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WOOD-BASED 3D PRINTING

Potential & limitation to 3D print a window frame with pure cellulose & lignin

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FINAL REPORT

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POTENTIAL & LIMITATION TO 3D PRINTING A WINDOW FRAME WITH PURE CELLULOSE & LIGNIN AS FEEDSTOCKS

Building Technology Track

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ABSTRACT

With a building industry that is responsible for a large amount of our carbon emissions, a rising population, and the over-extraction of resources, architects and engineers have the responsibility to use environmentally friendly products. Lignin and cellulose are the most abundant biopolymers on earth and produce a lot of waste by ending up burnt or in landfills. Thus, a great field of research is currently explored with cellulose and lignin waste as an alternative to petrochemical-based products. Coming from the pulping and paper industry, lignin waste could be implemented through the use of an additive manufacturing process to reduce or avoid the necessity to cut trees. Also, 3D printing elements with lignin and cellulose as feedstocks have not yet been explored. Thus, this master thesis aims to promote wood waste as an ecological contributor to the building industry through the use of an additive manufacturing process. This research will be driven by 3D printing a window frame as there is a lack of replacing or enhancing existing window frames. Moreover, large-scale 3D printing companies are faced with the problem that the interface between window frames and 3D printed walls does not perfectly fit within each other. As current fabrication processes to produce building elements are based on flat regular machinery and 3D printing technology is based on curved stacking layers, a perfect connection could only be implemented by 3D printing a window frame. Thus, after understanding the explored limits and possibilities of 3D printing with a wholly bio-based material coming from its waste in regard to mechanical and printability properties, a window frame will be designed and printed as a proof of concept. The final results have shown the potential of 3D print elements in a cold extrusion process with lignin and cellulose in combination with water and methylcellulose. However, more research is necessary to improve the material and printability properties of the recipe to become a fully reliable and integrated facade component to replace existing building components or improve the connection between window frames and habitats.

Keywords: Lignin, cellulose, wood, bio-based, 3D printing, additive manufacturing, window

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01 | INTRODUCTION

01 | 1 Research Problem & Problem Statement

Research Problem & Problem Statement

This research paper will address the challenge to innovate with wood waste to inspire and spread the beauty of designing with nature. This paper will not only point out the general problem of our current ways to build but also offer scientific research based on 3D printing wood waste to understand how it can be used to address these ongoing challenges. As Neri Oxman describes in an interview with Dezeen, "We must understand that nature is a co-client and we must requestion our relationship with nature" (Oxman, 2021).

Overall Research Problem

Before getting into the context of 3D printing with biomaterials, we must question and understand why we are using advanced technologies in the age of automation. As Cedric Price mentioned in 1966: "Technology is the answer, but what was the question?"

Standard vs Customized

What is the use of advanced fabrication processes within the field of architecture? Does complexity come at a cost?

As Mollie Claypool explains, mechanical matrices such as molds, casts, dies, or stamps massively produced with either a subtractive or additive technology allows customization to compete with current production processes (Claypool et al., 2019). A great example is the design and construction of the glory façade for the Sagrada Familia. Mark Burry who is the Senior Architect to the Sagrada Familia Basilica Foundation since 1979, was able to complete the façade from the surviving fragmented drawings made by Gaudi by using parametric softwares, allowing 'fast and accurate changes' (Craswell, 2018). Digital design and 3D parametric modeling software have been able to unravel the complex geometries of Gaudi's work to be understood, archived, and accelerate the construction process (Burry, 2011). Also, the sequential roof from Fabio Gramazio and Matthias Kohler at ETH, Zurich has shown how to assemble a freeform wooden roof in a layering process where every piece is irregular and would cost the same as regular ones. They have proven that the correlation between form and cost has changed today thanks to the use of parametric tools. Finally, the Institute for Advanced Architecture of Catalonia has researched since 2001 on how 3D printing permits architects and engineers to customize our built environment, build faster, cheaper, and sustainably (IAAC, 2019). As we are now aware that 3D printing offers a certain degree of freedom to design at a low cost, we must ask ourselves how 3D printing technology can be used in a sustainable and circular manner? Can we 3D print with biomaterials such as cellulose and Lignin?

Sustainability & Circularity

With a rising population that is expected to reach 10 billion people by 2050 (United Nations 2015), global warming, and resource depletion, the built environment has the a responsibility to act quickly as it is a major contributor to global man-made greenhouse gas emissions (Pablo Van der Lugt, 2020). One of the many different ways to achieve zero net carbon emissions on a global scale by 2050, is to use low-carbon materials such as wood. Naturals (hardwood, softwood, bamboo) are estimated to be one of the last supplies available in the coming up century (Pablo Van der Lutgt, 2020). Wood can be managed and used abundantly by replanting its trees. We could argue that wood deserves the grade "sustainable" more than other materials (Markus Hudert, Sven Pfeiffer, 2019). However, we can also add value to the way wood is harvested by utilizing its waste. In Europe itself, we disregard 25 million tonnes of wood annually (Storaenso, 2020). More specifically, forestry and agricultural waste in the Netherlands include relevant quantities of lignin and cellulose. Waste and bio-based materials have considerable potential to be used and reused in the building industry. A great example is the exploded view beyond the building, exposed at the Dutch Design week in 2021 (Leboucq, 2021). Within all organic materials, Cellulose and lignin are one the most abundant organic polymers on earth [Chiujdea et al., 2020]. These biocomposites can be renewable alternatives to petrochemical-based products (Opedal et al., 2019). Today, we can use alternative products that are environmentally friendly materials and avoid using polluting ones such as insulating foam. Designers of the built environment can think of replacing mundane elements that are massively used with sustainable ones. An important tool to exploit the potential of waste materials into an artifact is 3D printing technology. Cellulose and Lignin themselves have been 3D printed either in combination with bioplastics or more interestingly, pure (Liebrand, 2018). The application of 3D printing biomass components is a hot topic today and is widely used (Zhang et al., 2020). 3D printing with pure lignin and cellulose was made possible thanks to the research made by Thomas Liebrand in 2018 at TU Delft. As the material recipe is mainly only using feedstocks, there is the possibility to produce wood without having to cut trees and reuse its waste to be further re-printed. In a circular approach, the recipe of Thomas can be recycled to easily replace components that become deficient. Thus, it would be interesting to see if his material recipe can be 3D printed to design elements for the building industry. Therefore, after the research done by Thomas Liebrand, this graduation project aims to continue his research by combining pure lignin and cellulose via 3D printing as a feedstock to develop an element for the building construction market. On a larger scale, my graduation project aims to transform and vision an architecture of customization at a low cost, produced sustainably and efficiently. More specifically, I will take a window frame as a case study to see if it can be 3D printed and if it has the potential to be used and certified to enter the construction market.

Main Problem Statement

We must ask ourselves: why 3D print window frames? How and what will the design of the window frame be driven by?

Design Application

Openings in architecture have shown throughout history that their geometry is required to be measurable and understood by constructors to be properly built. Openings can bring many possibilities that can get away from the standard, traditional, openings and expand it's their geometrical capabilities by using additive manufacturing. A great example is a research conducted by IAAC. Their students were able to 3D print with clay a range of openings to be printed without any support in a constant paste to accelerate the printing process (Chiou et al., 2020). Another great example is the reconstruction of Notre-Dame-De Paris. After the catastrophic fire that destroyed the cathedral in 2019, the French president Macron stated that the reconstruction of the cathedral will only take five years. However, as the renovations require specialized craftsmanship such as stone cutters or woodworkers, a Chinese company called Omni-CNC showed the potential of stone and wood carving with CNC machinery and waterjet cutting to speed up the process with precision (Omnicnc, 2019). Therefore, CNC milling technology would ease the building of complex window frames for gothic cathedrals. Another possibility is to 3D print window frames for 3D printing houses. After interviewing Marijn Bruurs from Witteveen+Bos, he has elaborated his interest in my graduation topic. He explained that the interface between the window frames and 3D printed concrete buildings is still traditional, such as the 3D printing houses in Eindhoven, built in 2019. The complexity of a window frame can be utilized to offer a larger spectrum to design custom habitats. Another example is the Tecla house design by Mario Cucinella Architects and the WASP team in Massa Lombarda in 2021. They have proven that 3D printing a double dome with clay was possible thanks to customized highly efficient frames which were engineered and produced by Capofferi (WASP, 2021). Thus, printing a window frame on-site could be done to ease the printing process and also allow a better connection between elements.

Design Goal

As no study is made on the application of 3D printing cellulose and lignin as a feedstock, the design objective of this research is to design an essential element for the building industry. Therefore, 3D Printing a window frame can offer another typology of its own and possibly allow to replace any defective pieces in the restoration of buildings or push forward the capabilities to 3D print habitats by optimizing their performances with printed window frames. My research will conduct a bottom-up approach, meaning from a powder base of cellulose & lignin material to reassemble its structure to form a window frame with additive manufacturing. Thus, the design of the window frame is already limited by the use of additive manufacturing and its material recipe. After conducting some tests and experiments, their results will help and guide the design of a window frame by understanding the limitations and advantages of 3D printing with wood waste. Once the literature review and interviews are collected into tables the tests and evaluations can be conducted. Moreover, the boundary conditions of the recipe when printed will allow to frame the final shape of the design. Therefore, after P3, the printed shape will be established by the limitations and advantages of the gathered findings within a 6 months' timeframe.

01 | 2 Research Question & Sub Questions

Thomas Liebrand who is an alumni student from TU Delft was able to extrude the recipe of cellulose and lignin without any additional plastics in 2018. From there, my colleague Alexsander Coelho and I will take over the research to see the potential and limitations of Thomas's recipe to produce a 3D printed element to later enter the construction market. In the "Method Description", the individual and group tasks will be explained. As I will be researching on a window frame and Alexsander on a structural node, we will both conduct different individual tests to avoid repetitive tasks and achieve a design by the end of the master thesis.

Thus, the main **research question** is:

What are the potential and limitations of 3D printing with pure cellulose and lignin a window frame ?

Different methods will be applied over the entire process of this research paper. The list of methods and phases explained in the “Methods description” will answer these **sub-questions:**

Contextual framework (background)

Why are we looking into additive manufacturing and wood waste?

How can it be used sustainably & circularly?

What is the state-of-the-art technology with wood waste?

Design Evaluation

What are the constraints that need to be considered? (process fabrication, scale of print, access to machinery at the University, material mixture)?

Which printing process is better for 3D printing with cellulose and lignin as a feedstock?

How can we improve the material recipe made by Thomas Liebrand?

Which tests are necessary to evaluate a window frame?

Design Integration

Can we 3D print a window frame?

Which limitations and advantages will influence the shape of the window frame?

Can we replace and/or enhance the performance of a window frame with additive manufacturing?

01 | 3 Methodology

As the design is a fundamental part of the research to create new insights, knowledge, and a printed product with a discourse that is practical and theoretical written to be accessible and validated by experts, my research strategy is named: Research by Design. This research is based on project-based experimentation by using all currently available technologies regarding digital design and fabrication in architecture with the use of robotic printing. The design process is an idea-driven design process as I already know that I want to 3D print a window frame as a case study. However, with a bottom-up design development process as it is involving a range of scientific methods for evaluating and adapting the design decisions. Features of this process are interdisciplinary with a step-by-step systematic development and feedback loop to evaluate each step. Lastly, the design outcome is less predictable and less dependent on personal aesthetic taste.

Phase 1: Literature Reading, Review & Interviews (theory) will find and identify the answers to the sub-questions in the 'contextual background '.

The paper that I will be producing, gathers literature papers, interviews, and visits to obtain enough information on 3D printing with wood (Material, Fabrication, Application). Each category is investigated to conduct a research & design plan to further establish scientific experiments. The literature sources were organized by establishing keywords in response to the research question and sub-questions. First concerning the material: "wood", "lignin", "cellulose", "wood fiber" and secondly to the printing technology: "3D printing", Additive manufacturing", "wood filament". Finally, Universities that are experts in the field of robotic fabrication and digital design were also taken into account in the research: "Stuttgart ICD", "IAAC", "UCL", "TU Delft", "ETH". The literature sources were consulted in reviewed journals and in the TU Delft repository. The further exploration of these keywords was then used in Scopus for relevant and accurate articles, books, and academic researches. Among all findings, only relevant papers with a large number of equivalent keywords were selected. Also, the year of publication and amount of people who cited the publication was taken into account. As an efficient working station, the organization of my findings was first organized with an application called "liquid text" to easily find and review them. Then they were organized according to three topics: Material, fabrication, application, and further re-organized after proofreading each paper.

Phase 2: Literature Survey (writing) will explain and answer the sub-questions in the 'contextual background'

Once the literature reading, literature review, and interviews are gathered, the literature survey can be written by answering my research question and sub-questions. Descriptive research is identified (why, how, what).

Phase 3: Material Research (practice) will explain and answer the sub-questions in the 'Design Evaluation"

As Alexsander will be researching on a structural node and I will be researching on a window frame, our tests will have different focuses. We will decompose the complexity of this research into specific features to be analyzed. Alexsander will be researching the mechanical properties of our findings and I will be working on the printability of our findings. We will first explore how we can improve the recipe done by Thomas Liebrand by testing, evaluating, and validating the material mixture for an LDM or FDM process. Once the material mixture and printing process are validated, printing experiments will be conducted at the LAMA lab and tested in the CiTG laboratory with the help of Christian Louter and Giorgos Stamoulis to gather a dataset of the mechanical properties of our recipes.

Phase 4: Prototype & Production (practice) will explain and answer the sub-questions in the 'Design Integration"

After validating our findings, we will be able to understand the limitations and potentials of 3D printing our material recipe to guide the design of the window frame and structural node. The final prototype is established individually.
All these Phases englobe the methodology of co-design or interdisciplinary as Achim Menges describes [Bhattacherjee, 2019]. It is the ability to use digital technologies to rethink the materiality of buildings, the construction systems, fabrication processes, and design methods at the same time and in feedback with each other. (Figure 1) describes how the tasks will be divided between Alexsander and I during the next 6 months of our scientific research. (Figure 2) proposes the diagram of the research structure, including argumentation and methodology.

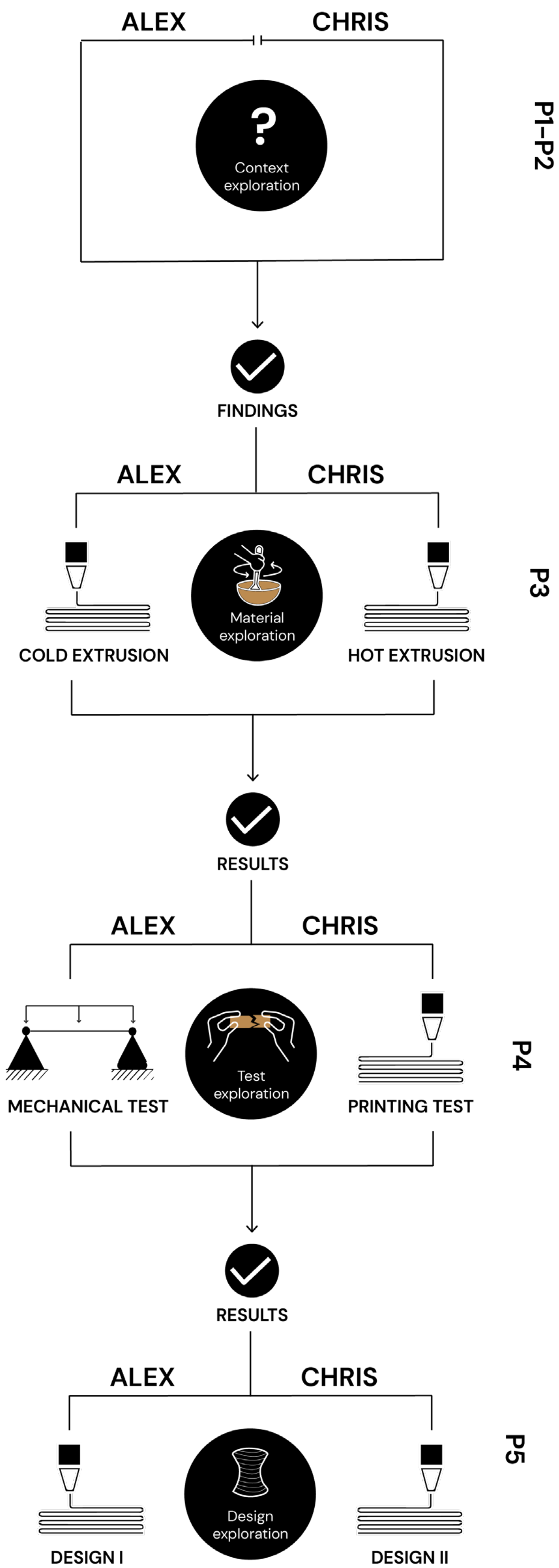


Figure 1: Diagram of the research structure, argumentation and methodology. Source: own

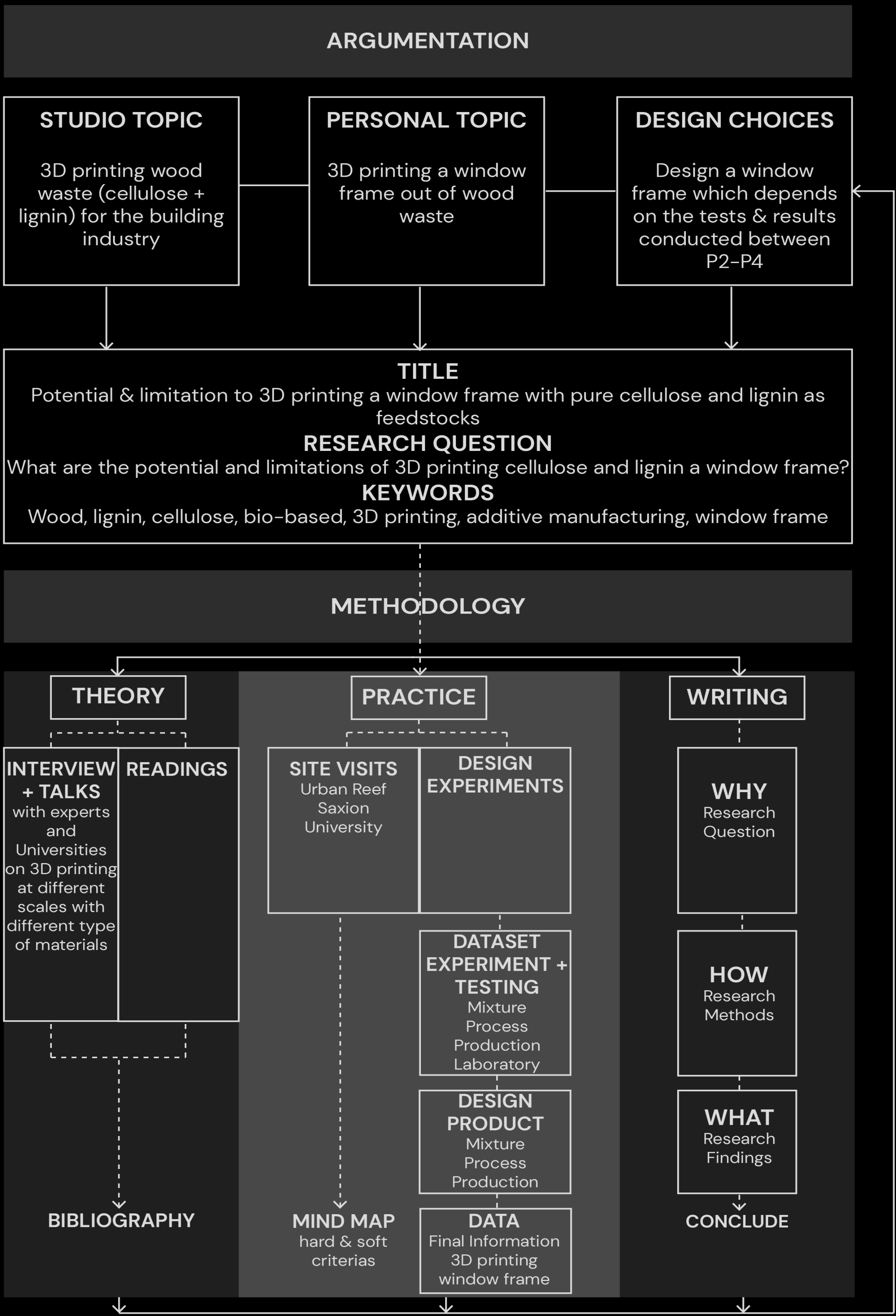


Figure 2: Diagram of the research structure, argumentation and methodology. Source: own

01 | 3 Timeline

The timeline (figure 3) is an essential part of the research to vision and validate the final outcome of this thesis. As explained in the research question, my colleague Alexsander Coelho and I will be working together on multiple experimental, exploratory material recipes to find the limitations and potentials of our thesis. We will both conduct different experiments to validate the design of our final product. Therefore, the timeline was divided into 7 phases from thinking to execution according to material, robotic, mechanical tests availabilities, and expertise between Alexsander Coelho and myself.

