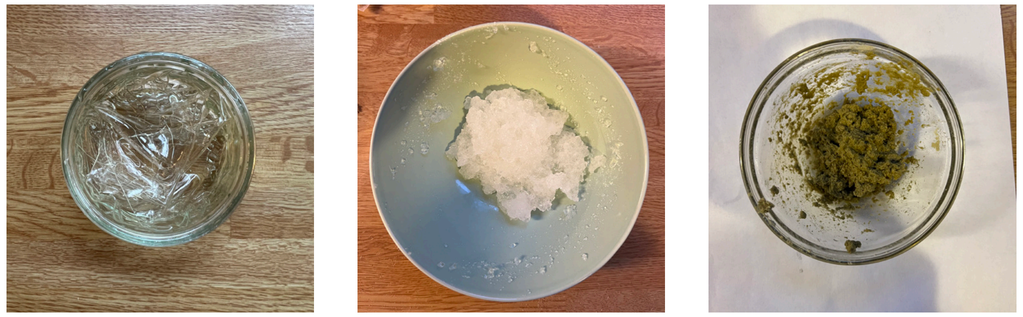


Figure 145: Process with gelatin

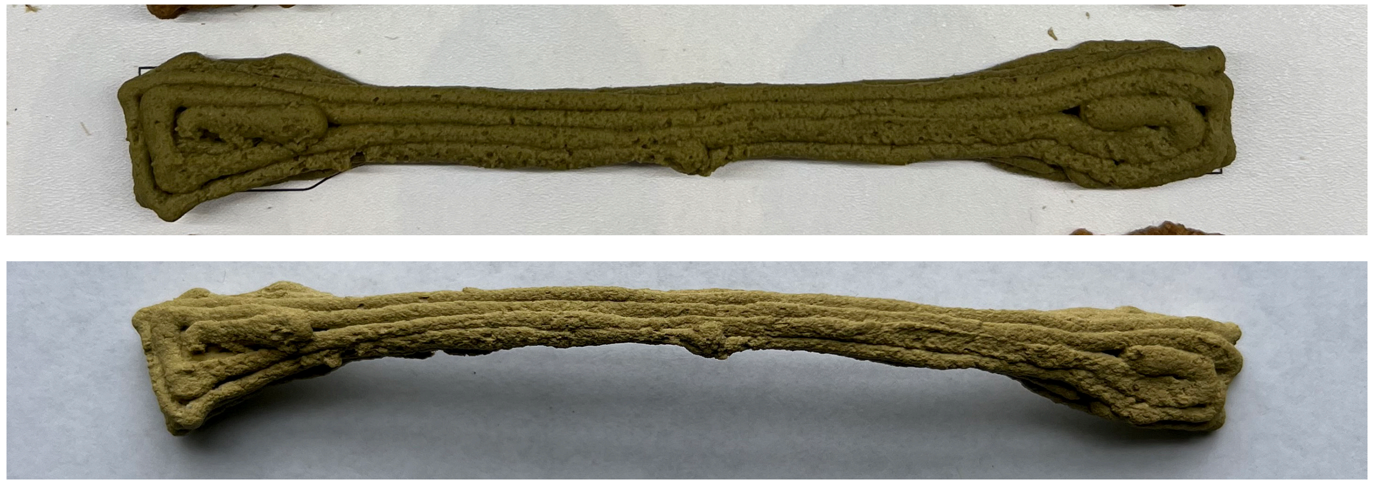


Figure 146: Mixture result with gelatin before and after drying

Mix 4C_Gelatin

Gelatin paste 20g
Dust 0100 5g
Fibers 200400 SF 2g

Ratio binder: filler = 2,8:1

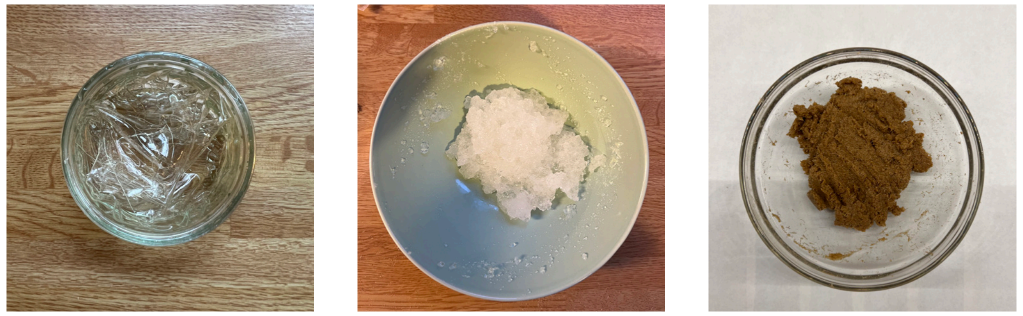


Figure 147: Process with gelatin

Figure 148: Mixture result with gelatin before and after drying

Mix 4D_Gelatin

Gelatin paste 20g
Green Bamboo dust 3g
Fibers 200400 SF 2g

Ratio binder: filler = 4:1

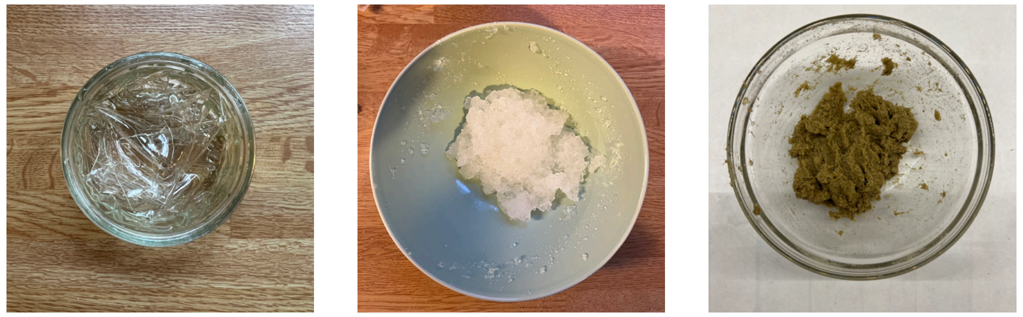


Figure 149: Process with gelatin

Figure 150: Mixture result with gelatin before and after drying

Mix 5A_Xantham gum

Xantham gum 15g
Dust 0100 5g

Ratio binder: filler = 3:1

Figure 151: Process with xantham gum

Figure 152: Mixture result with xantham gum before and after drying

Mix 5B_Xantham gum

Xantham gum 15g
Green Bamboo dust 5g

Ratio binder: filler = 3:1

Figure 153: Process with xantham gum

Figure 154: Mixture result with xantham gum before and after drying

Mix 5C_Xantham gum

Xantham gum 15g
Dust 0100 3g
Fibers 200400 SF 2g

Ratio binder: filler = 3:1

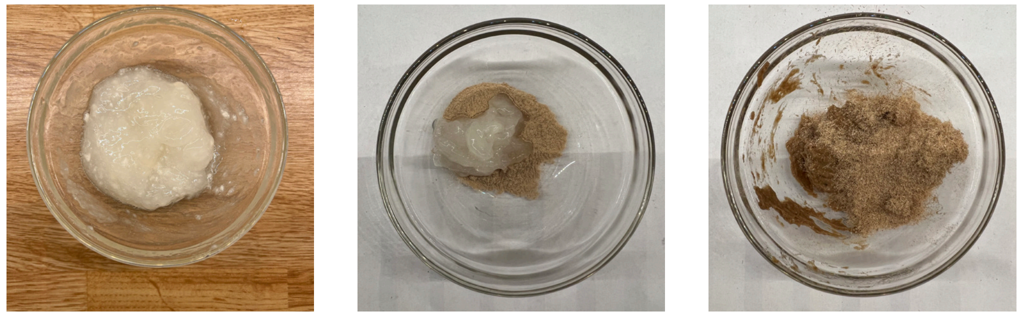


Figure 155: Process with xantham gum

Figure 156: Mixture result with xantham gum before and after drying

Mix 6A_Collagen Peptides

Collagen peptides 5g
Water 6g
Dust 0100 5g

Ratio binder: filler = 2,2:1

Figure 157: Process with collagen peptides

Figure 158: Mixture result with collagen peptides before and after drying

Mix 6B_Collagen Peptides

Collagen peptides 8g
Water 10g
Green Bambo Dust 5g

Ratio binder: filler = 3,6:1

Figure 159: Process with collagen peptides

Figure 160: Mixture result with collagen peptides before and after drying

Mix 6C_Collagen Peptides

Collagen peptides	6g
Water	4g
Dust 0100	2g
Fibers 200400 SF	1g

Ratio binder: filler = 3,3:1

Figure 161: Process with collagen peptides

Figure 162: Mixture result with collagen peptides before and after drying

Mix 7A_Eco-glue

Eco-glue	20g
Dust 0100	5g

Ratio binder: filler = 4:1

Figure 163: Process with eco-glue

Figure 164: Mixture result with eco-glue before and after drying

Mix 7B_Eco-glue

Eco-glue	20g
Green Bamboo dust	5g

Ratio binder: filler = 4:1

Figure 165: Process with eco-glue

Figure 166: Mixture result with eco-glue before and after drying

Mix 7D_Eco-glue

Eco-glue	20g
Dust 0100	2g
Fibers 200400 SF	2g

Ratio binder: filler = 5:1

Figure 167: Process with eco-glue

Figure 168: Mixture result with eco-glue before and after drying

Mix 8A_Wood glue

Wood glue 20g
Dust 0100 5g

Ratio binder: filler = 4:1

Figure 169: Process with wood glue

Figure 170: Mixture result with wood glue before and after drying

Mix 8B_Wood glue

Wood glue 20g
Green Bamboo dust 5g

Ratio binder: filler = 4:1

Figure 171: Process with wood glue

Figure 172: Mixture result with wood glue before and after drying

Mix 8C_Wood glue

Wood glue 20g
Dust 0100 2g
Fibers 200400 SF 2g

Ratio binder: filler = 5:1

Figure 173: Process with wood glue

Figure 174: Mixture result with wood glue before and after drying

Mix 8D_Wood glue

Wood glue 20g
Green Bamboo dust 2g
Fibers 200400 SF 2g

Ratio binder: filler = 5:1

Figure 175: Process with wood glue

Figure 176: Mixture result with wood glue before and after drying

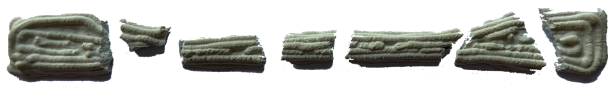
3.11 Results Matrix

Filler / Binder	Bamboo dust 0100	Green Bamboo dust *Sasa tsuboiana*	Dust + Fibers 0100 + 200400 SF	Green Dust + Fibers *Sasa tsuboiana* + 200400 SF
Corn starch				
Potato starch				
Tapioca starch				
Gelatin				
Xantham gum				
Collagen Peptides				
Eco-glue				
Wood glue				

Faults during drying process

Filler / Binder	Bamboo dust 0100	Green Bamboo dust *Sasa tsuboiana*	Dust + Fibers 0100 + 200400 SF	Green Dust + Fibers *Sasa tsuboiana* + 200400 SF
Corn starch				
Potato starch				
Tapioca starch				
Gelatin				
Xantham gum				
Collagen Peptides				
Eco-glue				
Wood glue				

Mechanical Testing

Binder \ Filler	Bamboo dust 0100	Green Bamboo dust *Sasa tsuboiana*	Dust + Fibers 0100 + 200400 SF	Green Dust + Fibers *Sasa tsuboiana* + 200400 SF
Corn starch				
Potato starch				
Tapioca starch				
Gelatin				
Xantham gum				
Collagen Peptides				
Eco-glue				
Wood glue				

Remaining Specimens

Binder \ Filler	Bamboo dust 0100	Green Bamboo dust *Sasa tsuboiana*	Dust + Fibers 0100 + 200400 SF	Green Dust + Fibers *Sasa tsuboiana* + 200400 SF
Corn starch				
Potato starch				
Tapioca starch				
Gelatin				
Xantham gum				
Collagen Peptides				
Eco-glue				
Wood glue				

Potential Mixtures

Filler / Binder	Bamboo dust 0100	Green Bamboo dust *Sasa tsuboiana*	Dust + Fibers 0100 + 200400 SF	Green Dust + Fibers *Sasa tsuboiana* + 200400 SF
Corn starch				
Potato starch				
Tapioca starch				
Gelatin				
Xantham gum				
Collagen Peptides				
Eco-glue				
Wood glue				

3.12 Summary of Findings Second Material Experimentation

Reflecting on the second phase of material exploration, it is interesting to note that some of the most promising materials from the first phase did not perform well in the second phase.
The optimal three mixtures were chosen based on the mechanical test and other factors such as printability, cost, and bio-based status. The testing process revealed an interesting correlation between potato starch and eco glue, as the latter is derived from potato starch. To ensure an effective and efficient testing process, only one binder was chosen for the initial printing test. The choice of binder was based on two factors: whether it was bio-based and its cost-effectiveness. Consequently, potato starch and eco glue were selected, with potato starch being the more cost-effective option.

During the testing process, it was observed that glue is susceptible to drying faster in contact with air, making it difficult to extrude. However, potato starch was found to be more convenient due to its ability to be reconstituted to its initial consistency by adding water even if it dries during the printing process. This property of potato starch contributes to its cost-effectiveness, sustainability, affordability, and hopefully resistance. Additionally, potato starch is readily available in the market, unlike eco glue which required a specific shop for its procurement.
In conclusion, to proceed with the printing test, potato starch is a promising binder due to its cost-effectiveness, sustainability, and ease of use. These properties make it an affordable and readily available option for a wide range of users, with potential resistance being an added advantage.

3.13 Final mixture preparation

In order to proceed with the printability test, a large quantity of the potato starch mixture needed to be produced. After various iterations of different proportions, the optimal consistency was achieved by using specific amounts of each ingredient, as displayed in the figure below.

Due to the large quantity needed, the mixing process proved to be challenging. The filler and potato starch-water mixture had a tendency to clump together, resulting in an uneven mixture or powder loss. To overcome this, Dr. Barbara Lubelli whose the coordinator of the Heritage & Technology laboratory (room K Midden 01.10) at the BK lab at the faculty of Architecture and the Built Environment, kindly provided the use of a clay mixer. This ensured that the mixing process was easier and resulted in a more homogeneous paste that could be printed effectively.

500g water | **100g potato starch** | **120g bamboo dust** | **60g bamboo fiber**

Figure 177: Ingredients final mixture.

Figure 178: Mixture procedure with clay mixer.

The process of creating the paste involved several steps, starting with weighing all the necessary ingredients. The potato starch was then combined with cold water and mixed until fully dissolved. The pan was placed on a heating stove and the mixture was continuously stirred until it boiled. After approximately 7 minutes, a thick paste was formed and the mixture became transparent. The mixture was then cooled in the mixer for a brief period before adding 1/3 of the dust and starting to mix. Another 1/3 of the dust was added, followed by half of the fibers. The remaining fibers were added, followed by the remaining dust. The mixture was mixed thoroughly until it became a thick paste ready for printing.

By following these steps and using the clay mixer, the optimal potato starch mixture was produced and ready for further testing in the printability test.

3.14 Conclusion

Following the first round of experimentation, it became apparent that a second phase was necessary to refine the selection of binders and achieve a more reliable choice for optimal printability. While the range of binder options was not limited, it was important to narrow down the choices to reduce variability. In contrast to the first experimentation, which focused solely on the extrudability of the mixture, the second phase involved using the same shape for all mixtures to visually observe deformation and shrinkage of the extruded paste.
In selecting potential binders for printability testing with the robot, various factors were considered, including insights gained from the first experimentation. It is important to note that, at this stage, choices were subjective based on objective parameters. Additionally, considerations such as time, situation, and the desired final product were kept in mind during the selection process. While manual extrusion made it difficult to provide a scientific evaluation of material properties, it was noted that the binder needed to have a glue consistency to enable successful extrusion.
It is important to note that the mixtures not chosen are not necessarily ineffective or unusable, but rather, choices were based on subjective considerations. The chosen mixtures were then printed in the same precise shape, with three layers overlapping.
While there may be other potential binders to be tested, it was important to maintain focus and set a deadline within the available timeframe. Overall, the second phase of experimentation was crucial in refining the selection of binders and improving the reliability of the printability testing phase.

4

Computational Workflow

4.1 Overview

In order to proceed with the printability exploration, it is essential to set up the hardware and software required for the printing process. The Laboratory for Additive Manufacturing in Architecture (LAMA Lab), located in room BG.West.250 and coordinated by Paul de Ruiter, provides the necessary instruments to test the ability of the mix with potato starch to be printed using a robotic arm. This mixture has been identified as the most promising one from the material investigation.

The printing process involves two crucial factors that need to be controlled: the amount of extrusion and the movement, which are managed by the extruder and robotic arm, respectively. The figure presented shows the setup required for successful printing.

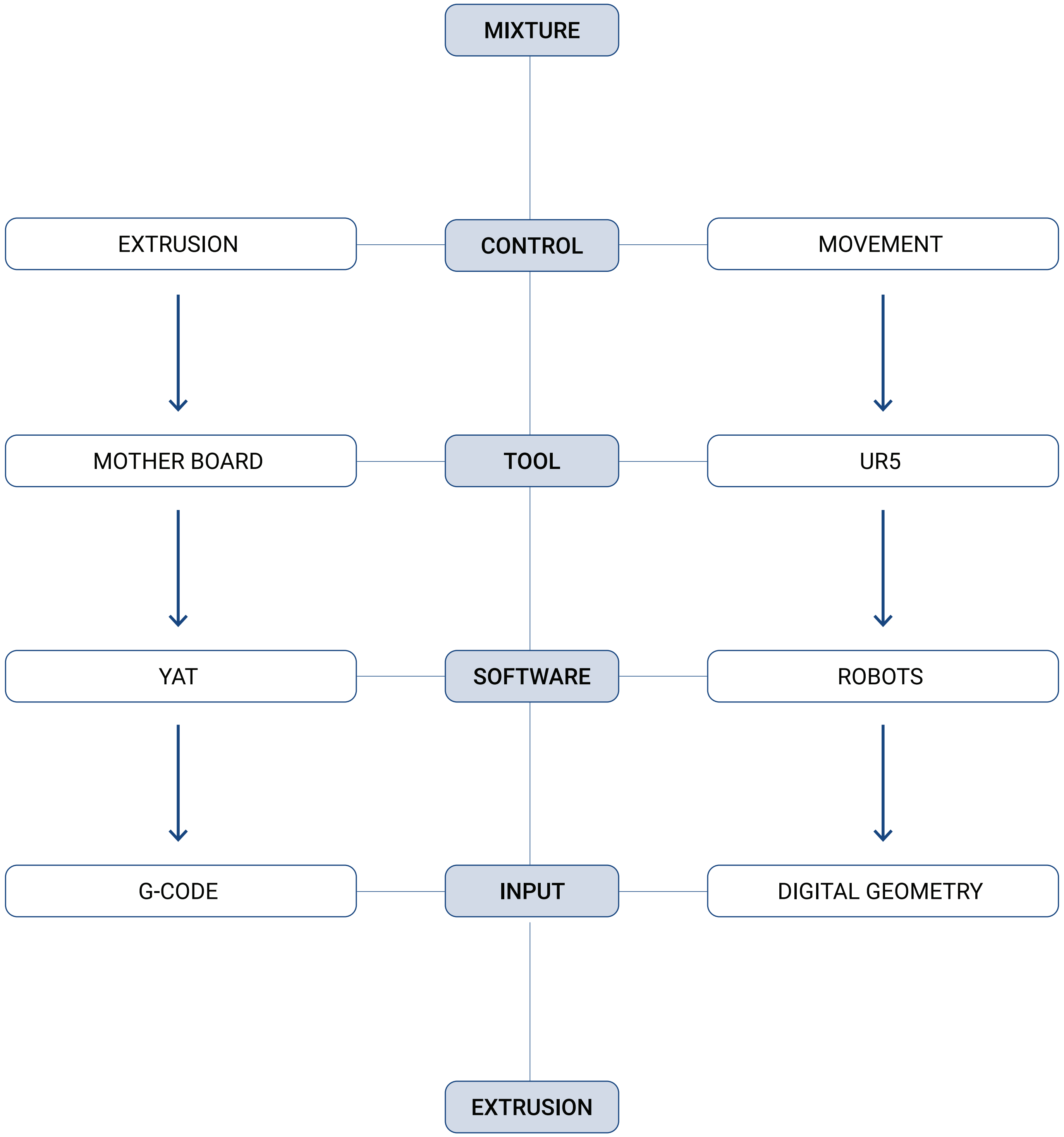


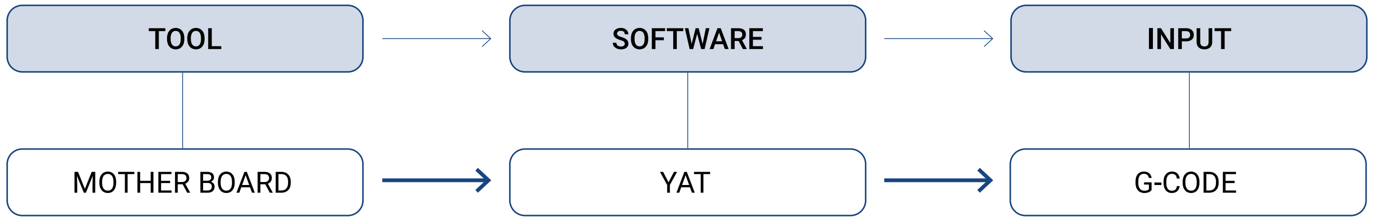
Figure 179: Computational Workflow scheme.

To begin with, the extruder needs to be installed, configured, and tested before it can be mounted on the robotic arm. The second phase involves setting up the robotic arm, understanding its operation, and conducting final testing.

Each step in this chapter is explained in detail to ensure a smooth transition from the mixing phase to the printing phase. This includes the installation and configuration of the extruder, understanding its operation, testing it, setting up the robotic arm, and conducting final testing.

4.2 Control Extrusion

In order to streamline the printing process, we utilized the LDM WASP extruder XL 3.0 for controlling extrusion. It should be noted that the extruder can only be used with the Delta WASP 40100 Clay, and thus, a special connection had to be made. To facilitate this connection, a stepper motor was attached to the motherboard and controlled the extruder.
To operate the stepper motor, software capable of elaborating the G-Code was required.



4.2.1 Motherboard Setup

In order to establish a successful connection between the Duet 3 mainboard 6HC and a computer via USB, it is necessary to refer to the instructions provided by Duet on their website: https://docs.duet3d.com/en/How_to_guides/Getting_connected/Getting_connected_to_your_Duet.
Once the connection has been established, it is important to configure the network connection of the Duet 3 mainboard 6HC before G-Code can be sent. To communicate with the Duet via the USB cord, a terminal emulator called YAT is used.

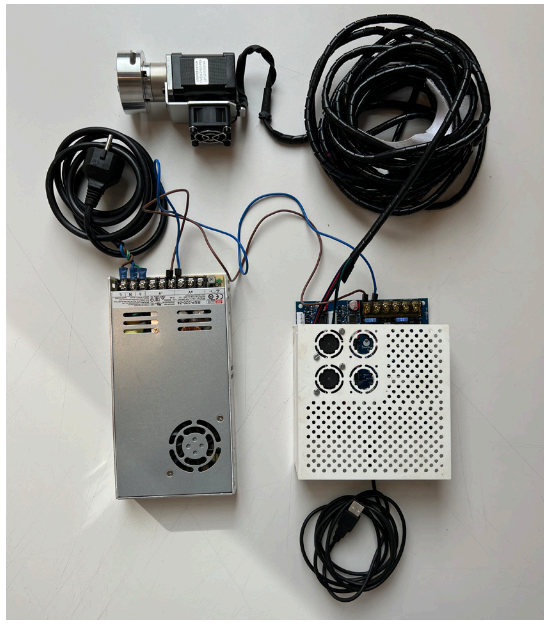


Figure 180: Motherboard.

4.2.2 YAT

In order to ensure successful printing, it is essential to calibrate the speed and pressure of the stepper motor in accordance with the paste's consistency and nozzle diameter prior to incorporating robotic arm movements. To achieve this, YAT, a user-friendly and feature-rich serial terminal, serves as the interface for the Arduino motherboard. This allows for the sending of commands to start and stop the stepper motor, as well as specify its speed and number of spins.

To begin the calibration process, the wiring configuration must first be established. Once complete, the torque rotation of the stepper motor can be tested by sending the "T0" message to enable tool recognition. Following this, the stepper motor's rotation can be initiated by sending the G-Code command.

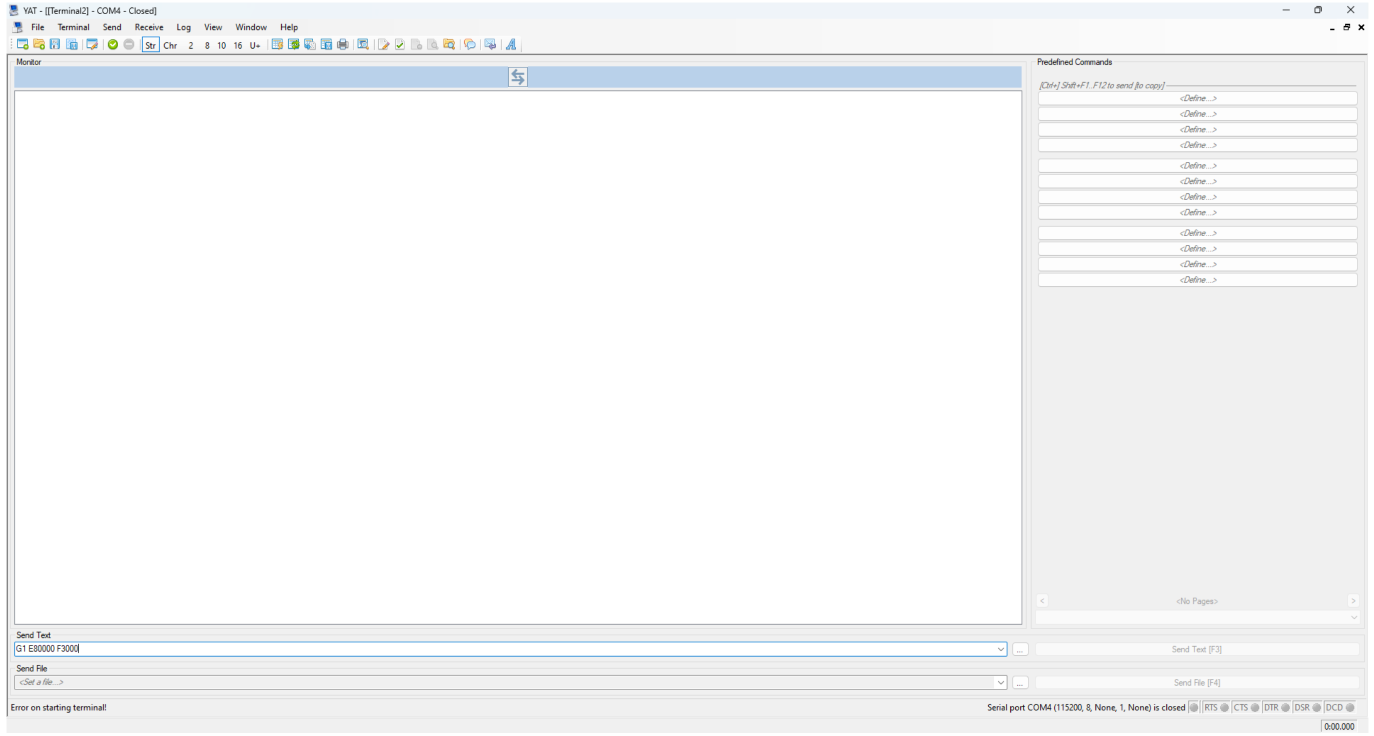


Figure 181: YAT interface.

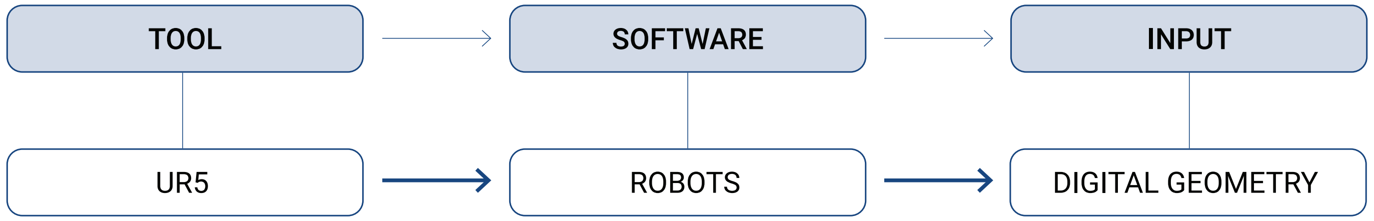
4.2.3 G-Code

In additive manufacturing, the instructions for machine movement and extrusion are contained in a text file called G-Code. It is an alphanumeric language that uses orders made up of a letter and a number, with the letter "G" used to designate the machine's regulated movements. Orders beginning with "G" are therefore more common, hence the name "G-Code" (Cuevas et al., 2021). The firmware of the machine reads and executes the G-Code instructions.

The G-Code commands used in this study include:
G1, which describes an extrusion movement at a specific speed.
E, which is the extrusion rate or volume of material in millimeters. The flow rate is determined by the nozzle diameter and the ratio of material entering the extruder to the material already present. The value differ as the geometry changes.
F is the feed rate or speed, measured in mm/m, and can be a constant or variable, resulting in different outcomes. The speed used in this study for a 4mm nozzle is from between 1500 to 3000, it may vary depending on the mixture's consistency and geometry.

4.3 Control Movement

Once the extruder is set up, the next step is to use a robotic arm to move the geometry that will be printed. In this case, the UR5 robotic arm can be monitored and remotely operated through a Grasshopper plug-in. In order to create a toolpath that the robotic arm can follow, the geometry must be elaborated.



4.3.1 UR5

Two different robotic arms are available from LAMA: the COMAU NJ-60-2.2, an industrial robot, and the UR5, a collaborative cobot robot. Either of the robotic arms can be used for additive manufacturing, but the primary difference between them is their payload capacity. The UR5 can handle up to 5 kg, while the COMAU can handle up to 60 kg. The specialized tool for this project has a total payload of 4 kg, so the required component size and workflow rate will depend on both robotic arms.

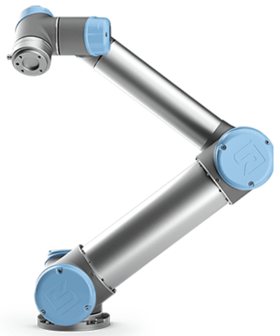


Figure 182: UR5.

Figure 183: COMAU NJ-60-2.2

After considering Alexsander and Christopher's recommendations, it was decided to start with the UR5. This was because investigating the printability of the selected mixture was crucial to understanding its behavior. If the working space could not be reached by the UR5, the final prototype could be printed using the COMAU.

To operate the UR5, it was directly connected to the computer using a router. The robot can be operated remotely using a software created using the Grasshopper plug-in "Robots" or locally using the teach pendant.

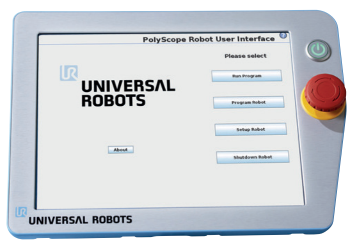


Figure 184: UR5 teach pendant.

4.3.2 "Robots"

The Rhino visual programming interface includes a plug-in called "Robots," which facilitates the creation and simulation of robot programs for various robot manufacturers such as ABB, KUKA, UR, and Staubli. To install the plug-in, one can search for "Robots" in Rhino 7's Package Manager command.