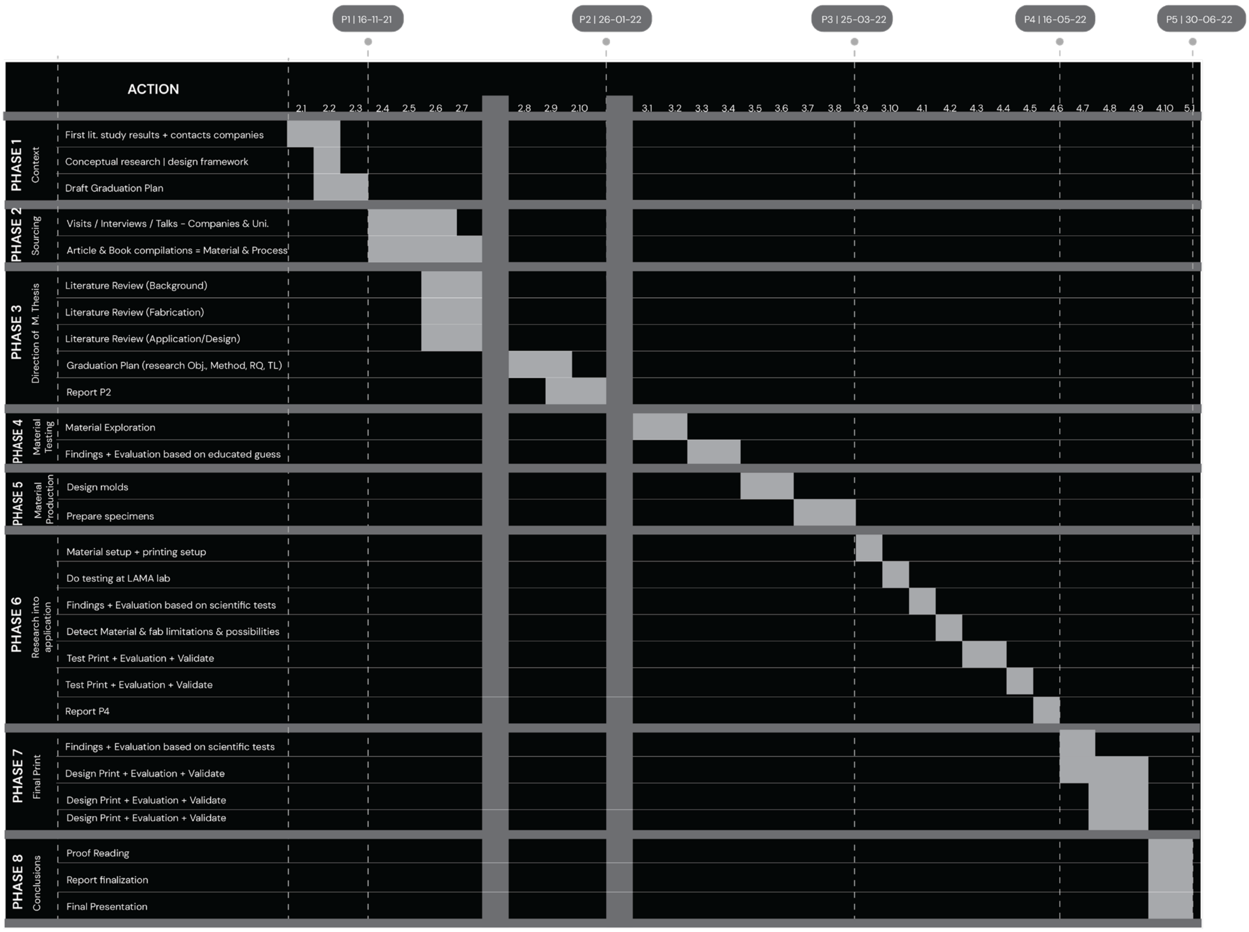


Figure 3: Timeline
Source: own

02 Overview

02 | 1 Material

02 | 1 | 1 Importance to change our construction habits

“Over the past 200 years, humankind’s impact on the planet has instigated a climate disaster, escalated biodiversity lost, and intensified pandemic threats associated with commercial wildlife trade” (Oxman, 2021). Today, the system that we have created for ourselves is responsible for the over-extraction of resources which has led to the depletion of sacred materials and created a large amount of waste. Therefore, designers of the built environment have to quickly act and understand how to design with sustainable and circular principles. According to Lindstrom, we must understand how materials make us think, feel, and act, to provide new avenues for designing products and new materials (Mikael Lindstrom, 2018). Designers need a level of sensitivity to first work with materials before designing to fully consider what a material can do and wants to be. As Prof. dr. Karana said: “Materials have no meaning they get them” (Karana, 2018).

02 | 1 | 2 History of wood

The illustration of Cesare Cesariano in 1521 of an accidental fire generated a social gathering leading to the creation of languages and eventually triggered ‘the mimetic act of architecture’ (Osman, 2011). The fire symbolized the milestone in human evolution which would have never occurred if wood did not exist (see Figure 1.0). Also, the painting of the primitive hut theorized by abbé Marc-Antoine Laugier, describing the classical system of the “column, entablature, and pediment”, revolutionized the way we approach structures and architecture thanks to wood (see Figure 1.1). Moreover, history would have never been written if paper never existed. Thanks to the great inventions, and the development of paper, the written language proliferated (Kurlansky, 2016). Wood has allowed societies to prosper over time and can therefore be considered to have “environmental virtues” (Cogdell, 2018). Wood has always been a protagonist in the history of humankind, which is why we must take care of our forests. As Sebastião Salgado said: “the trees are the hair of our planet” (2012) and without them, humanity would be a blank page.

Figure 1.0: Cesariano (1521)
Source: https://originsofarchitecture.files.wordpress.com/2012/11/cesariano-fire.jpg

Figure 1.1: The primitive Hut by Marc-Antoine Laugier (1755) Source: https://en.wikipedia.org/w/index.php?title=The_Primitive_Hut&oldid=1090694722,

02 | 1 | 3 What is it used for?

Today, trees are cut down for many reasons. Their harvest serves the building industry, paper industry, fuel for cooking, fuel for heating, natural dye and to be converted into large-scale agricultural lands. The deforestation caused by the production of soybean, palm oil, and cattle ranching for the meat industry is responsible “for the release of 340 million tons of carbon to the atmosphere every year” (Nepstad et al. 2008). Furthermore, wood harvesting in the pulp and paper industry is considered to be one of the most important producers in the world, serving approximately 5 billion people worldwide (Bajpai, 2015). Therefore, we must understand whether enough wood can be used in large quantities to meet our needs.

02 | 1 | 4 Is there enough wood? Availability vs Scarcity

The magic of wood is that it can be replanted to grow conversely to minerals. A great example is the reforestation project at the RPPN Bulcão Farm in Brazil made by Sebastiao Salgado and his wife. Founded by the Instituto Terra, they planted “2.5 million seedlings from 297 native species from Atlantic forest” (Fabriz, 2016) to reforest the area and bring it back to life after 15 years of hard work (see Figure 1.2, 1.3). Hence, wood has the flexibility to grow abundantly. Only in Europe, there is an area of 180 million hectares of wood that is available per year, this is 40% of the EU land cover at a growth of 0.3% hectares of wood per year. Half of those forests are sustainably managed and certified by the FSC and PEFC (Lugt, 2021). Thus, by managing the forest we can take advantage of the entire cycle of wood to arise new possibilities for energy production and sustainable environmental practices (Ibañez et al., 2019).

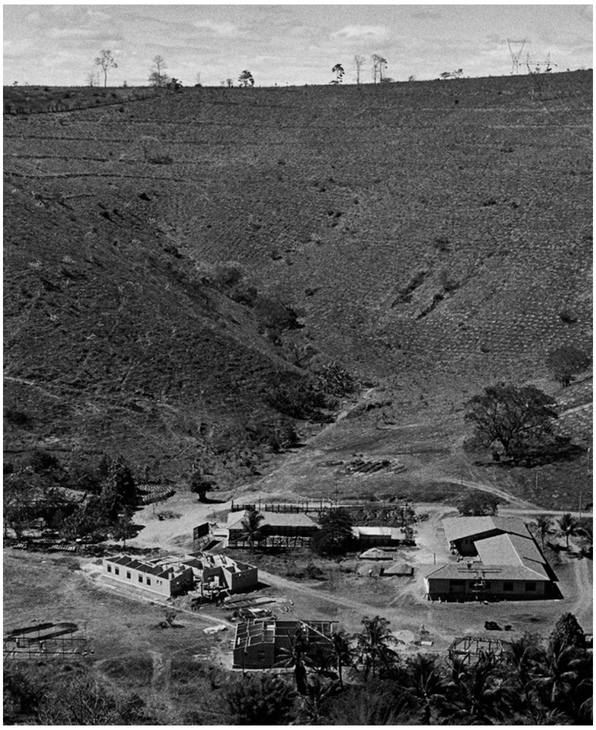


Figure 1.2: Before forest restoration
RPPN Bulcão Farm 2001/2013 – © Sebastião Salgado
Source: https://institutoterra.org/o-instituto/

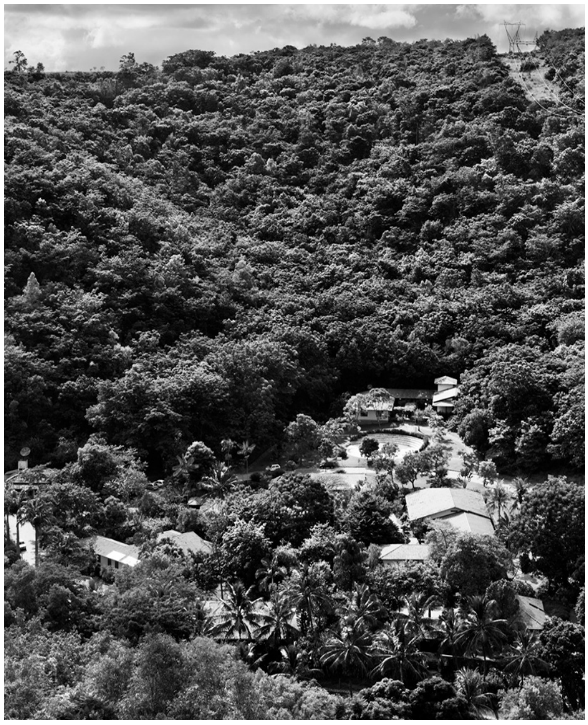


Figure 1.3: After forest restoration
RPPN Bulcão Farm 2001/2013 – © Sebastião Salgado
Source: https://institutoterra.org/o-instituto/

02 | 1 | 5 The expansion of wood as a building material

According to Pablo Van der Lugt, hardwoods, softwoods, and bamboo will be the only remaining materials available after 2090. His diagram (Figure 1.4) shows the number of years left for the most important material reserves for the building industry (Lugt, 2020). Also, according to Dr. Julian M Allwood, cement in its current form cannot be used in the construction industry as its production involves the emission of carbon (Allwood, 2020). Thus, through the evolution of material use, wood is now coming back as a strong candidate for wider adoption in the construction market due to its environmental grade, excellent energy performance, low cost, and flexibility. “Wood is progressively a material of choice for many architects and builders” (Cogdell, 2018). If we were to compare the stiffness and strength of wood, concrete, and steel, softwoods are a great competitor to steel (Ramage et al., 2017). In figure 1.5, we can understand that the strength to weight and elastic modulus to weight ratio indicated that concrete has the lowest strength and elasticity with about 18 (N/mm2)/(kg/m3) compared to softwood, which has the

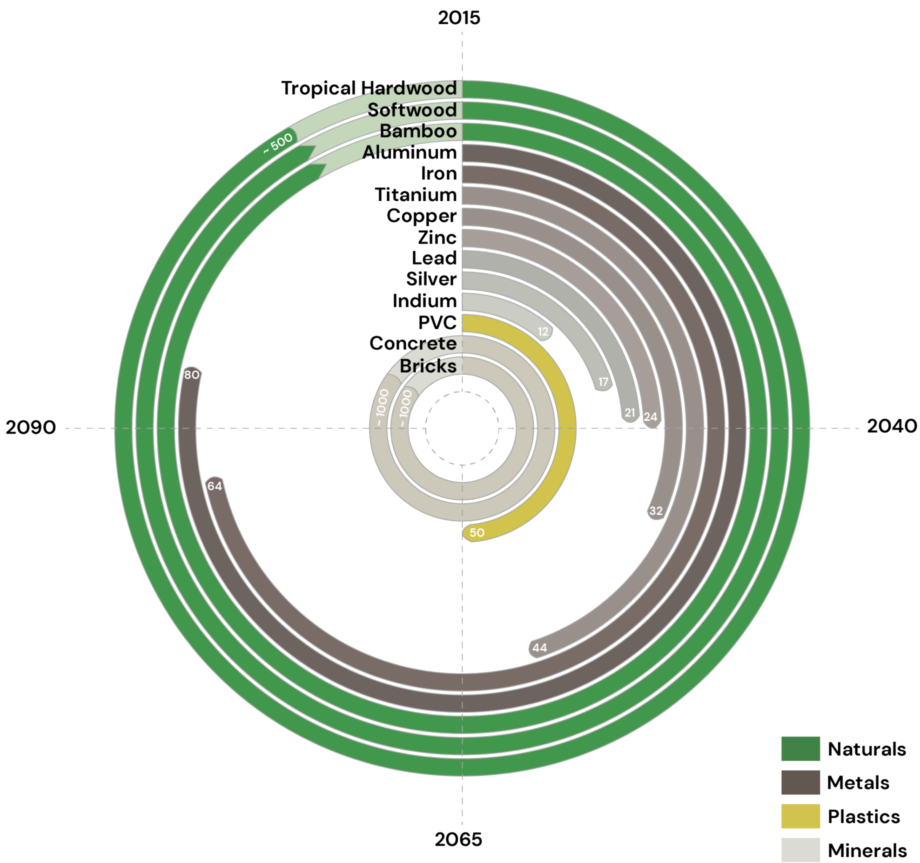


Figure 1.4: Estimated remaining material supplies worldwide (Lugt, 2021)
Source: Tomorrow's Timber: Towards the Next Building Revolution

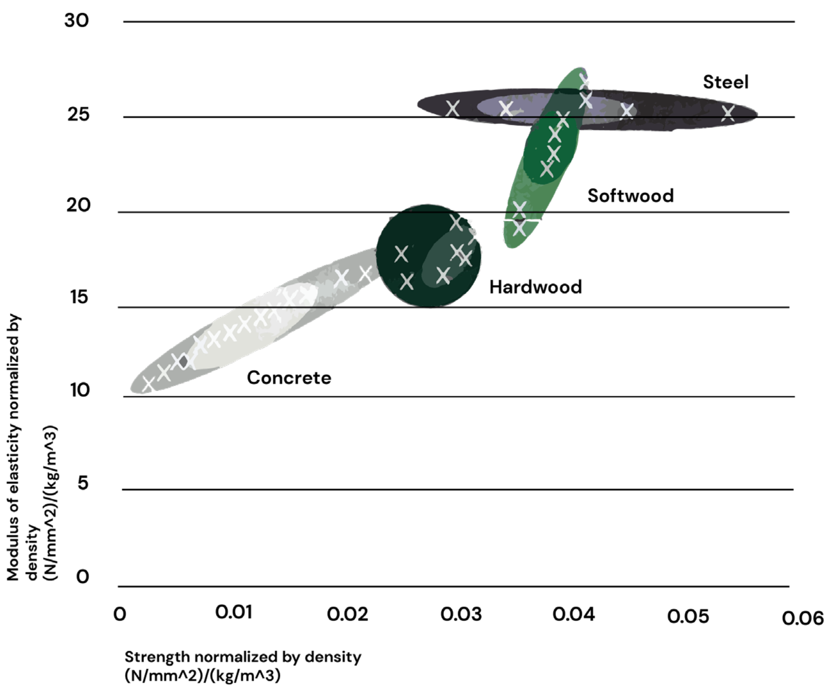


Figure 1.5: Structural efficiency (Lugt, 2021)
Source: Tomorrow's Timber: Towards the Next Building Revolution

highest elasticity of around 27 (N/mm2)/(kg/m3). Moreover, mass timber is five times lighter than concrete, which is a great advantage for building lighter structures than an identical building built in concrete (Lugt, 2020). Lastly, wood is a renewable resource with low energy use compared to steel, concrete, or masonry. (Ximenes et al., 2013; Skullestad et al., 2016). Hence, the methods used by the building industry have to fundamentally change by either reverting to wood or other natural compounds (Allwood et al., 2019). Today, mass timber is disrupting the construction industry field because it is produced in controlled environments and produced with a high-level quality where the construction time and building cost are more or less the same as prefab concrete (Lugt, 2020). A great example is the world's biggest wooden skyscraper (85.7 meters) designed by Voll Arkitekter, built with prefabricated cross-laminated timber elements (see Figure 1.6). Moreover, if the timber construction is maintained in dry conditions, it will be preserved. A telling example is the temple Horiyu-Ji in Napa, Japan built 1500 years ago which is still standing in perfect condition (see Figure 1.7). Moreover, the great advantage of using mass timber, is that it can extinguish itself to not burn (Lugt, 2020). So, mass timber is a safe fire-resistant material. Also, mass timber is a renewable material that can have many life cycles. Timber houses can first live for 50 years or longer (1st life) then can be rebuilt if it was designed to be demountable and live for another 50 years (2nd life). Then, it can be turned into chipped panels or furniture (3rd life) and lastly into bio-energies (4th life) (Lugt, 2020). Nonetheless, only 9.1% of our materials worldwide were being recycled in 2020 and are now down to 8.6% (Haigh et al., 2021) which shows the urgency to illustrate how mass timber can become fully circular. Finally, a 2018 study by Pollinate in Australia had more than 1,000 respondents exposed to wood in office space and reported that timber did improve their productivity, and concentration, and lower their stress levels (Knox et al., 2018). Hence, the myths about wood being dangerous and impermanent can now be disseminated to one of safety, durability, sustainability, circularity, and pleasure. After understanding the benefits that

Figure 1.6: Mjøstårnet, Brumminddal by Vollark (2019)
Source: http://vollark.no/portfolio_page/mjostarnet/

Figure 1.7: Horyuji Temple (607)
Source: https://www.japan-experience.com/all-about-japan/nara/temples-shrines/horyuji-temple-nara

we can get from wood, we must understand how wood is chemically structured.

02 | 1 | 6 How does wood work?

There is a certain beauty to admire when it comes to the ecosystem of a tree. Trees are able to absorb CO2 from the atmosphere and transform the sun's energy into sugar. The natural formula of Photosynthesis allows trees to get their needed nutrients and energy to grow and also offers oxygen for living creatures. Wood consists of three basic elements: carbon, hydrogen, and oxygen (Liebrand, 2018). The three main components of plants and trees are cellulose, hemicellulose, and lignin (Yang et al., 2020). Wood, more specifically softwoods, consists of cellulose (40-45%), hemicellulose (25-30%), and lignin (25-35%) that acts as a binder within and between its cell walls, see figure 1.8. The cellulose and hemicellulose are combined in strands called microfiber, which is bound by lignin (providing compressive strength) and together form fiber cell walls. "The cell walls have four layers, of which the middle layer (S2), with strands mostly oriented in the longitudinal direction, has the largest thickness and the most significant impact on the wood's properties" (Lugt, 2020). Wood consists of tubular cells set in the longitudinal direction in a lignin matrix. However, wood is known to be an anisotropic material which means that it behaves differently in a longitudinal or perpendicular direction along the grain (Liebrand, 2018). Because of this phenomenon, wood is considerably stronger when it is parallel to the grain, see figure 1.9 (Lugt, 2020). Wood is a natural material derived from trees that can differ in properties, depending on their "location, climate, soil, and other local circumstances. The mechanical properties also differ, depending on the location of the extracted material from the trunk (e.g., heartwood and sapwood), but also the time of the year that the tree has grown" (Lugt,

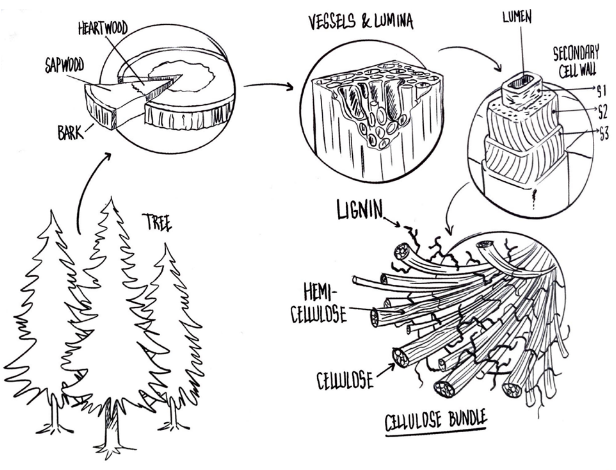


Figure 1.8: Structure of wood (Lugt, 2021)
Source: Tomorrow's Timber: Towards the Next Building Revolution

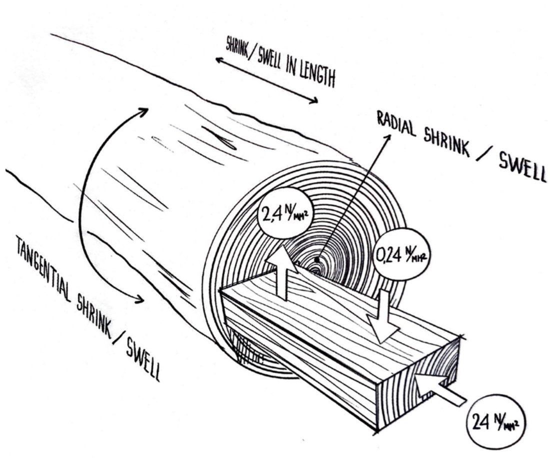


Figure 1.9: Structure of wood (Lugt, 2021)
Source: Tomorrow's Timber: Towards the Next Building Revolution

2020). In addition, water plays a central and dual role in the life of a tree. Trees need water to grow and survive. When water is too present, it can become an enemy causing "shrink and swelling" (Lugt, 2020). The water is stored in the tissue of the tree, as it is a hygroscopic material, meaning that it can maintain its moisture content in relation to its humidity level (Skaar, 1988). If the moisture level is above 30%, the fibers get saturated (Fiber saturation point) and make the wood cells swell especially in the tangential direction and radial direction (Lugt, 2020). Also, if moisture is present in the cell walls, it can cause the installation of fungi and insects, leading to the degradation of the tree. The durability of a tree depends on its kind. However, wood modification is the most effective method to increase the durability and stability of a tree (Lugt, 2020). Research has been conducted by the University of Stuttgart in 2019 on the design of the Urbach tower which identifies the advantages of the behavior of wood when it swells and shrinks after being in contact with a certain level of humidity to produce curved elements. It is as Achim Menges calls: "an investment into form in order to build with fewer materials" (Menges, 2021). The Urbach tower shows how the wood is shaped from itself by an arrangement of the grain in different directions in a controlled environment which leads to a predicted form, self-shaped components to create thin and curved structures (see Figure 1.10). Also, Arthur Mamou-Mani describes wood as "the most flexible, most democratic material because you can shape it and adjust it in many ways. Wood is a very accessible material, very light, it's sturdy, it's carbon-neutral, and comes in all the "off-the-shelf formats" (Mamou-Mani, 2021).