The following describes the parts used to control the robotic arm's movement in the Grasshopper plug-in.

The "Create Tool" component constructs a tool, such as the extruder, which is defined by a Tool Center Point (TCP) that determines its direction and location. The tool's weight is initially 4 kg, but it may increase depending on the weight of the mixture in the cartridge. The tool is created using the mesh from the tool's model.

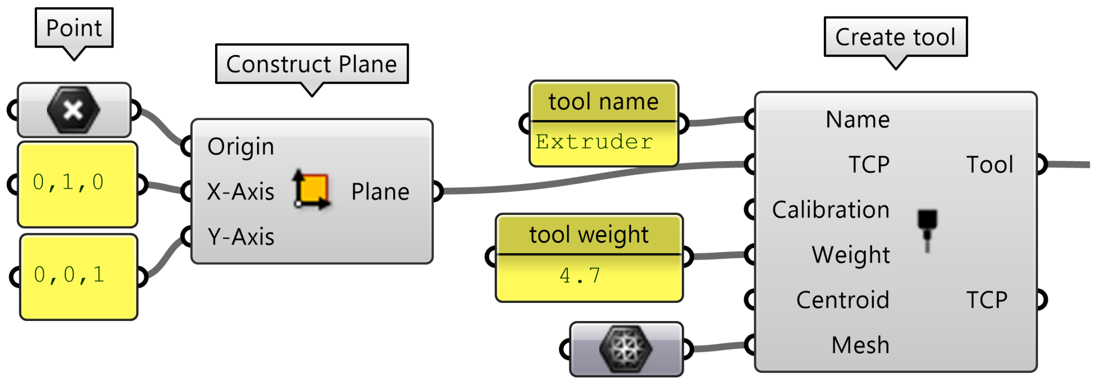


Figure 185: Create Tool component.

The "Create Target" component refers to the geometric planes that are described later in the report. By changing the robot's shoulder, elbow, and wrist, the robot's configuration can be modified. This parameter also aids the robot in adjusting its position to avoid collisions.

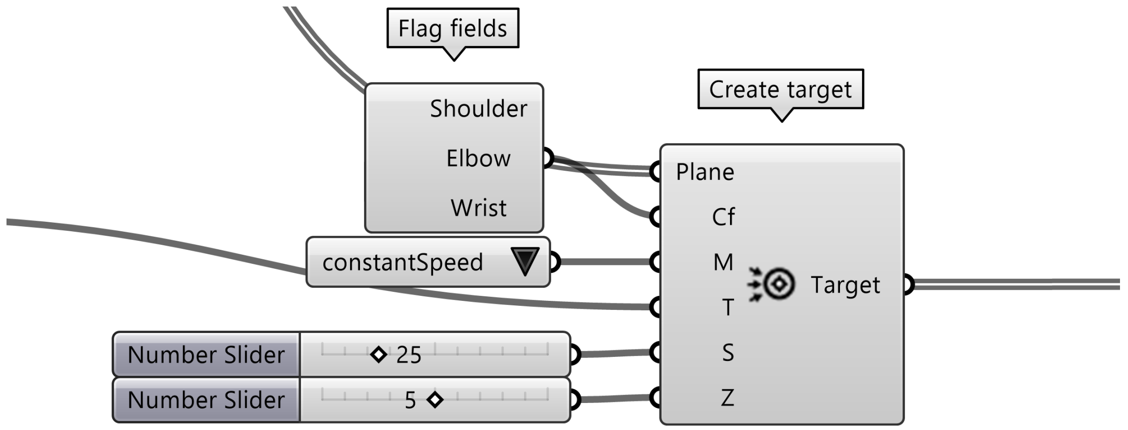


Figure 186: Create Target component.

The "Motion" component controls the robot's movement from one location to another.
The UR5 is capable of linear movement (MoveL), joint movement (MoveJ), and process movement (MoveP), which moves linearly at a constant speed but does not allow for sharp angles.

However, MoveP is necessary for printing, and the plug-in was modified to include it. A modified text output of "Robots" called "constantSpeed" was created by Konrad Junger, which enables the creation of MoveP. This modification can be downloaded from this website: https://github.com/KonradJuenger/Robots/releases/tag/0.1.2.

The previously created tool is linked, and the robot's movement speed is entered in millimeters per second. To ensure smooth and constant movement, the printing process speed and robot position must also be coordinated. The zone parameter blurs the radius of the waypoint to prevent the robot from stopping at every point.

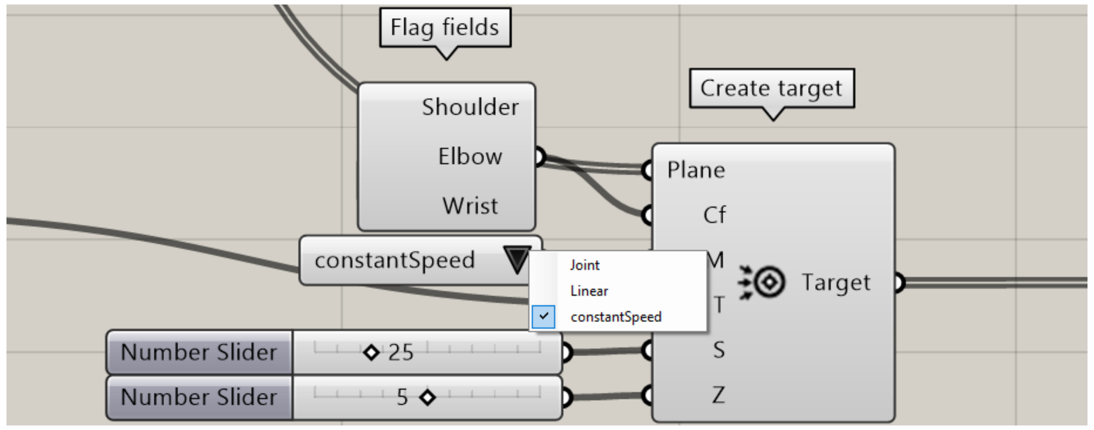


Figure 187: Motion parameter.

To load the robot system's data, the individual robotic arm's information must be entered. The TUDelft-LAMA-UR5 library is included in the system and chosen as the input component.

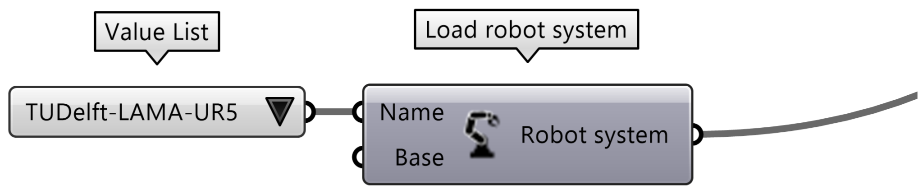


Figure 188: Library input.

The "Create Program" component generates a program name and links the tool to the robot system. The step size is reduced to 0.1 mm/s to ensure precise arm motion. The program is transferred to the device using a USB card and a remote connection.

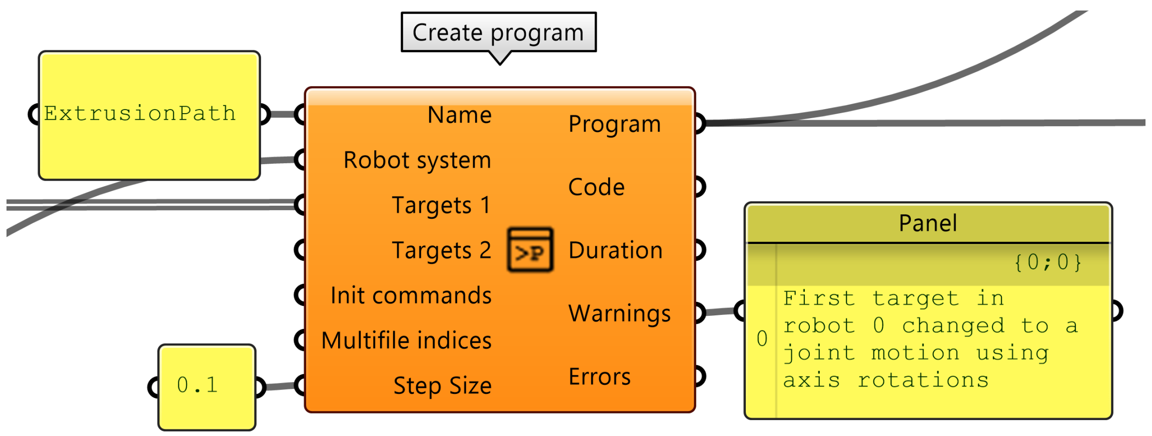


Figure 189: Create Program.

Before running the program, it is recommended to simulate it first using the "Program Simulation" component to detect collisions.

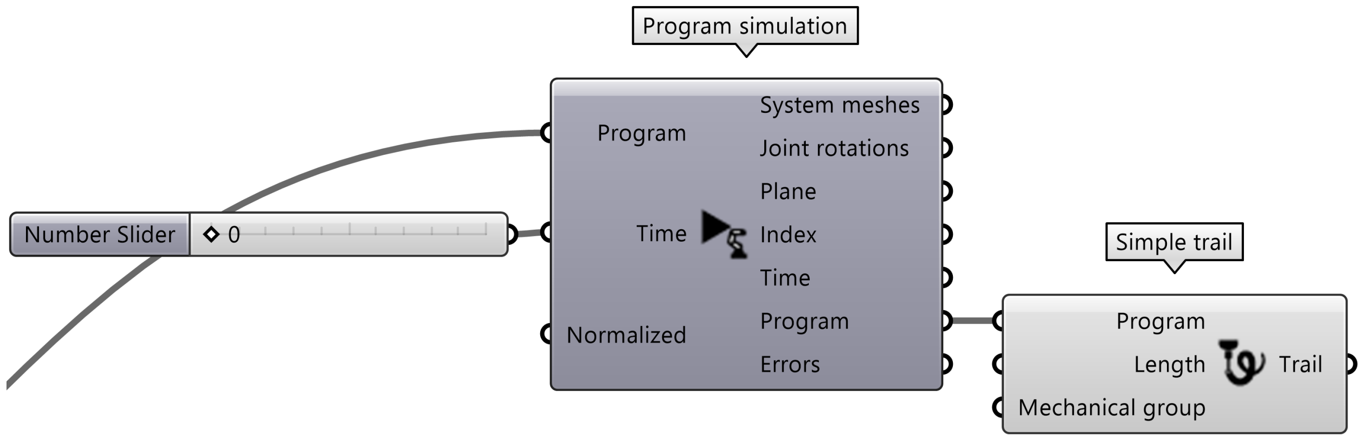


Figure 190: Program Simulation component.

Once the simulation is complete, a remote connection is established between the computer and the UR5 control box using an ethernet cable connected to a router. The plug-in requires the router's IP address to direct the robot's movements.

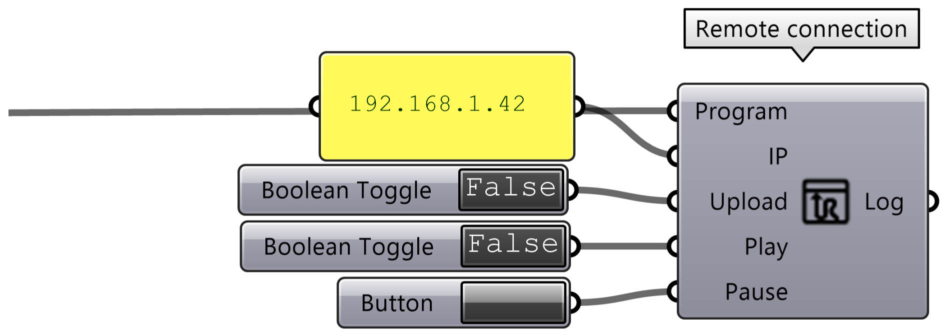


Figure 191: Remote connection component.

4.3.3 Digital Geometry

As previously mentioned, before using the Create Target tool, the user must define a plane in the software. These waypoints or targets must be reached by the robotic arm to create the toolpath it will use to travel between them.

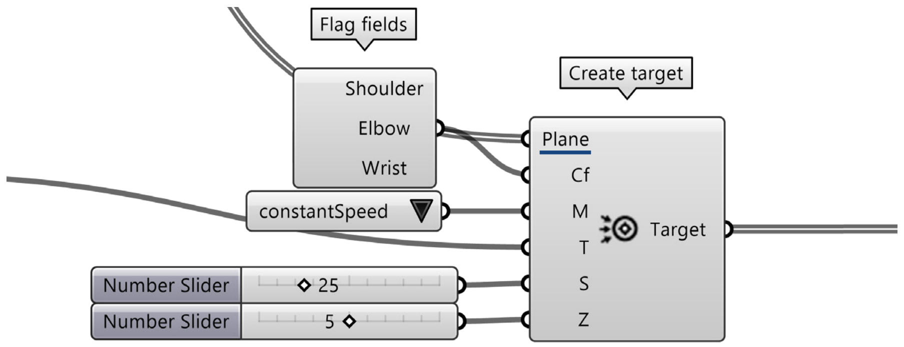


Figure 192: Plane Input.

To create these waypoints, a mesh or extruded geometry with the desired height can be used as a starting point. In order to extract curves that follow a specific path for 3D printing, curves must be extracted from the mesh or geometry.

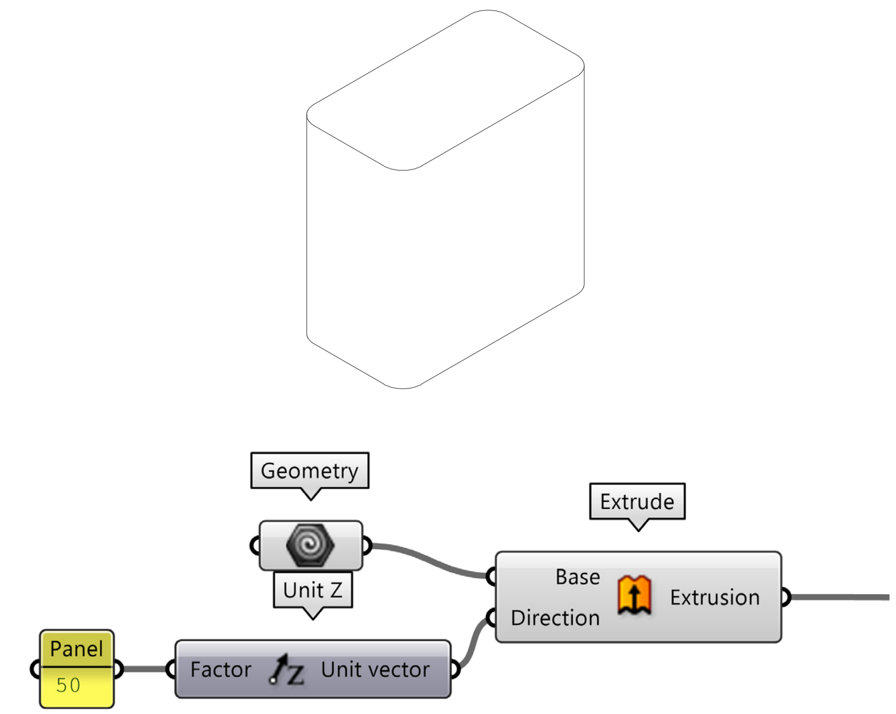


Figure 193: Geometry.

To extract these curves, the Contour tool can be used to create sections of the 3D object using virtual planes perpendicular to a given direction, in this case, the Z axis. The layer height in additive manufacturing is determined by the distance (in mm) between these sections, which is based on the diameter of the nozzle being used.and the consistency of the mixture.The Contour component will divide the mesh, resulting in closed polylines. The robotic arm will move from one closed polyline to the next, advancing to the next layer.

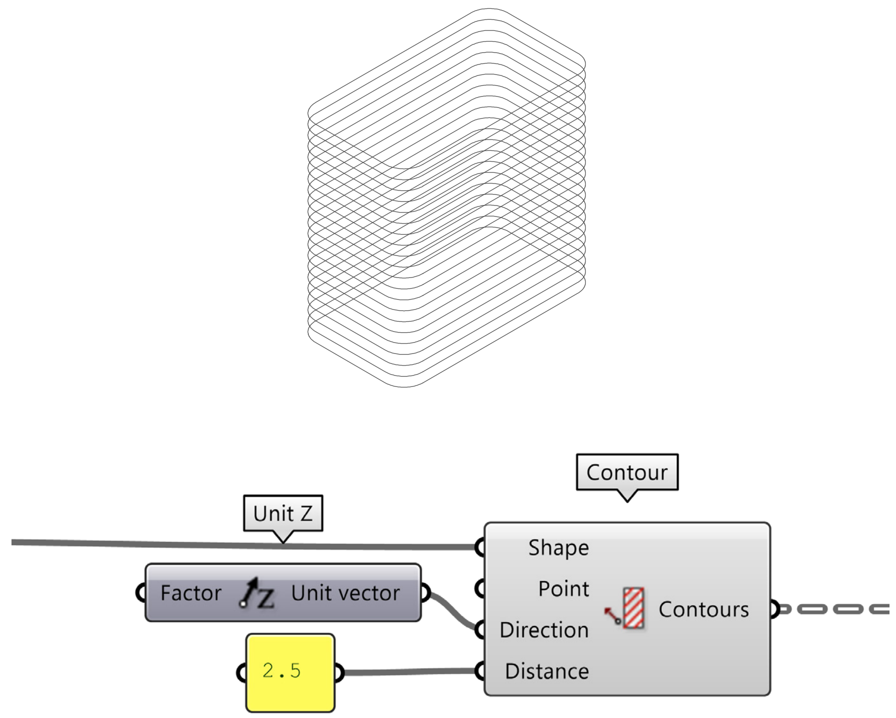


Figure 194: Contour.

However, a challenge in this process is that pausing extrusion as the arm moves to the next layer is inconvenient because the extruder needs to be controlled individually.

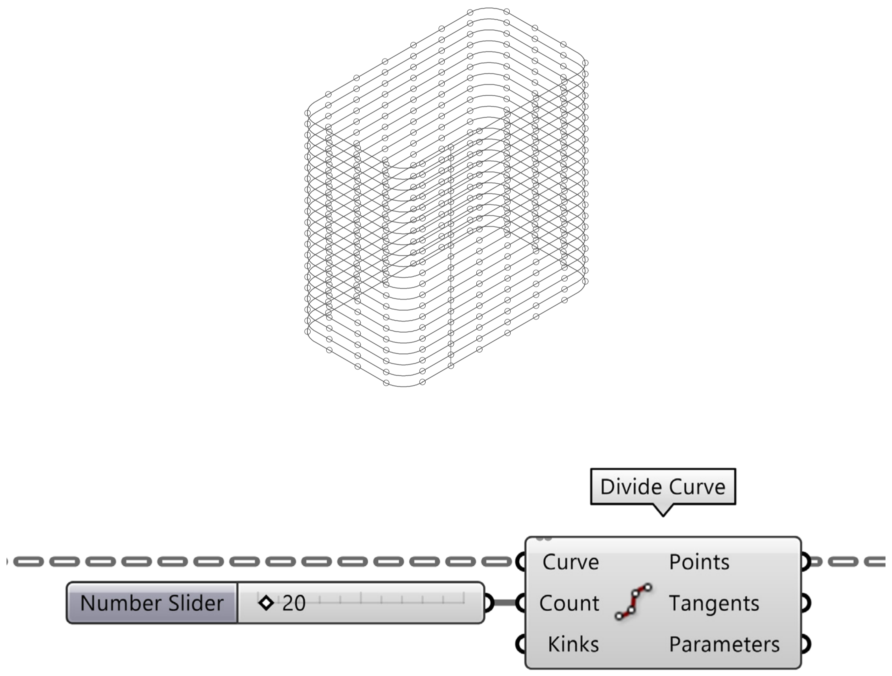


Figure 195: Divide Curve.

To overcome this issue, the points can be removed, the list flattened, and a continuous polyline can be produced. By doing this, the extruder can be prevented from stopping and leaving an excess of material in the path's vertical segment.
The best solution is to create a continuous polyline by establishing a specific slope between the final point of one polyline and the second point of the next. To achieve this, the Cull Index tool is used to delete the first item from the list. Then, the Flatten Tree tool is used to create a continuous polyline by creating a single list of all the points.

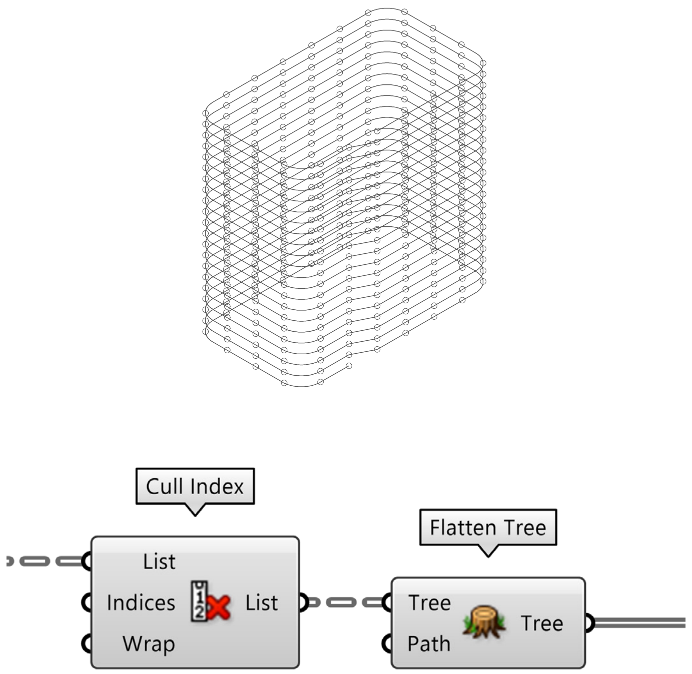


Figure 196: Flatten Tree.

Finally, the flattened list of points can be transformed into planes and connected to Create Target at the end.

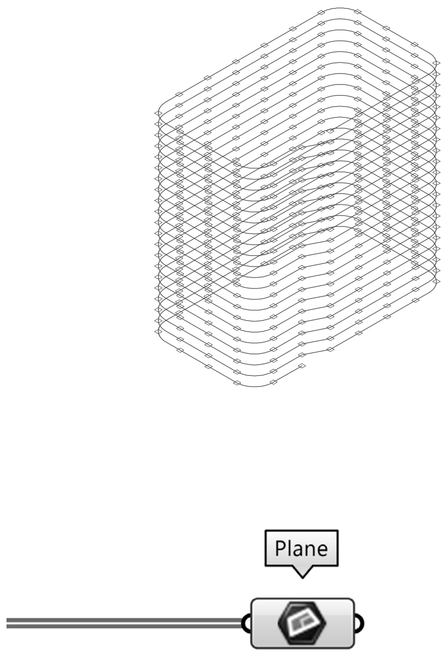


Figure 197: Planes conversion.

4.4 Conclusion

In conclusion, while the workflow of the printing process could have been simpler with a more streamlined setup of the extruder and robotic arm, printing was successfully to create simple shapes using Rhinoceros and Grasshopper. These shapes were crucial in testing the printing process, evaluating the potential and installations of the material and method, and carrying out printability tests.

Despite the challenges faced, objectives were achieved and valuable insights gained into the 3D printing process using the LAMA tool. Moving forward, these learnings can be applied to future projects to improve the efficiency and effectiveness of the printing process.

5

Printability Exploration

5.1 Overview

During the material exploration phase, each mix was tested for its extrudability using a syringe, either manually or with a caulking gun. After identifying the most promising mix, the printability investigation phase was initiated to explore the potential of additive manufacturing using this mix. All of the additive manufacturing exploration was carried out at LAMA, using additional components attached to the robotic arm for the extrusion process.

The main topic of this chapter are geometrical characteristics of the potato starch mixture when the extruder is set up to the flange of the robotic arm and the stepper motor has a constant velocity rotation to extrude a smooth paste. To gain a better understanding of the advantages and limitations of creating a self-supporting wall, several tests were conducted to evaluate height, overhang, layer overlap, and infills.

5.2 Experiment Design

In the printability trials, three independent phases were conducted to explore the geometry's maximum height, degree of angle, and wall overlap. Guidance was sought from Max Latour at Urban Reef to identify the design criteria for the self-supporting wall. The behavior of the material was studied through trial and error during the design process, aided by these tests.
These tests were crucial to prototype the final shape of the self-supporting wall, as they provided information on material behavior and printing restrictions. The quantity of material needed for the print was estimated by printing the first layer and calculating the total number of curves using a "Panel" component in Grasshopper. The final number was entered into the g-code that was sent on YAT.

To gain pertinent information on printing restrictions and material behavior, successful extrusions and collapsed constructions were allowed to cure for at least three days. Failed prints were recycled for use in later extrusions. Test subject designs were continuously modified based on feedback from each iteration.

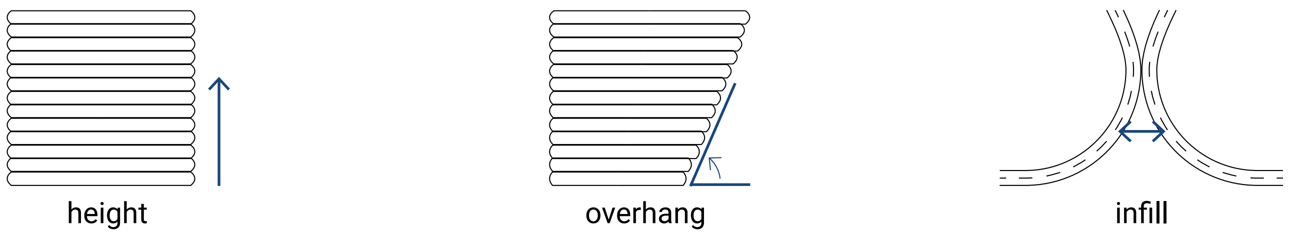


Figure 198: Exploration setup

5.3 Material Setup

The printability investigation involved testing different feedstock mixtures to find one that had good performance and was easy to extrude. After careful consideration, a mixture based on potato starch as a binder was chosen due to its extrusion-prone properties and ease of handling. This mixture also had the added benefit that a small amount of water could be added if it became too dry or adherent.

The material batch was calculated to be the appropriate size to fill the extruder cartridge completely, and the recipe used produced approximately 700g of material, with ratios determined from the Material Exploration chapter. The mixture is typically heated during production, but it cools down as it is prepared for extrusion.

Filling the cartridge correctly is critical to avoid air bubbles that can compromise the integrity of the printed shapes. Therefore, the paste was flattened onto a PVC film, pressed, and rotated into the cartridge in a careful procedure that was repeated until the container was full. Overall, the chosen feedstock mixture proved to be an effective and practical choice for the printability investigation.

Figure 199: Filled cartridge.

5.4 Geometry

A rectangular form with filleted corners that had a maximum length of 50mm on its longest side was extruded and printed in order to assess the design's structural soundness and stability. The model was printed using a 4mm nozzle and had a single-line wall with no infill.
Upon printing, the rectangular shape achieved a maximum height of 80mm. However, it was observed that the cylinder shape used in a previous thesis exhibited superior stability, as it was able to reach a height of 100mm. These findings suggest that the cylindrical shape may be better suited for achieving optimal stability in similar design applications.

Rectangle - 20 mm

Figure 202: Printed rectangle - 20 mm

Figure 203: Dried rectangle - 20 mm

Rectangle - 50 mm

Figure 200: Printed rectangle - 50 mm

Figure 201: Dried rectangle - 50 mm

Rectangle - 80 mm

Figure 204: Printed rectangle - 80 mm

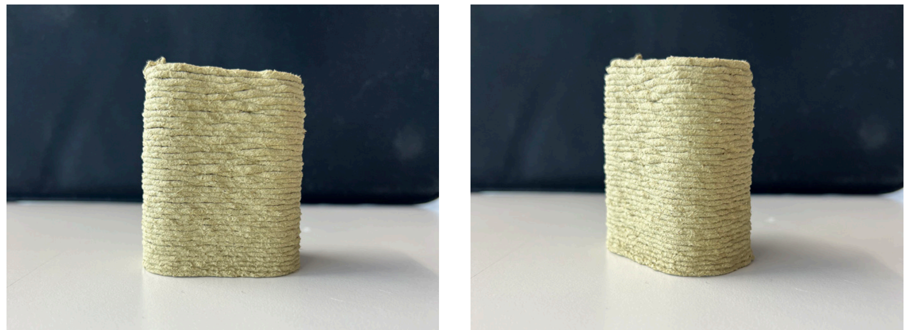


Figure 205: Dried rectangle - 80 mm

Rectangle - 100 mm

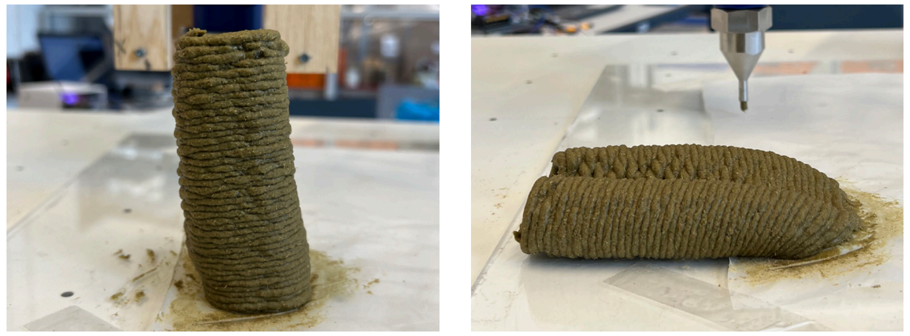


Figure 206: Printed rectangle - 100 mm

Figure 207: Dried rectangle - 100 mm

Cylinder - 100 mm

Figure 208: Printed cylinder - 100 mm

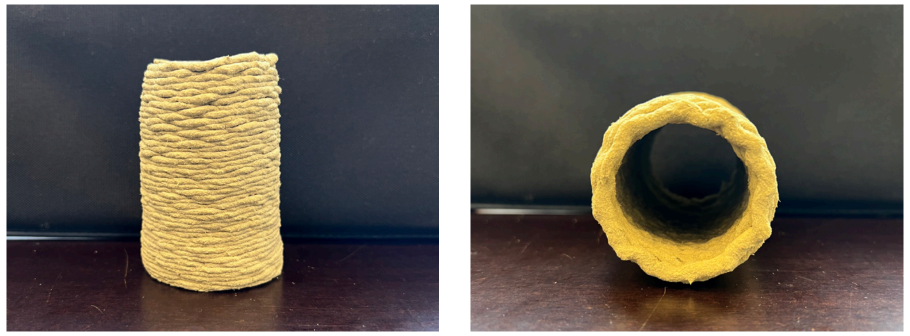


Figure 209: Dried cylinder - 100 mm

Cylinder - 120 mm

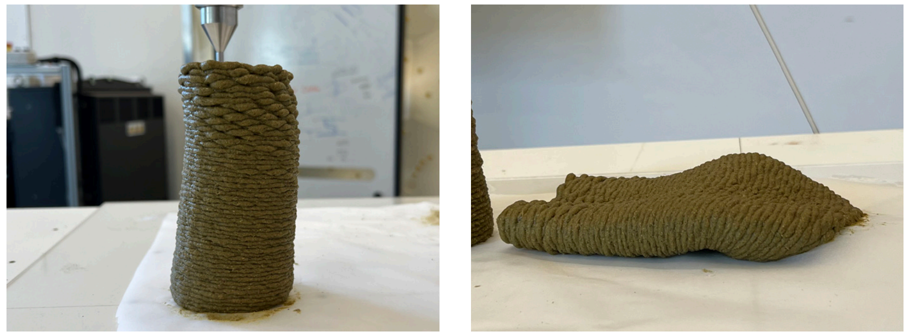


Figure 210: Printed cylinder - 120 mm

Figure 211: Dried cylinder - 120 mm

5.5 Overhang

In the printability investigation, the same geometry that was used to test maximum height was also used to investigate the impact of inclinations of 80, 75 and 70 degrees on one of the longest sides of the wall. The models were designed with a single-line wall and no infill, and printed using a 4 mm nozzle. Each geometry was 50 mm in height, and while none of them collapsed, the print with a 70-degree inclination showed a wavy pattern that was not intentional.

This result highlighted the importance of testing different parameters and angles to fully understand the behavior of the material and the limitations of the printing process. Further exploration and optimization of the printing parameters could lead to improved results in future iterations.

80 degree - 38.82 mm

Figure 212: 80 degree dried.

75 degree - 48.2 mm

Figure 213: 75 degree dried.

70 degree - 58.87 mm

Figure 214: 70 degree dried.

5.6 Overlapping

A 50 x 50 mm square was filled with a curve resembling the hatch of an insulation with a 4 mm and 6 mm space between the lines at their closest points in order to test the viability of using a curvilinear shape in the design. The model was then printed with a 4mm nozzle, extruded to a height of 50mm, with a single-line wall and no infill.

Surprisingly, both extrusions went well, and there were no collapses while the print was being made. Upon inspection, it was observed that when using the 4mm gap, the walls touched without overlapping, which was deemed too close for optimal performance. However, with a 6mm gap, the walls touched, demonstrating that this distance may be more appropriate for this particular design.

Distance 4 mm

Figure 215: Overlap 4 mm dried.

Distance 6 mm

Figure 216: Overlap 6 mm dried

5.7 Summary of findings

During the printability investigation phase, a mixture with remarkable height was produced, measuring 80 mm tall and featuring a 50 mm by 30 mm rectangle. When there was neither an infill nor a supporting structure, circular designs demonstrated greater stability than straight walls. When tested with a 20-degree slant, the material was able to create interesting patterns despite not being able to maintain the shape completely.

The samples were joined using a 4mm nozzle at both 4mm and 6mm distances. However, during the drying phase, mold appeared after 3-4 days. Based on interviews with Julian Jauk, a PhD student from the University of Graz, and Johan Kocks, the manager of R&D at Bambooder, it is hypothesized that starch is susceptible to fungal growth and using demi-water in a sterilized environment may prevent mold appearance.

To hasten the drying process and inhibit fungi growth, the LAMA-provided hydrator at 70 degrees Celsius could be used. In addition, applying vinegar on the dried specimen could prevent future mold growth.

A noteworthy observation is that bamboo dust 0100 was utilized when the quantity of *Sasa tsuboiana* dust was insufficient. This resulted in an interesting discovery; after the drying process, the layers did not adhere properly, leaving gaps between them.
Johan Kocks provided an explanation for this occurrence:

- The bamboo dust 0100 is still considered a fiber, rather than dust.
- The chemical composition of the dust could differ significantly from that of the green dust, which is derived from a mix of leaves and stems, whereas the 0100 dust is derived solely from the stems of the bamboo. Leaves are typically richer in proteins required for photosynthesis, some of which may be capable of forming polymer chains when reacting with water, thereby improving the stability of the extruded material.
- It is possible that differences in chemical composition and material performance could result from the use of different bamboo species. However, this difference should not be significant in general.

During another printing phase used for mechanical testing, 0100 dust was utilized once again. In this case, the interlayer bonded well as the mixture was less viscous than in previous attempts. It is worth mentioning that bamboo dust 0100 could be a potential substitute for *Sasa tsuboiana* dust.

Figure 217: Molding, drying, separation.

5.8 Conclusion

During the material investigation phase, it became apparent that handling and combining raw materials to produce a workable feedstock for additive manufacturing was challenging. To confirm the material's extrudability and identify any production difficulties, the printability investigation stage was undertaken.

The feedstock based on potato starch as a binder performed exceptionally well in extrusion, even at low pressure. The material demonstrated good consistency, viscosity, and adhesion without offering resistance to extrusion. A robust inter-layer connection prevented the structure from dragging during extrusion, and the exterior surfaces hardened quickly within 24 hours, with an overall curing time of 3 days.

However, fungal development was observed in the material, which may impact its stability and characteristics. Although challenging to prevent due to the natural and entirely bio-based composition of the material, this issue did not hinder the research from progressing.

Further improvements to the material recipe are required to address the variability observed in the combination, which may impact the design criteria of the prototype. The higher distortion during hardening was found to be caused by elevated water content. Once these challenges are overcome and a good understanding of the potential, constraints, and difficulties faced are achieved, the design criteria can be evaluated and explored in the creation of the prototype.

6

Design

6.1 Overview

The aim is to create a mechanically informed infill that is tailored to the loads on specific parts of the building component. The design process begins with the creation of the shell, which defines the overall geometry of the building component. The design of the building component was heavily influenced by the novelty of the material and the fabrication process. The geometrical constraints resulting from the printability exploration played a crucial role in determining the shape of the geometry.
Subsequently, different infill geometries are subjected to mechanical testing to evaluate their fracture behavior. Based on these test results, a customized infill geometry is devised.

To determine the optimal density distribution within the infill, a structural analysis is conducted. This analysis involves mapping the density of the infill based on the variable cell size and arrangement. The goal is to identify areas that require higher density to withstand greater loads, as well as regions where lower density can be employed without compromising structural integrity.

Once the density mapping is established, the component is designed to generate the toolpath necessary for printing it using a robotic arm. The details of the prototype creation process will be discussed in the subsequent chapter, providing insights into the implementation of the design.
Overall, the design choices made were well-informed and tailored to the specific properties and limitations of the material and the fabrication process.

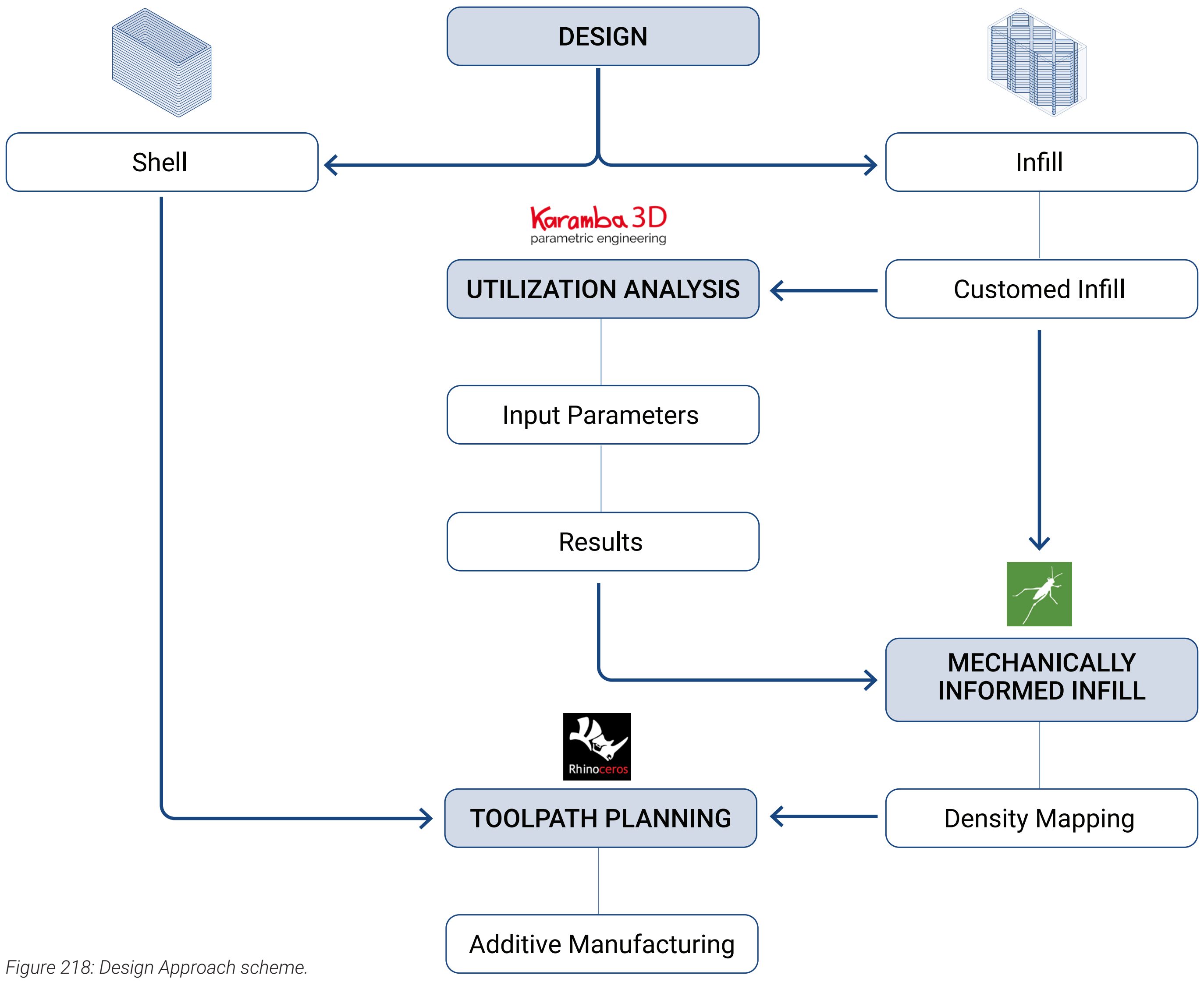


Figure 218: Design Approach scheme.

6.2 Building Element

Considerable thought was given to the selection of the building element for this research. It was recognized that due to the innovative nature of the material and fabrication process, it would be ill-advised to create a design intended to bear heavy loads. Furthermore, as the primary focus of the thesis was to demonstrate the feasibility of printing bamboo, considerations such as weather and fire resistance were disregarded and because of that it would be better to define a building element that wouldn't have those parameters accounted from the beginning.
Already the choice was narrowed to an interior element that would not face the external environments and as mentioned before cannot bear significant loads.

Therefore, the emphasis was placed on creating a self-supporting wall with built-in benches that could serve as a proof of concept for the printing process.

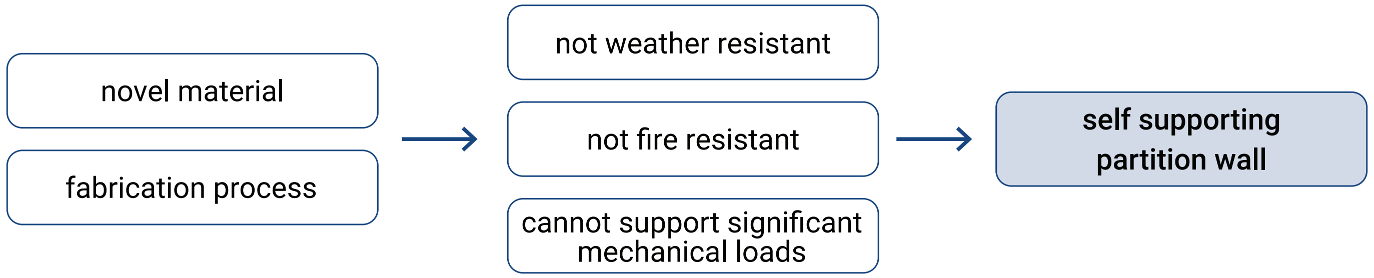


Figure 221: Building Element Criteria

This is case is relevant because while similar designs have traditionally been achieved through the cutting of entire pieces of wood, additive manufacturing offered a more efficient means of production by minimizing waste.
The component was designed to serve both functional and structural purposes, with the curves and shape of the structure intended to create benches, while also supporting the overall stability of the wall.

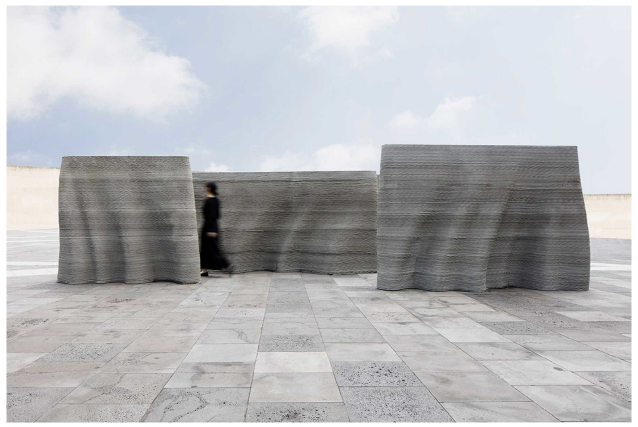


Figure 219: The Curtained Wall, SWNA, 2019. Source: theswna

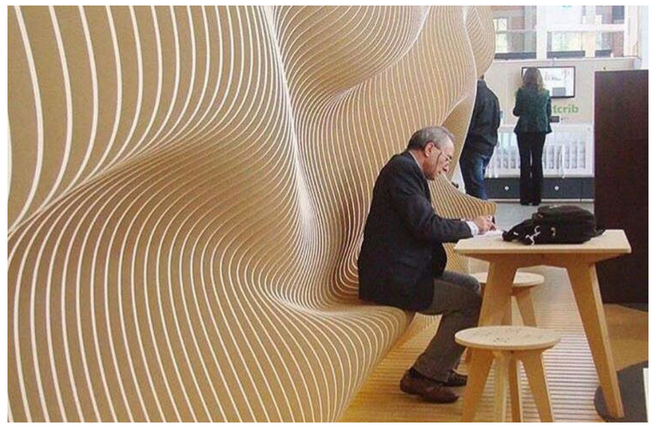


Figure 220: Pavilion Ricchezze, AABB. Source: aabbstudio

6.3 Shape Design

The initial concept for this research was to demonstrate the potential of the novel material and fabrication technique. Therefore, the design had to be carefully considered to incorporate the capabilities of the selected mixture and additive manufacturing technology.

To ensure that the geometry was feasible for printing, the design began by lofting different sections of a partition wall and benches on both sides. The height of the wall was set to the minimum required for a partition wall, and the bench was designed to provide adequate seating space with proper backrest and leg space.
Due to the limitations of the printing exploration, rounded corners were necessary for the geometry's borders, as sharp angles could not be produced with the circular nozzles of the WASP printer. The inclusion of curved shapes also allowed for greater heights to be reached during the printing process.

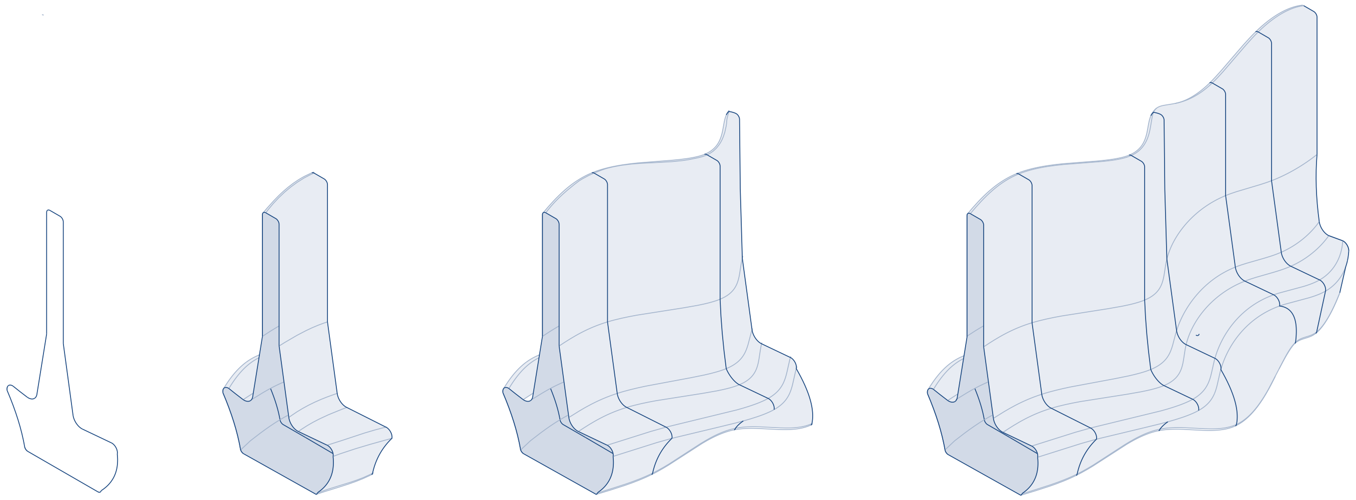


Figure 222: Concept Loft

In additive manufacturing, the printing direction typically follows a vertical approach, building the object layer by layer from the bottom to the top. In the case of this project, it was determined that printing the building component along its Z-axis would present challenges. With the LDM (Liquid Deposition Modelling) technique, achieving a closed surface in the seating area and avoiding collapse with the overhangs would be difficult.

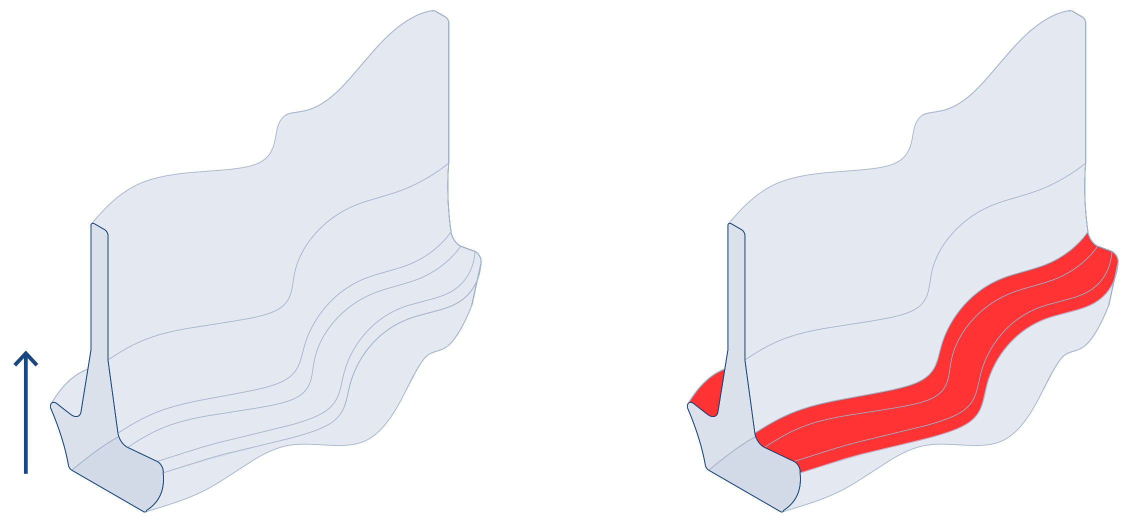


Figure 223: Problematic printing vertical approach

As a result, it was decided that the cross-section of the component should be parallel to the printing bed. By aligning the cross-section parallel to the printing bed, the printing process can be carried out more effectively and overcome the limitations posed by the Z-axis orientation. This approach ensures better stability and reduces the risk of structural issues during the printing process. Additionally, it allows for improved accuracy in achieving the desired shape and geometry of the component.

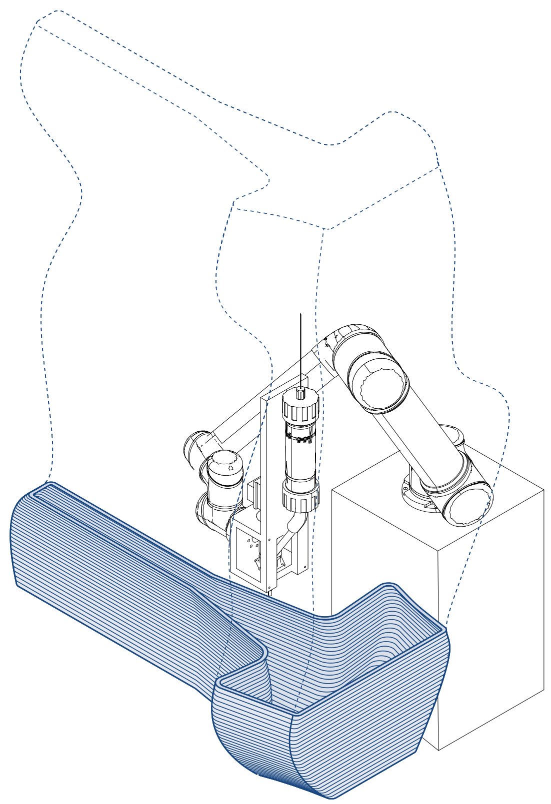


Figure 224: Printing direction

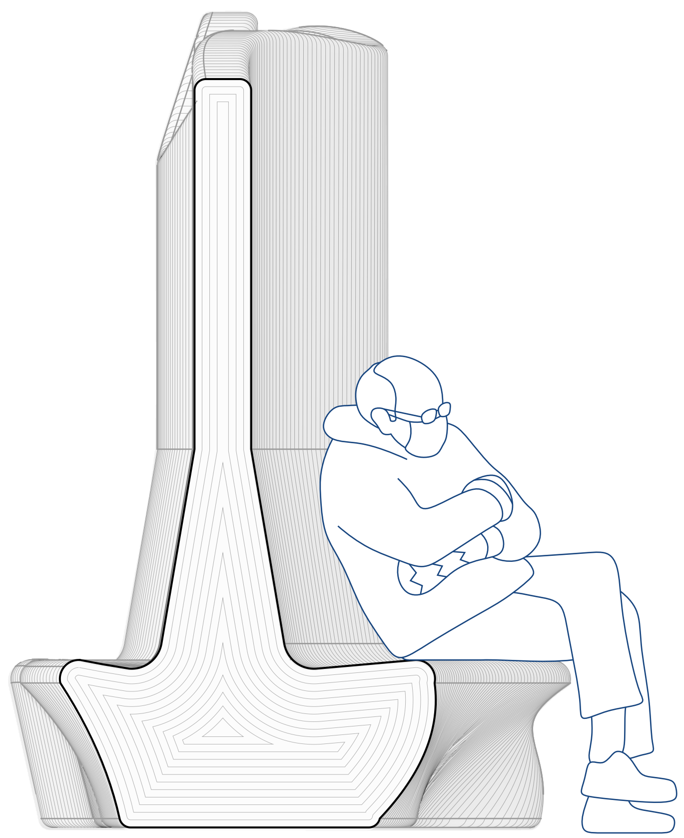


Figure 225: Elevation 1:20

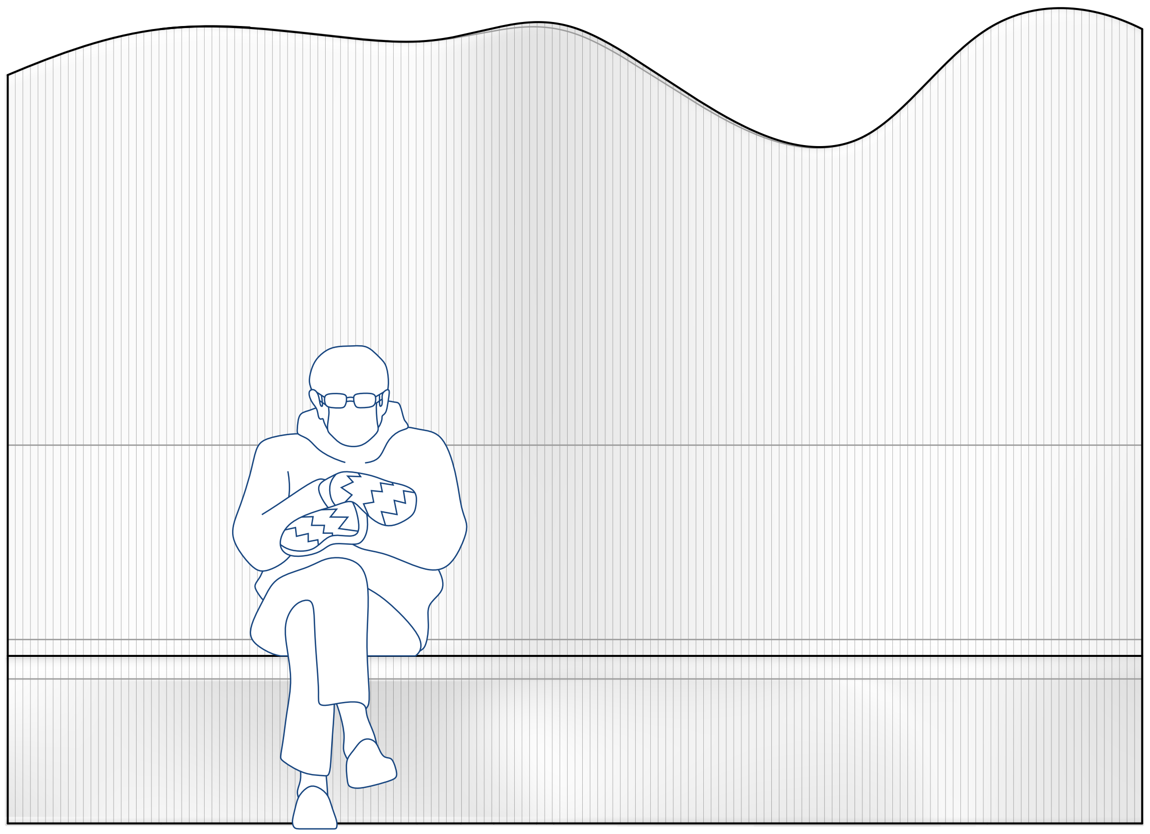


Figure 226: Elevation 1:20

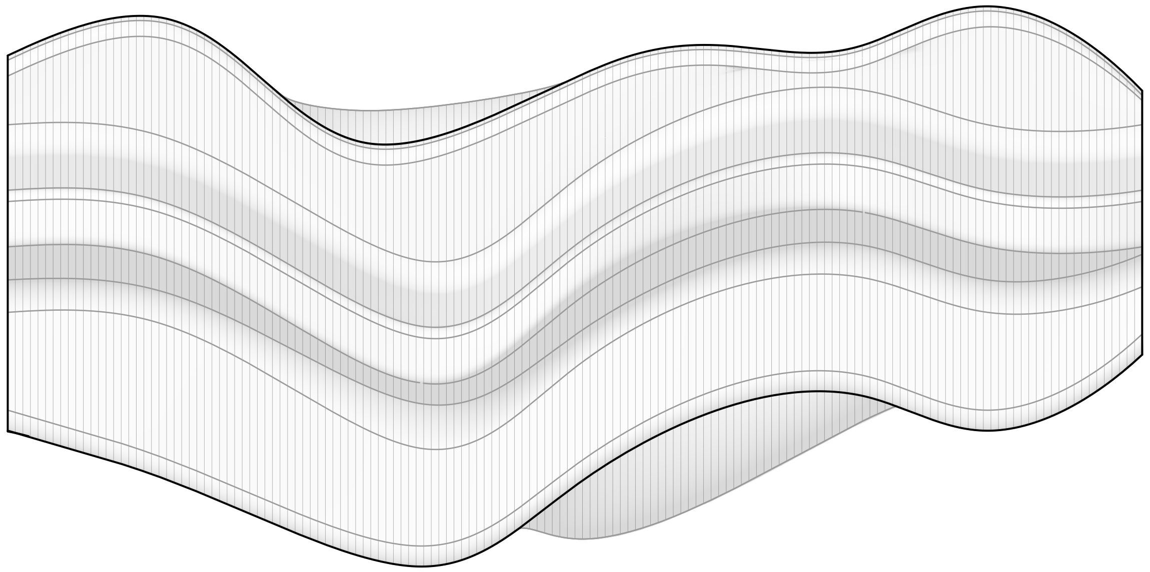


Figure 227: Plan 1:20

Additive manufacturing technologies offer the advantage of reducing material waste compared to conventional processes. When designing with conventional methods, a significant amount of material is often wasted as shown in Fig. 228. However, additive manufacturing allows for more efficient use of materials, as it enables precise deposition of material only where it is needed.

The chosen design represents just one of the countless possibilities that can be explored. Depending on the specific space and function where the component will be placed, alternative designs can be developed to meet specific requirements and constraints.