Figure 1.10: Urbach Tower, Achim Menges (2019)
Source: http://www.achimmenges.net/?p=21454

02 | 1 | 7 Cellulose

It wasn't until 1838 that cellulose (C6H10O5) was discovered after the use of papermaking by the French chemist, Anselme Payen (Kurlansky, 2016). As described previously, trees are made out of cellulose, hemicellulose, and lignin. However, cellulose can also be found in the cell walls of almost all plants such as algae, fungi and secreted by some species of bacteria. It is one of the basic building blocks of all plants with around 33% of cellulose made from sugar compounds produced by photosynthesis. Also, it can be made from recycled provenance such as sawdust, cardboard, and agricultural lignocellulosic waste (Chiujdea et al., 2020). Therefore, cellulose is one of the most organic compounds in the world (Vijay et al., 2018). Cellulose is used for the production of insulating materials, for paper and textile production as well as in the food industry to stabilize the mixture of fruit pulp and water in orange juice (Peters et al., 2017). Cellulose from wood, bark, grasses, cotton, silk, and seaweed can be used to make paper (Kurlansky, 2016). As cellulose is used in various industries, it is considered a serious alternative to petroleum-based raw materials. Also, cellulose-based composite materials can be compostable by naturally returning into nutrients to the living environment. They can also store inorganic carbon compounds which reduces greenhouse gas emissions (Chiujdea et al., 2020). Like starch, cellulose is a carbohydrate that is made up of a large number of glucose units and has high levels of crystalline. This crystallinity causes cellulose to have a high melting point, which makes it unsuited for thermoplastic processing and insoluble in conventional solvents. However, the exact numbers depend on the original source of the material (Liebrand, 2018). Lastly, the nanostructure of cellulose crystallization acts like sugar making it ten times stronger than steel (Shoseyov, 2018). Thus, cellulose can have a high tensile and compressive strength.

02 | 1 | 8 Lignin

The word lignin is derived from the Latin word: lignum. Lignin is a major constituent in the structural cell walls of all higher vascular plants (Gosselink, 2011). Lignin is a substance that holds cellulose fibers together, it is a natural reinforcer to cellulose in nature, serving as a binder that cross-links polysaccharides to confer strength (Giachini et al., 2020). Therefore, the structure of lignin provides the necessary resistance to the biological and chemical degradation of plants. Lignin is a hardening substance in the cell walls of wood (Peters et al., 2019). Also, lignin acts as a compatibilizer between the hydrophilic fibers and hydrophobic matrix polymer, thus strengthening the fiber-matrix interface (Opedal et al., 2019). Thus, lignin offers great physical strength, and rigidity to the tissue and cell structure of plants and individual fibers (Banu et al., 2019). A higher amount of lignin content was found, mainly in the biomass such as softwoods (25-35%) and Hardwoods (16-24%) (see figure 1.11). However, grasses contain less lignin such as hemp (under 4%) and sugarcane (2-3%). As the lignin content is much lower in grass fibers, these are therefore a great source for the paper industry if their fibers are broken down efficiently (Kurlansky, 2016). Whereas trees that have high levels of lignin are sturdy enough for the construction industry. “Each year, over 50 million tons of lignin are produced worldwide as a side product from biorefineries, of which 98% are burned to generate energy. Only 2% of the lignin has been used for other purposes, mainly in applications such as dispersants, adhesives, and fillers” (Opedal et al., 2019). Lignin is the most abundant natural resource of bio aromatics. The total lignin amount present in the biosphere exceeds 300 billion tons and increases by approximately 7% every year (Mastrolitti et al., 2021). Moreover, lignin has lower energy content than coal. The energy value is limited to 50 US Dollars/dry tons (Wang et al., 2019). Thus, cost-efficient valorization of lignin into value-added products offers a significant opportunity to enhance operational efficiency and generates additional revenue so that the production of bioethanol or other products from the hydrolyzed carbohydrates becomes more competitive (Opedal et al., 2019). The notable properties of lignin are high abundance, low cost, biodegradability, high carbon content, high aromaticity, and reinforcing capability which makes it a good candidate for biocomposites (Opedal et al., 2019). However, Lignin valorization processes still need development due to the recalcitrant nature of lignin which restricts its potential to produce valuable products (Banu et al., 2019). Although wood is composed of cellulose, hemicellulose, and lignin, the conducted research will not work with hemicellulose as it is a polysaccharide just like cellulose.

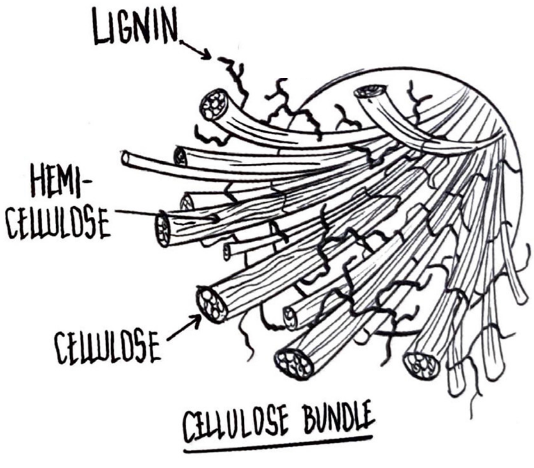


Figure 1.11: Structure of wood (Lugt, 2021)
Source: Tomorrow’s Timber: Towards the Next Building Revolution

02 | 1 | 9 Forest and agriculture waste?

We could think of natural waste produced by trees when half of the wood's waste is carbon coming out of the atmosphere. Wood stores carbon at a high level, where it is estimated that 1 cubic meter of wood captures almost 1 tone of Co2 (Smedley, 2019). Nevertheless, a lot of waste and residues can be found in agriculture and forest waste. The energetic value of agriculture and forest waste in Europe is 4.5 Å~ 1012 MJ/y (Bilgen et al., 2016) which shows that it has a big potential for energetic commercialization. Also, forest wastes are utilized as feedstock for integrated gasification processes. Therefore, agricultural wastes are under-exploited (Bilgen et al., 2016). In 2012, only 5.5% of waste was converted into biofuels for the export of all agricultural products in the Netherlands (Goh & Junginger, 2013). The CE Delft seen in figure 1.12 shows how agriculture has great potential for sustainable biomass worldwide (Strangers et al., 2020). "Forest residues are a byproduct from forest harvesting, which is a major source of biomass for energy. This includes thinning, cutting stands for timber or pulp, and clearing lands for construction or other use that also yields tops and branches usable for bioenergy. Wood waste is mostly the result of wood processing industries like sawmills, plywood, panels, and other wood product supplies, which may generate a significant number of byproducts. The main types of waste include sawdust, off-cuts, trims, and shavings that can be further pressed into wood pellets. Common sources are forest residues, thinning's, treetops, and limbs, and low-quality fiber that is unwanted by other industries or lacks a local market" (Belyakov, 2019). The large amount of waste provided by agriculture and forest lands can be interesting to be used for biofuels. Therefore, we must look into other industries which are already extracting cellulose and lignin as one to be brought apart and put back together.

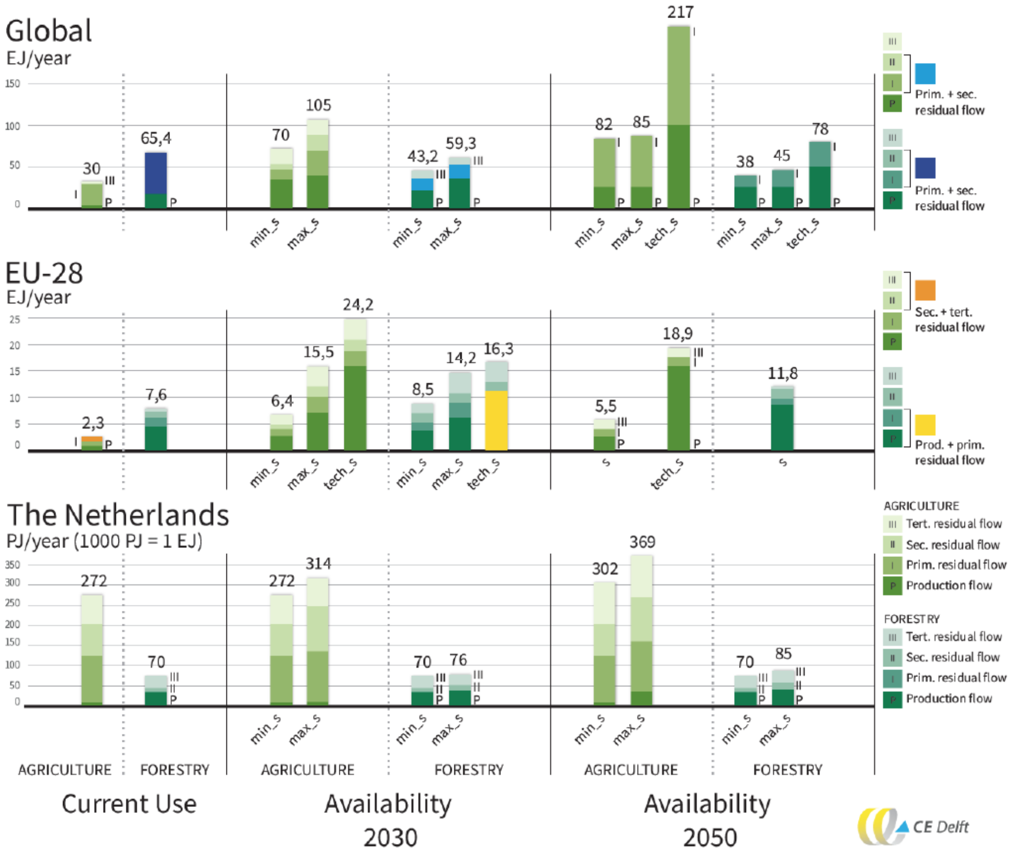


Figure 1.12. Current and future (2030 and 2050) availability of biomass stemming from agricultural and forestry flows for use in energy and material applications worldwide, in the European Union, and in the Netherlands.
Source: CE Delft (2020)

02 | 1 | 10 Lignin, sustainable sourcing?

Paper is made from a tree where its primary source, cellulose is broken down and mixed with water, and converted into pulp to then be processed into very thin layers of woven fibers (Liebrand, 2018). “Cellulose is what chemists call “a straight-chain polymer,” which means that while other starches tend to coil or spread out, cellulose fibers remain in stiff rods with hard outer walls that are not soluble in water” (Kurlansky, 2016). In the process of making paper, the first step is to separate cellulose from lignin fibers. These fibers have to go through a process of “chopping, beating, cooking, and soaking before they can be separated” (Kurlansky, 2016). The paper would have then been thought to weave together and become diluted into a solution to create think sheets in a mold with a screen. Such a great discovery was not invented until 1879 by Carl F. Dahl who invented the kraft process, a German word for “strong” (Kurlansky, 2016). The Kraft process is an elaborated system where wood chips are treated with sodium hydroxide and sodium sulfide to break the bond that holds cellulose to lignin to then wash away the remaining lignin for the paper to appear white. It was not until the 1940’s that the

Kraft process took over the paper industry over old sulfite processes in Europe and in the United States (Kurlansky, 2016). Today, the amount of wasted lignin coming from the paper industry is around 50 million tons per year (Liebrand, 2018). Thus, we must think of how we can use the waste that comes from the paper industry.

02 | 1 | 11 Cellulose, sustainable sourcing then?

The second main ingredient in any recipe with lignin is cellulose. Cellulose can be extracted as a feedstock with sustainable principles to avoid the use of the pulping and paper processes. In the pulp and paper mills the process to produce paper generates large amounts of waste coming from various materials such as ash, dregs, grits, lime mud, and pulp mill sludge (Simão et al., 2018). The waste provided by the paper industry could already provide cellulose from its waste. However, cellulose can also be found in our wastepaper. Instead of acquiring cellulose from a pulping process that requires high energy consumption and chemical processes such as kraft or soda, we can look into other alternatives to find cellulose in a pure form. The most optimal way to gather cellulose in large quantities is by simply using wastepaper. According to the EPA, the United States environmental protection agency which used statistics from the American Forest & Paper Association (AF&PA) has estimated the total generation of paper and paperboard in municipal solid waste to be 67.4 million tons in 2018 with a recycling rate of 68.2 %. Corrugated boxed have the highest recycling rate of 96.5 %. The amount of paper and paperboard that was burnt was estimated at 4.2 million tons and landfills received 17.2 million tons of MSW paper and paperboard. Thus, the wastepaper has currently no commercial significance, except for a few percent used in paper recycling (Haile et al., 2021). Therefore, there are large quantities of cellulose from our paper waste that could be utilized for better use. Lastly, another interesting method to extract cellulose is via agriculture and plant waste. For example, an interesting plant-based is sugarcane. A large amount of sugarcane trash such as in Iran exceeding 7600 t/year according to FAO in 2020 (Haroni et al., 2021) can be extracted to produce cellulose at a nanoscale. The research conducted by Shahi has proven that sugarcane bagasse can become highly crystalline cellulose using a low frequency ultrasonication method (Shahi et al, 2020). Therefore, sugarcane is a great renewable resource that can become a great advocator for sustainable processes to extract cellulose. Lignin and cellulose are great biodegradable polymers that can be reinforced with bio-based agents to replace petroleum-based composites (Chiujdea et al., 2020). As Ronald Rael says: “the future of materials and specifically wood, will be made from what we treat as waste today (Rael, 2021). As there is a large amount of cellulose and lignin waste in our environment, we must understand the innovations that come with them around the globe.

02 | 1 | 12 State of the art: cellulose & or lignin

For as long as we can remember, natural polymers such as wood and cotton have been used in food, clothing, and construction materials. The industrial revolution led to the rise of the first (human-made) biobased plastics and synthetic materials. Celluloid, a material based on cellulose, was first discovered in 1860 and was already being used as a replacement material for ivory around the turn of the century. Not long thereafter, rayon and cellophane were introduced as materials for clothing and packaging. In the first half of the twentieth century, a different type of polymers, produced from petrochemical raw materials such as petroleum, became dominant. Materials made from these polymers have shown spectacular growth over the past century and are known as synthetic plastics. (Molenveld et al., 2020). Today, the use of wood is transforming by applying wood waste into byproducts. The book named: Material's Progress: Innovations for Designers and Architects published in 2019 by Sascha Peters, and Diana Drewes is a great reference that provides the necessary ongoing innovations in relation to cellulose and lignin. Therefore, a few state-of-the-art innovations with cellulose and lignin will be revealed.

Noodles made out of cellulose (figure 1.13): The Japanese textile company named Omikenshi Co. was able to produce noodles from cellulose and konjac root as a way to consume low-fat nutrients to increase the prosperity of Japanese consumers against the rise of obesity (Peters et al., 2019).

Figure 1.13. Noddles made out of cellulose
Source: Materials in Progress: Innovations for Designers and Architects (2019)

Biodegradable abrasives for toothpaste (figure 1.14): Many cosmetic and body care products use cheap abrasives, binders, and fillers made from microplastics. IMWS which stands for The Fraunhofer Institute for Microstructure of Materials and Systems developed biodegradable toothpaste and body scrubs with cellulose bits from beechwood, oats, maize, and wheat (Peters et al., 2019).

Figure 1.14. Biodegrable abrasives for tooothpaste
Source: Materials in Progress : Innovations for Designers and Architects (2019)

Paper-wrapped architecture (figure 1.15): The dutch company Fiction Factory developed the Wikkelhaus (wrapping house) as a way to utilize the full potential of cardboard. Each module is made from steel structural frames which are wrapped multiple times with recycled cardboard paper to produce prefabricated modules that are cost-effective, light, and sustainable (Peters et al., 2019).

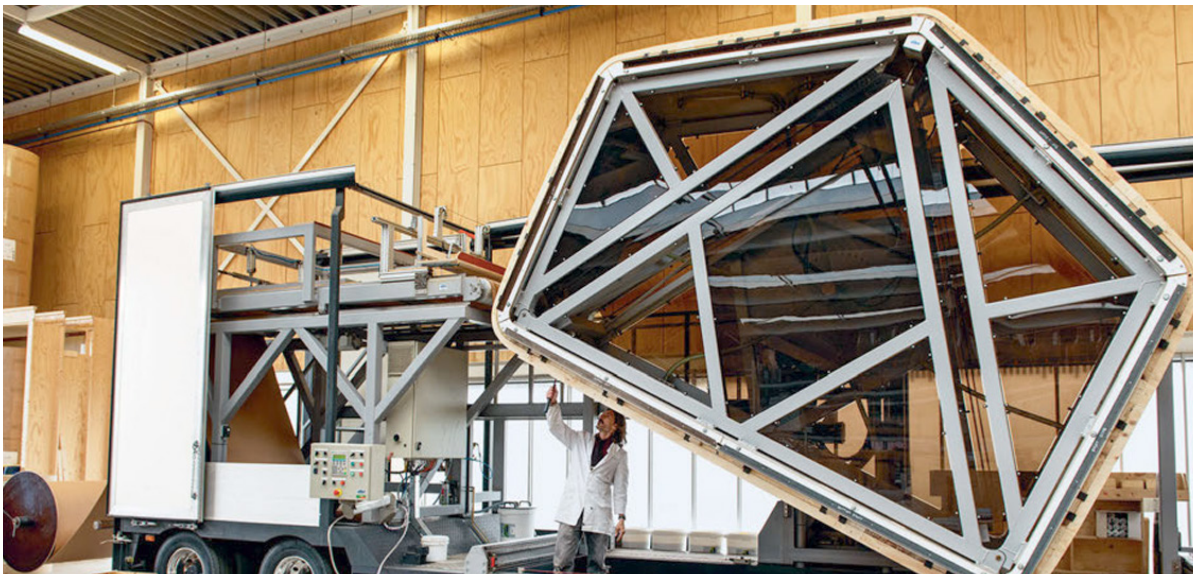


Figure 1.15. Paper-wrapped architecture
Source: Materials in Progress : Innovations for Designers and Architects (2019)

Hygroscopic shape-changing material (figure 1.16): The Hygroskin Pavillon exhibited at the University of Stuttgart has shown the potential for the wood to act as a climate-adaptive material used in the construction industry. The research established by Achim Menges and his team has shown how wood can change in its shape in response to a certain level of moisture content. At a microscope level, the properties of the material can be identified to predict the final shape and or become part of a facade element by implementing a panel that can either open or close in response to certain humidity levels (Peters et al., 2019).

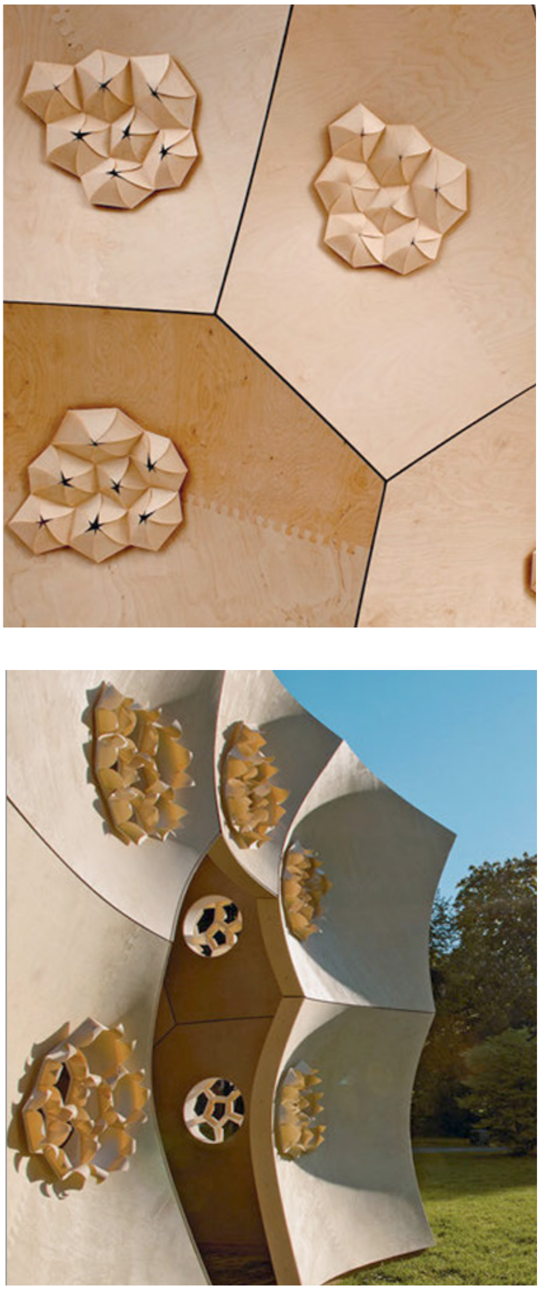


Figure 1.16. Hygroscopic shape-changing material
Source: Materials in Progress : Innovations for Designers and Architects (2019)

02 | 2 Additive Manufacturing

02 | 2 | 1 Why technology?

Living with the logic of modernism and the industrial revolution, the Fordist framework of production was driven by reducing human labor into specialized, simple, repetitive tasks, embodying the total separation of mind and body (Retsin et al.., 2019). Based on an economy of scale where the more copies you make, the cheaper it becomes, the more you buy something, the cheaper it becomes, humans were thought to act and feel like a machine. An example is the drawing of "En l'an 2000" from Villemard that shows how an architect is reduced to his actions and only executing what the robot can do, therefore discretizing the ability of an architect to create (see Figure 2.0). Today, there is a paradigm shift in our economy, which is mass standardization to mass customization, a "society without scale" (Carpo, 2017). The revolution of post-modernism is the fact that we can 3D print the same copy of an artifact or a different one at the same unit cost. The revolutionary discoveries of sciences and laws led by people such as Galileo and Newton are now changing towards the algorithm and logic of computers to achieve better results by using the logic of what Mario Carpo calls "massive trial and error". Thus, there is a paradigm shift that affects the way we capture reality, model reality, reproduce and conceptualize it. We are shifting from projected images from Leon Battista Alberti's in his treatise Della Pittura, 1435 to now 3D scanning, and printing. Just as paintings were the dominant technology of modernity, 3D printing, scanning, etc. will be the next dominant culture, aesthetical technology of digital post-modernity according to Mario Carpo. The exhibition called "Robots in Captivity" was on view in the priory of Buitenplaats Doornburgh in 2021 made by the visual artist Bram Ellens (see Figure 2.1). He investigates ethical questions about robotics and algorithm. With the rapid technological growth and our dependence on technology,

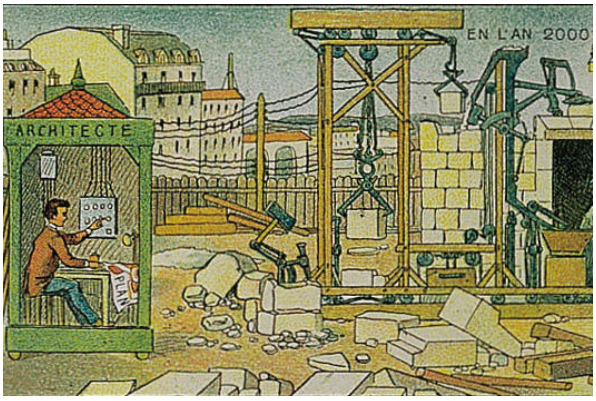


Figure 2.0: En L'an 2000, Villemard (1899-1910)
Source: https://www.laculturegenerale.com/30-images-incroyables-de-lan-2000-imagine-en-1900/

Figure 2.1: Robots in Captivity, Bram Ellens (2021)
Source: https://www.buitenplaatsdoornburgh.nl/binnenkort-robots-in-captivity/

Ellen questions if robots have more control over humans and if there is a danger to them in an age of the digital revolution. We can also consider robots to be creatures and not things, according to Madeline Gannon (2021). According to Gannon these large, intelligent, and potentially dangerous nonhumanoid machines indicate the transition of significant advancements for manufacturing, but also an opportunity to explore human-centered interaction design. This technophobia of robots owning our craft and minds is changing to one of having the robot becoming the agent of our hands to craft. The first digital turn was when we could design and fabricate with a CNC milling machine. CNC machines could fabricate with precision and produce non-standard, variable parts (Retsin et al.., 2019). However, CNC milling results in a large amount of waste due to the subtractive approach of removing material. It would also require a large amount of labor to assemble parts. A technology emerging in the construction industry is 3D printers and robotic arms. The unique abilities of 3-axis printers to 6-axis robotic arms, all follow a straightforward pattern of speed, precision, strength, endurance, and programmability to customize paste to be extruded depending on the number of axes it has to move with. The robot is positioned in a certain direction to extrude with a nozzle a certain material in a laminated way. "The most versatile tool for computer-driven making is the robot, generally seen as a versatile device for carrying out physical tasks, hence the ideal bodily extension, so to speak, for an electronic mind that is not capable of making independent, intelligent choices" (Retsin et al., 2019). Robota in Czech which means 'forced labor' was described as artificial people in the 1920s (Retsin et al.., 2019). Today, the prevailing purpose for a robot is to function as a servant: the more complicated task it can achieve, the better (Gannon, 2018). The design of the tasks or actions to be performed by a robot is only to execute what it is asked for. "Robot depends on us as much as we depend on them" (Gramazio, 2021). It all comes down to the relationship between architects and technology, human and robots. Now, digital technologies implement conceptual and physical materialization through rapid prototyping and digital design to build artifacts as solutions to design problems (sass & Oxman, 2006). Digital design fabrication is based on learning by making methods (Lesgoold, 2001). Also, we are witnessing the transition from automated to autonomous systems of production fabrication machines where they can dynamically see and respond to their changing environment (Gannon, 2021) to further extend our creativity. The status quo of robotic thinking today is led by many architects such as Achim Menges in which the robotic arm is efficiently replacing and reducing human labor while achieving complexity and high building material resolutions (Georghe, 2010). The "Digital design thinking" (Menges et al., 2011) allows architects of the future to use algorithms to go beyond technical efficiency and use the digital tools for "discovering dreams, poetry, resonance, metaphysics..." (Rashid, 2018). Universities such as CITA in Copenhagen, ETH Zurich, ITKE

Stuttgart, and IAAC are implementing the critical consideration of technology as a driver for thinking, forming, and producing architecture. There is a paradigm shift in learning by doing, more creative thinking, and fabrication to increase the relevance of architecture. The power of advanced design tools such as parametric design and additive manufacturing are the new tools that provide the parameters to access the freedom of designing in architecture. Jimenez Lai once said: “One of the reasons why architects are often attracted to philosophers, partially, has to do with making sense of the world around us as well as the making of worlds, and in our case, the realities we create can be as real as concrete. These kinds of ideas, of wild imagination, go into the question of how you make a world”. The complexity of our own imagination can be formed and shaped based on tools that are handed to architects today. We are now living in a time where mass customization with either subtractive or additive technology is possible and costs the same then mechanical matrices such as molds, casts, dies, or stamps (Claypool et al., 2019). We must understand that a computer is simply a tool for thinking. Just like a gardener owning a toolkit, architects can own a 3D printer or a robotic arm.

02 | 2 | 2 Is digital design and fabrication reliable?

Digital and parametric design is still questioned to this day because of its liability. Architects and engineers need to be able to prove that 3D printing is a reliable source to construct habitats or elements for the building industry. Therefore, we will now look into different projects that have proven the potential of digital fabrication tools, industrial robots, and parametric software, as the new apparatus to become part of our built environment. A great example is the design and construction of the glory façade for the Sagrada Familia (see Figure 2.2). Mark Burry who is the Senior Architect

Figure 2.2: Glory Facade, Sagrada Familia, Antoni Gaudi
Photo:RMIT
Source: http://thedesignwriter.com.au/tag/facade/

to the Sagrada Família Basilica Foundation since 1979, was able to complete the façade from surviving fragments of drawings by using parametric software to make 'fast and accurate changes' (Craswell, 2018). Digital design and 3D parametric modeling software have been able to unravel the complex geometries of Gaudi's work to be understood, archived, and allow construction to continue at a significantly accelerated pace (Burry, 2011). Also, the sequential roof from Fabio Gramazio and Matthias Kohler at ETH, Zurich has shown how to assemble a freeform wooden roof in a layering process where every piece is irregular and would cost the same as a regular one (see Figure 2.3). They have proven that the correlation between form and cost has changed today thanks to parametric tools. Another example is Galaxia designed by Arthur Mamou-Mani (see Figure 2.4). In only 18 days a team of 140 volunteers was able to complete a 60 meters wide intricate structure of 400 modules thanks to the rules of computational and parametric design. The process of the project was about assigning teams to the right spot, and then each team would take ownership of those pieces. Finally, the WASP team and Mario Cucinella Architects were able to prove in 2021 the potential of 3D printing with earth on a large scale (see Figure 2.5). Named Tecla, the dual dome-shaped house was printed in only 200 hours (Schoof, 2021). The Institute for Advanced Architecture of Catalonia (IAAC) is also researching since 2001 on 3D printing with clay as a way to customize our built environment, and build faster, cheaper, and sustainably (IAAC, 2019). Therefore, there is a shift today in building an alternative material culture in architecture. Many architects are rethinking how to operate with natural materials using

Figure 2.3: Sequential Roof, ETH Zurich (2016)
Source: *https://ita.arch.ethz.ch/archteclab/sequential-roof-.html*

Figure 2.4: Galaxia, Mamou-Mani (2018)
Source: *https://mamou-mani.com/project/galaxia/*

computational design and robotic fabrication. according to Achim Menges, technologies today are going beyond the scope of humans' ability and intuition of designs (Menges, 2021). Also, today, we can use alternative products that are environmentally friendly materials and avoid using polluting ones such as insulating foam. Designers of the built environment can think of replacing mundane elements that are massively used, with sustainable ones. The application of 3D printing biomass components is a hot topic today and is widely used (Zhang et al., 2020). Many biomaterials are being 3D printed for better use such as the research conducted by Thomas Liebrand in 2018 at TU Delft on 3D printing with pure lignin and cellulose. His research had shown that there is the possibility to produce wood without having to cut trees and reuse its waste to be further re-printed. Thus, a new field of research is then established by implementing the work done by Liebrand to 3D print elements for the building industry.

Figure 2.5: Tecla house, engineered by WASP & designed by Mario Cucinella (2021)
Source: https://www.3dwasp.com/en/3d-printed-house-tecla/

02 | 2 | 3 Can we 3D print cellulose and/or lignin?

Today, 3D printing through Fused Deposition Modelling (FDM) is a widely used method to efficiently and quickly prototype advanced and complex shapes. The FDM process creates a physical object by laying down material, layer by layer on a flat surface according to a digital model (Abdullah et al. 2006). 3D printing with biomaterials such as cellulose and lignin has been a hot topic over the past five years, and "the number of patents for 3D printing with cellulose has reached about 5100, almost double the number before 2000" (Zhang et al., 2020). To access the wood's capacity in a meaningful way, an interactive design approach has to take place with the use of computational design and fabrication tools (Krieg et al., 2014). Cellulose in 3D printing is perhaps the most revolutionary way to rethink wood (Pawlyn, 2019). Recently, hardwood lignin and kraft softwood lignin have been applied to manufacture filaments for FDM, based on acrylonitrile-butadiene-styrene and PLA polymers, respectively (Domínguez-Robles et al. 2019). Yang also agrees that cellulose and 3D printing are being heavily studied as it is one of the most potential candidates for 3D printing (Yang et al., 2018). Also, lignin - considered to be one of the most abundant materials on earth - is being 3D printing as a reinforcing agent to enhance and improve the performance of 3D printed objects (Yang et al., 2018). Lignin also can enhance the strength properties of

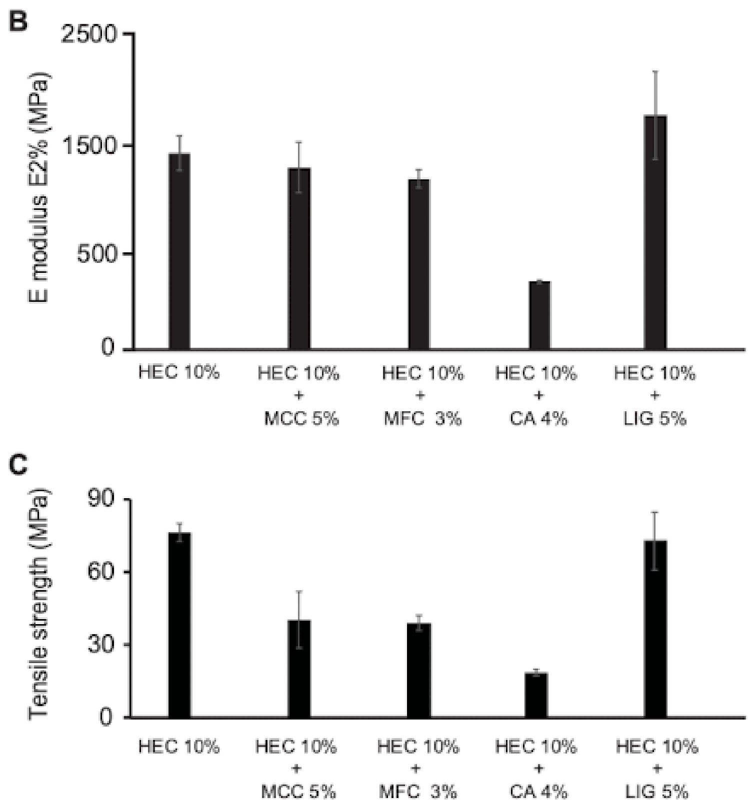


Figure 2.6. (B) compares the E modulus of the base material and the various modified solutions. (C) Compares the tensile modulus of the base material and the modified solutions.
Source: Giachini et al., 2020

wood powder-based filaments (Liu et al., 2019). According to Opedal's research, bio composites mixed with lignin can be extruded with a good level of flowability and no observable agglomerations (Opedal et al. 2019). However, lignin and cellulose have never been developed as a stand-alone material with a 3D printing manufacturing process until 2018. The research of Thomas Liebrand has shown that in a cold process pure lignin and cellulose were a potential recipe to be 3D printed (Liebrand, 2018). 3D printing with cellulose and or lignin is possible in both a cold and hot process.

02 | 2 | 4 Which printing process is best for lignin + cellulose?

According to the research done by Thomas Liebrand, an FDM process might be the key to success. As lignin has a melting temperature of around 150 degrees, it will start "cross-linking once the molecules are heated" (Liebrand, 2018). However, we must take into account that the production of pure lignin composites is limited by their high thermal transition temperature and high flow resistance (Nguyen et al., 2018). If we were to only 3D print with lignin, it would become too brittle (Richard, 2021). For this reason, lignin is mixed with other polymers such as PLA and starch to favor its melting behavior and flow. This suggests that lignin with biocomposites are reliable alternatives to 3D print products (Opedal et al. 2019). The research conducted by Giachini at the University of Stuttgart has shown that lignin combined with cellulose allows good printability and increases the stiffness of the printed parts and tensile strength of the material mixture when heated (see Fig. 2.6) (Giachini et al., 2020). Also, at the University of Saxion, Ivo Vrooijink & Ferrie Van Hattum, who are researching thermoplastic composites, were able to extrude a material recipe with 80% recycled wood and polypropylene in a hot process. The University of Saxion was also able to print with cow feces and PLA at 140 degrees with constant pressure. Furthermore, according to dr. in. Richard Gosselink from the University & Research of Wageningen, a cold process is an additional challenge as the binder between the cellulose and lignin is not yet a natural solvent that can be easily removed from the extruder. According to Gosselink, 3D printing with cellulose and lignin has great potential as lignin is a hydrophobic material, a good UV stabilizer, and a flame retardant. However, lignin does not give enough strength because of its low levels of crystalline. Therefore, adding wood fibers or cellulose would be an improvement of the recipe to act as a reinforcement agent of the matrix. As Cellulose is known to be insoluble in water and a non-thermoplastic polymer, marrying both materials could achieve great results. Wood is now being thought of in a different way where we start from the microscale structure of the lignin and cellulose to be reassembled into a wood artifact. Lastly, Dunia Agha from ISMD TU Darmstadt was investigating to upgrade the paste of Thomas Liebrand from (lignin, acetone, water, and cellulose) in a cold process by substituting the acetone with another solvent called DMSO to avoid a fast evaporation rate of the mixture and avoiding stiffness. She concluded that DMSO helps with softening the paste and had a slower reaction to evaporation. Thus, 3D printing cellulose and lignin as feedstock to achieve high structural properties appears to have better results in a hot process. However, a cold process also seems plausible.

02 | 1 | 5 State of the art: 3D printing cellulose & or lignin

From literature findings and interviews conducted with experts involved in both education (teaching) and the profession (practitioners), we will now look into different 3D printing applications that were made with cellulose and or lignin in a cold and hot process to determine which material recipe is the most reliable source to design artifacts.

Forust, 3D printing sawdust (Figure 2.7):

They were able to 3D print sawdust at a high volume to be affordable, sustainable, and reliable. They have been using 3D printing as a medium to manufacture architectural components with bio-composite mixtures with a binder jetting technology. (own website)

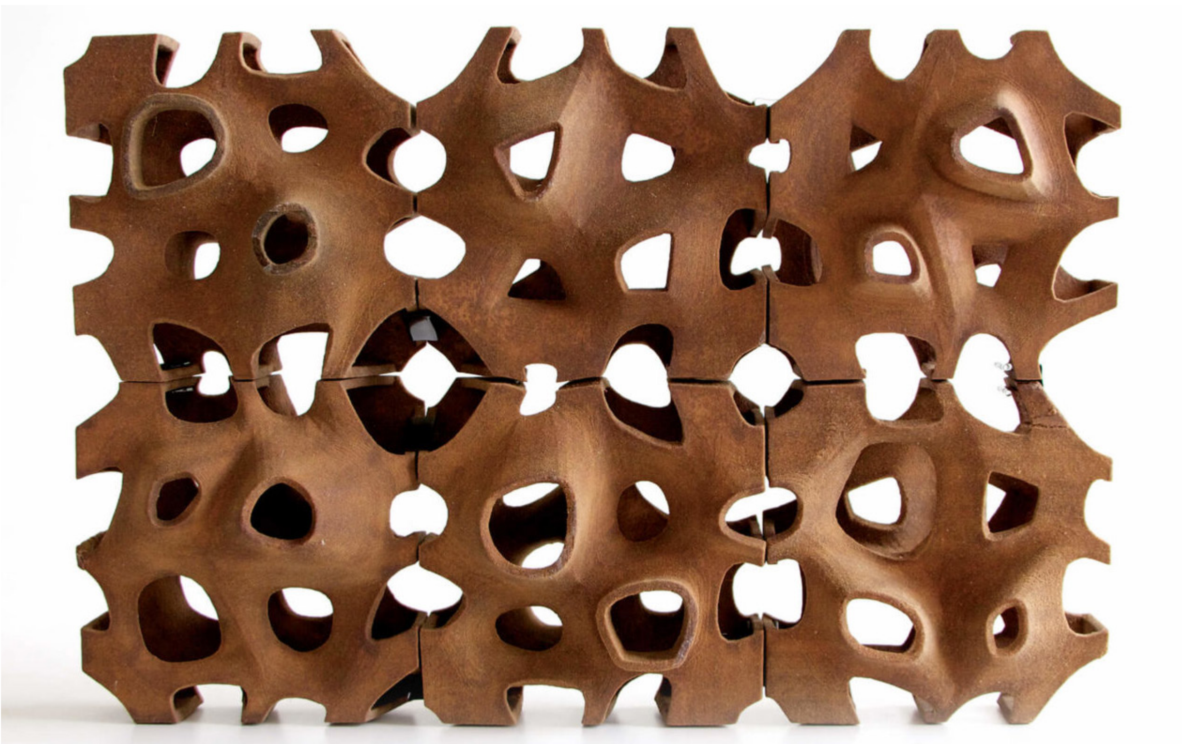


Figure 2.7: Forust, 3D printing with binder jetting technology
Source: https://www.rael-sanfratello.com/ventures/project-five-j37rz

Thomas Liebrand, 3D printing lignin and cellulose (Figure 2.8, 2.9, 2.10):

Liebrand was able to print wood waste by combining lignin, cellulose, acetone, and water. According to him, further research should focus on optimizing the mixture to ease the 3D printing process. Also, research should be done to achieve higher aesthetics (Liebrand, 2018).



Figure 2.8, 2.9, 2.10: Thomas Liebrand, TU Delft
Source: https://repository.tudelft.nl/islandora/object/uuid%3A2856a86c-d862-48b1-924e-1f3ce74647b3

CITA, 3D printing cellulose based biopolymers (Figure 2.11):

CITA's recipe incorporates cellulose floc, wood flour, xanthan gum, glycerol, and calcium with a concrete pump in a cold extrusion process. They looked into the changing properties of the recipe. They concluded that the behavior of the print was changing according to geometrical influence, the evaporative surface, loss of weight due to humidity, shrinking at 25% in height, unequal material distribution, and curing process (Interview by myself). The material behavior could be compared to dense foams. They are currently scaling up the process for an upcoming exhibition.

Figure 2.11: CITA, 3D printing cellulose based biopolymers
Source: https://2021.acadia.org/gallery/

RISE institute, 3D printing with wood waste (Figure 2.12):

RISE developed a biodegradable mixture with the WASP team at RISE in Umea, Sweden. The material they developed is biodegradable and intended to disintegrate or deteriorate naturally in the outdoors. They have tried different mixtures, but the final mixture was sawdust, water, wool paper glue, and bentonite. From their research on material recipes, they concluded that alcohol instead of water makes the material dry faster. Agar-agar and potato starch instead of using glue made the drying process longer. Bentonite was used to make the mixture elastic and help harden the material recipe. They also added 3 hairdryers on the printer while printing the artifact to dry faster. By using a 3MT from WASP, they used different nozzle sizes from 2-8mm. They concluded that the size of the wood particles matters to be printable. Thus, filtering and shredding the sawdust was essential to come out of the nozzle. In the end, they were able to print an 80 cm heigh vase in one and half days with 6 batches in a cartridge of 10-15 liters in continuous feeding. They suggested paying attention to the structural base of where the object would be printer. If the base is made out of wood, the base will deform and make the object move. Thus, putting a plastic bag beforehand onto the base is important (Interview by myself).