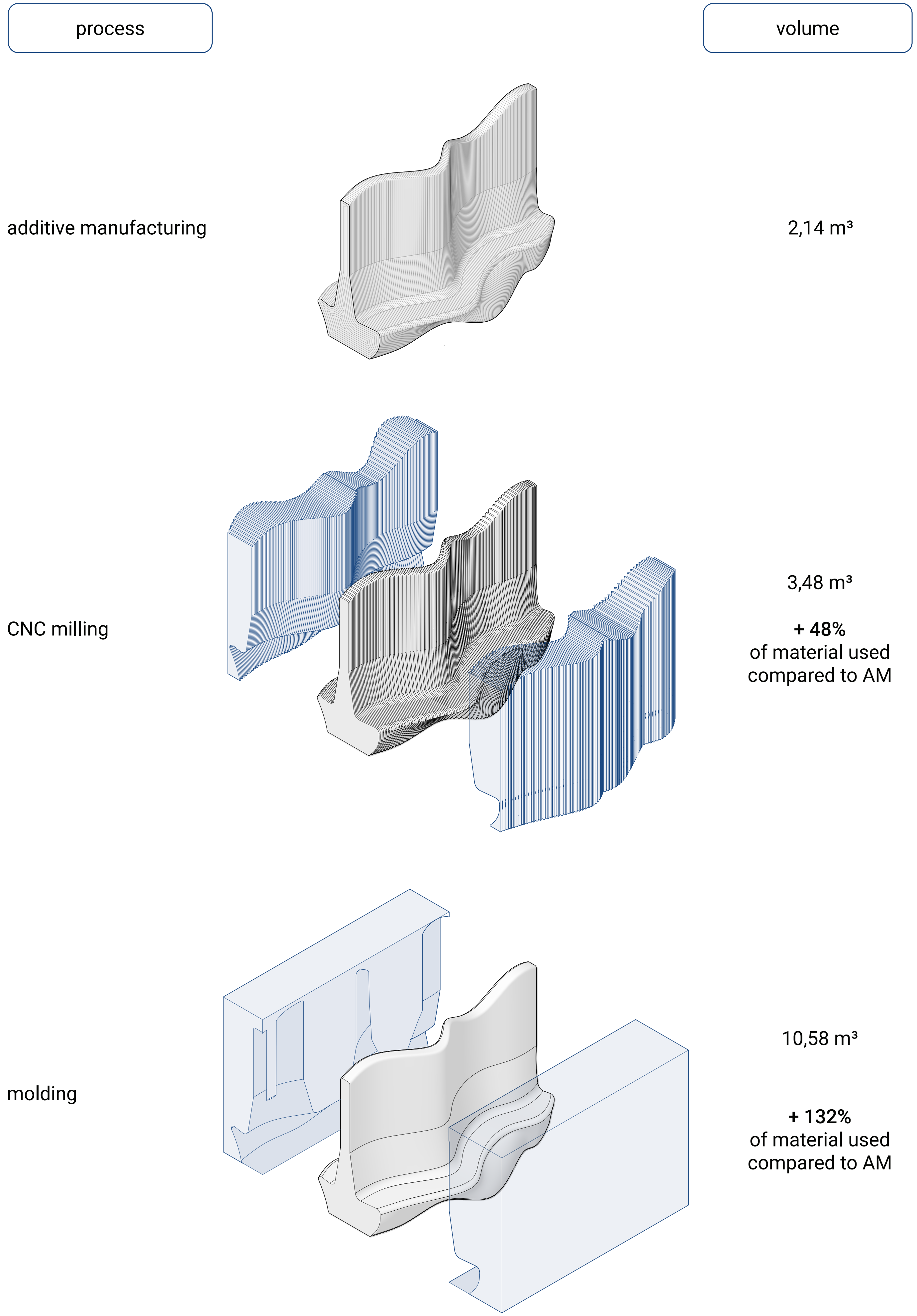
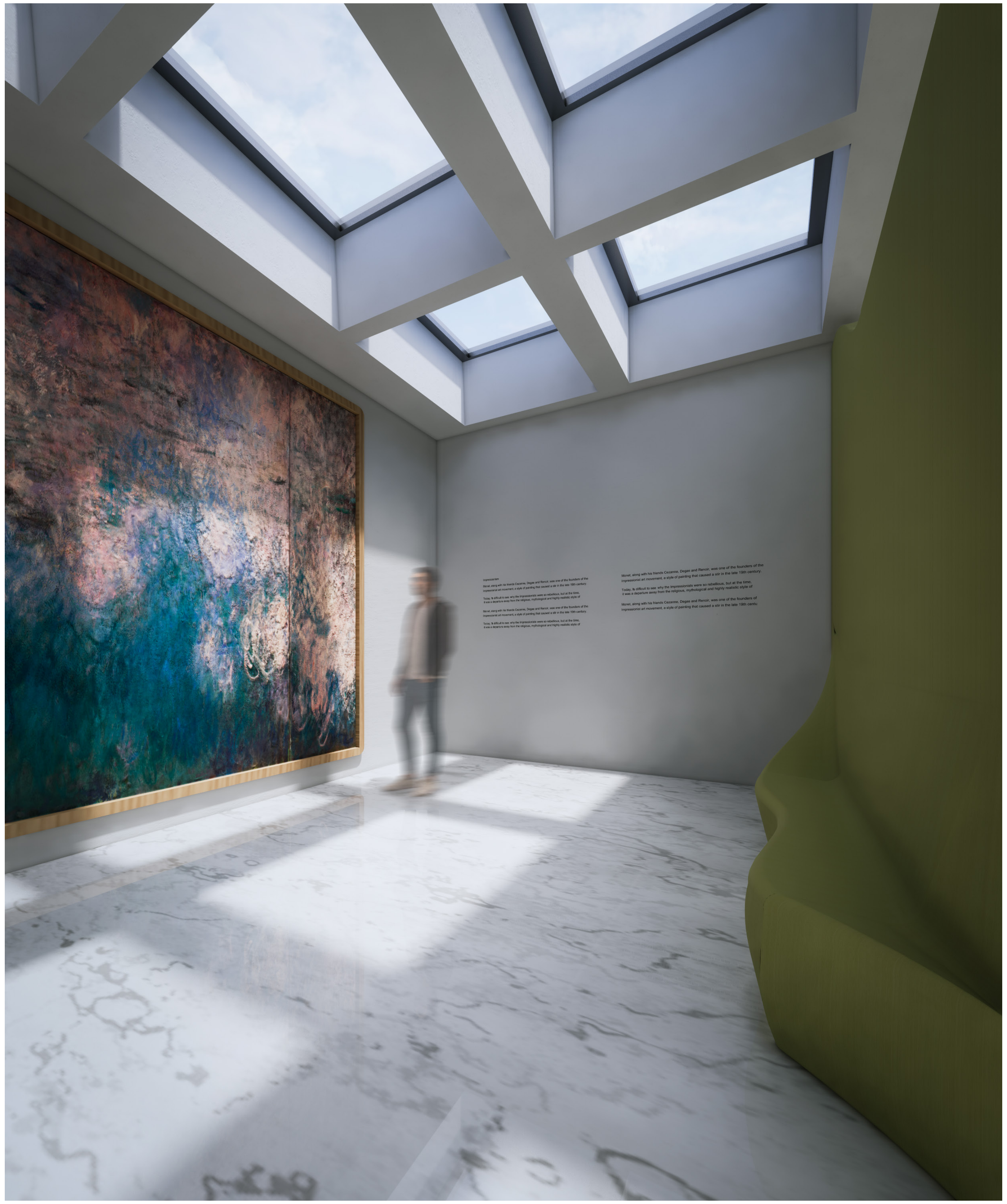


Figure 228: Traditional processes comparison

Figure 229: Render of building component applied in an office

Figure 230: Render of building component applied in a museum



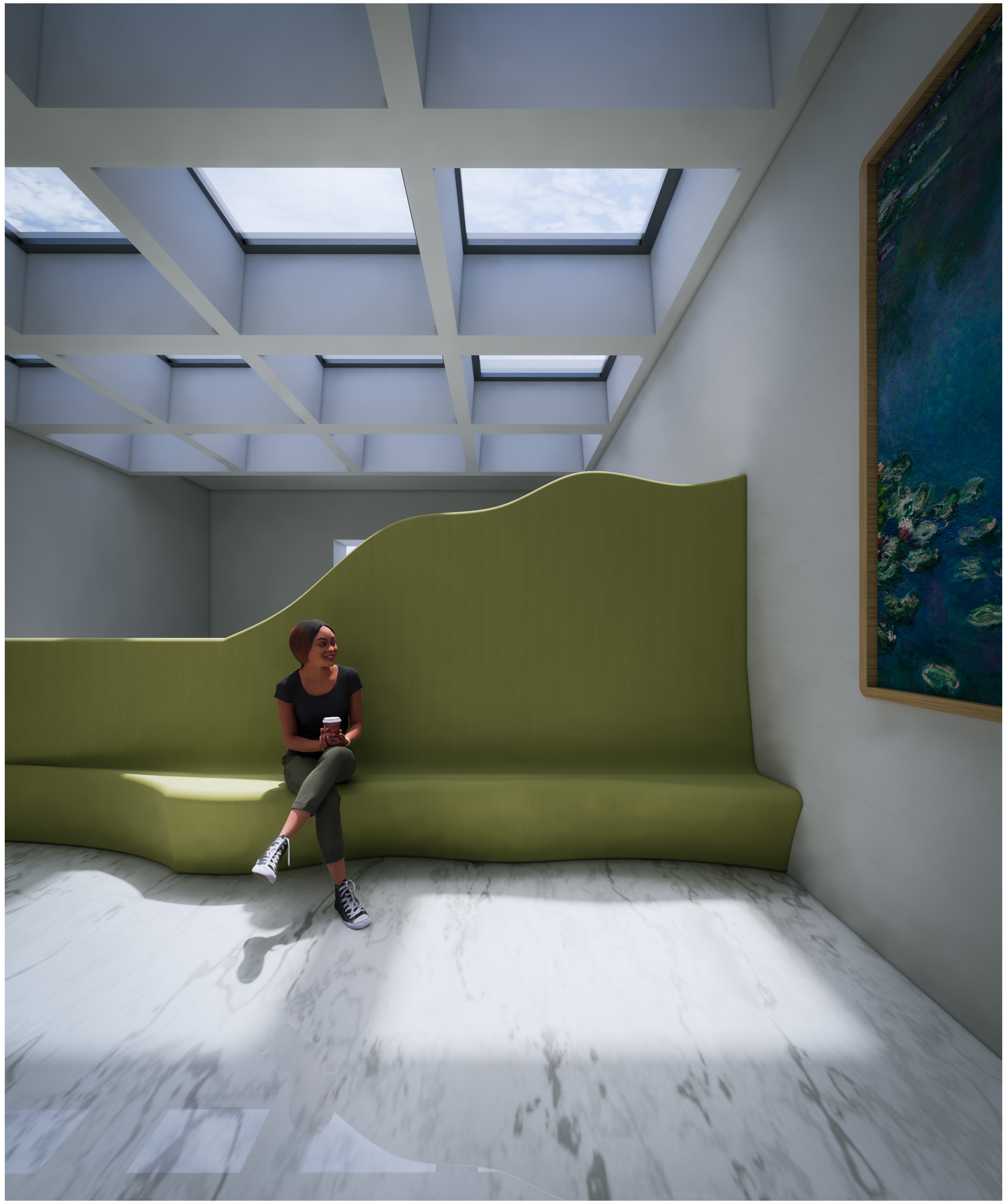


Figure 231: Render of building component applied in a museum

Figure 232: Render of building component applied in a museum

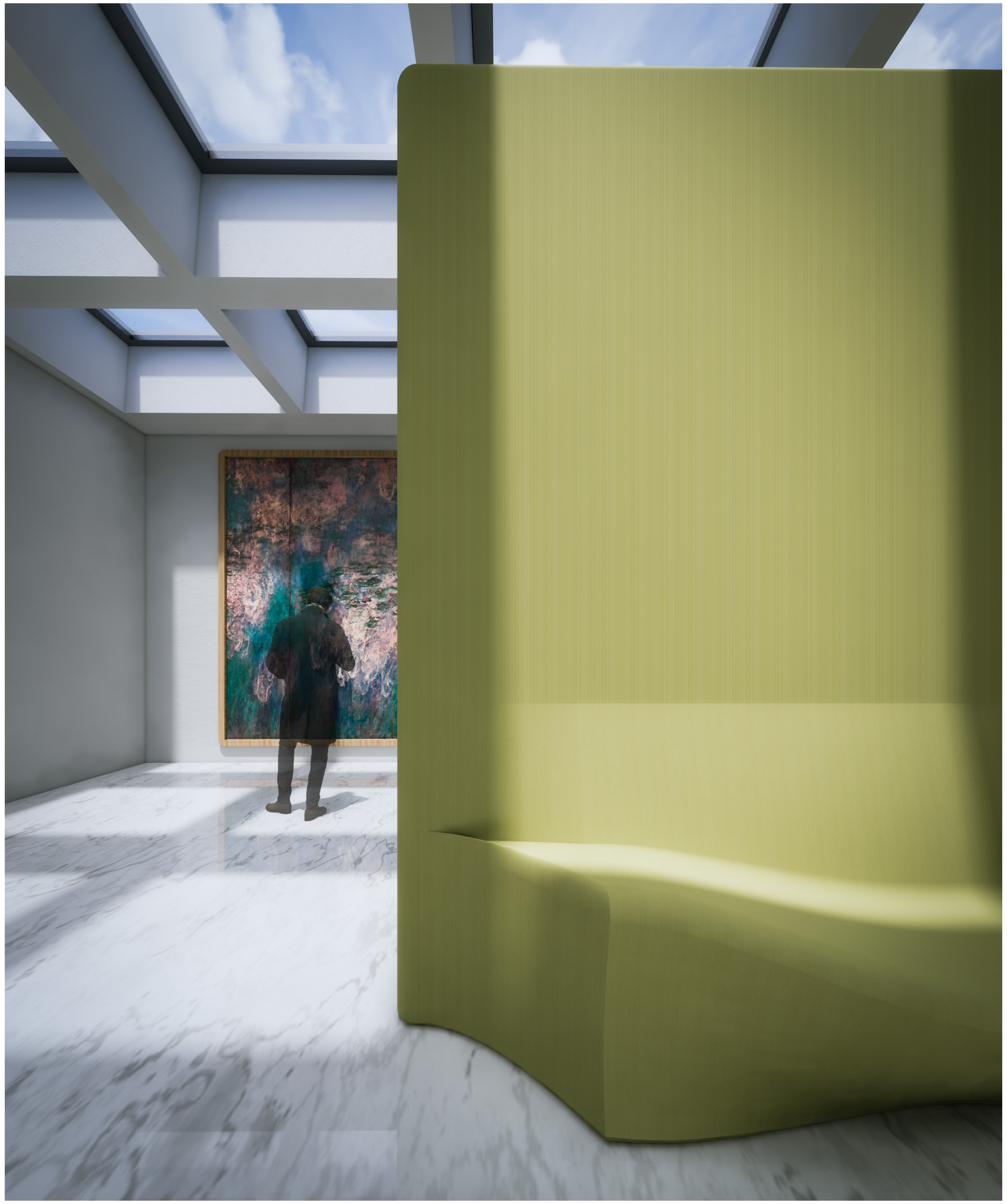


Figure 233: Render of building component applied in a museum

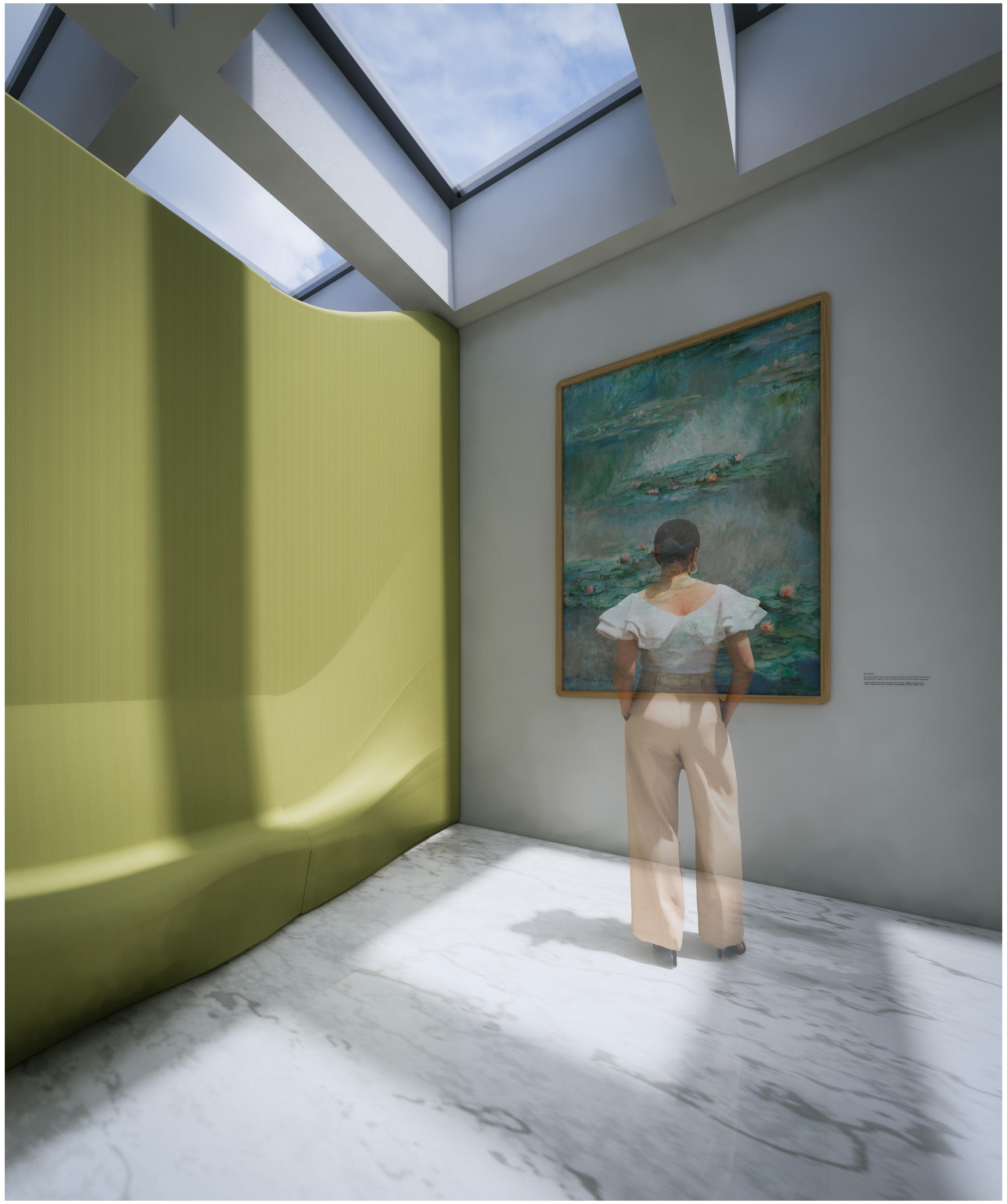


Figure 234: Render of building component applied in a museum

To allow for a more streamlined and efficient production process, the study will focus on a specific section, making the design and printing tasks more manageable. This approach helps to reduce complexity and potential challenges associated with printing the entire design, while still providing valuable insights into the structural performance and feasibility of the concept.

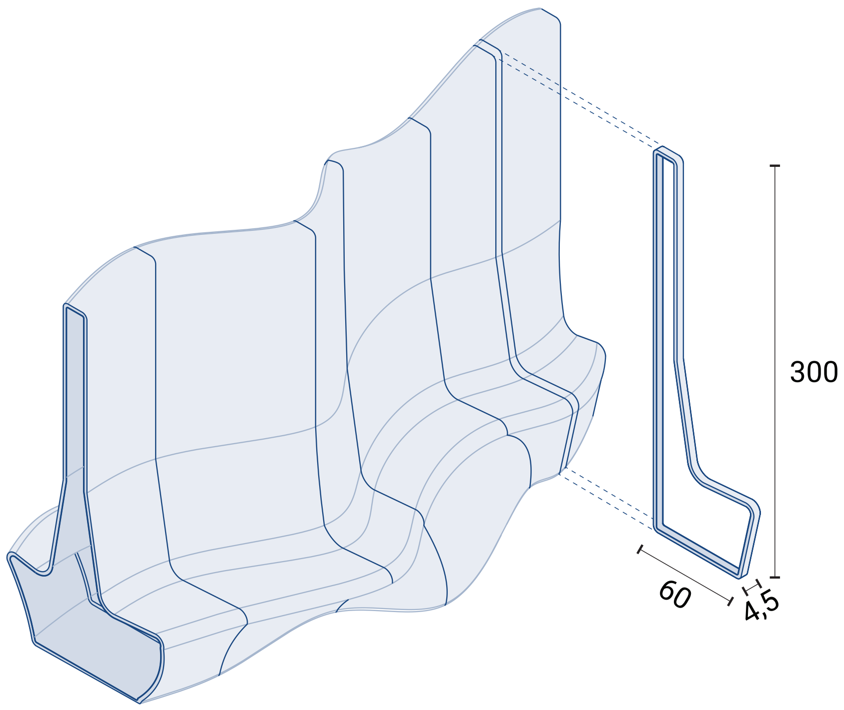
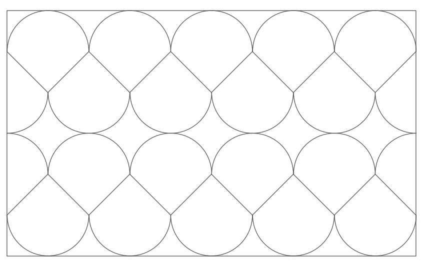


Figure 235: Specific section.

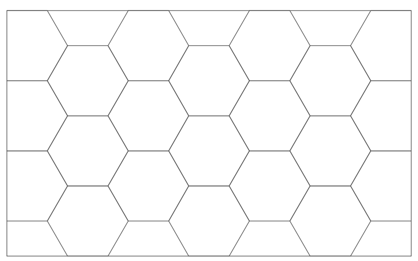
6.4 Design Infill

Mechanical testing was conducted to provide support in determining the most suitable geometry for the infill design. Although the specimens produced through additive manufacturing may not possess the same level of precision and reliability as those made from concrete, steel, or timber, the aim of the testing was to narrow down the options.



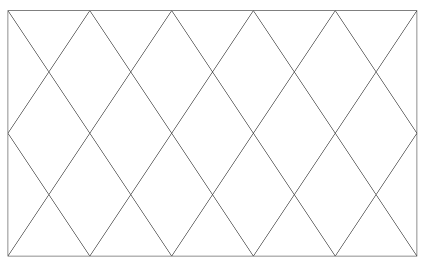
curved

This pattern was used in the previous thesis of Alexsander Coelho and Christopher Bierach.



honeycomb

The honeycomb infill is widely recognized as a popular choice due to its efficiency and strength. This infill pattern can be printed rapidly and offers substantial structural integrity, delivering strength in all directions.



rhombic

The rhombic geometry is specifically employed when strength is required primarily in the direction of the walls. This infill pattern is strategically designed to enhance the structural stability of the walls and provide reinforcement in the intended direction.

6.5 Mechanical test

The objective of the mechanical testing carried out in this study was twofold: to investigate the impact of potato starch on the geometry of the printed objects, and to improve the material's infill properties. As the field of bio-based materials for additive printing is still in its infancy, there are no established guidelines or standards for mechanical testing or test specimen creation. Therefore, this research is significant in comprehending the behavior of the potato starch mixture and laying the foundation for the development and evaluation of bio-based materials in additive manufacturing.

In summary, this study aims to advance the progress of bio-based materials for a wide range of applications by examining the mechanical characteristics of the potato starch combination and creating a framework for the testing and design of bio-based materials in additive manufacturing processes.

6.5.1 Experiment Design

The goal of this mechanical testing is to investigate how different specimen geometries perform under compression load, specifically to determine which geometry works best by analyzing at what load it fails and how it fails.
Three geometries were carefully chosen, designed, and printed, with three specimens for each geometry to enable a comparison between them. The specimens were dried and weighed before testing, and the direction of testing was perpendicular to the layers since the design is intended to bear loads in that direction. Compression testing was selected as the design primarily undergoes compression loads. The Mechanical Testing Lab at 3ME (Room 34 J-0-180) was utilized, and Dr. ir. Fred Veer provided assistance.

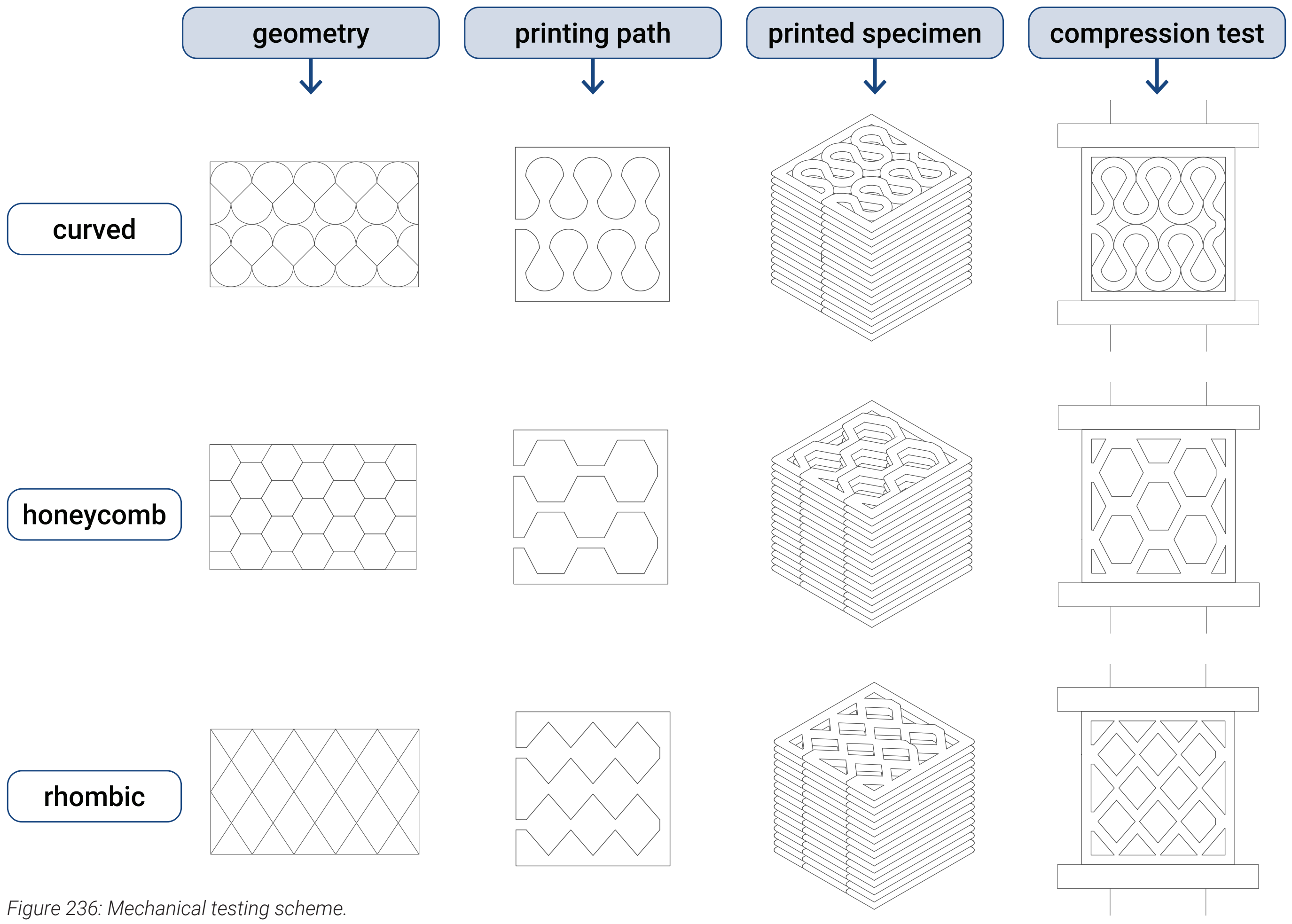


Figure 236: Mechanical testing scheme.

In order to conduct a compression test on the specimen, it is important to ensure that its orientation aligns with the printing orientation of the building component. As previously mentioned in the "Shape Design" section, the building component will be printed with its cross-section parallel to the printing bed. Therefore, to obtain accurate and reliable results, it is necessary for the specimen to have its layering oriented perpendicular to the compression plates, mirroring the orientation of the building component.
Aligning the specimen's layering perpendicular to the compression plates allows for a more direct evaluation of the structural performance and mechanical properties of the printed component. It ensures that the forces applied during the compression test are exerted in a manner that closely simulates the actual load-bearing conditions experienced by the building component in its intended application.

Pictures and videos of each specimen and numerical results from the machine were recorded, and the way in which the specimen failed was analyzed to gain valuable insights into selecting the appropriate infill geometry. The specimen results were compared to a table to determine the final geometry. This mechanical testing is a critical step in understanding the behavior of the potato starch mixture and developing a framework for designing and evaluating bio-based materials for additive manufacturing.

6.5.2 Specimen Printing

Regarding the design of the specimen to be able to make a good comparison the infill was designed inside a square 60 x 60 mm. Even if for the compression test it is suggested to have as cubic sample from the findings of the printability exploration it was thought to have a height of 40 mm instead of 60 mm since the higher it tries to print, the more probable that the shape would collapse or sag. This height though didn't prevent on a non-uniform shape, but this was already accounted since additive manufacturing doesn't allow the best precision.
The choice of the geometries for the infill are based on educated guessing. The curved that has a curved form that remind of a "insulation hatch" was chosen since it presents just curves and from the previous thesis of Alexsander and Christopher, they designed their prototype with a curved infill. The other linear infills are the ones usually applied in 3D printing which is the honeycomb and rhombic grid.
After the geometry is chosen the toolpath needs to be designed according to the printability exploration result, specifically the distance between the walls.
The dimensions of the geometries were tried to be as similar as possible. Taking into consideration the size of the nozzle used (4mm) and the distance between the walls. With the printing test made the final geometries that were printed are illustrated below.

Three specimens for each geometry was planned to be printed, with a total of 9 specimens to be mechanically test.
The selected mixture with the green dust ran out before being able to print all of them. Only 1 specimen for each geometry was printed. The other dust was used to print the remaining specimens since the goal was not to analyze the material properties but the effect of the geometry. Regardless it was also relevant to see differences of the results that confirmed the choice of the mixture using the green dust.
In this printing, mold didn't develop since they were put in the hydrator right after the printing was done, this is also a relevant result that is accounted in the printability exploration.

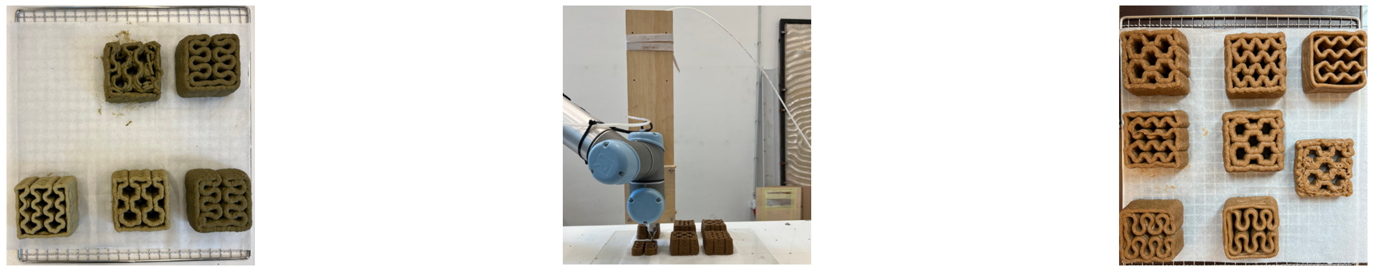


Figure 237: Specimen printing process.

1A_Curved Infill

Figure 238: Dried specimen.

During the mechanical testing, it was observed that specimen 1A began to split first in the opening of the infill at the junction of the curve, and then later at the upper corner. The splitting caused the specimen to divide and detach, and the most fragile points were identified to be at the highest and lowest points of the curve.

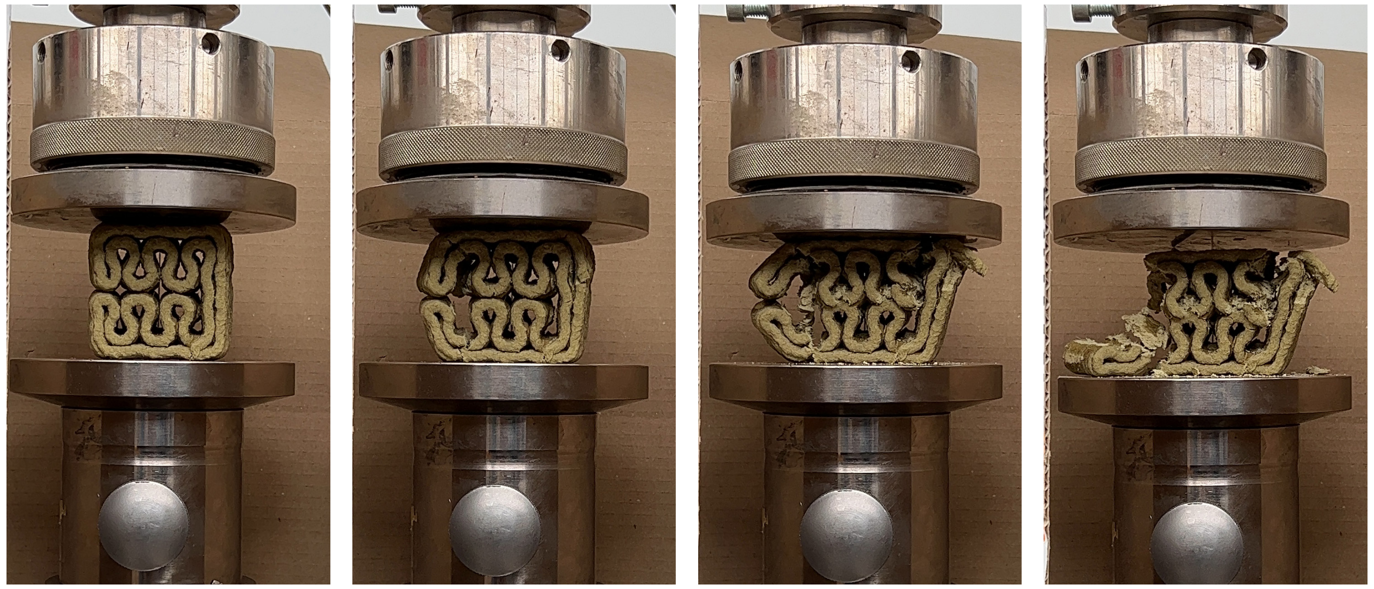
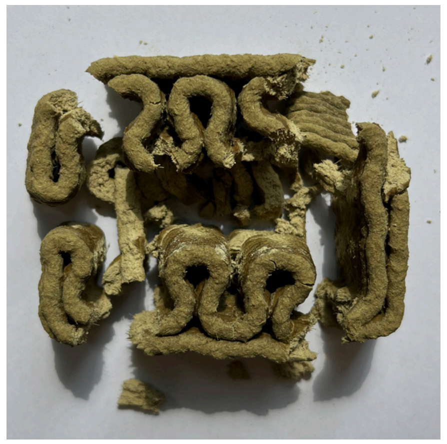
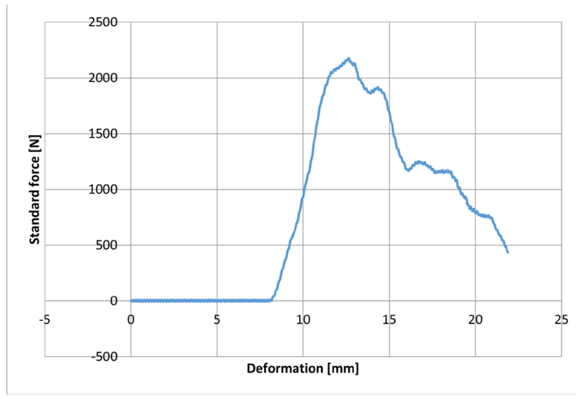


Figure 239: Compression phases.