Figure 2.12: RISE, 3D printing with sawdust and methylcellulose
Source: https://www.ronaldhelgers.com/

Urban Reef, 3D printing with papier mache and mycelium (Figure 2.13):

Urban Reef uses a sustainable printing strategy in a cold process by mixing kraft cellulose and clay. It was extrudable but difficult. He also tried to print mycelium and papier maché which ended up eating the paper. He then mixed mycelium and coffee beans with the clay which was the best mixture. He suggested paying attention when printing with cellulose when it is compressed in the extruder. Once the material exits the nozzle, the material expands immediately (Interview by me)

Figure 2.13: Urban Reef, 3D printing with mycelium and papier mache
Source: https://www.urbanreef.nl/

Marta Kvadrat, 3D print with wood fibers and PLA (Figure 2.14):

The Swedish start-up named BLB industries was able to print a wall made from PLA and 20% of wood fibers as a way to showcase affordable living conditions. The printed wall took around one week to produce with only ten components (Peters et al., 2019).

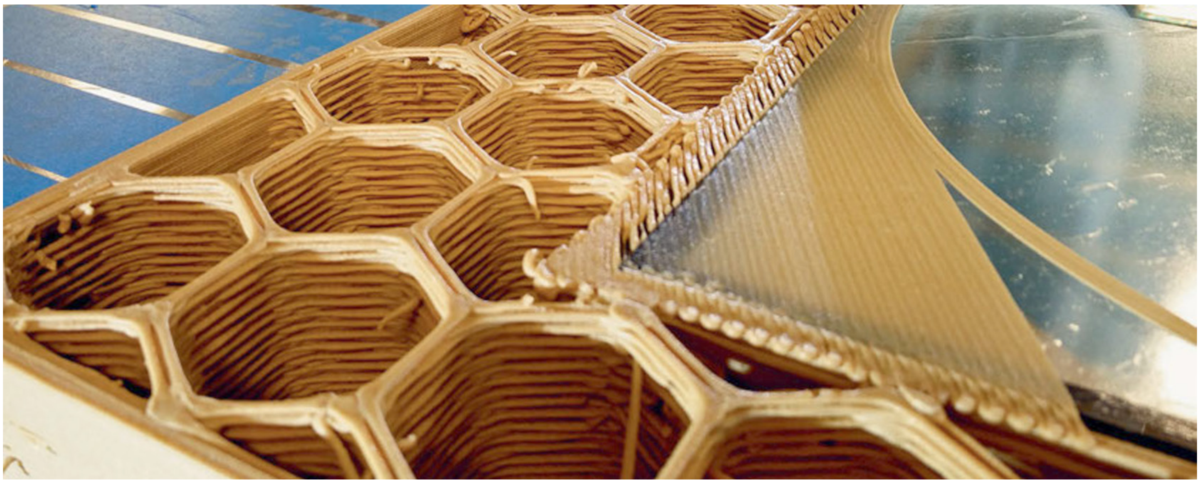


Figure 2.14: BLB Industries
Source: Materials in Progress : Innovations for Designers and Architects (2019)

University of Stuttgart, hygroscopic wood pressure filament (Figure 2.15):

At the University of Stuttgart, researchers created a wood filament named LayWood by cc-products to print a material that reacts to humidity and air. The investigation is to further print facade parts that can open when it is sunny or close when it is raining (Peters et al., 2019).

Figure 2.15: University, Stuttgart
Source: Materials in Progress : Innovations for Designers and Architects (2019)

twoBEars, Lignin Filament (Figure 2.16):

The German start-up called twoBEars created a biodegradable filament named BioFila based on thermoplastic lignin. The texture of the print can vary depending on the temperature used (Peters et al., 2019).

Figure 2.16: twoBEars
Source: Materials in Progress : Innovations for Designers and Architects (2019)

02 | 3 Conclusion

After conducting literature research and interviews with experts in the field of 3D printing wood, lignin, and cellulose in combination with a binding agent are printable. However, the possibility of extracting wood waste into a 3D printing component presents many questions regarding its reliability. Based on these findings, three charts (recipes, printing parameters, and final prototypes) will be created to guide the upcoming steps for this research paper, see Figure 2.17 During phase 3 of the material exploration, the recipe of Thomas Liebrand will be repeated as a base to further develop his recipe into a fully bio-based and printable one. What will be taken into the application is the suggestion made by Dunia Agha from ISMD TU Darmstadt who suggested substituting acetone with DMSO. Also, from the interview conducted with Ronald Helgers and Martina Bambi, methylcellulose and wood glue will be explored in combination with lignin and cellulose. Moreover, the interview with Max Latour from Urban Reef will guide the printing parameters (layer height, nozzle width, speed, etc.). The interview conducted with Gabriella Rossi from the University of CITA will help to predict the behavior of the material once it is extrudable.

MATERIAL MIXTURE

REFERENCES	THOMAS LIEBRAND, TU DELFT	GABRIELLA ROSSI, CITA	MARTINA BAMBI & RONALD HELGERS RISE INSTITUTE	MAX LATOUR, URBAN REEF	MAX LATOUR , URBAN REEF
BASE MATERIALS	CELLULOSE, LIGNIN, ACETONE, WATER	CELLULOSE, WOODFLOUR, XANTHAN GUM, GLYCEROL, CALCIUM	wood flour, water, methylcellulose (also tried wool paper glue, bentonite, alcohol, agar agar, potato starch)	PAPER PULP, COFFEE BEANS AND CLAY	White turning clay 1000-1300c, wit-witbaak, filter coffee, mycelium
RECIPE	10g WATER + 26g ACETONE + 40g LIGNIN + 5g CELLULOSE	cellulose floc 10%, woodflour 7% (sawdust), xanthan gum 2% (sugar) , glycerol 8% (sugar alcohol) , calcium 1%)	wood flour 600g, water 2070g, methylcellulose 135 g, color additive	7 liters of White turning clay 1000-1300c, 25% chamotte, 2% dry paper pulp	N.I.
PROS	- Homogenous - High viscosity - High adhesion	Avergae elastic performances: material behaviour is similar to dense foams	Bentonite helps to harden the material	N.I.	Successful material experiments to grow mycelium through a clay based material
LIMITATIONS	- Not a natural solvent - No mechanical tests made - Does not look like wood - Take time to dry	low strength properties (depend on fiber length)	- melts when wet - not biobased glue	The estimated proportions are not very accurate (clay is lost during the process)	N.I.

3D PRINTING

RESEARCH & REFERENCE	THOMAS LIEBRAND, TU DELFT	GABRIELLA ROSSI, CITA	MARTINA BAMBI & RONALD HELGERS RISE INSTITUTE	MAX LATOUR, URBAN REEF	MAX LATOUR, URBAN REEF
AM TYPE	LDM	LDM	LDM	LDM	LDM
TEMPERATURE	COLD PROCESS	COLD PROCESS (hot process in the future)	COLD PROCESS	COLD PROCESS	COLD PROCESS
NOZZLE SETTINGS	1.6 mm	N.I.	2-8mm	4 mm	3 mm
LAYER HEIGHT	2mm, 5mm	N.I.	0.2mm-0.4mm	4 mm	2.3 mm
LAYER WIDTH	29mm	N.I.	30MM	5 mm	4.5 mm
FLOW	200%, 600%, 800%	2 BAR PRESSURE	6 BAR PRESSURE	start:30-40 main:28	start:65 main:55-80
SPEED	5 mm/s	35 mm/s	NOT INDICATED	start:80 main:100	start:80 main:95-100
PROS	N.I	- Printable at a large scale - Geometrical freedom to design complex joints	- Large fibers = increase strength connects material better, small fibers = get a smoother, nicer finish	N.I.	Coffee grain enhances the structural capacities of the wet clay
LIMITATIONS	- Only printed with a syringe - Requires metal installation	- Evaporative surface - Dries unequally	- low drying process: Added 3 hair dries on the printer while printing the artifact - No scientifc tests	- Difficult to extrude because it contracted in the tank - When exits nozzle, material expands causes issues which increase the amount of layers printed.	N.I.

FINAL PROTOTYPE

RESEARCH & REFERENCE	THOMAS LIEBRAND, TU DELFT	GABRIELLA ROSSI, CITA	MARTINA BAMBI & RONALD HELGERS RISE INSTITUTE	MAX LATOUR, URBAN REEF	MAX LATOUR, URBAN REEF
SIZE	circle 38mm and triangle 40mm, height 150mm	80 X 50 X 25 cm	80 cm heigh	186 X 171 X 286 mm	186 X 171 X 286mm
SHRINKAGE	Medium	25 %	N.I.	N.I	N.I.
WATER ABSORPTION	Low	High	N.I.	High	High
CONCLUSIONS	N.I.	- Geometrical based influence: Cylindar loose 70% of its weight after 7 days - High evaporative rate: shrinks 25% in height (check infill structure of the cavities and amount of air)	Print 80 cm high continuous feeding vase with different colors in 1.5 days with 6 batches of 10-15L. Very strong when not in contact with water.	The speed and flow are percentages of the feedrate and extrusion value respectively, they depend on the code and pressure as well.	successful material experiments to grow mycelium through a clay based material with both coffee and paper pulp and those individually.

Figure 2.17
Source: own

03 MATERIAL : MANUAL PARAMETERS

03 | 1 Overview

Thanks to the collaboration with dr. ing. Richard Gosselink from the University of Wageningen, we were able to receive 20Kg of soda lignin which comes from straw and grass waste, and 1.2 Kg of kraft softwood paper. My colleague Alexsander Coelho and I will be working together during the material research phase (Phase3). As a Subtractive approach, we will first explore how we can improve the recipe proposed by Thomas Liebrand. We will then test, evaluate, and validate a series of material mixtures in a hot and cold process using different natural solvents to validate which paste is printable (see Figure 3.0, 3.1). Once the material mixture and printing process are valid, printing experiments will be conducted at the LAMA lab by myself, and Alexsander Coelho will test at the CiTG laboratory with Christian Louter and Giorgos Stamoulis the mechanical properties of our findings.

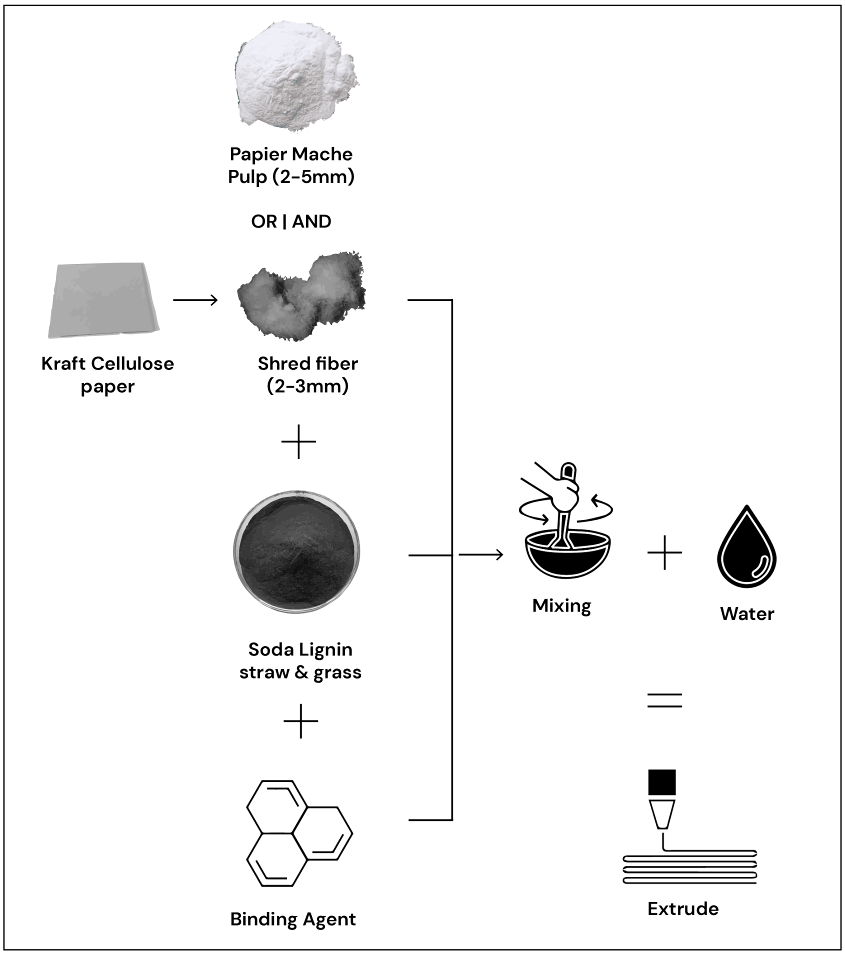
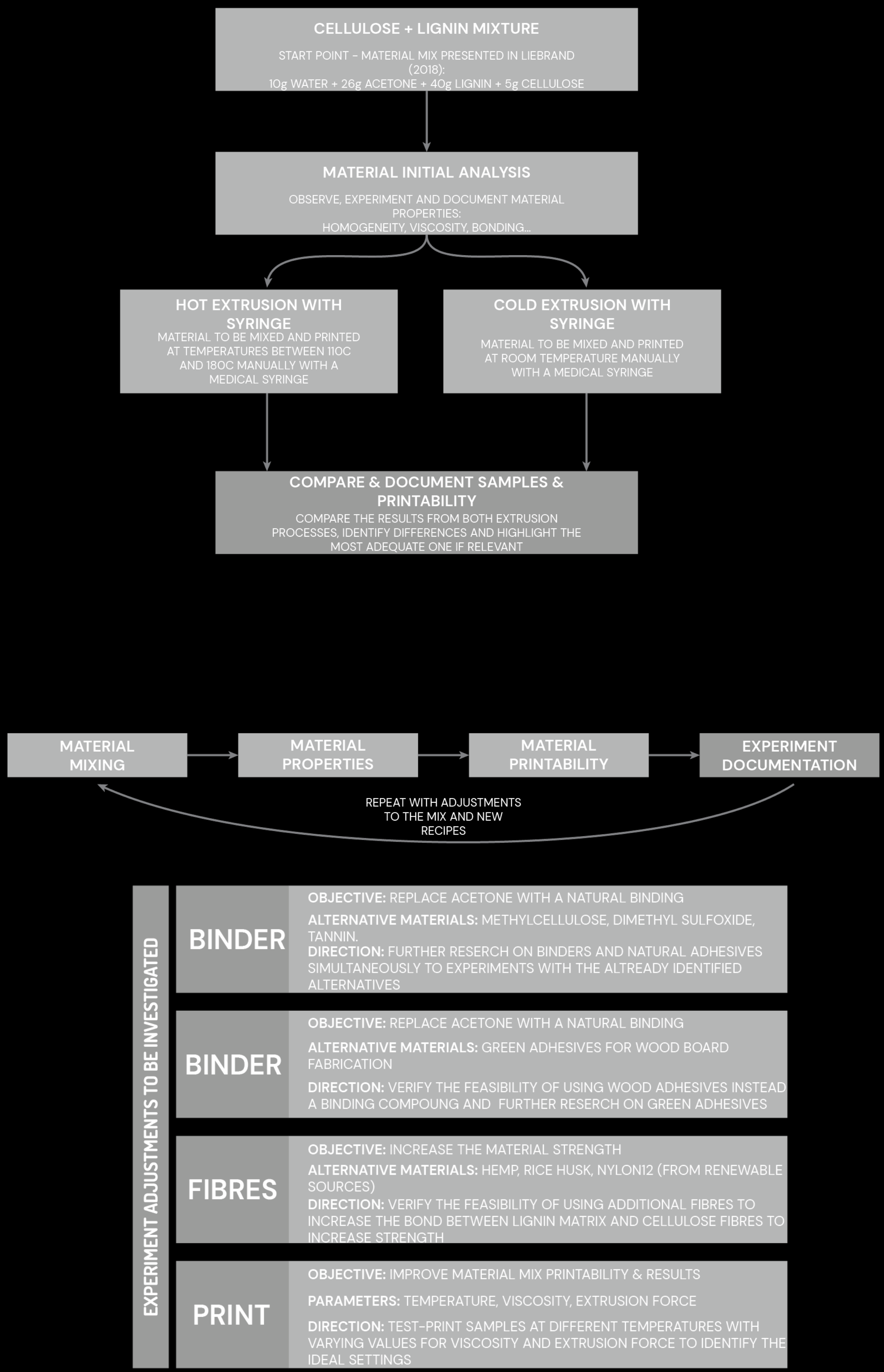


Figure 3.0: Process of Material mixing to extrude out of a syringe
Source: own

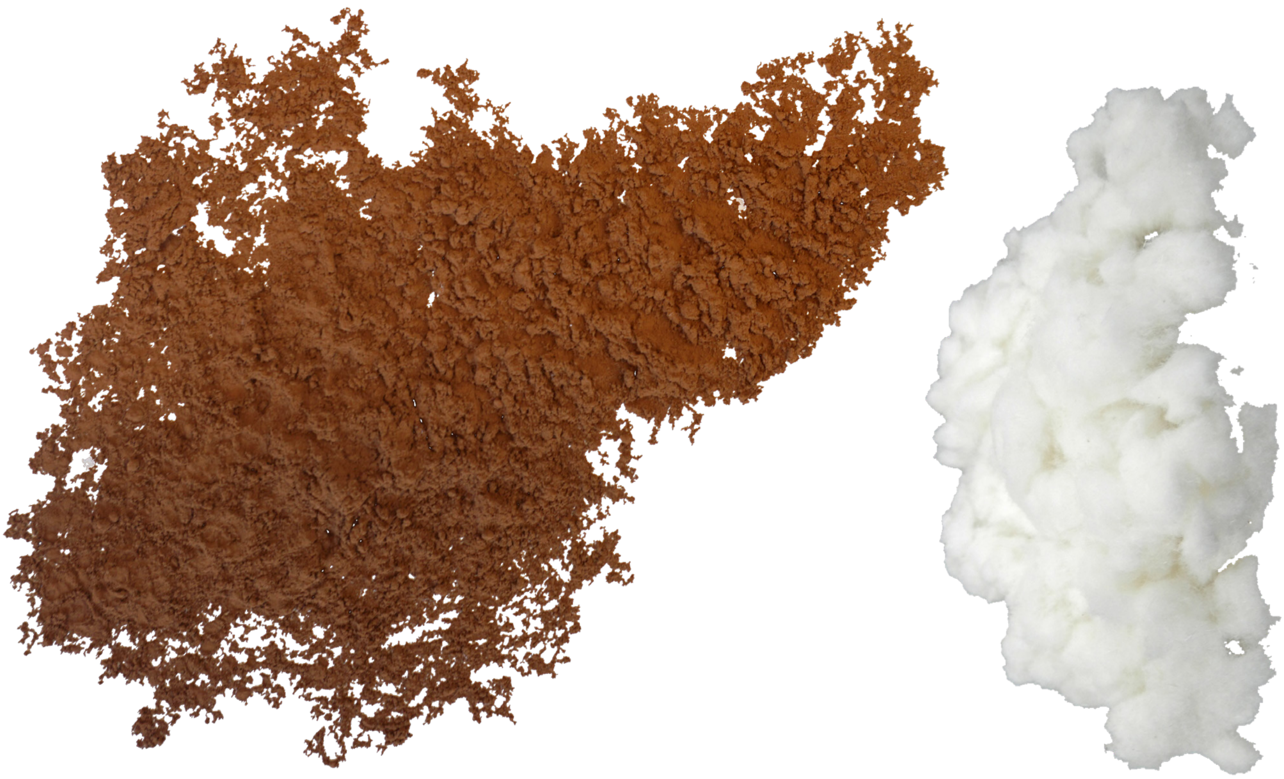


Source: own

Figure 31: Diagram of material exploration phase for a hot & cold process

03 | 2 Material Exploration

In the phase of material exploration, the lignin and cellulose (figure 3.2) were first tested individually without any binding agents to understand if they could become a paste. We quickly realized that mixing lignin and cellulose without a binder is unprintable with the use of a syringe. Therefore, multiple binding agents were tested in a cold and hot process to get a quick idea of which one would be the most promising agent. Each biding agent was tested based on our findings from scientific papers and interviews with experts in the field of 3D printing with biomaterials. Throughout the process of the material exploration, every promising binding agent was mixed with cellulose, and lignin and further refined and studied with different ratios and ways to mix to find the final recipe, which will be operating the 3D printing phase. For this reason, only the final phase, process, and outcome will be explained in this chapter.



Kraft Lignin from straw and grass waste

Kraft Softwood fibers

Figure 3.2: Process of Material research phase done in collaboration with Alexsander Alberts Coelho
Source: own

03 | 2 | 1 Workspace Setup

The experiments were conducted at the LAMA lab (Laboratory for Additive Manufacturing in Architecture) room BG.WEST.250 in the BK lab at the faculty of Architecture and the Built Environment to prepare and test all of the recipes except for hazardous materials, which were safely used in the Stevin laboratory at the civil engineering faculty of TU Delft. The room temperature of the LAMA lab was an important aspect to take into consideration as the recipes behave differently when drying according to their environment. For this reason, a digital Temperature- humidity Sensor DHT11 connected to an Arduino kit was used to measure the temperature and relative humidity of the room. The room temperature is at a constant 20 degrees Celsius with a relative humidity of 37%. Also, as my partner and I had to purchase the necessary equipment individually, the research done by Thomas Liebrand in 2018 was a great inspiration for understanding what the essential tools were to start with the experimentation phase (Figure 3.3, 3.4). The list shown below mentions the tools that were used throughout the entire process:

Measuring:
2 Scales (1g. up to 5 kg.) & (0.01g. up to 200g.)
2 Glass beakers (1L)
2 Metal or glass bowls (3L)
X Coffee Cups

Mixing:
1 Handmixer
1 Plastic cover for when mixing
1 Coffee grinder
2 Rubber Spatula
3 Spoons
Glass stirrer

Extruding:
X Syringes (100ml)
1 Electric caulking gun

Figure 3.3: Essential tools for the material research phase
Source: own

Cooking:
1 Hot plate
2 Saucepans (1 small & 1 big for bain-marie setup)
1 Thermometer

Storing:
Glass pots (250ml)
Petri dishes (150 X 15 mm)
Glass base for the DMSO and Acetone
Plexiglass base for the other mixes
(dimensions of the bases vary as they were bought from leftover scrap from Glashandel Zantman B.V. in delft)

Cleaning:
Lab Coat
Gloves
Sink Strainer
Sponge
Brushes
Kitchen Soap
Napkin
Mask

Non-necessary tools:
Filter Cone Paper
Fine mesh strainer
Pipet

Figure 3.4: Essential tools for the material research phase
Source: own

03 | 2 | 2 Material Test

According to the research done by Thomas Liebrand, scientific papers, and interviews, the homogeneity, viscosity, adhesion, extrudability, shrinkage, brittleness, bio-base, aesthetics, and curing time were the nine criteria that were considered throughout the material research phase (Figure 3.5). The most promising recipes were further compared and rated according to those terms to further test mechanically and their printability.

Homogeneity: A fully unified paste to achieve a high-quality print with optimal performances.

Viscosity: The more viscous the material, the harder the material will pass through the extruder (flow). A moderate viscosity level is the best for an extrusion.

Adhesion: The ability to stick and bond one layer to another.

Extrudability: Material to be pushed out from a nozzle. If the material is too dry, it will not extrude.

Shrinkage: if the material changes in size while or after printing. If the material shrinks, it is difficult to predict its behavior and thus print large objects.

Brittleness: If the material is too delicate it can easily break and lead to the collapse of the object.

Curing time: Time to fully cure, the faster it cures, the better.

Bio-Base: The degree of natural origin of the material.

Aesthetic: Appearance of wood-like material.

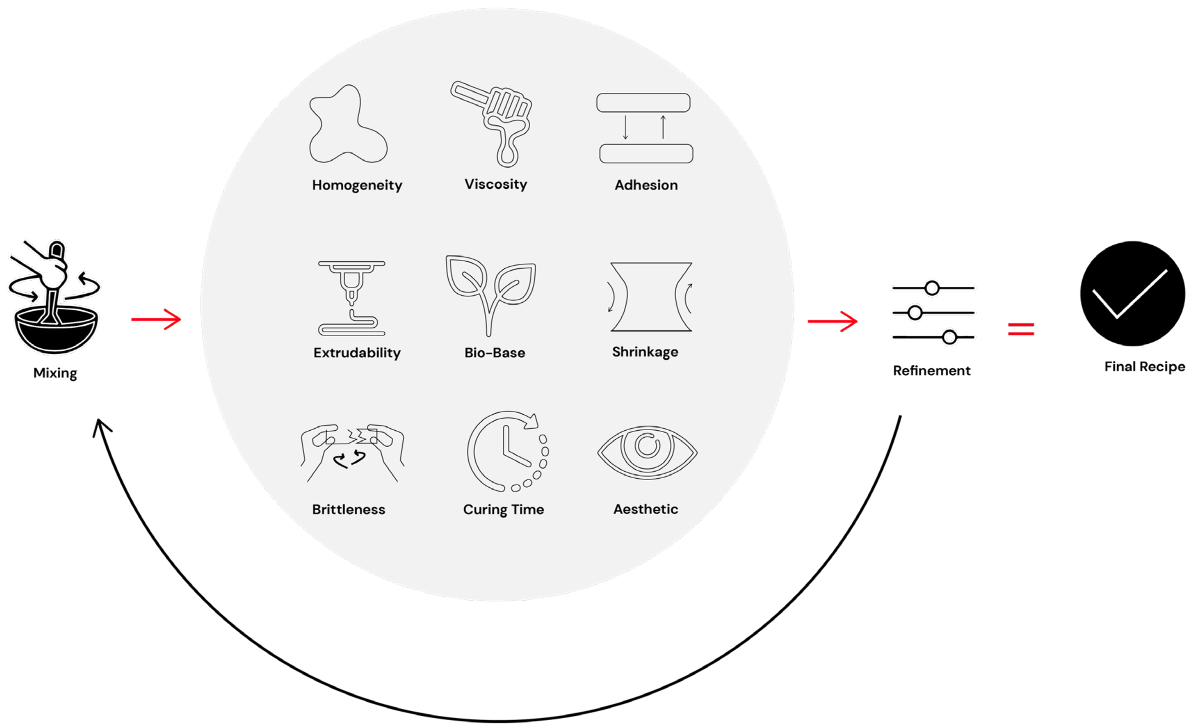


Figure 3.5: Process of Material research phase done in collaboration with Alexsander Alberts Coelho
Source: own

Figure 3.6: Acetone recipe
Source: own

Introduction

With regards to binding agents, the experiments started with the reproduction of the recipe developed by Thomas Liebrand in 2018 using acetone. Liebrand discovered that acetone was a binding agent that can be combined with lignin and cellulose to produce a printable recipe. Therefore, the reproduction of his final recipe was the initial phase of the material research phase. The reproduction of his recipe could not be fully explored as the used lignin is kraft compared to soda lignin. Also, the kraft cellulose was shredded with a coffee grinder compared to Thomas's method to use a material shredder. The acetone that was used in our tests was obtained from Kruidvat in Delft.

Process

To start with the experimentation, the kraft softwood cellulose was cut into filaments with a paper cutter in the “maquette hal” of Bouwkunde and further shredded into small fibers of around 1-2mm with a coffee grinder. Once the cellulose was well blended, it was mixed with an electric mixer to separate the fibers of the cellulose. The lignin is further added to the mixture. The cellulose and lignin are mixed in a 3-liter bowl with a plastic cover to avoid material loss through dispersion. However, it is impossible to entirely avoid and quantify this scenario. For this reason, 2-3g of lignin are added to compensate for the material loss. Once the lignin powder completely covers the total amount of the fibers in a dry state, a small amount of water is only added to help with the malleability of the mix. Lastly, the acetone is added and mixed until forming a homogeneous and viscous paste.

Outcome

The acetone mixture is easy to extrude with the caulking gun at a medium speed with a 3.8mm nozzle. It can produce a high-definition structure with great layer adhesion. Acetone is a promising binding agent (Figure 3.6, 3.7). We can conclude that mix 1 **does comply** with the attended results of this research paper. However, exposure to high levels of acetone can cause many health problems. Also, acetone will damage the surface of any plastic equipment. For this reason, glassware and metallic equipment are used. Also, a food dehydrator is required to make the drying process faster as this process can take several days. Last, it is very hard to clean and demands thorough cleaning to avoid any damage to the equipment.

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 1	24g Lignin, 2g Cellulose, 8g Water, 11.2g Acetone	Homogenous, easy to mix when using a mixer in a closed beaker, easy to extrude, viscous & black color	COLD MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 1	1	1	1	1	-1	0	0	0	-1	2

Figure 3.7: Table grading for Acetone
Source: own

Figure 3.8: DMSP recipe
Source: own

Introduction

Dunia Agha who did her research on 3D printing with paper at ISMD TU Darmstadt initially did some research on lignin and cellulose. Dunia Agha suggested substituting acetone with another solvent such as DMSO as acetone evaporates at a fast rate and therefore hardens and stiffens the paste. DMSO is in her opinion a solvent that slows the reaction to evaporation and softening of the final mix. According to the German company WoldoHealth, Dimethylsulfoxide is also a natural and organic solvent from the resin of a tree. For these reasons, DMSO was an interesting binding agent to test. The DMSO was obtained from WoldoHealth: https://www.woldo-health.cz/specialni-prostredky/dmso-dimethylsulfoxid-99-9--ph--eur--farmaceuticka-kvalita-300ml/. as their product is 99.9% pure. With a high level of purity, the DMSO has to be used above 18.5 degrees otherwise it will form crystals.

Process

In the first iteration, the ratio between DMSO and water was 1:1 – 10g each. Additionally, 10g of lignin and 1g of cellulose were combined with water and DMSO which formed a non-homogeneous paste, with moderate viscosity, and a low adhesion between each layer. However, it was easy to extrude with a syringe. Also, an additional 5g of papier-Mache improved the homogeneity and adhesion while maintaining its extrudability. The fourth iteration was a 1.5:1 ratio of DMSO and water – 15g and 10g respectively. Mixing it with 20g lignin and 1g cellulose formed a homogeneous paste with moderated viscosity, high adhesion, and easy to extrude. Adding 5g lignin and 2g cellulose kept the homogeneity and increased the viscosity and bonding, still within the threshold for a smooth extrusion. Lastly, the fifth iteration was a 2:1 ratio of DMSO and water – 20g and 10g respectively. Mixing it with 30g lignin and 2g cellulose formed a homogeneous paste with moderated viscosity, high adhesion, and easy to extrude.

Outcome

DMSO reacts similarly to acetone when mixed with lignin, creating a paste with high adhesion and moderate to high viscosity, depending on the material ratio but without the hazardous aspect. Water is still necessary to dilute the binder and avoid material dispersion. From these experiments, the ideal material ratios can be defined as 2:1 for DMSO/water, 1:1.75 for DMSO/lignin, and 1:8.75 for cellulose/lignin. As observed, higher quantities of lignin improve the bonding and viscosity even though turning the extrusion harder by drying the material and favoring the creation of chunks of fibers. The recipe is promising as it delivers stable and structured extrusions (Figure 3.8, 3.9). However, DMSO only solidifies in an environment that is under 18.5 degrees, which makes the material difficult to cure. Just like Acetone metallic and glassware equipment can only be used. Thus, we can conclude that mix 2 **does** comply with the attended results of this research paper.

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 2	25g lignin, 2g cellulose, 20g dmso, 10g water	Homogenous, hard to mix, viscous, easy to extrude & black color	COLD MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 2	1	1	1	1	1	0	0	-1	0	4

Figure 3.9: Table grading for DMSO
Source: own

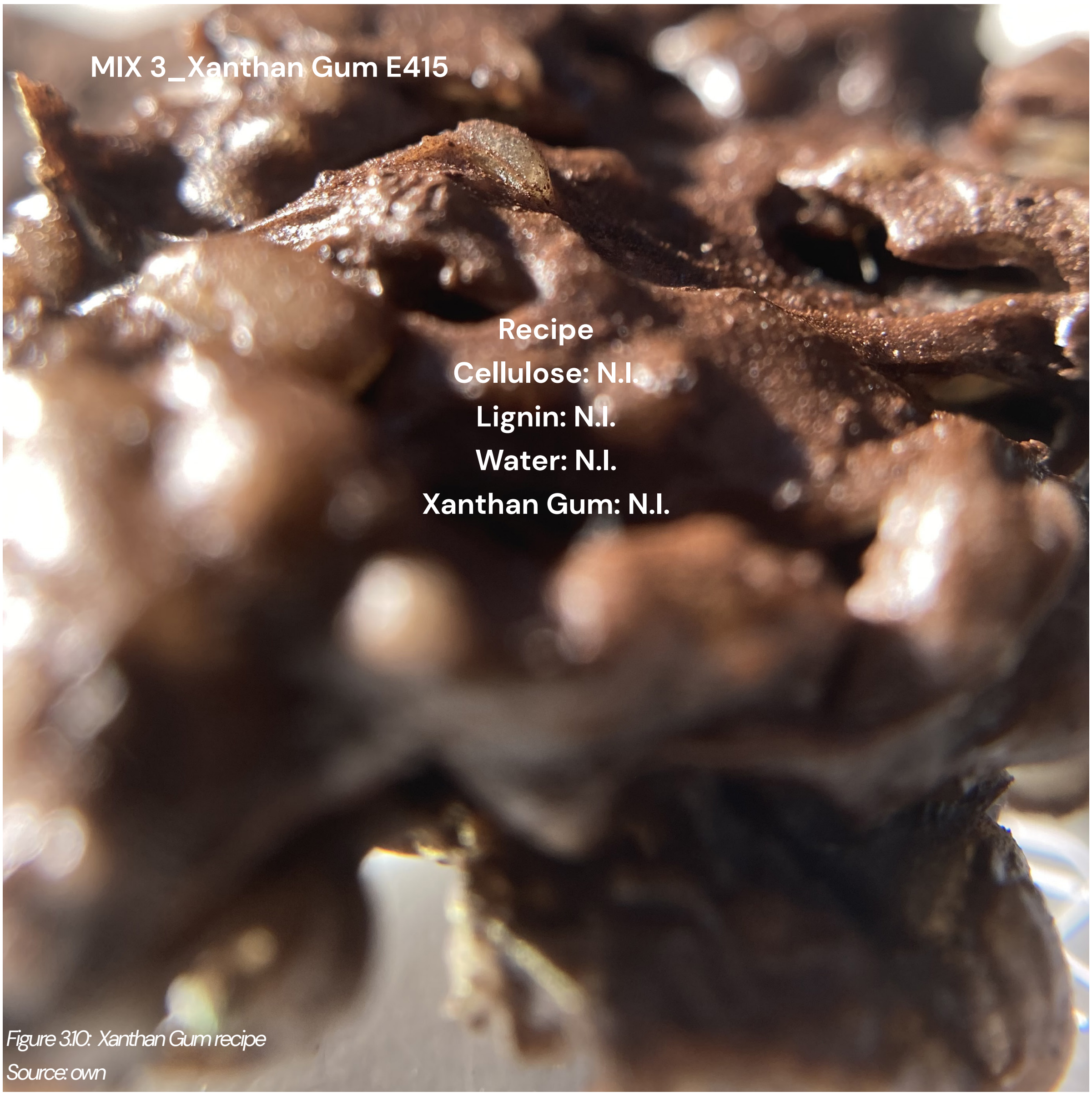


Figure 3.10: Xanthan Gum recipe
Source: own

Introduction

Xanthan gum is an "extracellular polysaccharide that is soluble in cold water" (Sworn, 2021).
Xanthan gum is a pure dietary fiber that can be used to thicken recipes and even becomes a gel-like structure. The Xanthan Gum that was used can be found online on the website of vita2you: https://www.vita2you.de/xanthan-gum.html.

Process

Since the purpose of this experiment was to understand the behavior of the material and how it reacts when combined with cellulose and lignin, no fixed measurements were used, only the recommended proportions from Vita2you were measured with a 1:2 ratio for the xanthan gum and water.

Outcome

Xanthan gum needs to be mixed with water to activate its thickening agent. When xanthan gum was solely combined with lignin, the result appeared as a homogeneous gel with high viscosity and moderated adhesion. Mixing xanthan gum with cellulose and/or papier Mache did not change the consistency, but made it less homogeneous, with chunks of fibers. Xanthan gum mixed with water created a gel and did not mix well with lignin. All of the conducted experiments with xanthan gum, independent of the material and water proportions, resulted in gel-like samples which do not completely solidify. The outcome of Mix 3 was non-homogeneous covered in residual lignin powder, which retained the gel-like consistency and did not solidify (Figure 3.10, 3.11). Therefore, mix 3 does **not comply** with the attended results of this research paper.

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 3	Lignin, Cellulose, Water, Xanthan Gum	Non-homogeneous covered in residual lignin powder, which retained the gel-like consistency and did not solidify	COLD MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 3	-1	-1	-1	-1	1	0	0	-1	-1	-5

Figure 3.11: Table grading for Xanthan Gum
Source: own

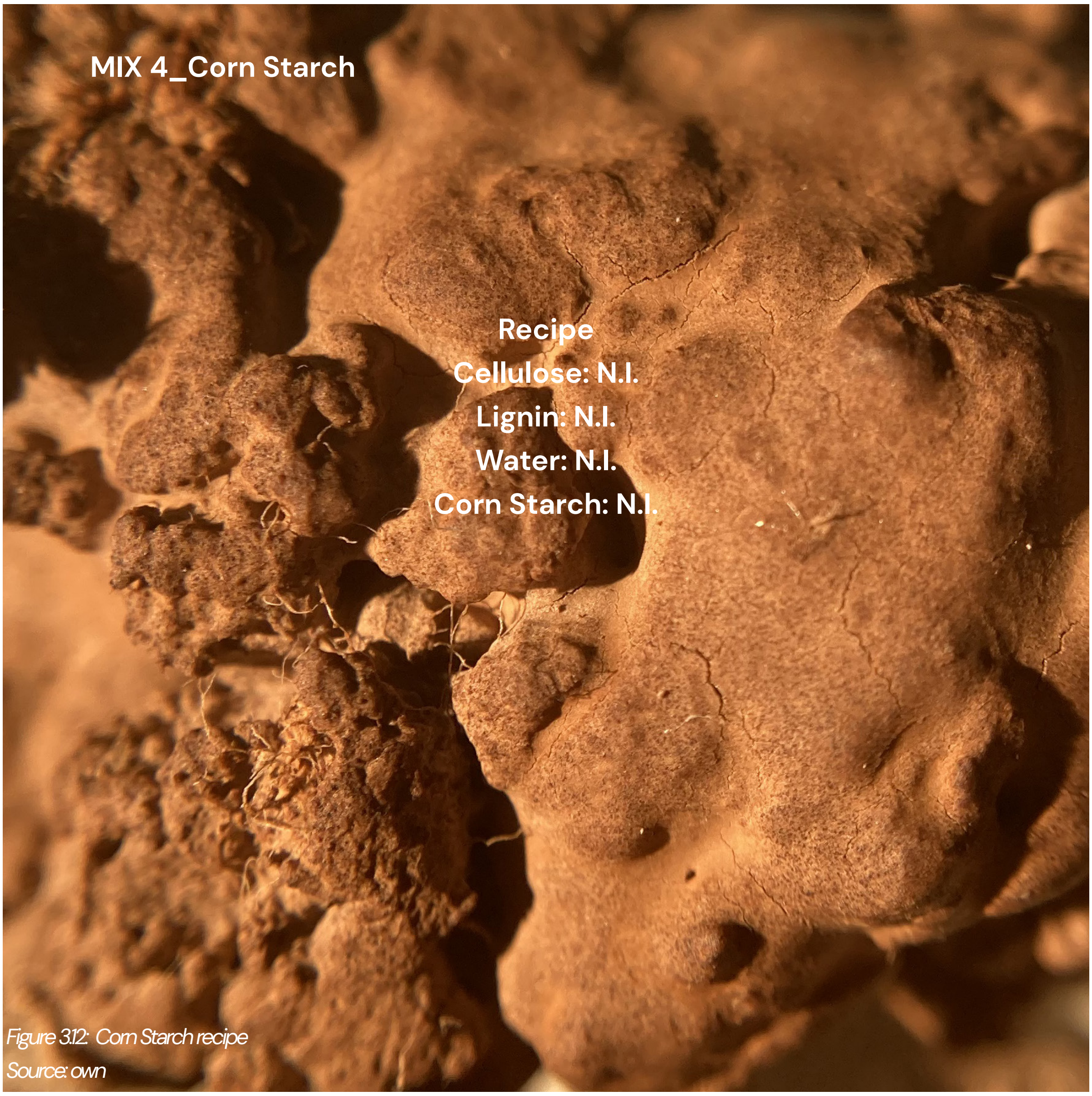


Figure 3.12: Corn Starch recipe
Source: own

Introduction

"Corn starch is a white, tasteless, odorless powder, used in food processing, papermaking, and the production of industrial adhesives (Synder, 1984)". Corn starch was another binding agent that was interesting to test as it is used in the papermaking industry acting as a flocculant and binder for coatings. The corn starch that was used for Mix 4 can be found here: https://www.orientalwebshop.nl/en/knorr-kingsford-s-corn-starch-420g.

Process

The first iteration was a 1:1 ratio of corn starch and water – 10g each. Mixing it with 10g lignin and 1g cellulose resulted in a non-homogeneous, crumbly, and dried mix. Adding 10g of water transformed the material into a non-homogeneous paste with chunks of fibers agglomerated that are non-viscous and with no adhesion. The other iterations with a 0.5:1-0.25:1-1.5:1-2:1 ratio all delivered a non-homogeneous paste with chunks of fibers, low viscosity, and no adhesion. As a final attempt to create an extrudable mix, the experiment with a 1:1 ratio of corn starch and water was replicated at high temperatures. After a few more failed trials, which also resulted in non-homogeneous pastes, mixing the corn starch and lignin before adding water at a 3:1 ratio – 30g corn starch and 10g lignin – delivered a homogeneous paste. When mixed with 1g cellulose, it resulted in an extrudable material with moderated viscosity and adhesion.

Outcome

All cold mixes with corn starch failed at creating an extrudable paste. Materials did not bind well, and the result was constantly a non-homogeneous paste with chunks of fibers agglomerated with water. Lignin did not build strong bonds with any of the ingredients, becoming brittle and powdery once the samples dried. The final attempt with a hot mix proved to be successful at delivering an extrudable material. However, the homogeneity, viscosity, and adhesion characteristics are not as promising as previous mixes with DMSO and other binding agents (Figure 3.12, 3.13). Therefore, mix 4 does not comply with the attended results of this research paper.

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 4	Lignin, Cellulose, Water, Corn Starch	Extrudable material. However, the homogeneity, viscosity, and adhesion characteristics are not as promising as previous mixes	HOT MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 4	0	-1	-1	-1	1	0	-1	0	1	-2

Figure 3.13: Table grading for Corn Starch
Source: own

Figure 3.14: Glycerine recipe
Source: own

Introduction

Glycerin is a liquid that is odorless and colorless. It comes from vegetable origins and is used in cosmetic products as a smoothener (De-Tuinen). The product and description of the component can be found here: https://www.drogisterij.org/product/De-Tuinen-Glycerine.html.