Specifics:

Weight 72 g

F max 2177 N
dL at F max 12,6 mm

F break 435 N
dL at F break 21,8 mm

Figure 240: Compressed specimen.

2A_Curved Infill

Figure 241: Dried specimen.

On the other hand, specimen 2A exhibited a different pattern of breakage. The upper corner of the curve separated and the specimen broke along the curvature, with the back of the specimen breaking first as it was the first contact with the plates.

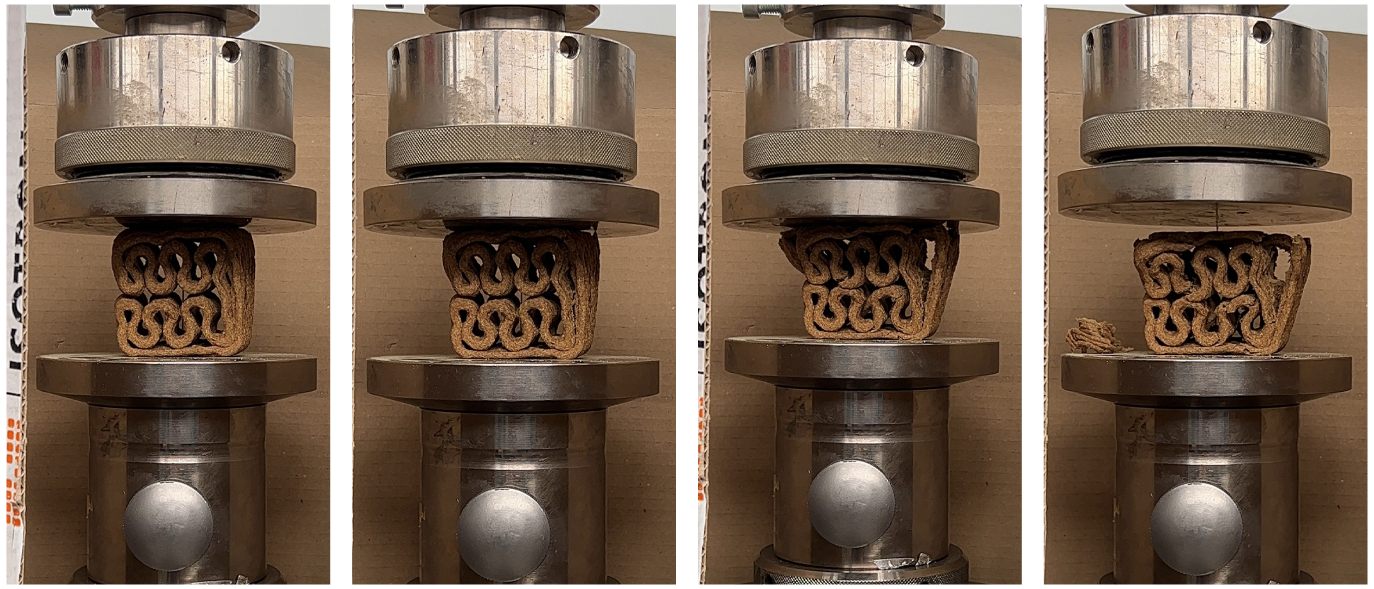
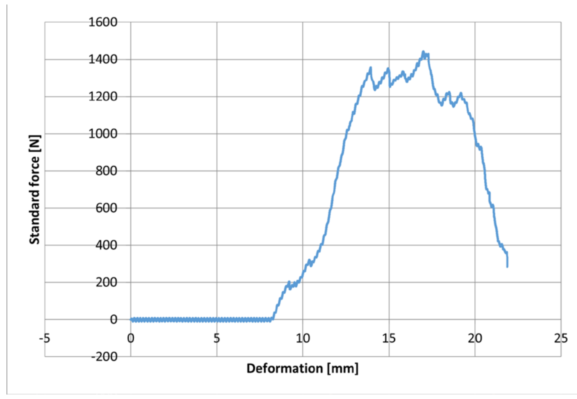


Figure 242: Compression phases.

Figure 243: Compressed specimen.



Specifics:

Weight	43,6 g
F max	1443 N
dL at F max	16,9 mm
F break	283N
dL at F break	21,8 mm

3A_Curved Infill

Figure 244: Dried specimen.

Specimen 3A showed a similar pattern of breakage to 2A, where the outer layers broke first. These observations were made during the mechanical testing and were recorded through pictures and numerical results extracted from the testing machine. The findings provide useful insight into the behavior of the specimens under compression load and aid in the selection of the most suitable infill geometry.

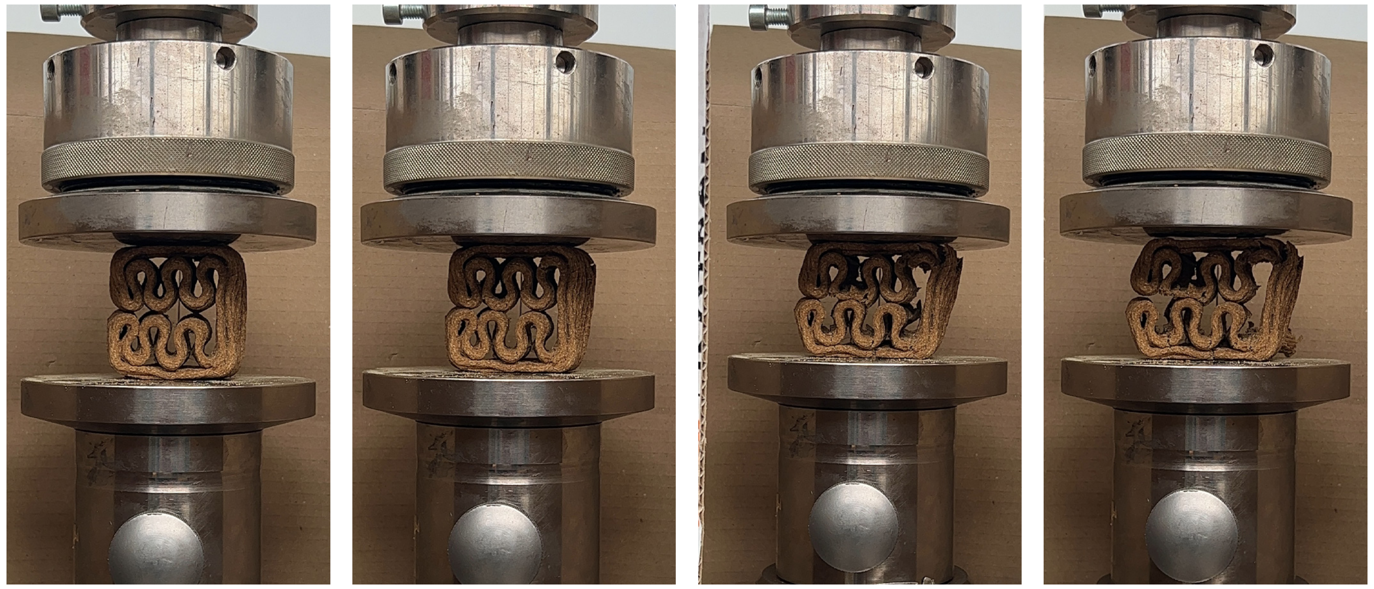
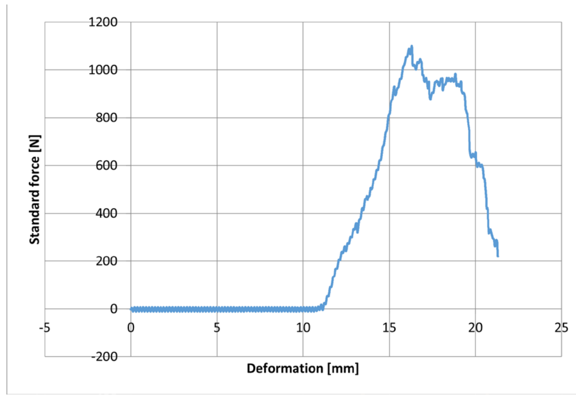


Figure 245: Compression phases.

Figure 246: Compressed specimen.



Specifics:

Weight	34,9 g
F max	1099 N
dL at F max	16,3 mm
F break	219 N
dL at F break	21,3 mm

1B_Honeycomb Infill

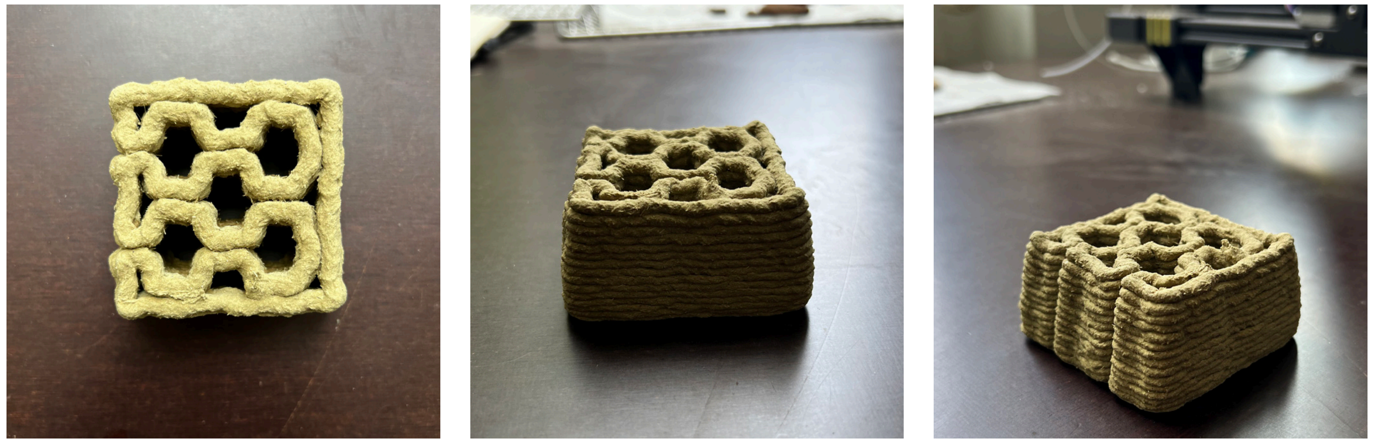


Figure 247: Dried specimen.

For 1B, the upper corner of the specimen would break first, while the hexagonal infill showed resilience, not breaking immediately but after some expansion. The break was more prominent on the vertices part of the hexagon, while the opened part did not break.

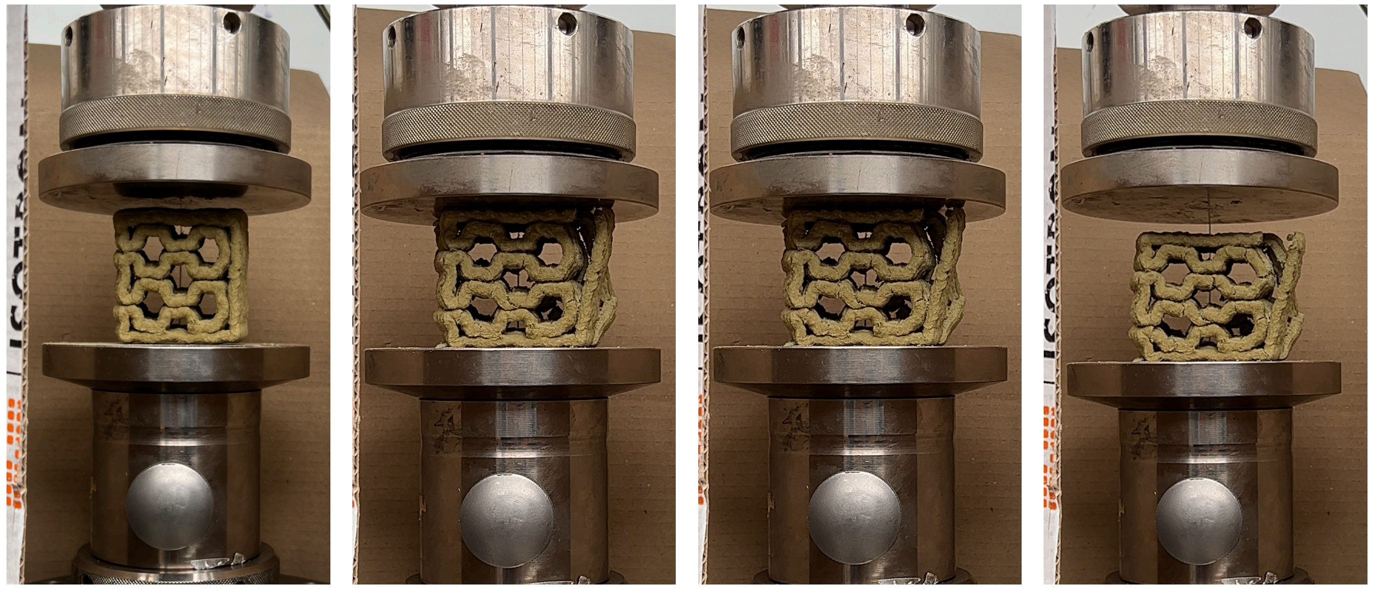
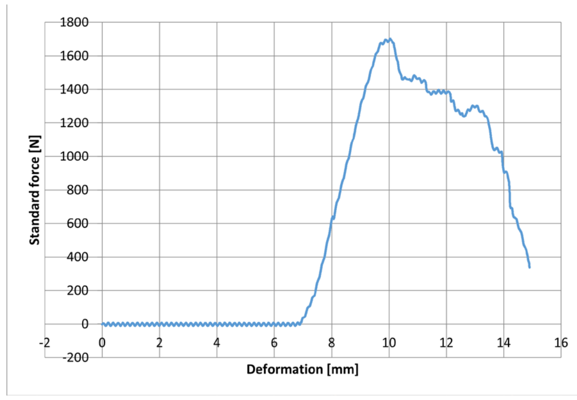


Figure 248: Compression phases.



Specifics:

Weight	66,8 g
F max	1702 N
dL at F max	10 mm
F break	337 N
dL at F break	14,9 mm

Figure 249: Compressed specimen.

2B_Honeycomb Infill

Figure 250: Dried specimen.

For 2B, no significant break was observed, but the outer perimeter of the specimen cracked halfway up its height.

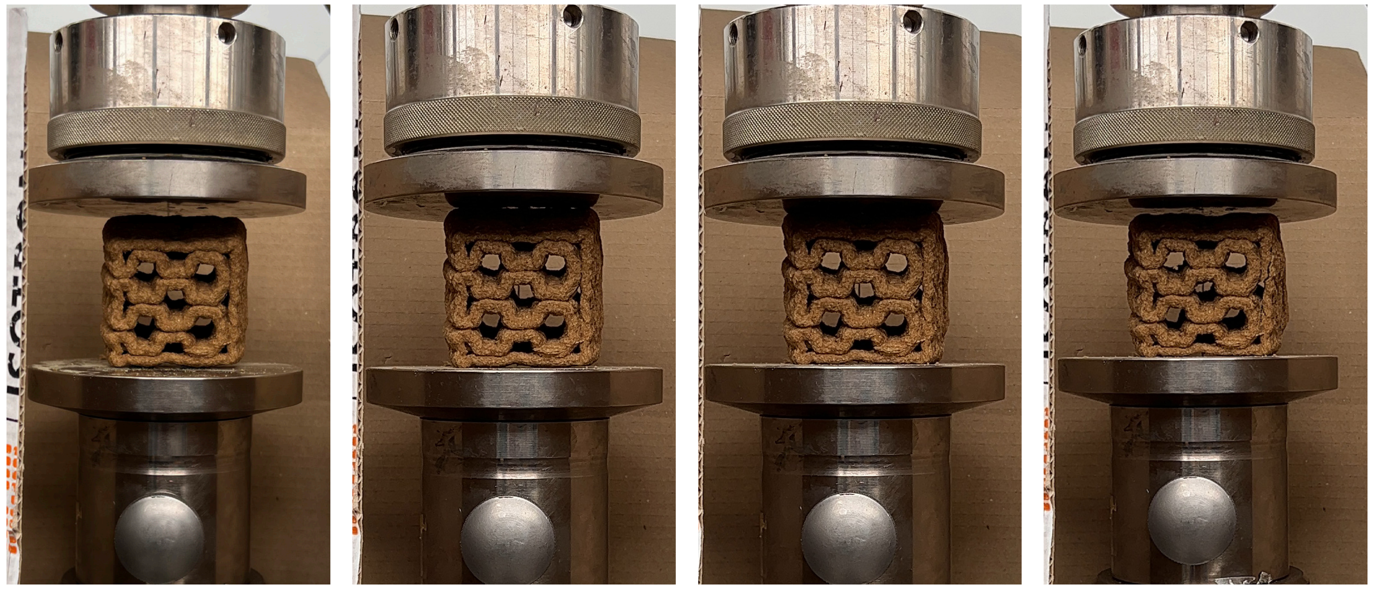
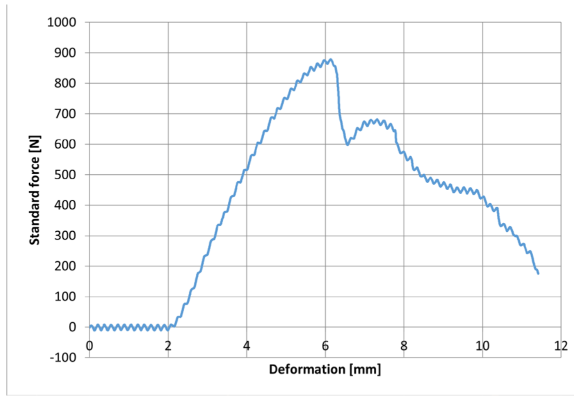


Figure 251: Compression phases.



Specifics:

Weight	68,5 g
F max	879 N
dL at F max	6,13 mm
F break	175,5 N
dL at F break	11,4 mm

Figure 252: Compressed specimen.

3B_Honeycomb Infill

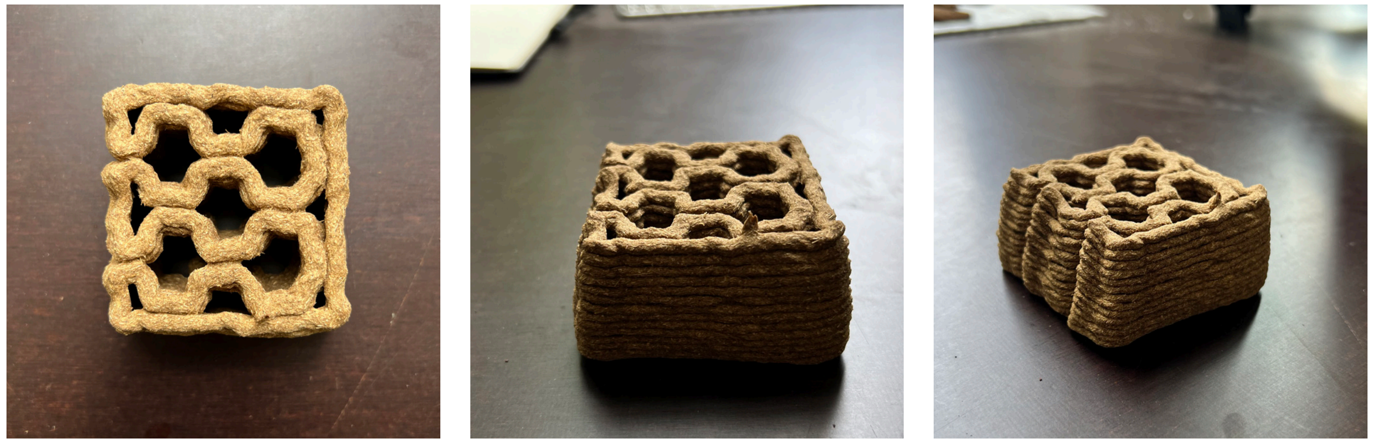


Figure 253: Dried specimen.

For 3B, one side of the specimen detached completely from the infill, but the geometry remained intact.

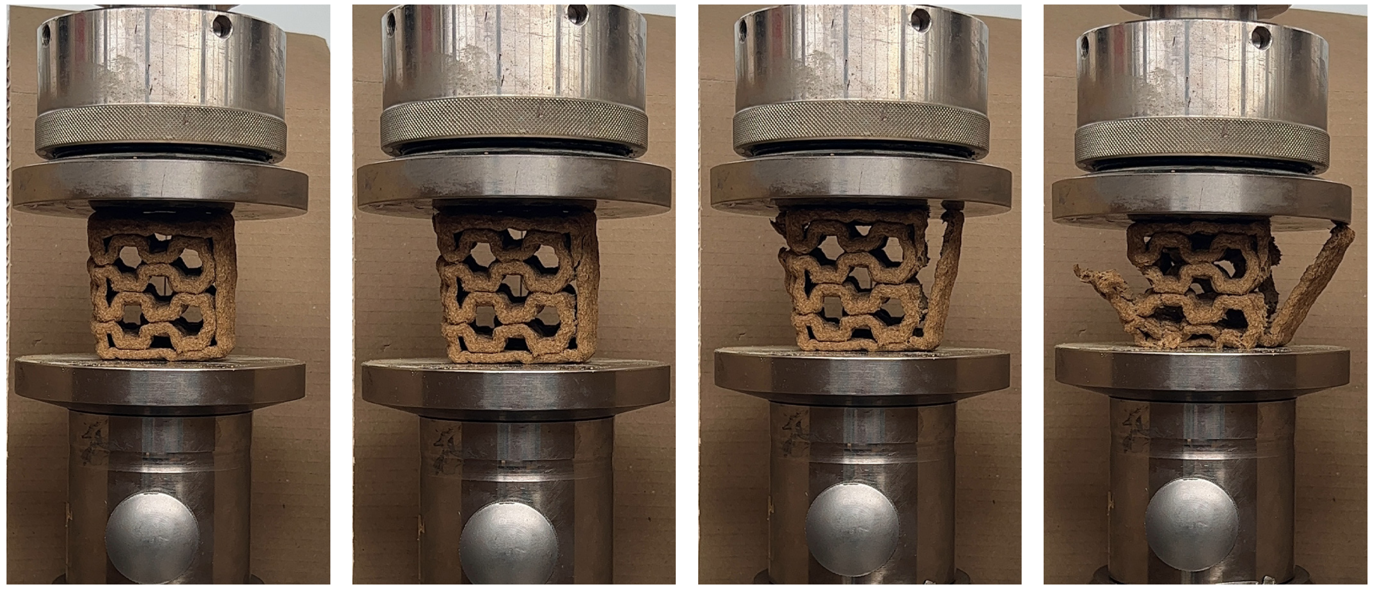
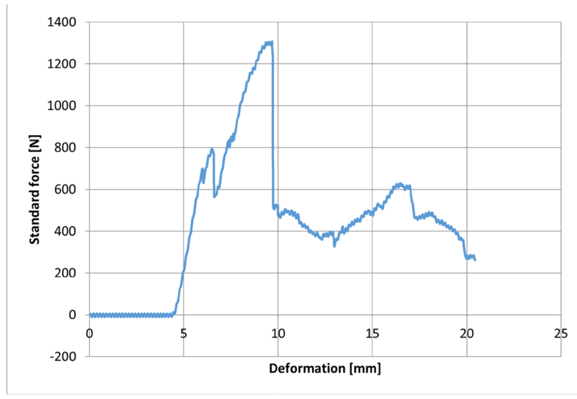


Figure 254: Compression phases.

Figure 255: Compressed specimen.



Specifics:

Weight	45,7 g
F max	1308 N
dL at F max	9,6 mm
F break	261,7 N
dL at F break	20,4 mm

1C_Rhombic Infill

Figure 256: Dried specimen.

Regarding the third set of specimens with the rhombic grid infill (type C), the mechanical testing results showed that the weakest point of the geometry was at the vertices. In specimen 1C, the side detached from the vertices and broke, splitting the specimen in half.

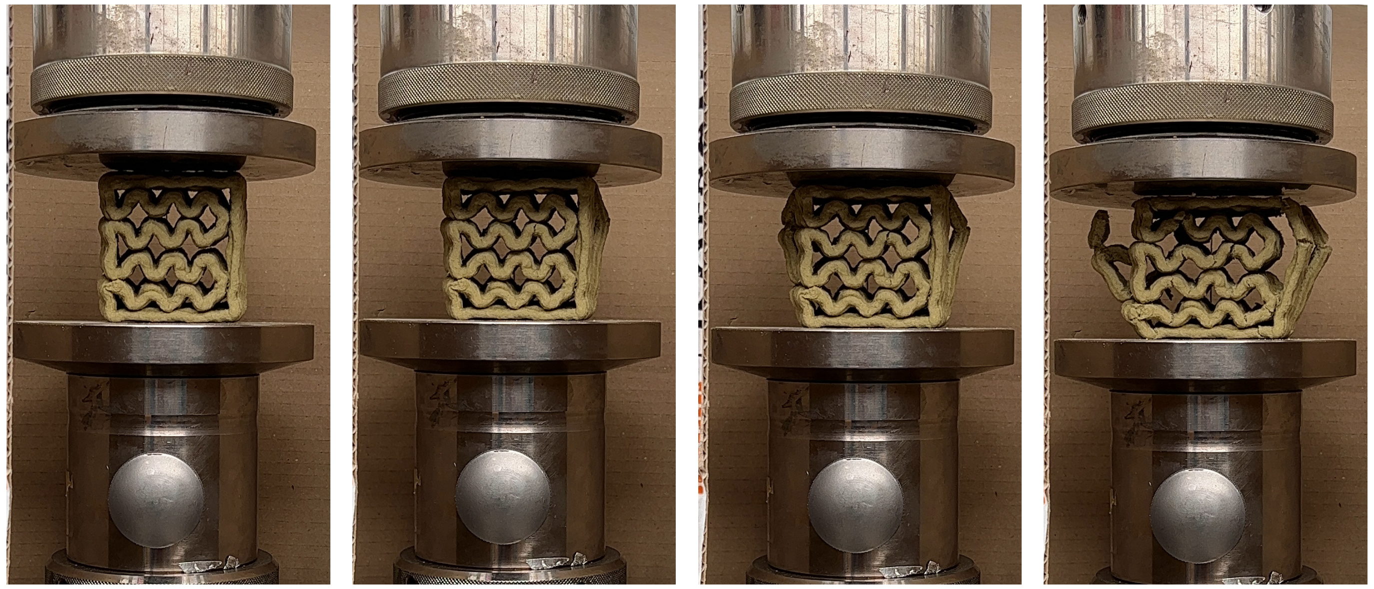
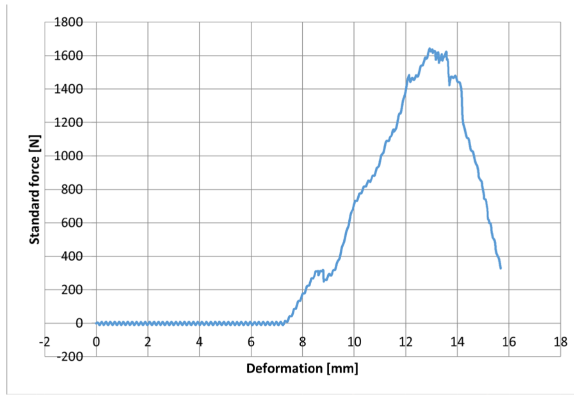


Figure 257: Compression phases.

Figure 258: Compressed specimen.



Specifics:

Weight	62,2 g
F max	1641 N
dL at F max	12,9 mm
F break	327 N
dL at F break	15,6 mm

2C_Rhombic Infill

Figure 259: Dried specimen.

A similar result was observed in specimen 2C, where the side detached from the vertices and the lower part completely cracked at the point where the vertices were in contact.

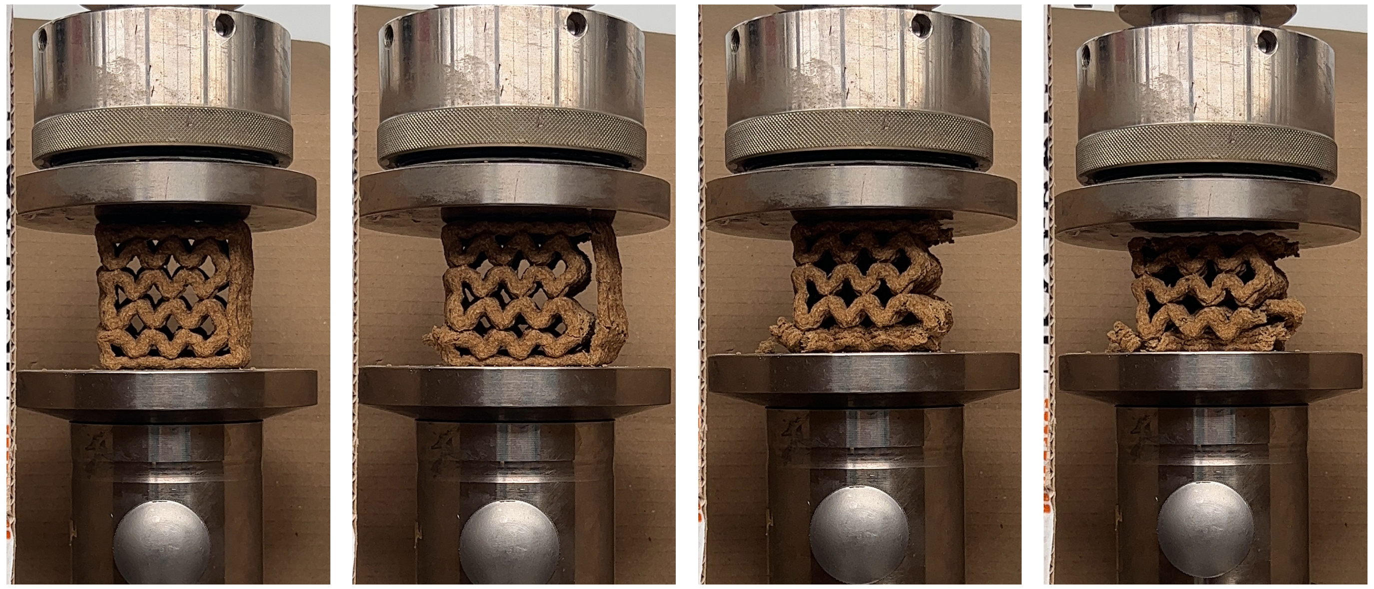
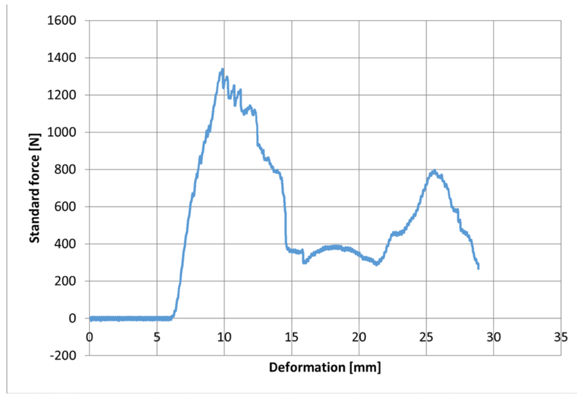


Figure 260: Compression phases.