Process

At a 1:1 ratio of glycerine and lignin - 10g each, did not combine until 1g cellulose was added. The mixture resulted in a homogeneous gel with low viscosity and adhesion. More lignin (5g) and cellulose (1g) were added, finalizing with a homogeneous and extrudable paste. To assess the influence of heat, glycerine (25g) was mixed with hot water (100g) at a 1:4 ratio, creating a non-homogeneous solution. Added 25g lignin – in increments of 5g – continued with 5g papier mache and finally 2g cellulose, resulting in a homogeneous, dry, and crumbly mix.

Outcome

There were no significant differences in the material behavior between cold and hot processes. Both resulted in homogeneous pastes with moderate to low viscosity and adhesion, extrudable by hand with a syringe. Overloading it with cellulose and papier-mache fibers (second iteration) turned it into a dry material with a crumbly aspect and a gel-like consistency, not extrudable (Fifure 3.14, 3.15). Therefore, Mix 5 does **not comply** with the attended results of this research paper.

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 5	Lignin, Cellulose, Water, Glycerine	non homogeneous with low viscosity and adhesion, not extrudable by hand. dry material with a crumbly aspect & gel-like consistency	COLD OR HOT MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 5	-1	-1	-1	-1	1	0	0	-1	0	-4

Figure 3.15: Table grading for Glycerine
Source: own

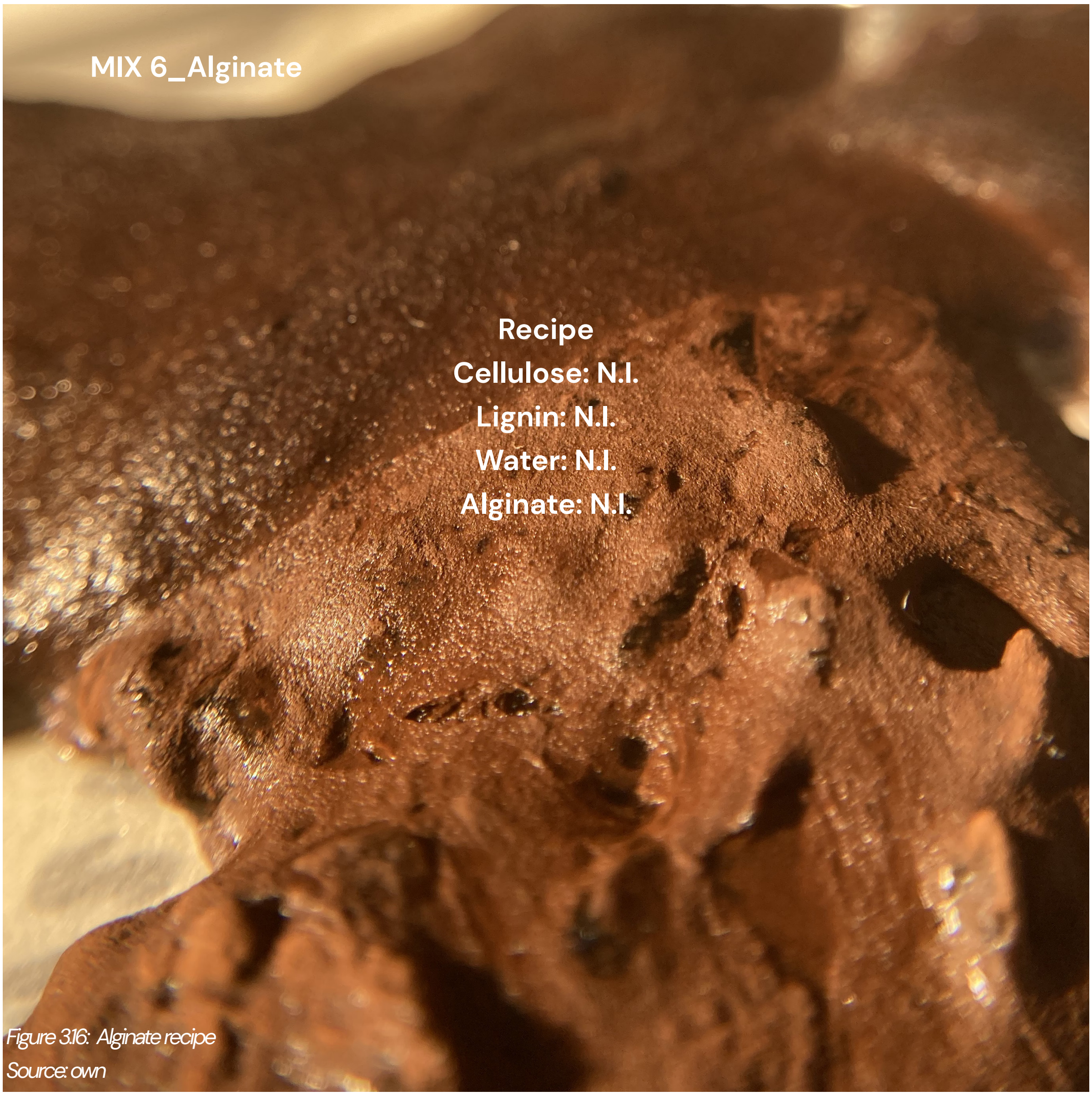


Figure 3.16: Alginate recipe
Source: own

Introduction

"Alginate is a biocompatible polymer and It is a natural polysaccharide, extracted from brown seaweeds. It is used as a 3D culture matrix because it provides support for integration of cells and acts as a platform for cellular growth" (Priyadarshini et al. 2020). Alginate is a thickener or gel binder which is used for emulsions in different cosmetic products. In the case of Mix 6, sodium alginate was purchased from Jojoli: https://www.jojoli.nl/natriumalginaat.html as it is soluble in water and can be mixed with polymers.

Process

A mix with a ratio of 1:1 of alginate and water – 10g of each – was prepared. It resulted in a non-homogeneous solution with chunks of gel. An additional 40g of water was added to the mix which would not dissolve the chunks of the gel, even when heated. When Adding 5g of lignin and 1g of cellulose, the material consistency remained similar to a gel. Mix 6 was homogeneous but with extremely low viscosity and adhesion.

Outcome

The experiments were planned on a similar structure as the previous ones, with ratios of 1:1, 0.5:1, 0.25:1, 1.5:1, and 2:1 for alginate and water. Although the first iteration was showing similar behavior to xanthan gum, and glycerin, it did not present promising results. Therefore, the remaining experiments were scrapped (Figure 3.16, 3.17). We can conclude that mix 6 does **not comply** with the attended results of this research paper.

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 6	Lignin, Cellulose, Water, ALGINATE	similar behavior to xanthan gum	COLD OR HOT MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 6	-1	-1	-1	-1	1	0	0	0	0	-3

Figure 3.17: Table grading for Alginate
Source: own

Figure 3.18: Bone Glue recipe
Source: own

Introduction

"The term animal glue usually is confined to glues prepared from mammalian collagen, the principal protein constituent of skin, bone, and muscle. When treated with acids, alkalis, or hot water, the normally insoluble collagen slowly becomes soluble" (Ebnesajjad, 2015). Bone glue is used to repair joints, veneers, and more. The Bone glue that was purchased online from Labshop: https://www.labshop.nl/beenderlijm/?gclid=Cj0KCQjw37iTBhCWARIsACBt1Izi16W1KVgB0tTvcr1sTy3rPqbm2Rh_jdjn5dmW557ZHdDJV8buA8EaAj6hEALw_wcB. The bone glue comes as granules which need to be dissolved in water for a week to absorb the water. Then hot water is added from 45 to 80 degrees to turn the granules into a soft liquid.

Process

100g were mixed with 100g of water at 80C and kept under constant heat until fully diluted into a 1:1 ratio of bone glue and water solution.
For the first experiment, 50g of this solution were added to 10g lignin – a ratio of 5:1 respectively – and 2g cellulose by using a recipient in a water bath. The result was a watery and non-homogeneous paste, with low viscosity and adhesion. For the next attempt, no water was used, melting 50g of softened glue directly in a recipient in a water bath, and mixing it with 10g lignin and 2g cellulose at constant heat. The result was a homogeneous paste, with high viscosity and adhesion, but not easy to extrude by hand.

Outcome

The softened glue had already a large amount of water incorporated and did not require any additional liquid to melt. Once that was understood, the mix resulted in a stable and homogeneous paste. The disadvantage of bone glue is the strong smell and appearance (Figure 3.18, 3.19). We can conclude that mix 7 does **not comply** with the attended results of this research paper.

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 7	Lignin, Cellulose, Water, Bone glue	Homogeneous paste, with high viscosity and adhesion, but still not easy to extrude by hand.	HOT MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 7	1	1	1	0	1	-1	0	0	-1	2

Figure 3.19: Table grading for Bone Glue
Source: own

MIX 8_Wood Glue

Figure 3.20: Wood Glue recipe
Source: own

Introduction

Wood glues are adhesives which are made from natural or synthetic raw materials to bond wood. In the case of this Mix 8, a Polyvinyl acetate glue was here used as it is the most “widely used water-dispered adhesive. PVA is made up of a water-based emulsion of a widely used type of glue, referred to variously as wood glue, white glue, carpenter’s glue, school glue, or PVA glue” (Kaboorani et al. 2015). The wood glue is from BISON and is water-resistant. It was obtained at GAMMA: https://www.gamma.nl/assortiment/bison-houtlijm-extra-750-gram/p/B483548. A bio-based glue would be interesting to test. However, they were not available on the market. A bio-based resin is being tested by the MOSO Internationals BV company and will be soon available on the market.

Process

In a recipient a water bath method was used with 30g of wood glue mixed with 10g of lignin. In a 3:1 ratio respectively, resulted in a homogeneous paste with high viscosity and high adhesion. No fibers were added since the mix was already difficult to handle and extrude. The experiment was replicated in a cold process and presented similar results, with only the sample color varying. The addition of 1g of cellulose resulted in a homogeneous paste with high viscosity and adhesion.

Outcome

Wood glue created some of the most stable and strongest samples from all the previous experiments. Despite the chemical origins, which could also be bio-based, pending further research, it created a homogeneous material with adequate properties for a cold extrusion process (Figure 3.20, 3.21). We can conclude that mix 8 does **comply** with the attended results of this research paper.

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 8	10g Lignin, 1g Cellulose, 30g Wood Glue	Use water bath method, mix is homogenous, easy to mix, medium hard to extrude by hand, & viscous	COLD OR HOT MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 8	1	1	1	1	-1	0	1	0	1	5

Figure 3.21: Table grading for Wood Glue
Source: own

Figure 3.22: Methylcellulose recipe
Source: own

Introduction

Methylcellulose is purified cellulose. MC can be dissolved in cold or hot water to become a gel like cosistency. It has the ability to become a gel when it is heated at above 45°C and returns to a liquid state when cooled down to approx 15°C. The product and description of the obtained product can be found here: https://www.amazon.co.uk/Special-Ingredients-Methocel-Premium-Quality/dp/B00IMIPU5W?th=1.

Process

For all iterations, cellulose paper was first sliced into strips which were then blended to separate the fibers. Lignin and methylcellulose were then added and blended – in an enclosed recipient to reduce material losses – until all fibers were fully covered with the powdery mix. At last, hot water at 80C minimum was added and the mix continuously blended until forming a watery and homogeneous paste with consistency, viscosity, and adhesion properties varying according to the mix temperature. For the first iteration, a ratio of 4:1 of lignin and methylcellulose – 20g and 5g respectively – was used, combined with 2g cellulose. However, it was blended for too long, resulting in a dry and crumbly mix. For a 5:1 ratio of lignin and methylcellulose – 25g and 5g respectively – was used, combined with 3g cellulose. The resulting mix showed moderate to high viscosity and high adhesion, drier and denser than the previous one due to the increased amount of lignin. At last, for a ratio of 6:1 of lignin and methylcellulose – 30g and 5g respectively – was used, combined with 3g cellulose. The result was a dry and dense paste that required an additional 5g of water, transforming it into a mix with even higher adhesion and viscosity than the previous one. Harder to extrude, it formed well-defined layered structures, with promising interlayer bonding.

Outcome

As expected, increasing the amount of lignin in the mix improves the viscosity and adhesion properties of the material, although it also increases its brittleness and tends to transform it into a dry paste. Water and cellulose fibers keep the mix homogeneous and the paste consistency necessary for a successful extrusion and product. From the experiments above, the outcome is that a proportion of 6:1 between lignin and methylcellulose proved to be the most promising recipe, as well as a proportion of 1:20 between cellulose and lignin. Additional experiments with increased amounts of fibers should be executed to potentially increase the material strength and flexibility (Figure 3.22, 3.23). We can conclude that mix 9 does **comply** with the attended results of this research paper.

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 9	25g Lignin, 3g Cellulose, 5g Methylcellulose, 60g Hot Water,	Homogenous, easy to mix when the water is warm (80C) otherwise hardens, brown color, the more viscous the worse the printability	HOT MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 9	1	1	1	1	1	-1	0	1	1	6

Figure 3.23: Table grading for Methylcellulose
Source: own

Figure 3.24: Beewax recipe
Source: own

Introduction

"Beeswax is a food-grade wax with a white color when it is freshly prepared. Later the color changes into yellow because of the presence of propolis and pollen colorants. The important quality of beeswax is its hardness. At low temperatures, beeswax exhibits higher rates of elasticity. The heating process changes the physical properties of beeswax. Shrinkage of heated beeswax occurs by 10% upon cooling. When the beeswax is heated at the temperature of 30–35°C, it attains the properties of plastics" (Stefan, 2009) (Menezes et al. 2018). The Beewax was purchased online from: https://www.amazon.co.uk/Beeswax-Beads-Yellow-Cosmetic-Grade/dp/B006662Q6I. It is a synthetic beeswax but comparable to normal beeswax.

Process

At first, the bee wax was mixed with hot water in a 1:1 ratio – 100g each – and melted using a recipient in a water bath, to keep a constant and high temperature without the risk of burning the mix. For the first experiment, 50g of wax/water solution were mixed with 10g of lignin – a ratio of 5:1 respectively – and 1g of cellulose. The result is a completely heterogeneous thick liquid with chunks of fibers partially covered in lignin and chunks of wax. For the next experiments, 30g of bee wax was melted and directly pourd in a recipient mixed with 30g of lignin, in a 1:1 ratio. The result was a homogeneous thick liquid, to which 2g cellulose were added. Fibers did not mix completely, creating a non-homogeneous paste with moderated viscosity and low adhesion.

Outcome

Despite mixing well with lignin, it created large chunks with cellulose and dried quickly, compromising the material's extrudability. The small samples were also brittle and appeared to be porous (Figure 3.24, 3.25). We can conclude that mix 10 does not comply with the attended results of this research paper.

MATERIAL PROPERTIES				
	INGREDIENTS	GENERAL OBSERVATIONS	TEMPERATURE	ROOM CONDITIONS
MIX 10	Lignin, Cellulose, Water, Beewax	non-homogeneous paste with moderated viscosity and low adhesion. Dried quickly, compromising the material's extrudability.	HOT MIX	20C ROOM TEMPERATURE 35% HUMIDITY

MATERIAL RATING										
	HOMOGENEITY	VISCOSITY	ADHESION	EXTRUDABILITY	BIO-BASE	SHRINKAGE	BRITTLENESS	CURING TIME	AESTHETIC	TOTAL
MIX 10	-1	-1	-1	-1	0	0	-1	1	-1	**-5**

Figure 3.25: Table grading for Beewax
Source: own

03 | 3 Conclusion

After comparing all of the final results from Mix 1 to Mix 10, the final recipes that proved to be the most promising ones were acetone, DMSO, wood glue, and methylcellulose. Therefore, each of these mixes was further examined. From hands-on experimentation to scientific testing's to printability testing's, it was important to examine each recipe in terms of its structural properties, water resistance, visualize its structure at a microscopic level and printability to understand which mixture could potentially succeed in becoming a valuable building product. Because of time constraints and the focus of each thesis, my colleague and I divided the tasks from mechanical to printability tests to further converge all of the work into one objective which is to 3D print pure wood for the construction industry. Therefore, the next chapter will be explained more in-depth by Alexsander Coelho and I will explain the installation of the equipment regarding software, hardware, and firmware and the limitations and potentials to print with wood waste.

04 MATERIAL: MECHANICAL PARAMETERS

04 | 1 Overview

As explained previously, Alexsander Coelho will be conducting the mechanical tests thoroughly and more details will be explained in his final report. However, materials and machines come together when it comes to 3D printing. Therefore, the water-resistance tests, microscopic testing, and structural tests will be acknowledged and compared to current materials used in the construction industry. Also, the production of the specimens will be explained more in-depth in this report as it involves 3D printing to produce the molds and the most promising recipe.

04 | 2 Mechanical Exploration

04 | 2 | 1 Water Resistance test

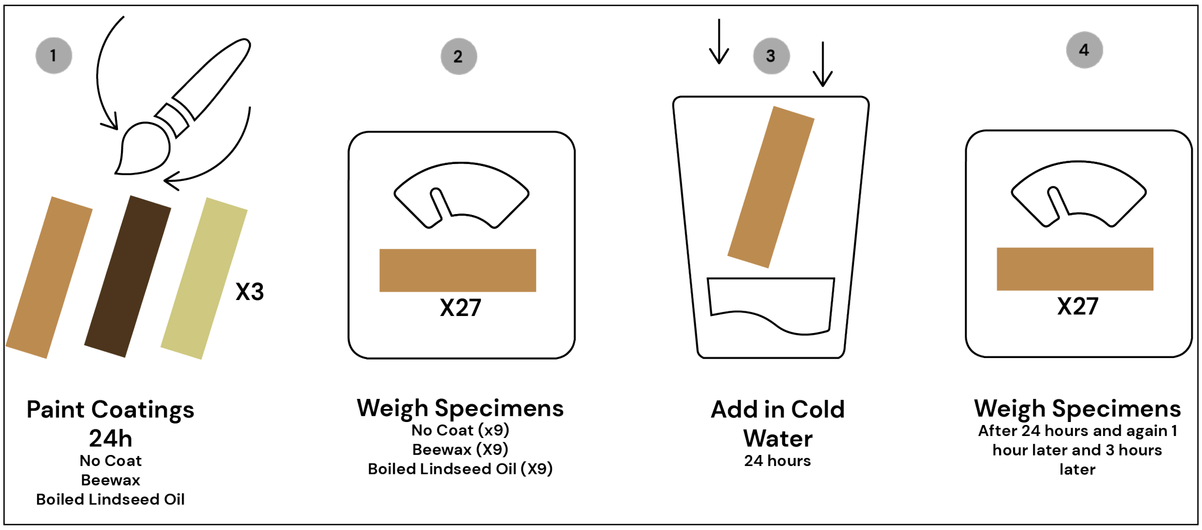


Figure 4.0: Procedure to test the water absorption content
Source: own

Each of the mixtures was either non-coated or coated with linseed oil, and bee wax for 24 hours to be further weighted and submerged in cold water for 24 hours (Figure 4.0). Each mixture was then compared to understand which mixture has the best repellency to water and if a coating would help. The decision to choose linseed oil and beeswax is because they are both hydrophobic materials and are treated to protect wood against outdoor weather conditions. The linseed oil can be found at Gamma. The water resistance test was produced to understand and compare if the four most promising mixtures could be used for outdoor applications. Similar to wood, all mixes are vulnerable to water absorption to a certain degree because of their cellulose content behaving as a hydrophilic one. The coatings between linseed oil and beeswax change the aesthetic look of the mixes and help to a certain degree the protection against water absorption. The most promising mixture in terms of printability, methylcellulose, was revealed to be the lightest material as the samples were floating when submerged in water during the entire process. However, because of the presumably high level of porosities in the material, the results were inferior to the other recipes with the highest absorption percentage and retention percentage compared to any other recipe. Nonetheless, a great difference was observed when coating the material with linseed oil and beeswax. In comparison to pine heartwood, the absorption rate with no coating varies from 100 % to 135% for the methylcellulose recipe (Figure 4.1). However, with a linseed coating, the methylcellulose reveals to have a better water absorption rate of 70 % in comparison to 84% for the pine heartwood (Lejavs et al. 2021). Thus, a protective coating on the methylcellulose recipe looks promising for future outdoor applications. As the three other mixtures have better performances with and without coatings, they could also potentially be used for outdoor usage.