Specifics:

Weight	53,6 g
F max	1339 N
dL at F max	9,87 mm
F break	265 N
dL at F break	28,8 mm

Figure 261: Compressed specimen.

3C_Rhombic Infill

Figure 262: Dried specimen.

However, in specimen 3C, the side also detached from the vertices, but the geometry did not break significantly.

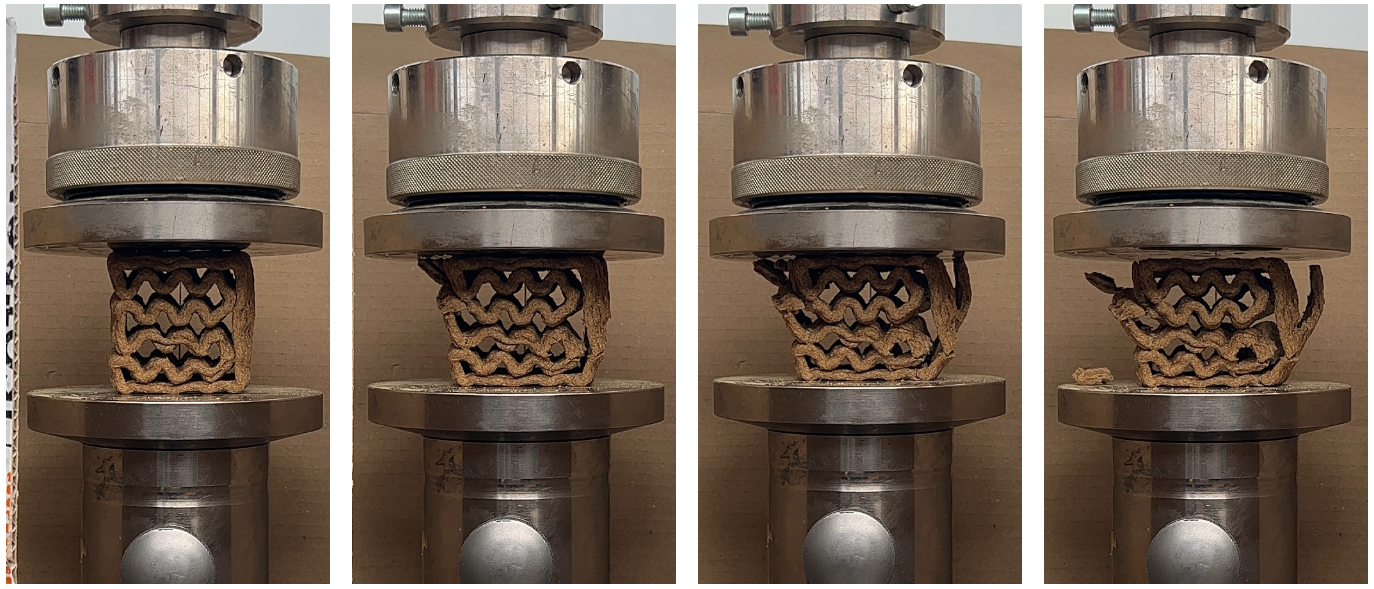
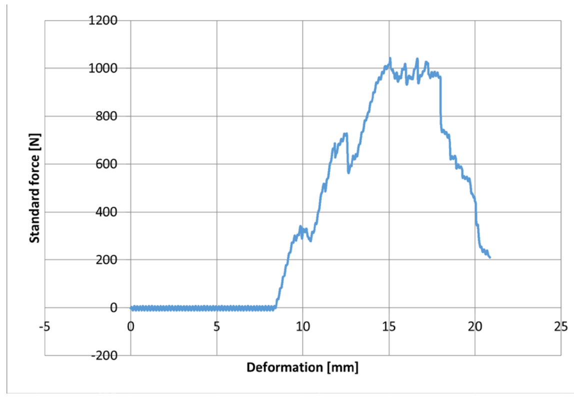


Figure 263: Compression phases.

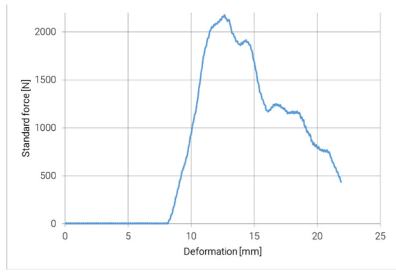
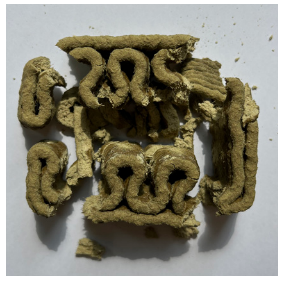
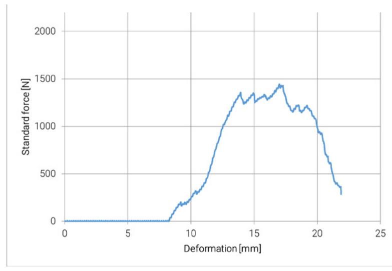
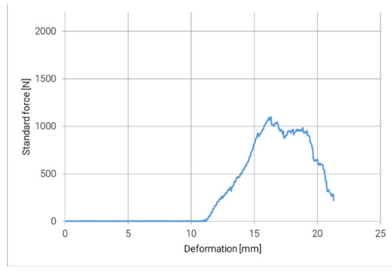
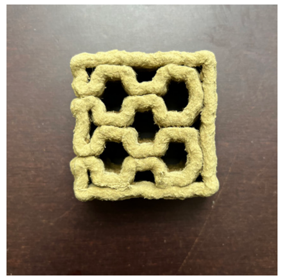
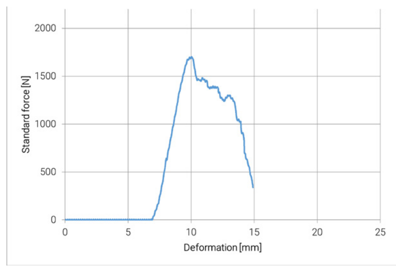
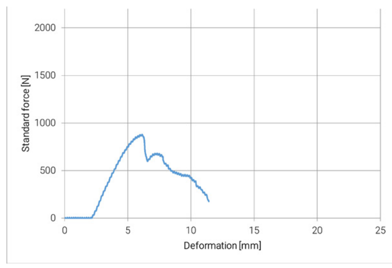
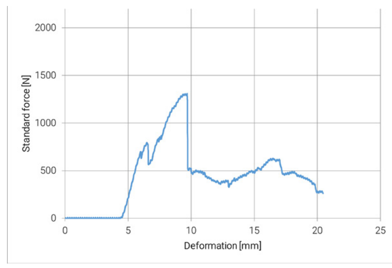
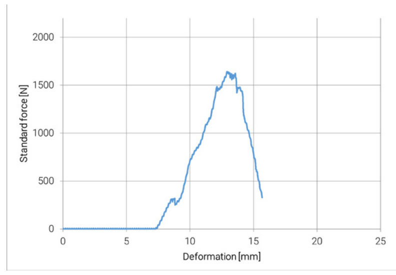
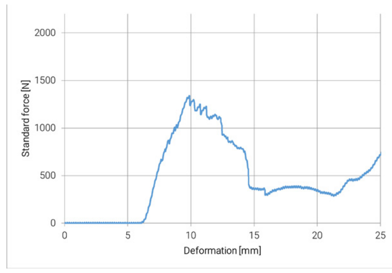
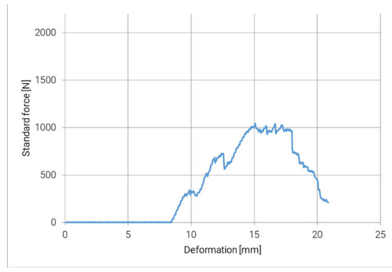


Specifics:

Weight	40,1 g
F max	1043 N
dL at F max	15,1 mm
F break	208 N
dL at F break	20,8 mm

Figure 264: Compressed specimen.

6.5.3 Results

Mixture / Geometry	Dust + Fibers *Sasa tsuboiana* + 200400 SF	Dust + Fibers 0100 + 200400 SF	
Curved	**1A** Weight 72 g F max 2177 N dL at F max 12,6 mm F break 435 N dL at F break 21,8 mm   	**2A** Weight 43,6 g F max 1443 N dL at F max 16,9 mm F break 283N dL at F break 21,8 mm   	**3A** Weight 34,9 g F max 1099 N dL at F max 16,3 mm F break 219 N dL at F break 21,3 mm   
Honeycomb	**1B** Weight 66,8 g F max 1702 N dL at F max 10 mm F break 337 N dL at F break 14,9 mm   	**2B** Weight 68,5 g F max 879 N dL at F max 6,13 mm F break 175,5 N dL at F break 11,4 mm   	**3B** Weight 45,7 g F max 1308 N dL at F max 9,6 mm F break 261,7 N dL at F break 20,4 mm   
Rhombic	**1C** Weight 62,2 g F max 1641 N dL at F max 12,9 mm F break 327 N dL at F break 15,6 mm   	**2C** Weight 53,6 g F max 1339 N dL at F max 9,87 mm F break 265 N dL at F break 28,8 mm   	**3C** Weight 40,1 g F max 1043 N dL at F max 15,1 mm F break 208 N dL at F break 20,8 mm   

6.5.4 Summary of Findings

It is important to note that all specimens were irregular and none were identical, even when the same geometry was used. The shape of the specimens tended to be more trapezoidal rather than cubic, which is to be expected given the nature of additive manufacturing. Nevertheless, the results were interesting.

From a visual failure perspective it was found that the more wall contact a geometry had, the more resistant it was to breaking. These results suggest that the rhombic grid infill may not be the strongest option compared to the other infill geometries tested. The detachment of the sides from the vertices indicates that there may be insufficient bonding between the infill and the outer walls, which is a potential weakness that could affect the overall strength of the structure. It is also worth noting that while the rhombic grid infill did not break significantly in any of the specimens, it did show signs of detachment and cracking, which could be a concern for applications requiring high strength and durability.
Conversely, the less contact it had, the more likely it was to detach, as was observed with the triangular infill. Specimens with more space, such as the vertices of the hexagon and the curve, were more prone to cracking. However, having a double wall increased the resistance of the specimens significantly, as was observed with the hexagon. The corner represent the most vulnerable point of the specimens.

Figure 265: Vulnerable points.

As a result of using unconventional fabrication techniques, such as uneven mixing, insufficient printing, and inconsistent curing, along with inherent dimensional differences among specimens, the test outcomes demonstrate significant variability across all material mixes. Consequently, relying solely on average values would not accurately represent the precise outcomes, as significant deviations exist. Therefore, the values obtained from the graph were taken with a substantial margin of error, providing valuable insights rather than precise measurements.

Analyzing the maximum force each specimen can withstand before experiencing plastic deformation, it is evident that the curved infill demonstrates superior resistance compared to the other specimens, while the rhombic infill exhibits the least resistance.

Regarding the mixture comparison, it was not the original intention to compare the two dusts. However, due to material scarcity, the decision was made to use the alternate dust. Nonetheless, it was observed that the mixture containing the green dust exhibited better resistance than the 0100 dust.

6.5.5 Conclusion

Determining the best infill pattern is challenging, but a comparison can be made to identify which pattern performed better than others. The rhombic infill is excluded due to its lower stability from both a geometrical and numerical standpoint. While the curved infill showcased better stability, it should be noted that in terms of the amount of mixture used, the curved infill required the most quantity as it was denser than the others, potentially contributing to its higher numerical values and improved performance.

The honeycomb infill pattern emerges as the preferred choice. Its selection is primarily based on the fact that it demonstrated improved structural stability due to the double wall configuration. However, it should be acknowledged that cracking occurred at the vertices of the honeycomb pattern.
Overall, while the irregularity of the specimens makes direct comparisons between them difficult, the findings suggest that the design of the infill geometry and wall thickness can have a significant impact on the strength and durability of 3D printed objects.

Considering the available rounded nozzle and the optimal movement of the printing robot, the insights gained from this mechanical testing guided the design of a customized geometry specifically tailored to facilitate the printing process. The proposed design features a honeycomb pattern with double walls to enhance structural stability, while the absence of sharp angles is addressed by employing curved lines as substitutes.

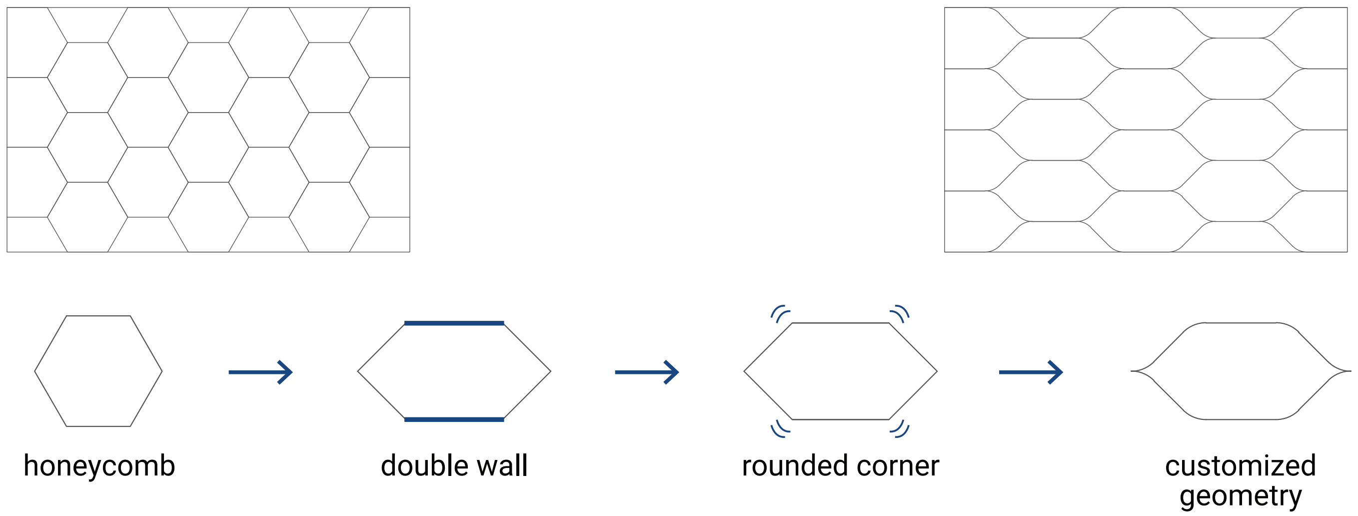


Figure 266: Customed geometry.

6.6 Mechanically Informed Infill

Additive manufacturing enables the realization of complex designs, not only in terms of visual aesthetics but also in terms of performance. By utilizing a grasshopper script, the material distribution of the component can be optimized within a specified space, considering loads and boundary conditions. This optimization process involves iteratively refining the material distribution.
To optimize the use of material and create a mechanically efficient infill, it is important to consider that the load on the component is not uniformly distributed. Therefore, it is unnecessary to have the same percentage of density in the entire geometry. Instead, the goal is to create an infill that is mechanically informed and tailored to the loads on specific parts of the component.

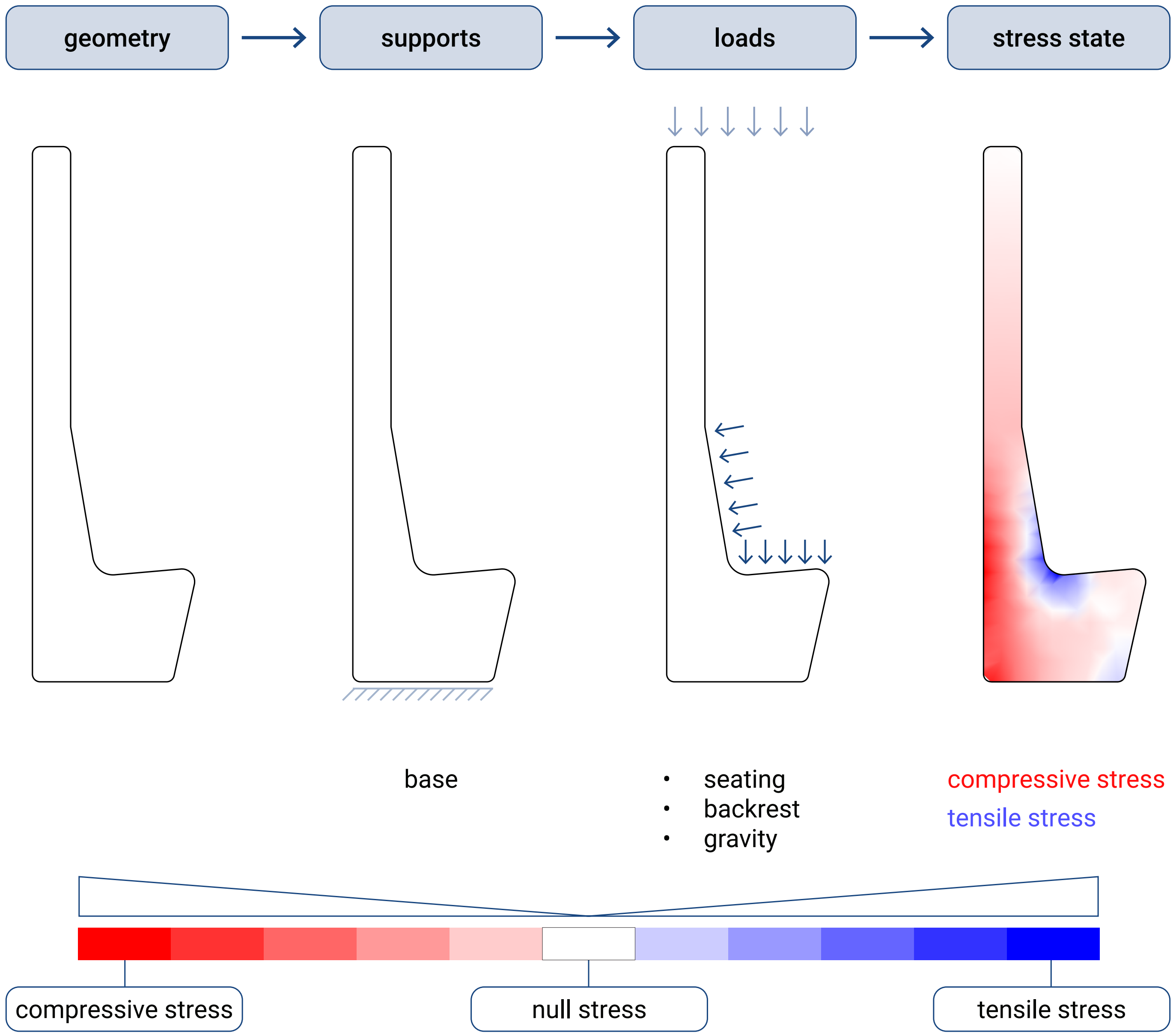


Figure 267: Color gradient parameters.

The idea is developed further with the selected section of the component as already stated. A structural analysis was conducted using Karamba, a Grasshopper plug-in, the results show the utilization, meaning the percentage of how much of material is used in that area.
The color gradient utilized in this study is divided into two distinct charts, each displaying opposite but equally intense expressions. These charts consist of three parameters: red and blue, representing the color legend's limits for compressive and tensile stress, respectively, while the color white represents a neutral or null stress state. The transitional gradients between these extreme colors form the intermediate shades.

6.6.1 Variable Thickness

To achieve a mechanically informed infill design, a consistent pattern dimension is employed throughout the component, while allowing for variable thickness. The results obtained from the mechanical testing reveal that a double wall configuration provides increased resistance. As a result, as the color intensity increases, the corresponding walls are designed to be thicker, accommodating the higher stress levels associated with the more intense colors. This approach ensures that the infill design is optimized to withstand varying stress conditions based on the color gradient, enhancing the overall performance of the component.

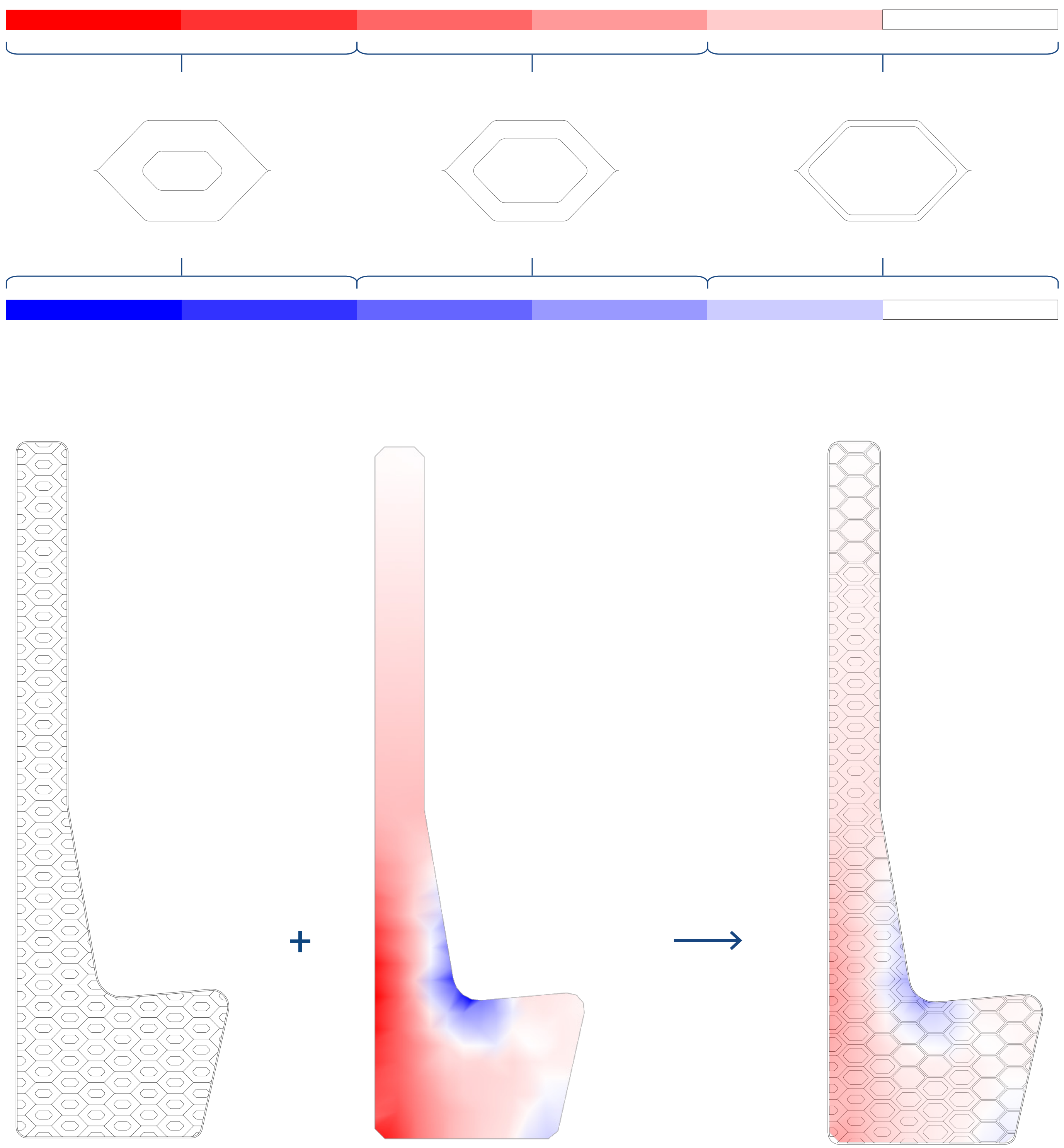


Figure 268: Variable Thickness.

6.6.2 Grasshopper Script

The mechanically informed infill process begins by generating the mesh geometry of the solid component. This mesh is then inputted into Karamba, where the type of support and load conditions are defined. The output of this process is a color gradient mesh that represents the stress distribution within the component.
Within this color gradient mesh, points that are closest to 0% stress are automatically identified as attractor points. These attractor points serve as reference points for the generation of the infill pattern.
The pattern generation is accomplished using the Ngon plug-in. In this process, the center point of each geometry is also highlighted and considered in the pattern generation.
Each center point is connected to the closest attractor point, and the distances between them are divided into three sections. These sections correspond to the three different thicknesses employed in the infill design. The thickness assigned to each section is inversely proportional to the distance, meaning that shorter distances result in thinner thicknesses.

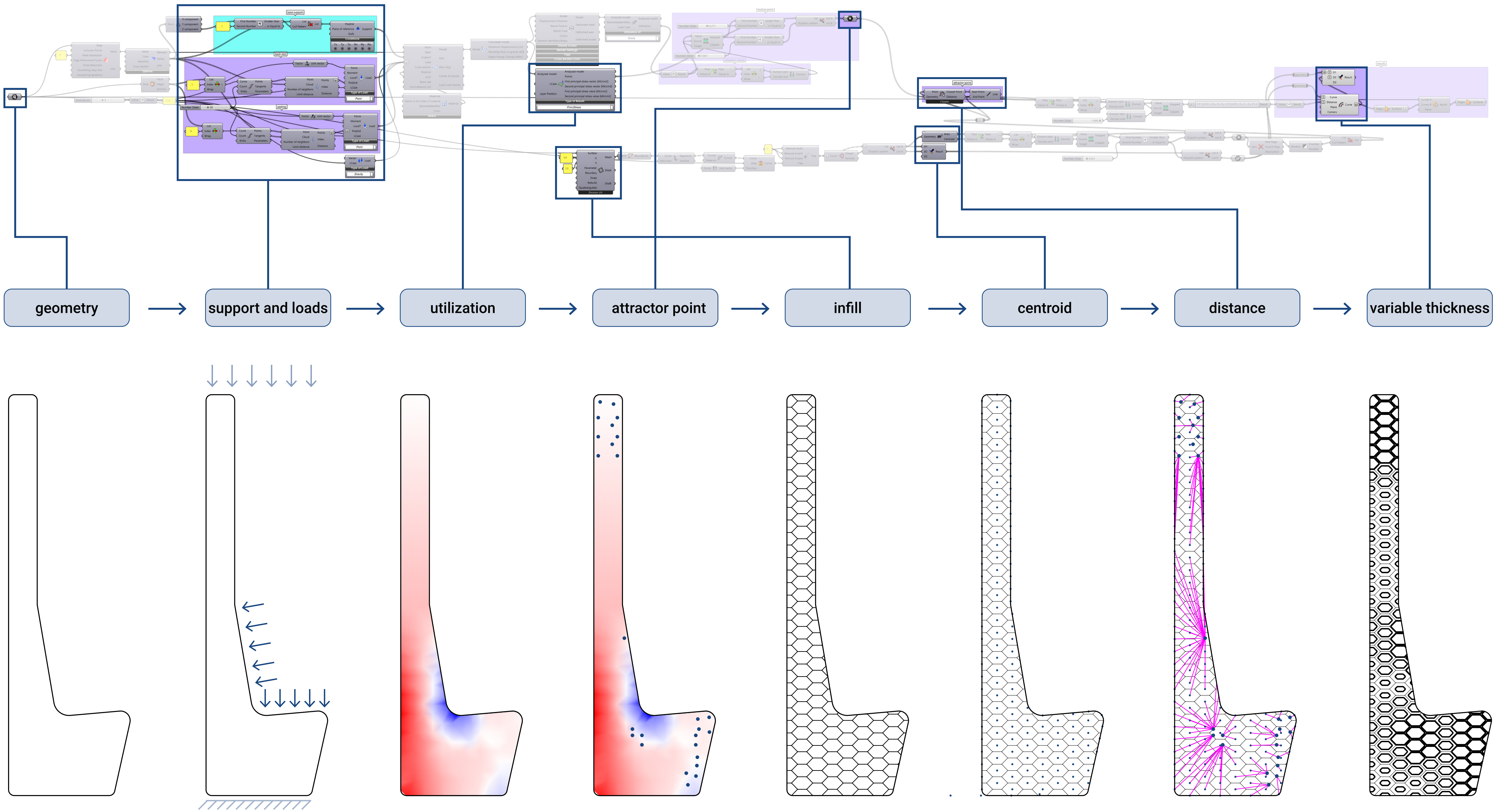


Figure 269: Mechanically Informed Infill Generation

By utilizing this method, the infill pattern is created, taking into account the stress distribution within the component. This approach ensures that the infill is optimized for the specific loads on the component, resulting in a more efficient use of materials and better overall performance.

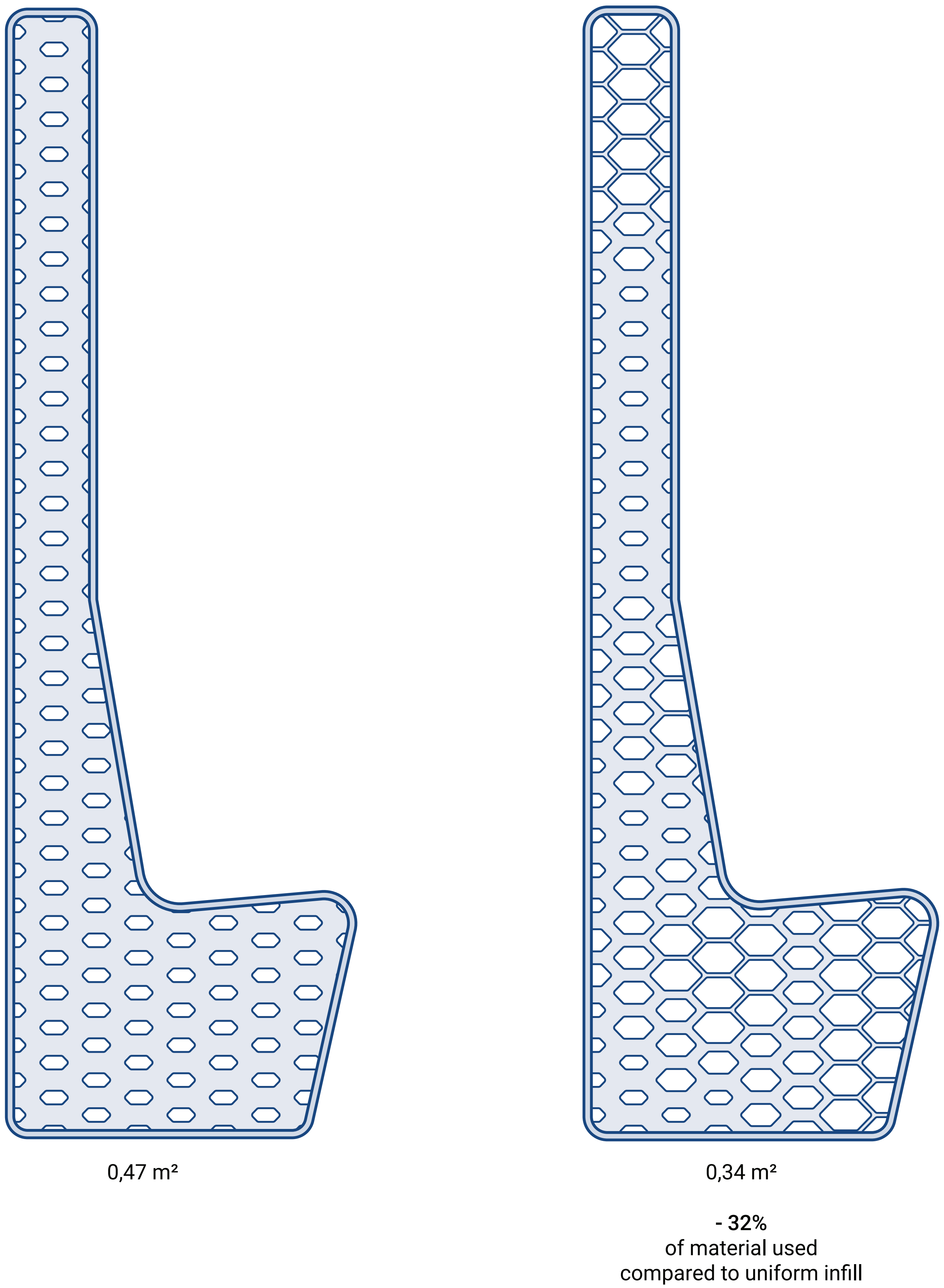


Figure 270: Material usage comparison

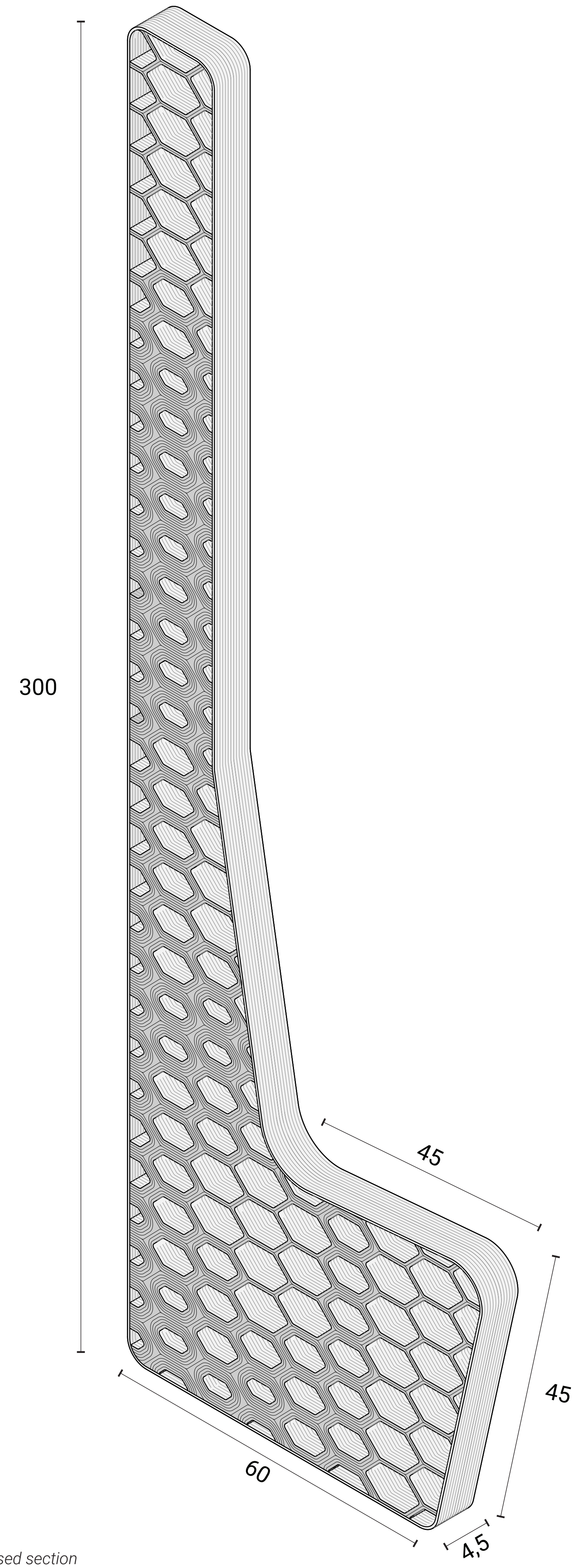


Figure 271: Axonometry focused section

7

Prototype

7.1 Overview

Due to limitations in space, available materials, and tools, it is not feasible to print the entire prototype for this thesis project. Instead, a smaller-scale version of the prototype will be printed using PLA on a 3D printer, specifically to showcase the infill design.

The primary objective of this thesis is to provide a proof of concept for printing with bamboo. To achieve this, a 1:1 scale fragment of the design will be printed with a 4 mm nozzle. The selected fragment corresponds to a specific area within the component, which is determined by the reachable working area of the UR5 robotic arm.

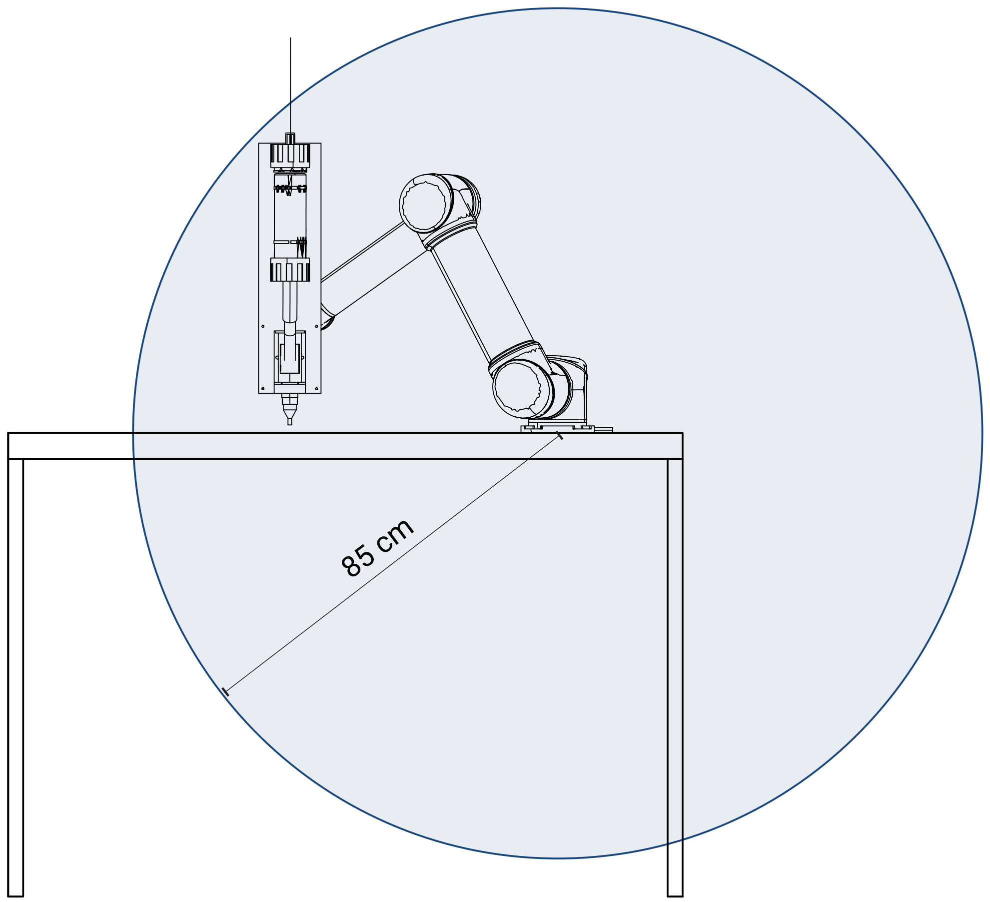


Figure 272: Working Aerea UR5.

Once the component is printed, it will undergo a natural drying process, with intermittent application of vinegar to prevent the growth of mold. This step is essential for ensuring the stability and durability of the printed prototype.

While the printed fragment represents a smaller portion of the overall design, it serves as a tangible proof of concept and provides valuable insights into the feasibility and potential of printing with bamboo.

7.2 Fragment Selection

The chosen fragment focuses on the bottom part of the component, as it encompasses the three different types of infill designs. This selection allows for a comprehensive representation of the infill variations within the design and demonstrates the capabilities and potential of the proposed approach.

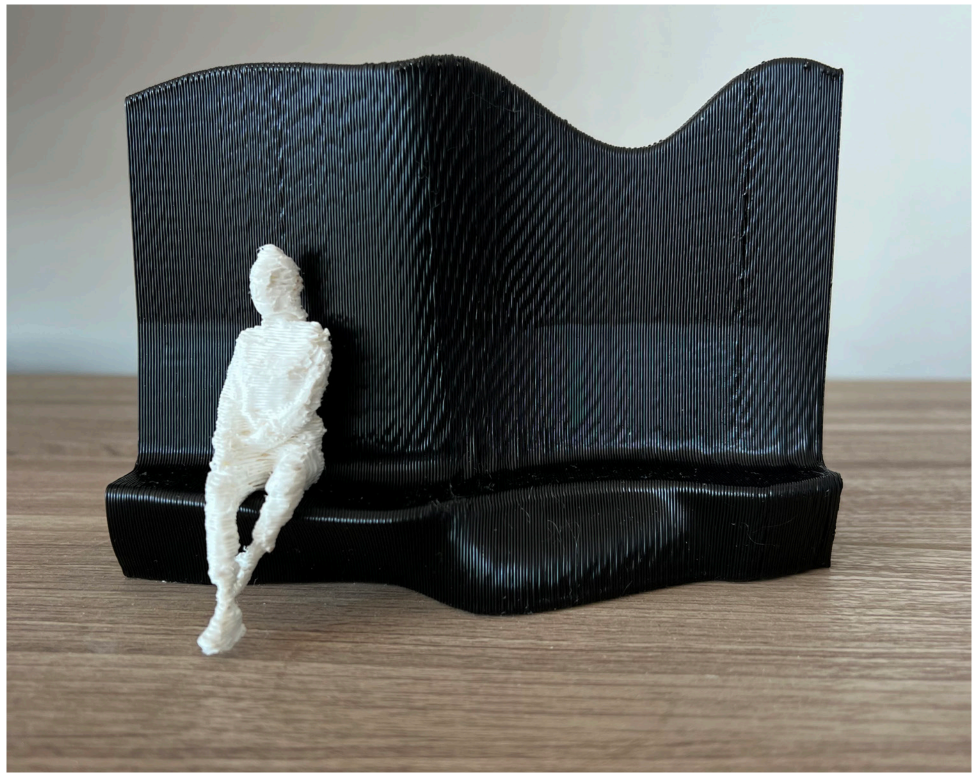


Figure 273: 3D printed PLA of the overall design, scale 1:20

Figure 274: Automated Infill, scale 1:7

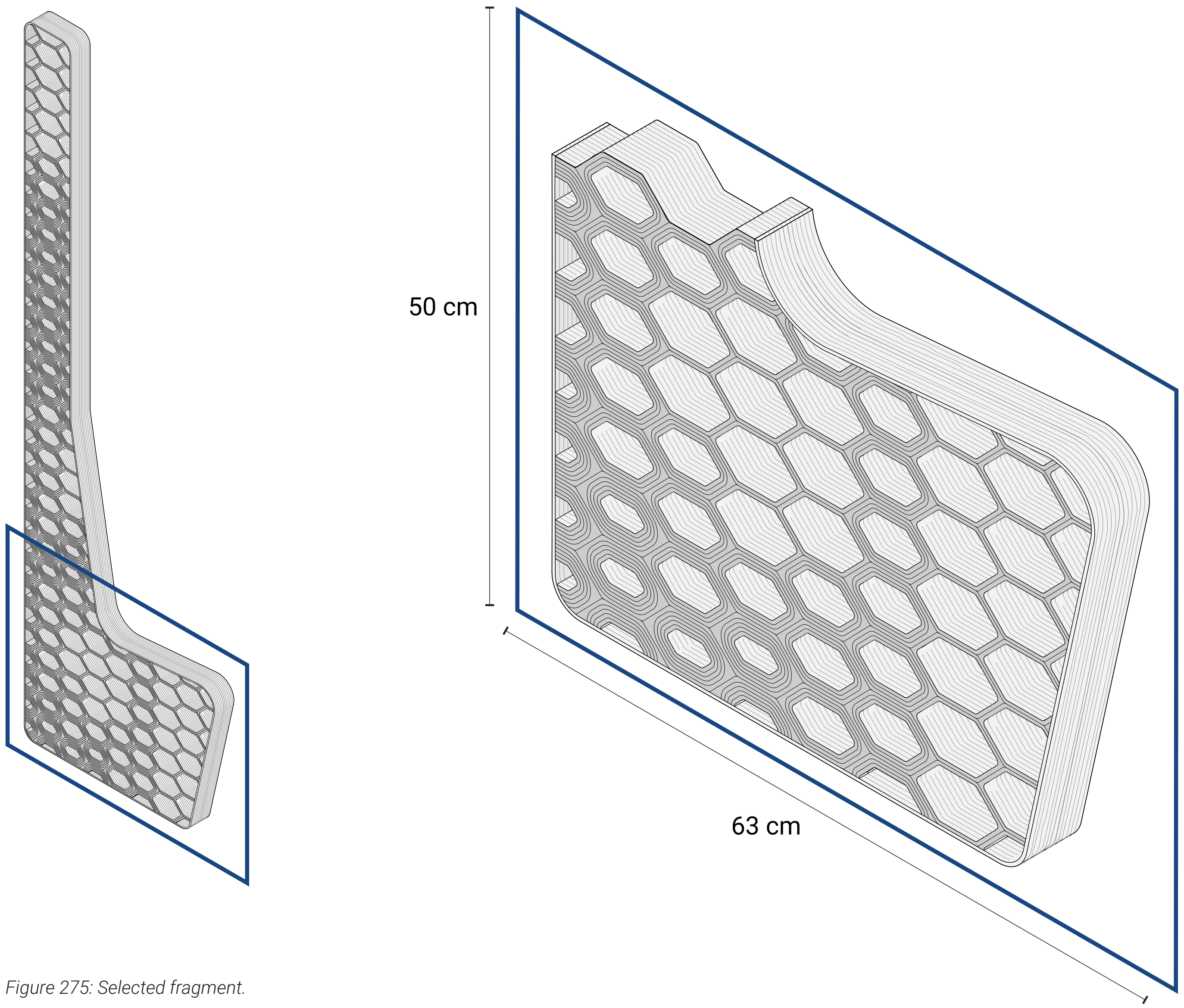


Figure 275: Selected fragment.

During the process of generating the toolpath for printing, an error was encountered in the grasshopper component. The error message indicated that the waypoint was out of target, indicating that the robot arm was unable to reach the designated point. As a result, the selected fragment had to be divided into two parts to ensure that all sections of the fragment could be accessed and printed by the robot.

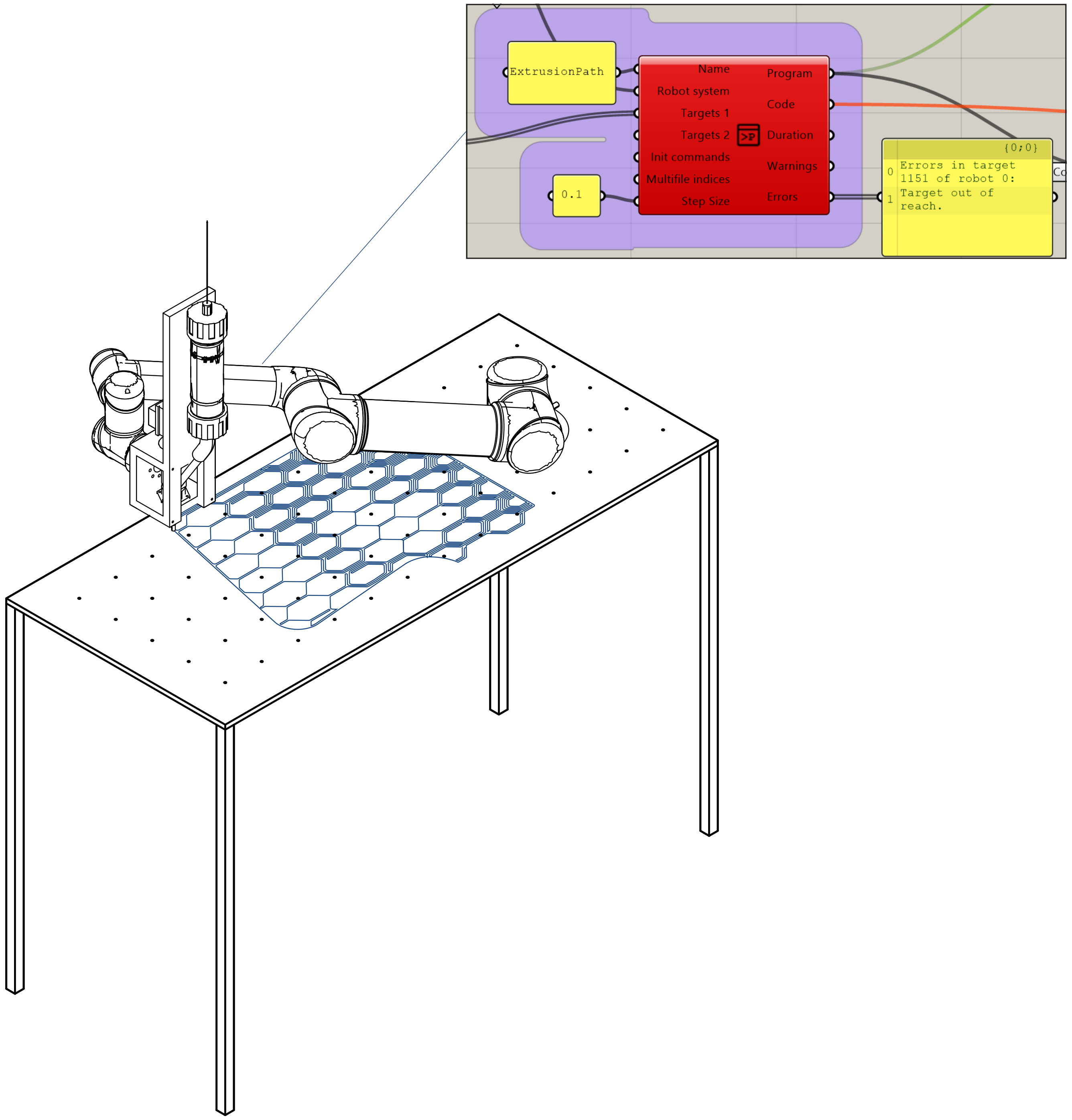


Figure 276: Component Error

7.3 Toolpath Generation

In order to achieve a successful print, it is crucial to generate a continuous and uninterrupted toolpath. To address this requirement, a toolpath was meticulously designed and simulated with the robot arm to ensure optimal printing results. Consideration was given to the distances between the walls, taking into account the findings from the printability exploration phase. This approach was implemented to prevent any potential issues such as layer overlapping and ensure the integrity and accuracy of the printed prototype.

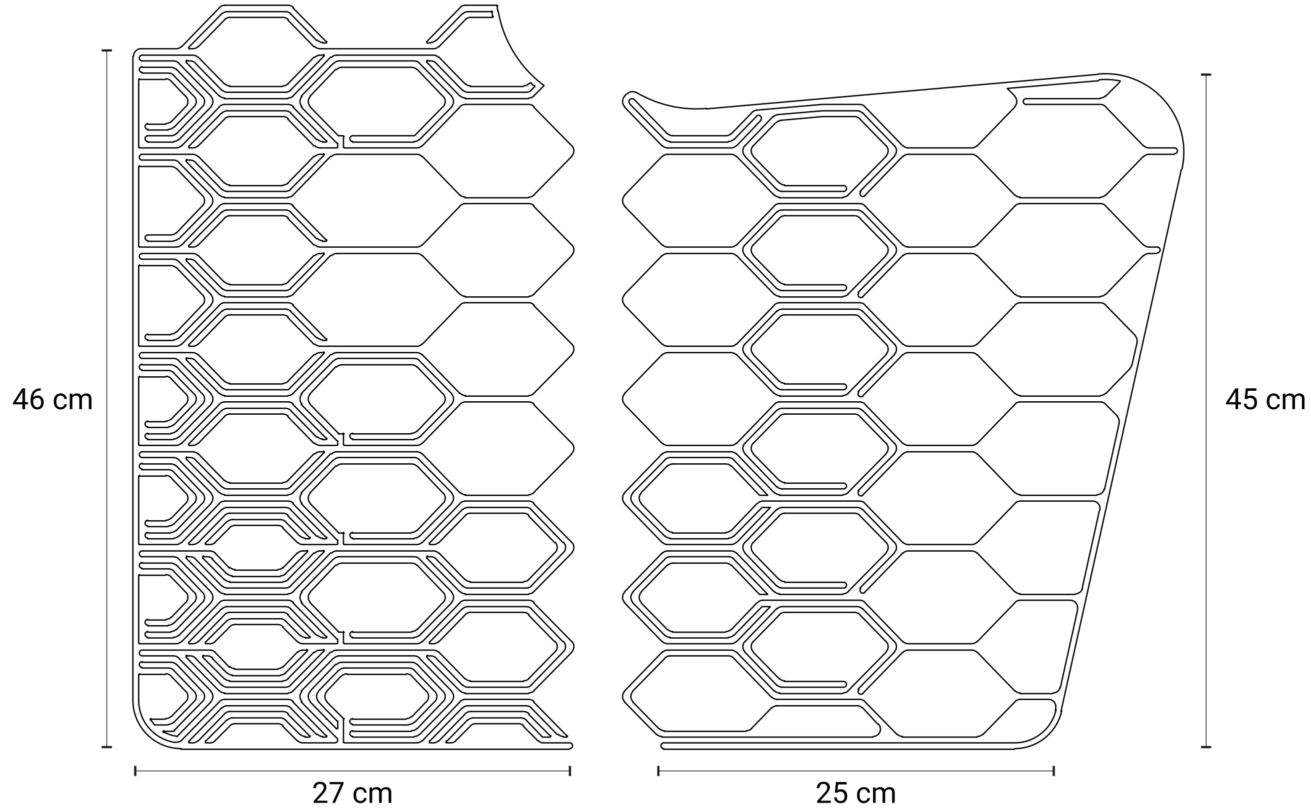


Figure 277: Toolpath scale 1:5

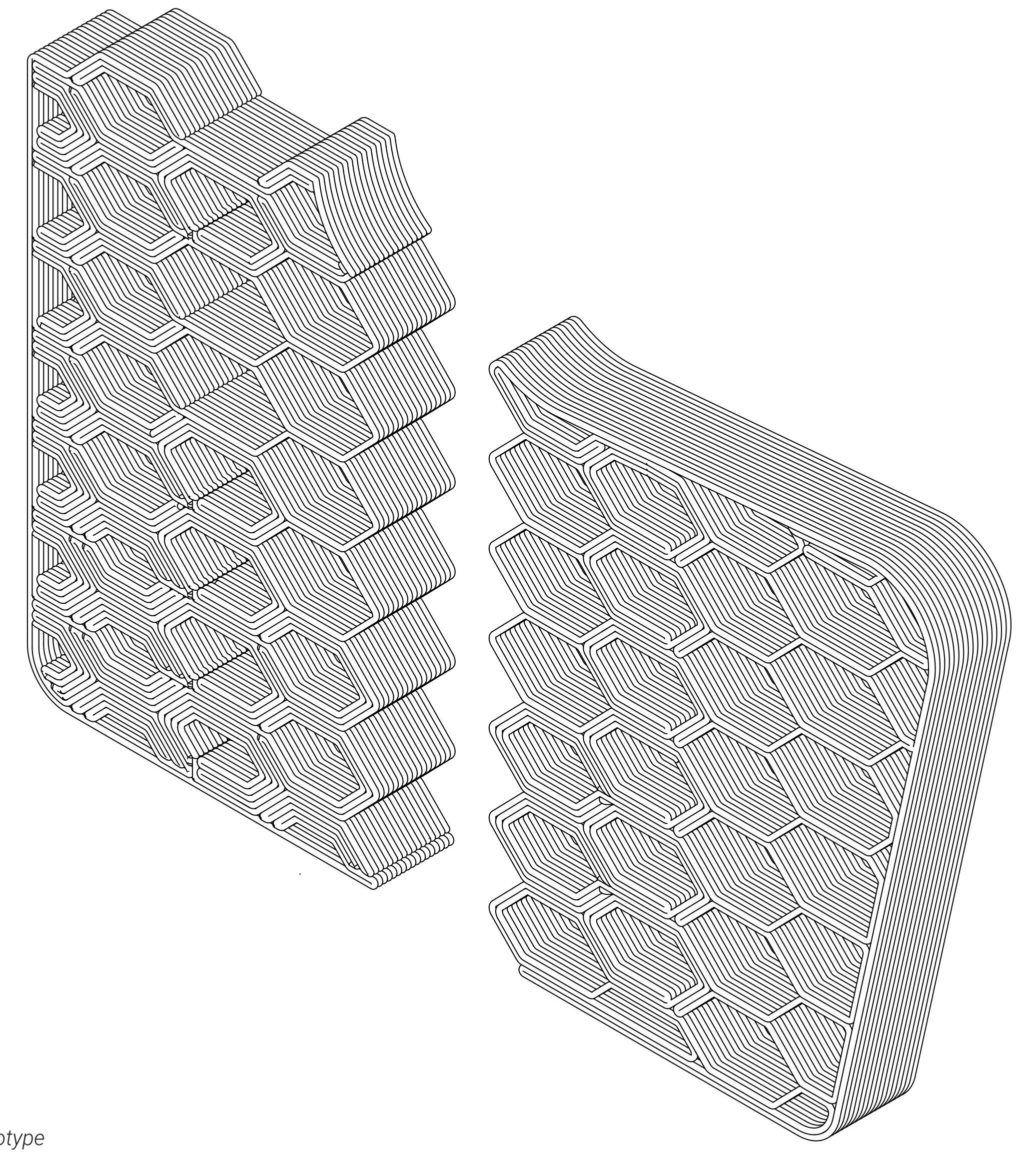


Figure 278: Prototype

7.4 Execution

The detailed procedure for the material exploration is provided in the dedicated chapter of the report. To ensure an ample quantity for testing, the prepared material quantity was five times larger than usual, allowing for the filling of approximately 10 cartridges.

Figure 279: Material Preparation

The printing of the two components took place in separate weeks, with a plastic-wrapped PVC printing bed utilized for both prints. It should be noted that the consistency of the material mixture varied from one printing session to another, and even throughout the day. As a result, adjustments were made to the pressure and speed of the extruder based on the observed consistency of the material at each instance.

To prevent excessive extrusion of material, particularly when the cartridge is nearly empty and higher pressure is exerted, a precautionary measure was taken. The cartridge was refilled with material after the completion of each layer, ensuring a consistent and controlled extrusion process throughout the printing procedure. This practice helped to maintain the desired quality and integrity of the printed components.

Figure 280: Cartridge Filling

7.4.1 First Fragment

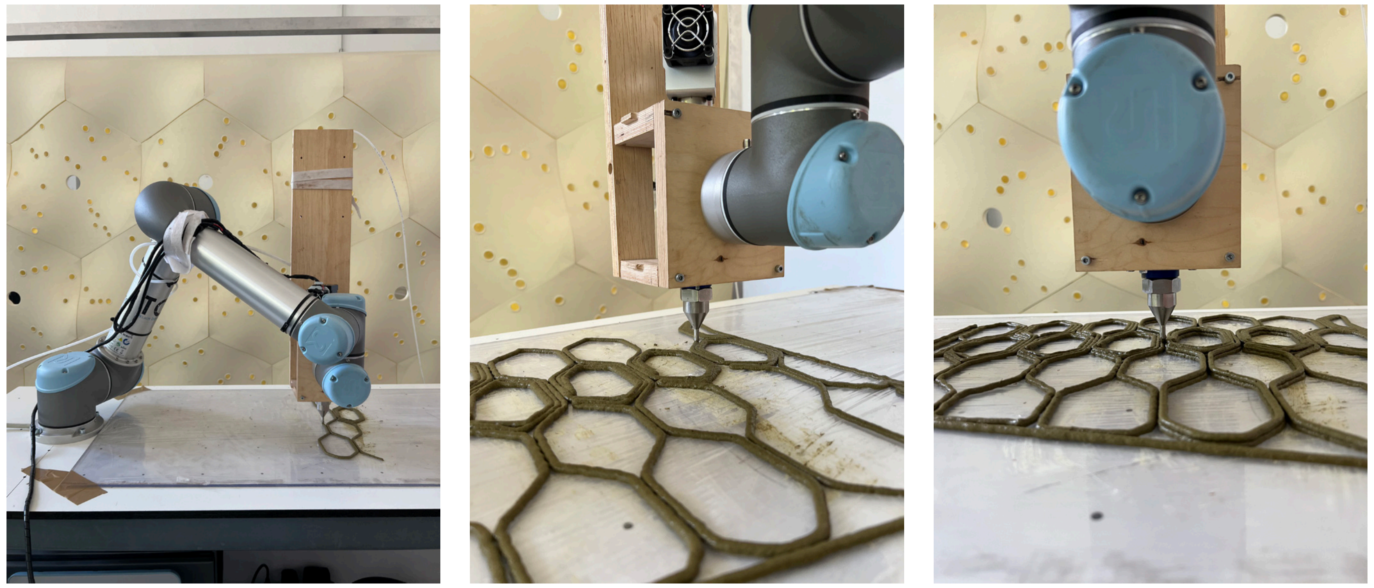


Figure 281: First printing

Figure 282: Mid printing

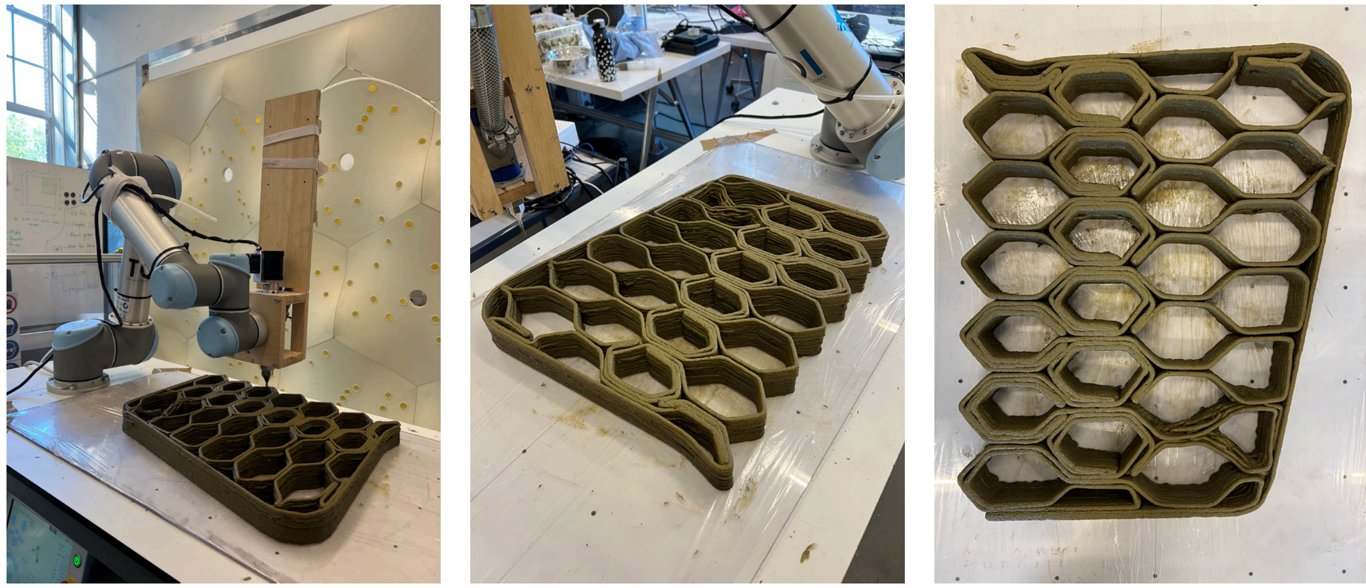


Figure 283: Final printing

7.4.2 Second Fragment

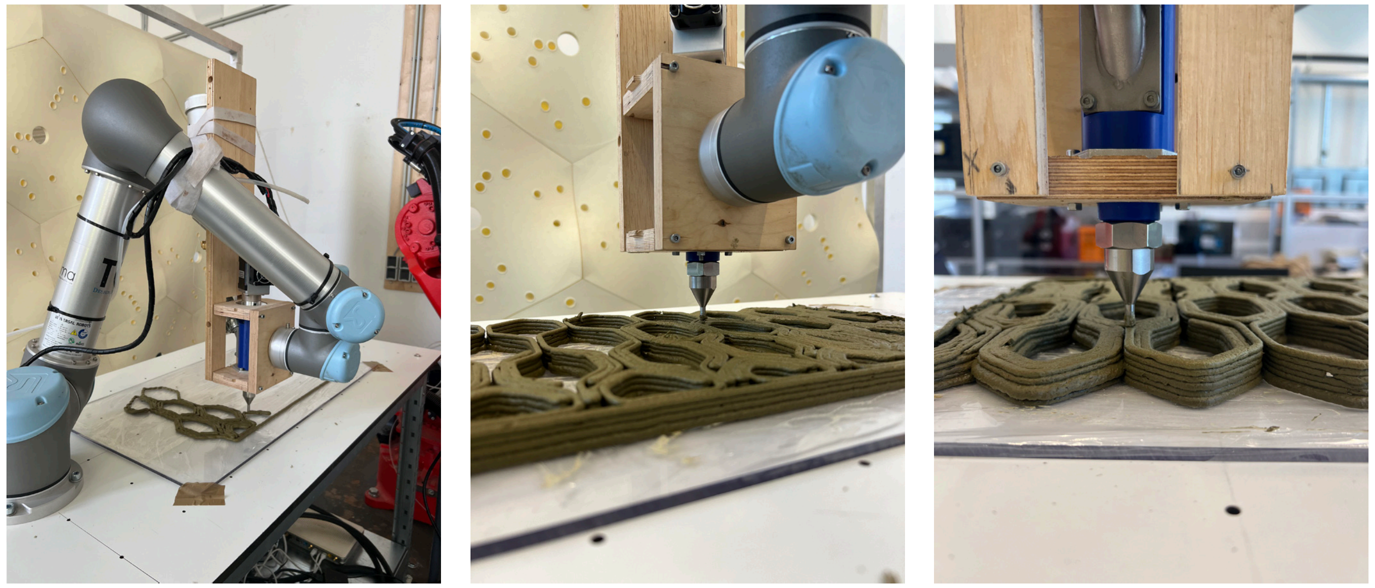


Figure 284: First printing

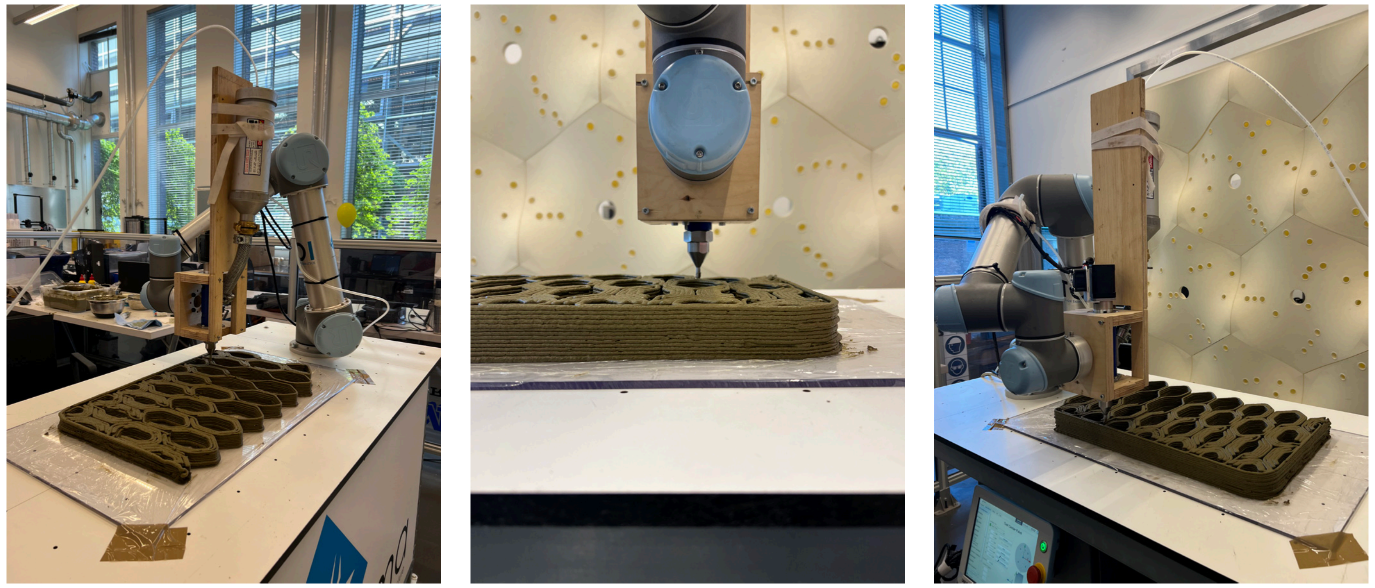


Figure 285: Mid printing

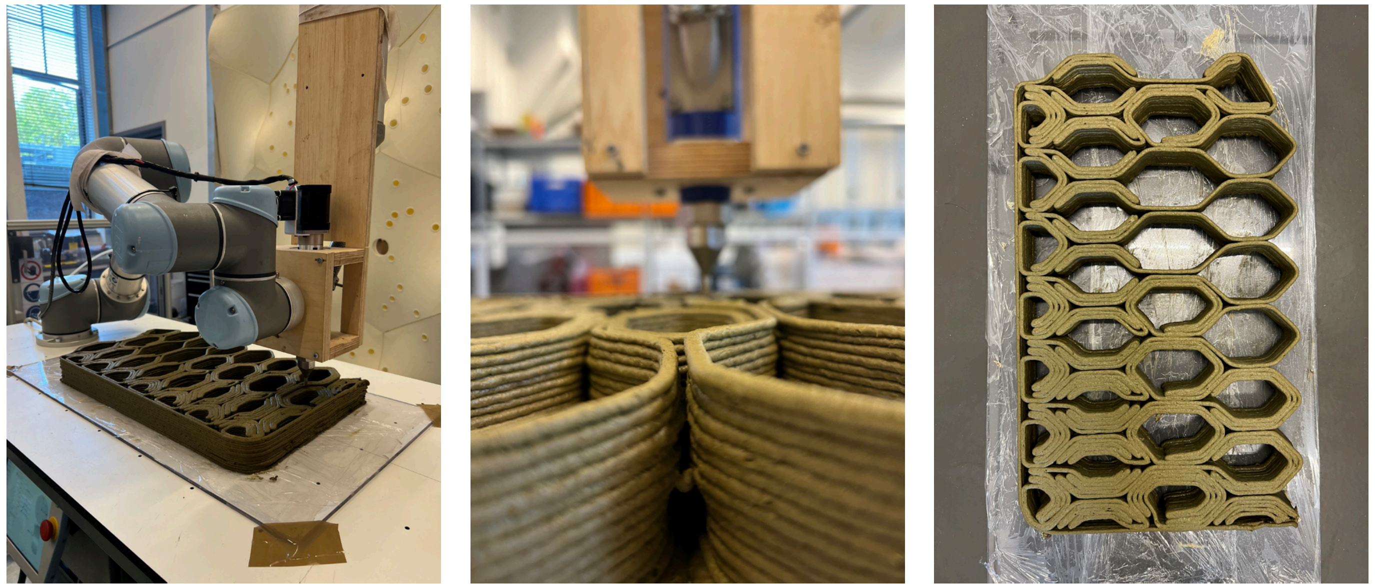


Figure 286: Final printing

7.5 Results

Due to time constraints, the printing process was limited to a height of 45 mm, equivalent to 16 layers of 3 mm each. This duration encompassed various stages, including tool preparation and cartridge filling, resulting in a total printing time of approximately 10 hours. Despite these limitations, the printing process demonstrated excellent stability and reliability.

The size of the two components posed a challenge in terms of fitting them into the hydrator for accelerated drying. Consequently, both components were allowed to dry naturally over a period of circa one week. Throughout the drying phase, a solution of vinegar was applied to the entire component on an almost daily basis. This measure served to eliminate and prevent the growth of mold. It is important to note that the drying process was not uniformly consistent across the entire component. Naturally, the areas with thinner thicknesses experienced faster drying compared to the rest of the component.

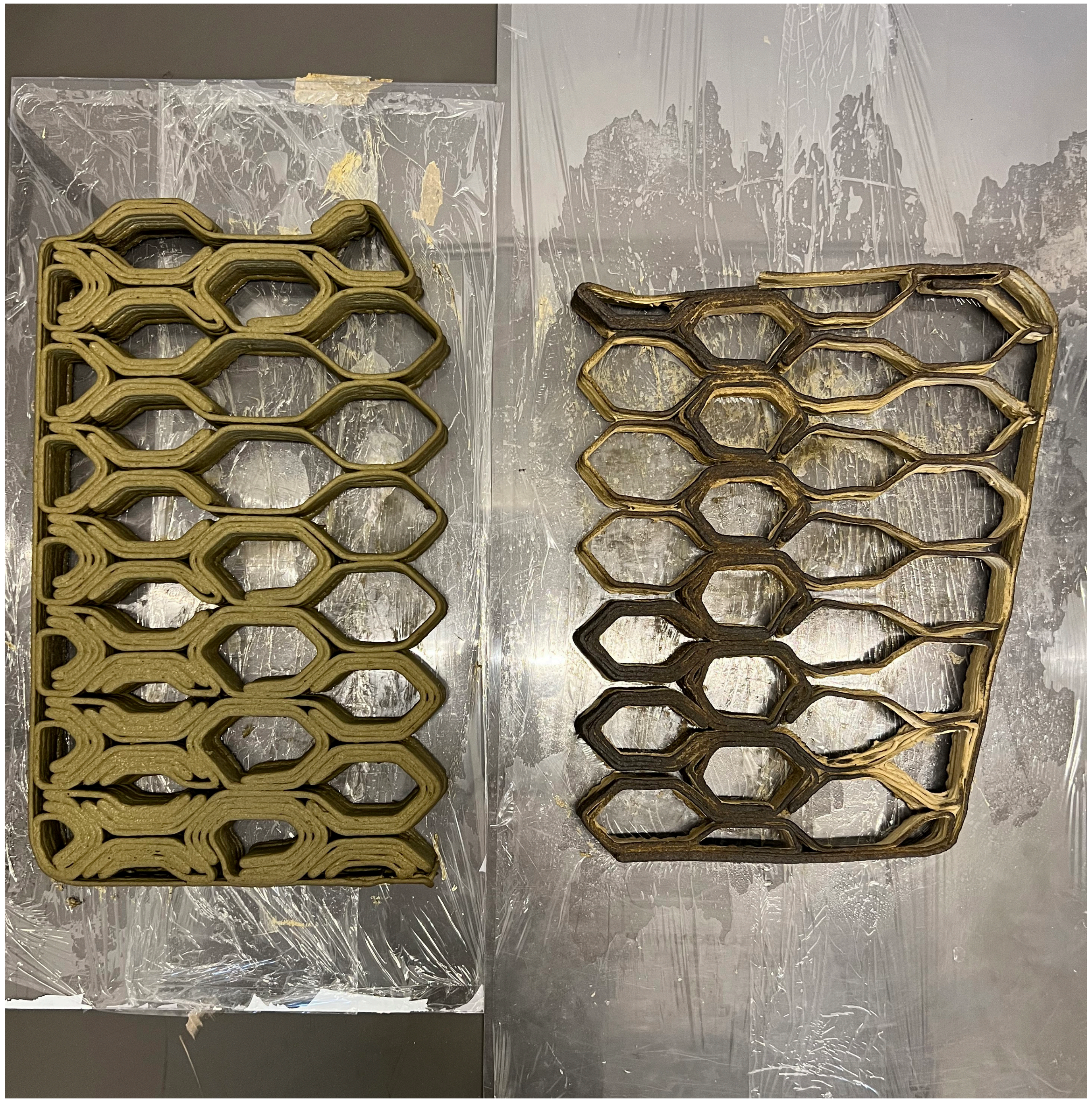


Figure 287: Final printing

7.6 Conclusion

The primary objective of the prototype was to demonstrate the feasibility of printing with the novel material mixture. However, the process presented several challenges along the way.

From a computational perspective, simulating the movement of the robot proved to be problematic, particularly when attempting to print the selected fragment as a single piece. Overcoming this hurdle required careful planning and adjustments to ensure successful printing.

The material preparation itself was an extensive procedure. A significant quantity of mixture was needed, making the creation of the binder a challenging task. The binder often formed lumps that necessitated an additional sifting process to prevent nozzle clogging. Mixing the dust and fibers with the binder required considerable strength and patience to achieve complete incorporation.

Each time the cartridge was filled, an extrusion test was necessary to determine the appropriate pressure and extruder speed. This trial and error process was crucial in avoiding under or over-extrusion during printing, necessitating the restarting of already printed layers.

Figure 288: Mixture problems

Figure 289: Final printing

The drying phase required diligent attention. As a fully bio-based material, the wet prototype attracted fruit flies, which needed to be addressed promptly. Additionally, every centimeter of the prototype had to be carefully brushed to prevent mold growth.

Unexpectedly, shrinkage became a significant issue during the drying process. The shape of the prototype underwent substantial changes, including the appearance of cracks. These factors posed concerns regarding the overall structural stability of the component.

Furthermore, the achieved height of the prototype was limited by the available time in the lab. However, based on the stability observed during the printing process, it is reasonable to assume that a greater height could be achieved with the material mixture.

The time dedicated to cleaning the tools was significant, as it involved thorough disassembly, cleaning, and reassembly of the components. This meticulous process was necessary to ensure the tools were free from any residual material, which could impact the quality and performance of subsequent prints.

Despite these challenges, the successful proof of concept in printing with the novel material mixture highlights the potential for further development and optimization in future iterations.

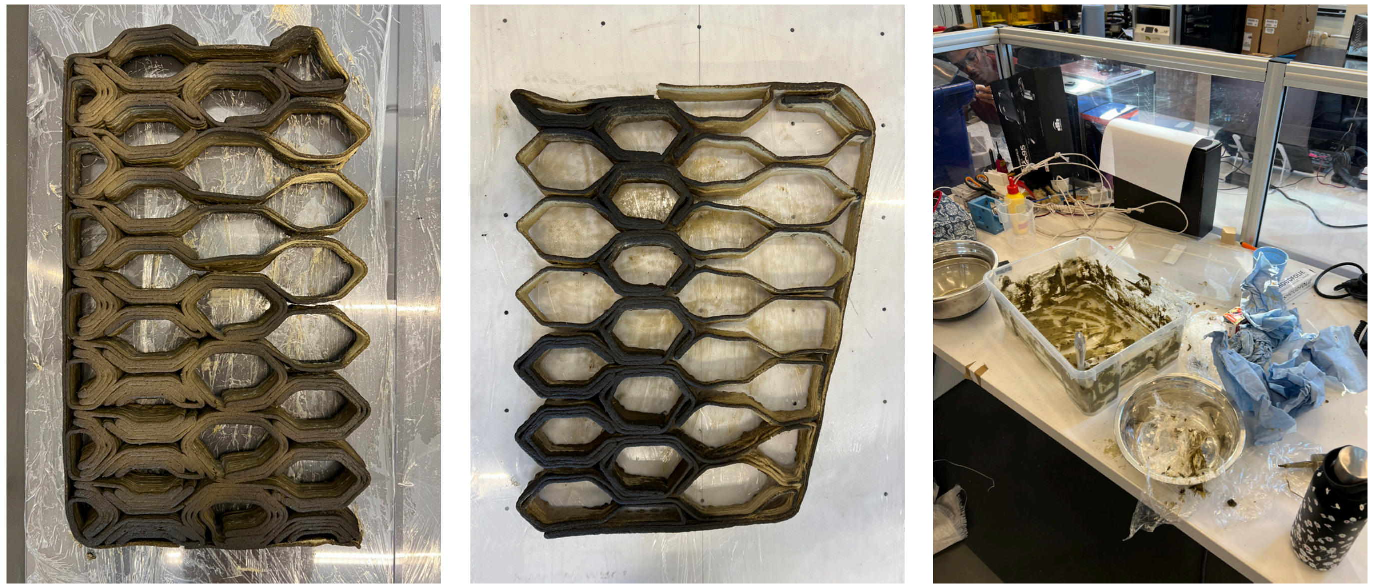


Figure 290: Shrinkage

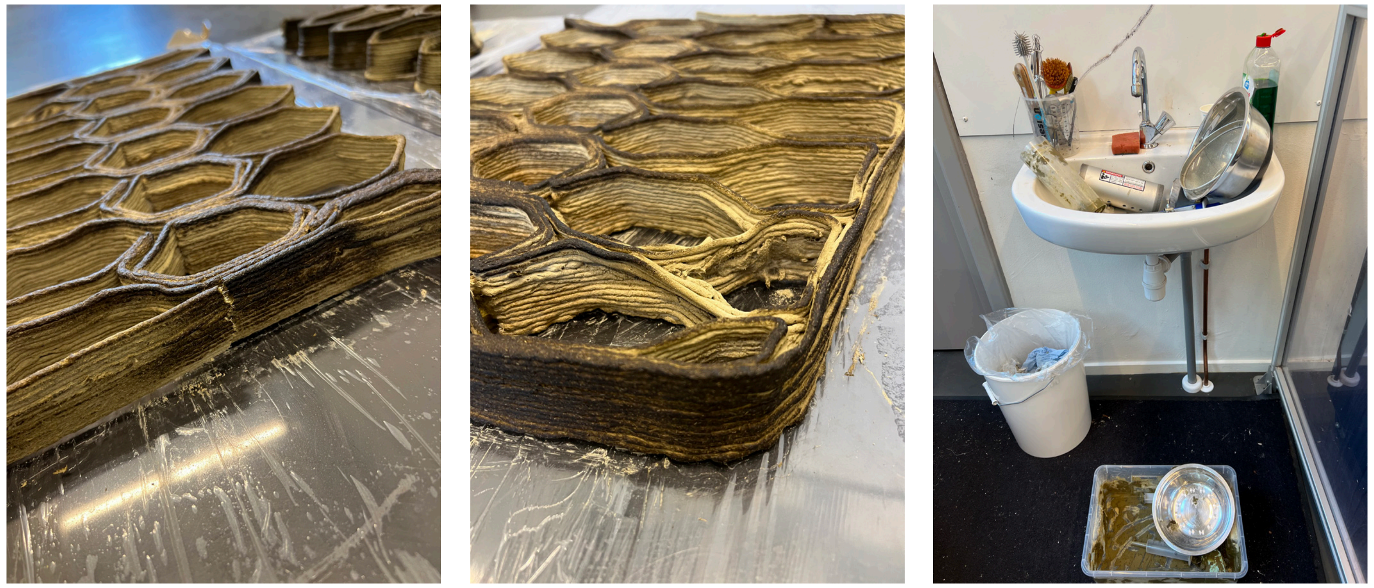


Figure 291: Cracking

8

Conclusion

8.1 Conclusion

The motivation behind this research stems from the pressing issue of climate change and the unsustainable consumption of conventional construction materials such as concrete and steel. While steps are being taken towards the use of sustainable alternatives like wood, the challenges of overconsumption and limited availability of wood resources remain. Bamboo, a fast-growing non-wood species, presents itself as a viable substitute. Although bamboo has been utilized in the construction industry for some time, its widespread adoption is hindered by the lack of established building codes and its unique hollow tube anatomy.

To address these challenges, this thesis focused on exploring the potential of using bamboo in the form of dust and fibers to create a building component through additive manufacturing technology. The objective was to assess whether bamboo could become a prominent material in the construction industry.

The initial phase of the research involved finding a recipe for a homogeneous mixture that demonstrated excellent viscosity and adherence, preferably using fully bio-based ingredients. Extensive material research was conducted, comparing non-bio-based binders with bio-based binders. Two evaluation methods were employed to assess the suitability of different mixtures.

During the material exploration stage, potato starch emerged as the most favorable binding agent, and it was subsequently employed in printability assessments. To establish an LDM 3D printing setup, a custom wiring system and tooling installation were created. Multiple printability tests, encompassing evaluations of maximum height, overhang capability, and overlapping, were performed. Challenges encountered during the drying process, such as fungal growth, raised concerns about the performance of the specimens.

Due to the novelty of the feedstock, mechanical properties of the material mixture were not directly tested, as they cannot be compared to conventional materials. The design of the building component faced numerous challenges, considering both its functional purpose and the limitations of the material.

In addition to the outline geometry, another important aspect of this thesis was the development of a mechanically informed infill to optimize the structural performance of the component while minimizing material usage. Compression testing of three different geometrical infills provided valuable insights, leading to the design of a custom geometry.

The use of bamboo as a construction material in additive manufacturing holds significant potential for the industry. While there have been limited studies conducted on a large scale with novel materials, this work demonstrates the promising capabilities and benefits of utilizing bamboo. However, it is important to note that further research and development are necessary to fully unlock and harness bamboo's potential as a sustainable and efficient construction material.

In conclusion, this thesis contributes to the exploration of bamboo as a sustainable material for architecture through additive manufacturing. The study highlights the challenges and opportunities associated with utilizing bamboo in the construction industry. With continued research and development, bamboo could play a significant role in fostering more sustainable practices in the building sector.

8.2 Future Research

This thesis serves as a starting point for further research and exploration in several areas. Building upon the foundation laid out in this study, future investigations can delve deeper into specific aspects of material properties, printing techniques, and design possibilities. These areas offer exciting avenues for expanding knowledge and advancing the use of bamboo as a sustainable construction material.

Material research presents numerous opportunities for future exploration. A detailed analysis of bamboo dust, particularly the differences between "green" dust and dust 0100, can provide valuable insights into their mechanical behavior when combined with potato starch. Further studies on binders can help identify more suitable alternatives that enhance the overall performance of the material. Additionally, investigating the growth of mold during the drying process, which is influenced by the water content, can lead to the development of preventive measures and a better understanding of its impact on the structure.

Refining the proportion of materials used and optimizing the mixing process are crucial areas for future investigation. Exploring the maximum amount of fibers that can be implemented without causing nozzle entanglement is essential to achieving desired mechanical properties. The effect of fiber implementation on the material's behavior should also be thoroughly examined.

In the field of printing, extensive research can be conducted on geometry exploration. Investigating and overcoming the limitations encountered during the printing process, such as overhangs, will unlock new possibilities for complex geometries. Leveraging the advantages of a six-robotic-arm system for extrusion opens avenues for designs that cannot be accomplished with traditional Cartesian printers. Additionally, exploring the integration of additive manufacturing with other fabrication methods can lead to innovative approaches in construction.

On the design front, countless possibilities exist for further exploration. Interior applications can involve creating different objects to showcase the versatility of the material. For exterior applications, rigorous investigations are needed to ensure the building components can withstand external weather conditions.

Further research can delve into the realm of 4D printing in relation to the printing of the prototype. The unexpected occurrence of shrinkage highlights the potential for exploring the dynamic nature of the material and its shape-changing capabilities over time. By studying and analyzing these phenomena, it becomes possible to design components that can adapt and accommodate such changes in shape.
Investigating the concept of 4D printing opens up new possibilities for incorporating time-dependent behaviors into the design and fabrication process. This can lead to the development of intelligent structures that respond and adapt to environmental conditions or specific stimuli. By integrating the understanding of material behavior and shape transformation, future research can explore the potential applications of 4D printing in construction, enabling the creation of components that possess enhanced functionality and performance.

To conclude, this thesis provides a foundation for future research endeavors in the realm of bamboo-based construction components. Future investigations should focus on in-depth studies of material properties, refining printing techniques, and exploring diverse design possibilities. By addressing these areas, researchers can advance the knowledge and application of bamboo as a sustainable and versatile material in the construction industry.

8.3 Reflection

Graduation Process

How is your graduation topic positioned in the studio?

This thesis titled "Breaking Ground with Bamboo" relates to two chairs within the Building Technology track. Design Informatics and Structural Design are involved and conducted under the guidance of Serdar Asut (Chair of Design Informatics) and Stijn Brancart (Structural Design & Mechanics) respectively.
The primary objective of this thesis is to develop a prototype using an innovative material and exert control over the fabrication process. Furthermore, the intention is to demonstrate the potential for scaling up the fabrication process to create building components through additive manufacturing, with computational design playing a pivotal role. The structural design aspect is crucial in comprehending the entire process, encompassing material characteristics and the mechanical properties of the prototype produced using additive manufacturing.

Both of these areas are directly relevant to the Building Technology Track, as they contribute to expanding knowledge in the field of additive manufacturing with bamboo. By utilizing a bio-based material and leveraging digital design and fabrication techniques, the aim is to enhance the sustainability and circularity of the built environment.

How did the research approach work out (and why or why not)? And did it lead to the results you aimed for? (SWOT of the method)

The thesis project follows a Research by Design approach, which proved to be the appropriate methodology for gaining insights into the material and production methods involved. The project encompasses research conducted in five main areas, aiming to establish a comprehensive workflow for the development of a building product.

The initial phase focused on acquiring a contextual understanding of the research topic through literature review and interviews with experts in the fields of bamboo and additive manufacturing with bio-based materials. The subsequent phases involved practical experimentation, providing valuable insights into the chosen methodology.

Phase 2 revolved around experimenting with and evaluating different material recipes, while phase 3 focused on the production of simple geometries. The final two phases were interconnected, involving the design of the building component and its subsequent prototyping. Each phase followed the other in a sequential manner, forming a chain of steps leading from the project's inception to its conclusion.

It is important to note that the practical experiments did not yield immediate desired results. The process involved exhaustive trial and error, as even when the initial iterations showed success, subsequent attempts with the same procedure often produced different outcomes. Numerous variables, including room conditions, ingredients, process variations, and timing, contributed to the variation in results.

Due to limited material availability, some experiments had to be omitted to avoid wasting resources on predicted unsuccessful outcomes. Nonetheless, the results obtained from the conducted research were highly significant and satisfying, enhancing our understanding of both the material and the overall process.

Societal Impact

To what extent are the results applicable in practice?

The utilization of bamboo as a material holds significant potential for sustainability, as it can be grown and harvested with minimal environmental impact. Its suitability for construction has already been recognized, and by utilizing bamboo in the form of dust, it becomes possible to efficiently utilize waste streams.

Additive manufacturing technology, although still emerging, is a promising process that continues to evolve and undergo extensive research. While it has yet to be widely integrated into practical applications, the existence of this technology opens up exciting possibilities.

In terms of the design proposal, previous efforts have already demonstrated the creation and successful printing of walls using different materials. Extensive research has been conducted to develop building products applicable to the built environment.

While this thesis contributes to the existing knowledge in these areas, there is still a need for further investigation and study of both the material and the manufacturing process. Scaling up production to a larger scale requires a deeper understanding and exploration of these elements.

Does the project contribute to sustainable development? What is the impact of your project on sustainability (people, planet, profit/prosperity)?

The construction industry is a major contributor to greenhouse gas emissions and environmental degradation. To address these issues, significant changes are needed to make the industry more sustainable and efficient in its use of materials and energy. It is crucial to design structures that are responsive to climate change and employ intelligent solutions.

Additive manufacturing, also known as 3D printing, is widely regarded as the future of the construction industry. This technology offers numerous advantages over traditional construction methods, including greater precision, flexibility, cost savings, faster production, and novel possibilities. Moreover, additive manufacturing enables the use of sustainable materials such as bamboo in an efficient and effective manner.

Incorporating bamboo into the construction industry brings both social and environmental benefits. Bamboo cultivation and processing can generate employment and economic opportunities, particularly in rural areas where bamboo is abundantly grown. As a highly renewable resource, bamboo offers a low environmental impact throughout its life cycle. By utilizing bamboo as a construction material, the industry can reduce its reliance on non-renewable resources like concrete, steel, and lumber, thereby lowering the carbon footprint of building projects.

Additive manufacturing technology enables the precise fabrication of complex shapes and geometries, expanding the potential applications of bamboo in construction beyond what traditional methods allow. This technology allows for the optimized utilization of materials, minimizing waste and leading to cost savings.

In conclusion, this thesis makes significant contributions to sustainability in multiple aspects, including the adoption of renewable building materials with a negative carbon footprint, the creation of economic opportunities, and the potential for more energy-efficient construction practices and material usage through additive manufacturing technology.

9

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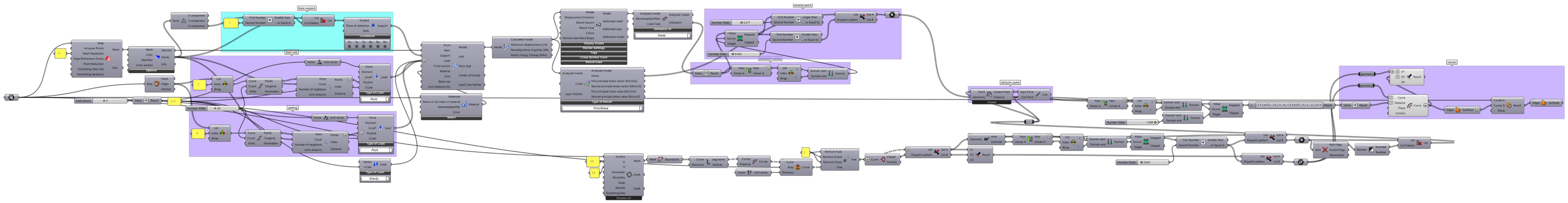
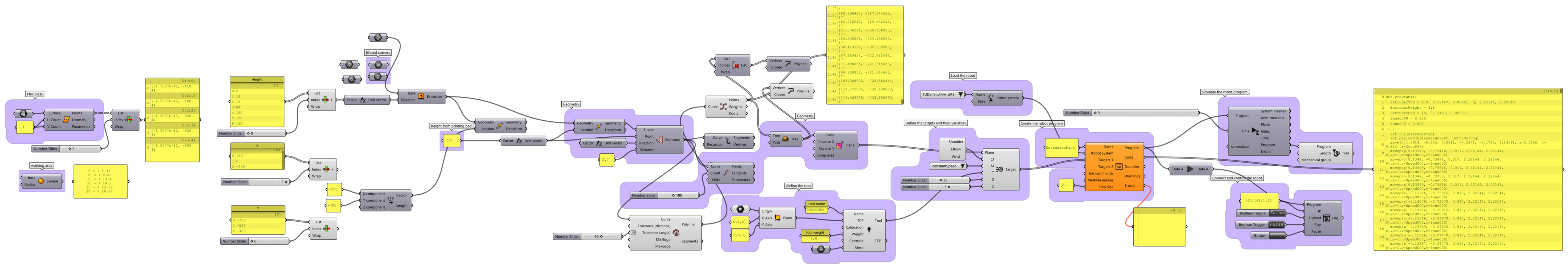
9.2 List of Figures

Appendix

Grasshopper Script - Automated Infill



Grasshopper Script - Prototype Printing



Mechanical testing

	F_{max}	dL at F_{max}	F_{Break}	dL at break	a_0	b_0	S_0
	N	mm	N	mm	mm	mm	mm²
Specimen 1	2177,3	12,62963	435,006	21,88638	100	100	10000
Specimen 2	1702,604	10,03789	337,1203	14,90158	100	100	10000
Specimen 3	1641,715	12,92795	327,6505	15,67454	100	100	10000
Specimen 4	1443,034	16,99966	283,332	21,87819	100	100	10000
Specimen 5	879,0014	6,133197	175,5248	11,41988	100	100	10000
Specimen 6	1339,65	9,874881	265,9953	28,86634	100	100	10000
Specimen 7	1099,834	16,30488	219,8658	21,29988	100	100	10000
Specimen 8	1308,88	9,671434	261,7451	20,44813	100	100	10000
Specimen 9	1043,339	15,07457	208,3222	20,86791	100	100	10000

Series	F_{max}	dL at F_{max}	F_{Break}	dL at break	a_0	b_0	S_0
n = 9	N	mm	N	mm	mm	mm	mm²
x	1403,929	12,18379	279,3958	19,69365	100	100	10000
s	396,3261	3,573211	78,87193	5,072218	0	0	0
ν [%]	28,22979	29,32759	28,22947	25,75561	0	0	0