WATER PROPERTIES COMPARISON

	WATER ABSORPTION LINDSEED COATING	WATER RETENTION LINDSEED COATING	WATER ABSORPTION NO COATING	WATER RETENTION NO COATING	REFERENCE
MIX 1: ACETONE	20.74%	3.48%	24.62%	2.16%	-
MIX 2: DMSO	30,80%	14.85%	28.23%	7.12%	-
MIX 8: WOOD GLUE	8.27%	3.91%	10.35%	4.82%	-
MIX 9: METHYLCELLULOSE	70.89%	30.52%	134.91%	58.79%	-
PINE HEARTWOOD	84%	-	100%	-	(Lejavs et al. , 2021)
PINE SAPWOOD	21%	-	100%	-	(Lejavs et al. , 2021)
SPRUCE WOOD	39%	-	100%	-	(Lejavs et al. , 2021)

Figure 4.1: Table comparing water absorption and retention percentage
Source: own

04 | 2 | 2 Microscope test

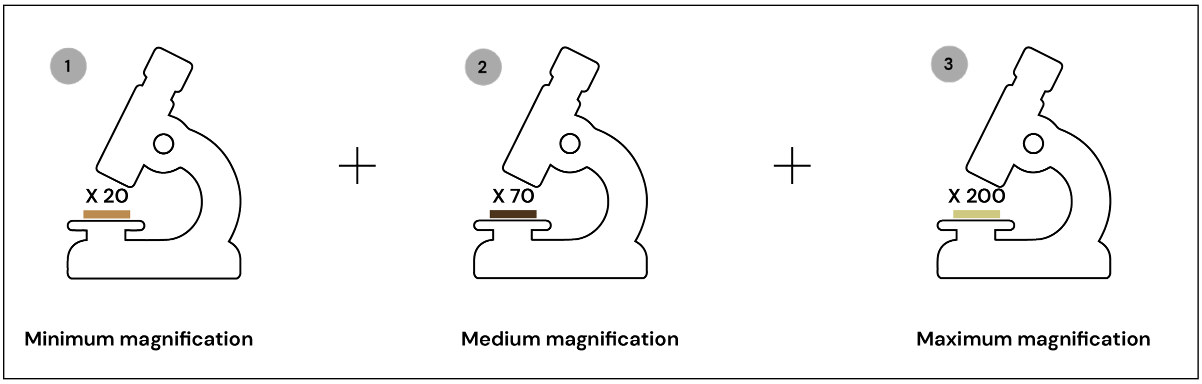
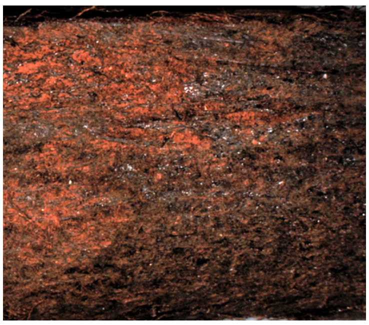


Figure 4.2: Diagram of Microscope, Keyence VHX-7000-Lens 20-200X
Source: own

To understand the porosity, homogeneity, and fiber behavior of Mix 1-2-8-9, a digital microscope, Keyence VHX-7000N-Lens 20-200X was acquired. A beam-type specimen from each mix was observed. All of the iterations were generated with a minimum and maximum magnification to observe different qualities of the material to capture an overall understanding of the mixture and also observe specific zones (Figure 4.2). From the microscope pictures, all the mixes appear impermeable with a fiber that is omnidirectional and a length that varies from 1 mm to 2 mm. Mix 9 (Methylcellulose) appears to be the most homogenous mixture with an even surface and an appearance of wood-like texture. Mix 8 (Wood glue) appears dense and even but is divided into two zones separated from its matrix and fibers. Mix 1 (Acetone) is not homogeneous with an uneven surface and the fibers are not well coated with its matrix. Mix 2 (DMSO) appears homogeneous but just like Mix 1 has some imperfections where the fibers are not well coated with its matrix and had the darkest tone appearing like tar. The methylcellulose mixture, uniformly coated with lignin and an even distribution of its fibers, proved to be the most homogeneous recipe. However, the concentration and the orientation of the fibers are in different directions, which may have a direct impact on the mechanical properties of the mixture. In comparison to the mixture made by Thomas Liebrand, we can observe that an extrusion process does affect the fiber's orientation, presenting one direction to the fibers in correlation to the lignin and acetone (Figure 4.3, 4.4).



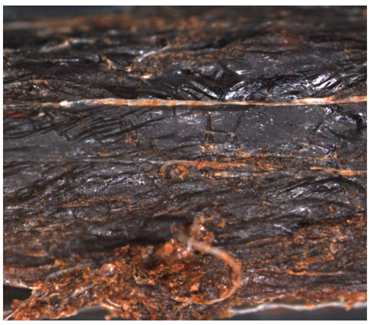


Figure 4.3 (left): unaligned fibers on surface of mix 1 (Acetone) when molding the material
Source: own

Figure 4.4 (right): aligned fibers on the surface of lignin with cellulose & acetone when extruding the material
Source: (Liebrand, 2018)

04 | 2 | 3 Strucutral test

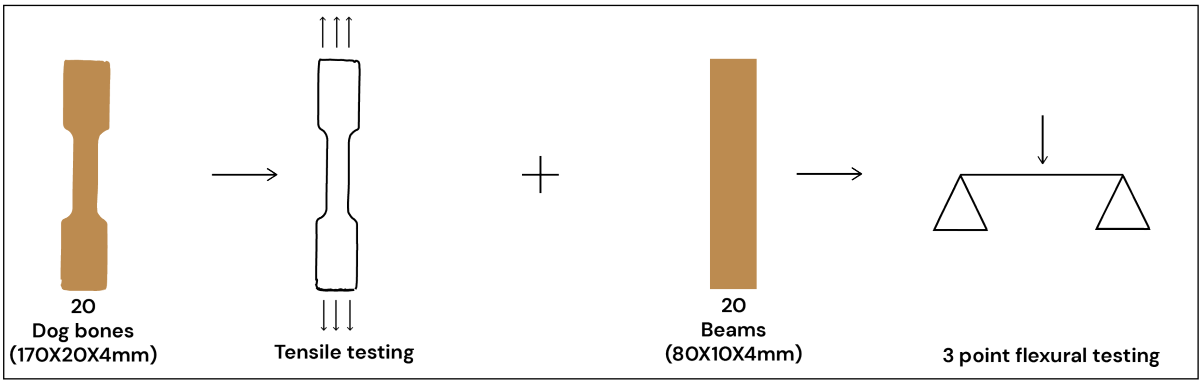


Figure 4.5: Process to test the structural properties of the beams and dog bones.
Source: own

Having access to the civil engineering lab thanks to the collaboration made with Christian Latour and the expert G.Giorgos Stamoulis from the Macro mechanic's laboratory, the four most promising recipes were tested mechanically in terms of their bending and tensile strength (Figure 4.5). Therefore, a series of beams and dog bones had to be produced with the correct dimensions. According to the EN-ISO standards, the dimension of the beams relied on NEN-EN-ISO 178 and NEN-EN-ISO 527-1 for the dog bones. The final dog bone dimensions were 210X22X4mm and the final beam dimensions were 150X20X4mm. Once the dimensions were known, the specimens were produced. However, as each recipe varies depending on its shrinkage level and drying time, it is critical to thoroughly consider the correct production method and drying process. Many trials and errors occurred to achieve the final shape and consistency of each specimen. Initially, the idea was to 3D print molds with male and female elements. However, there are two errors with this system. Firstly, many specimens have to be tested (40 beams and 20 dog bones), and each specimen requires its own mold. Therefore printing 60 molds would take too much time and it is not ecological. Secondly, the base of the negative mold would be completely closed which would prohibit air to circulate around the specimens and thus have a direct effect on the drying period

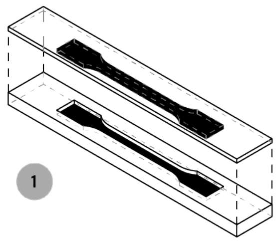


Figure 4.6: 3D printed mold
Source: own

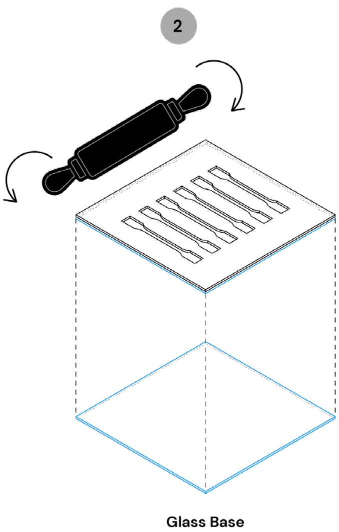


Figure 4.7: CNC mold
Source: own

of all specimens (Figure 4.6). The second idea was to CNC mill the negatives and place the board onto a solid base. The material would be placed into the negatives by using a rolling pin. A channel from the negative to the edge of the board needs to be chiseled off for the material to not overflow. Also, adding lignin can be used just like flour when preparing pastry dough to avoid the material sticking to the rolling pin. A mold release wax was applied onto the MDF to ease the separation of the material from the mold. Nevertheless, this technique was insufficient as the material was still sticking to the board and deformed the final specimens (Figure 4.7). Therefore, a third technique was designed. Similar to the Second idea but with the addition of a press. The press is made with 3 pieces that are glued to each other. It requires a flat board connected to an outer ring and the positive of the specimens which will be pressed into the negative of the base. However, we still encountered some problems with the material drying equally and removing the mold (Figure 4.8). The fourth idea was to vacuum the mold to further push the material out of the positive. However, the edges of the specimens were rounded and did not allow to dry the entire specimen in a homogenous way. Therefore, the production of the specimens resulted in two different techniques. In regard to the wood glue and methylcellulose, the material was rolled with PVC film onto the rolling pin to avoid the material to stick. Also, as the specimens had to be 4mm high, two 4mm boards were placed on the side of the preparation to guide the height of the material. Once the material is flat and dried for about 1 hour, a 3D-printed PLA cookie cutter was designed to cut the material. The minimum thickness of the cuter was 0.8mm, which allowed the material to be deeply engraved. However, a 3D printed metal cooking cutter would be better to fully cut the material. After 4 hours, the dough patches are placed on an elevated wire rack to dry on each side. It is then required to dry the mixture for at least 20 hours. Once the patches are completely dry, the excess material is split manually to achieve clean edges for each specimen (Figure 4.9). Regarding the acetone and DMSO mixture, another technique had to be applied to the material viscosity and drying time difference compared to the wood glue and methylcellulose. Therefore, a large negative mold was 3D printed with PLA at a low density (10%) to become fully flexible and ease the removable of the specimens. All of the molds were then elevated to let the material dry in a homogenous manner. Once the material had dried for 1 week for the acetone and 1 week

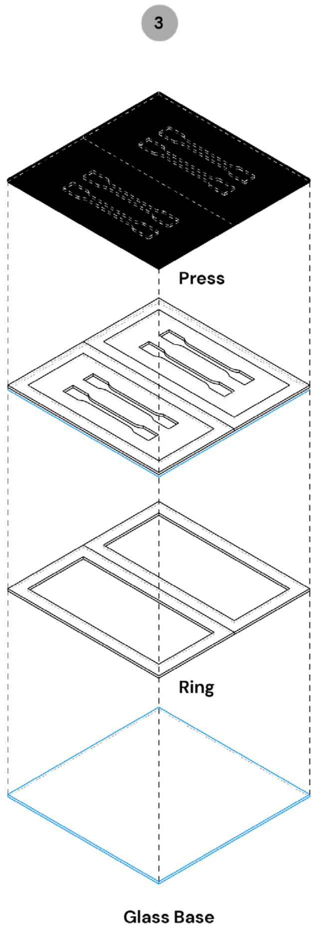


Figure 4.8: CNC mold (negative and positive)
Source: own

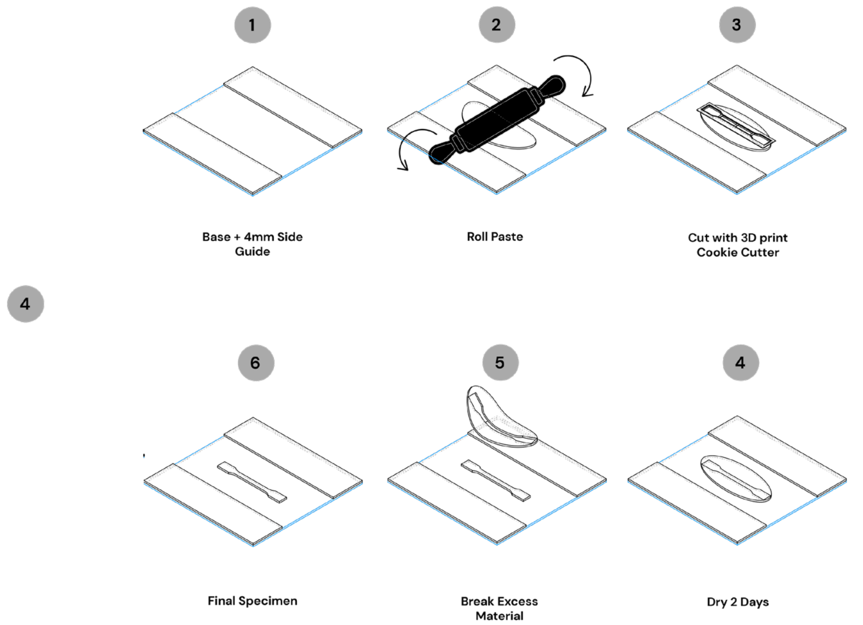


Figure 4.9: Method used for mix 8 and mix 9
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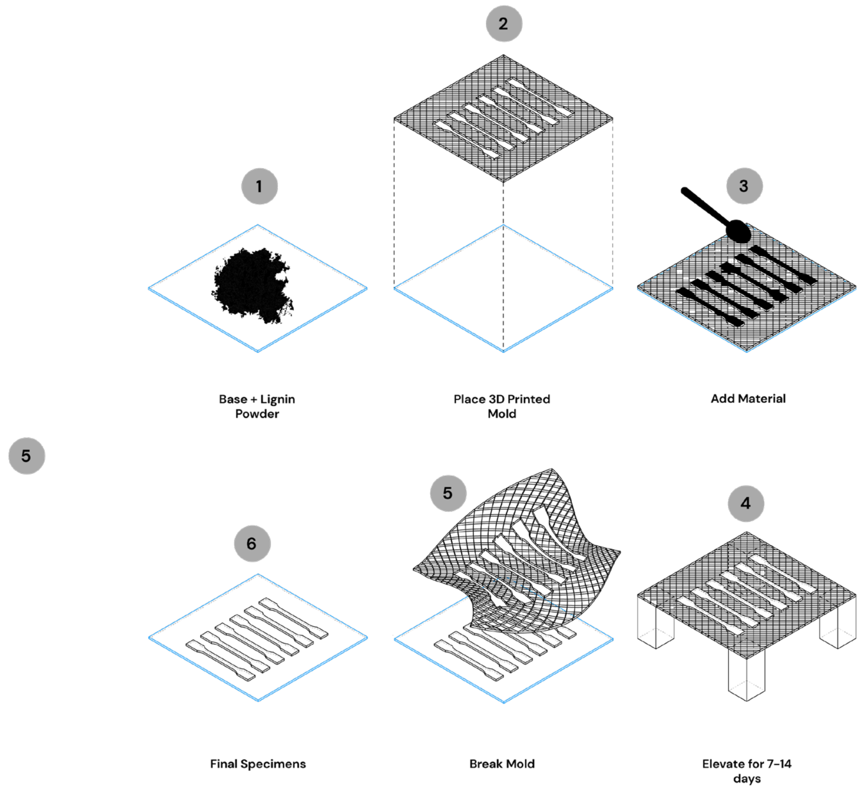


Figure 4.10: Method used for mix 1 and mix 2
Source: own

for the DMSO in a cold environment, it is removed from its flexible mold. Even though the specimens were all produced, the consistency of the acetone and wood glue was not fully dry after several days, even weeks. Therefore, a food dehydrator was required to ease the drying time (Figure 4.10). Once the specimens are ready to be tested, controlling software and registered software are used to control and understand when the material is deforming or breaking. The equipment used a universal testing machine that allows tensile testing and three-point flexural testing. Currently, the final results of all the most promising recipe (Mix 9: methylcellulose) did not meet the adequate levels to enter the construction market (Figure 11). From molding to 3D printing specimens, none can equate to the structural properties obtained by typical woods used in the construction industry. However, in comparison to another full bio-based material named fungal-like adhesive material (FLAM) by the University of Singapore University of technology and Design in 2018 (Sanandiya et al., 2018), the discovered methylcellulose recipe shows better results, showcasing the possibility of 3D printing structural elements such as columns and wind turbines elements (Figure 4.11). Moreover, the wood glue recipe reveals to be the strongest material amount the other recipes, with the highest flexural and yield strength. However, its stiffness can be compared to methylcellulose in terms of its modulus of elasticity. The acquired results from the Acetone mixture are inferior to the methylcellulose or wood glue mixture. The fabrication process and material mixing process of the tested samples revealed some irregularities that may have a large influence on their final results. Finally, as the DMSO (dimethyl sulfoxide) only hardens under 18C, all of the tests failed and remained elastic, not offering any resistance to tensile and compressive forces.

MECHANICAL PROPERTIES COMPARISON

	FLEXURAL STRENGHT	MODULUS ELASTICITY (BENDING)	YIELD STRENGHT	MODULUS ELASTICITY (TENSION)	REFERENCE
BEECH, AMERICAN	-	9.5 GPa	86.2 MPa	-	(USDA Forest Service, 2010)
OAK, OVERCUP	-	9.8 GPa	77.9 MPa	-	(USDA Forest Service, 2010)
PINE, EASTERN WHITE	-	8.5 GPa	73.1 MPa	-	(USDA Forest Service, 2010)
SPRUCE, ENGELMANN	-	8.9 GPa	84.8 MPa	-	(USDA Forest Service, 2010)
PARTICLEBOARD	-	2.8 - 4.1 GPa	15 - 24 MPa	-	(USDA Forest Service, 2010)
MDF	-	3.6 GPa	36 MPa	-	(USDA Forest Service, 2010)
OSB	-	4.4 - 6.3 GPa	22 - 35MPa	-	(USDA Forest Service, 2010)
PLYWOOD	-	7 - 8.6 GPa	34 - 43 MPa	-	(USDA Forest Service, 2010)
GLULAM	-	9 - 14.5 GPa	29 - 63 MPa	-	(USDA Forest Service, 2010)
PLA + WOOD POWDER	-	3 GPa	30 MPa	-	(Gardner et al., 2019)
PLA + LIGNIN (40WT%)	-	1.93 GPa	29.25 MPa	-	(Tanase-Opedal et al., 2019)
WOOD POWDER + GLUE	-	3 - 3.94 GPa	30 - 57 MPa	-	(Das et al., 2021a)
TECNARO ARBOBLEND	-	4.3 GPa	58 MPa	-	(www.albis.com)
FLAM!	-	0.26 GPa	6.12 MPa	-	(Sanandiya et al., 2018)
METHYLCELLULOSE MIX	8.59 - 10.60 MPa	0.67 - 1.05 GPa	3.21 - 4.06 MPa	0.33 - 0.56 GPa	-

Figure 4.11: Table comparing mechanical properties
Source: own

04 | 3 Conclusion

Water properties

Mix 9 (Methylcellulose) has proven to react more to a protective coating with beeswax or linseed oil in comparison to the other material mixes. However, the water absorption and water retention of mix 9 have the highest percentage in comparison to the other mixes. Wood glue has proven to have the lowest percentage in both categories. Thus, more research should be done by comparing the difference between kraft lignin and soda lignin in terms of repellency to water and integrating bio-based wood glues or bio-based resin glues within mix 9 to improve its hydrophobic characterization and achieve better results in comparison to pine heartwood without a coating.

Microscopic properties

The fiber alignment is spread in different directions for all the mixes. All the specimens were produced into a mold. In the research done by Thomas Liebrand, the hand-printed mixture appears to have fibers in one orientation such as the grain direction of the wood. Therefore, extruding vs molding the recipes does show a difference at a microscopic level with an isotropic non-homogenous distribution when the material is molded versus a 3D printing material that has an anisotropic orientation. Lastly, all the recipes show that the lignin bonds to the fibers. However, mix 9 (Methylcellulose) shows the highest homogenous matrix. which will ease the printability testing.

Structural properties

The novel material of Mix 9 (Methylcellulose) was the easiest recipe to mix, mold into specimens and fast to cure. However, it does not have great structural strength in comparison to any polymers with wood content, wood powder with glue, and PLA with lignin. However, according to Alexsander Alberts Coelho, mix 9 (MC) proves to have better tensile and bending strength in comparison to flam (fungal-like adhesive material) which is used to print columns and wind turbines. However, further tests should be explored by adding longer fibers or glue-like content in the methylcellulose recipe to enhance its mechanical properties. Additional fibers and clay-like content may also be explored to strengthen the material. Lastly, after testing the printed specimens with the methylcellulose recipe, in comparison to the molded specimens, it revealed that the modulus of elasticity and flexural strength were similar but mix 9 (Methylcellulose) had lower values for yield strength, tensile stress, and flexural modulus. It can be explained by the structure of the layers as they are aligned to each other and the shrinkage of the material after once dried. Also, there was a weak point on the dog bone specimens as they were not filled with material, leading to a rupture of the specimen at this exact location. More research should be implemented in 3D printing specimens to be structurally tested with adequate standards for higher accuracy in their final results.

05 ROBOT: MACHINE PARAMETERS

05 | 1 Overview

The printing setup was another step to take into account before printing with the robotic arm. As Mix 1-2-8-9 were all promising recipes, the available tools given by the LAMA lab directed which recipe would be tested. The LAMA lab offers a large pellet extruder (FDM) and a WASP extruder 3.0 (LDM). However, as the topic of this thesis is driven by the naturalness of the paste, making pellets or a filament was inconceivable as no thermoplastics were added. Therefore, the LDM printing setup was the only option with mix 8 (wood glue) and mix 9 (methylcellulose). As though mix 8 and mix 9 were both promising recipes to test, mix 8 is fabricated with a non-bio-based wood glue which clashes with the topic of this research. As explained previously, a bio-based resin will soon be available on the market by MOSO Internationals BV. Therefore mix 9 (Methylcellulose) is the final recipe that will operate the printing phase. The LAMA lab provides two different robotic arms. The UR5 is a collaborative cobot robot and the COMAU NJ-60-2.2 is an industrial robot. Both robotic arms would be suitable for 3D printing. The main difference between these two robotic arms is their payload. The UR5 can intake a load of 5kg. and the COMAU can intake a load of 60Kg. max. The total payload of the custom-built tool was 4kg. Thus, both robotic arms are suitable for printability tests. The main difference between each robotic arm is related to the required size of the components and the speed of their workflow. The physical setup for both robotic arms was designed and assembled and was studied in terms of their workflow to understand which robotic arm would facilitate the printing process (Figure 5.0, 5.1).

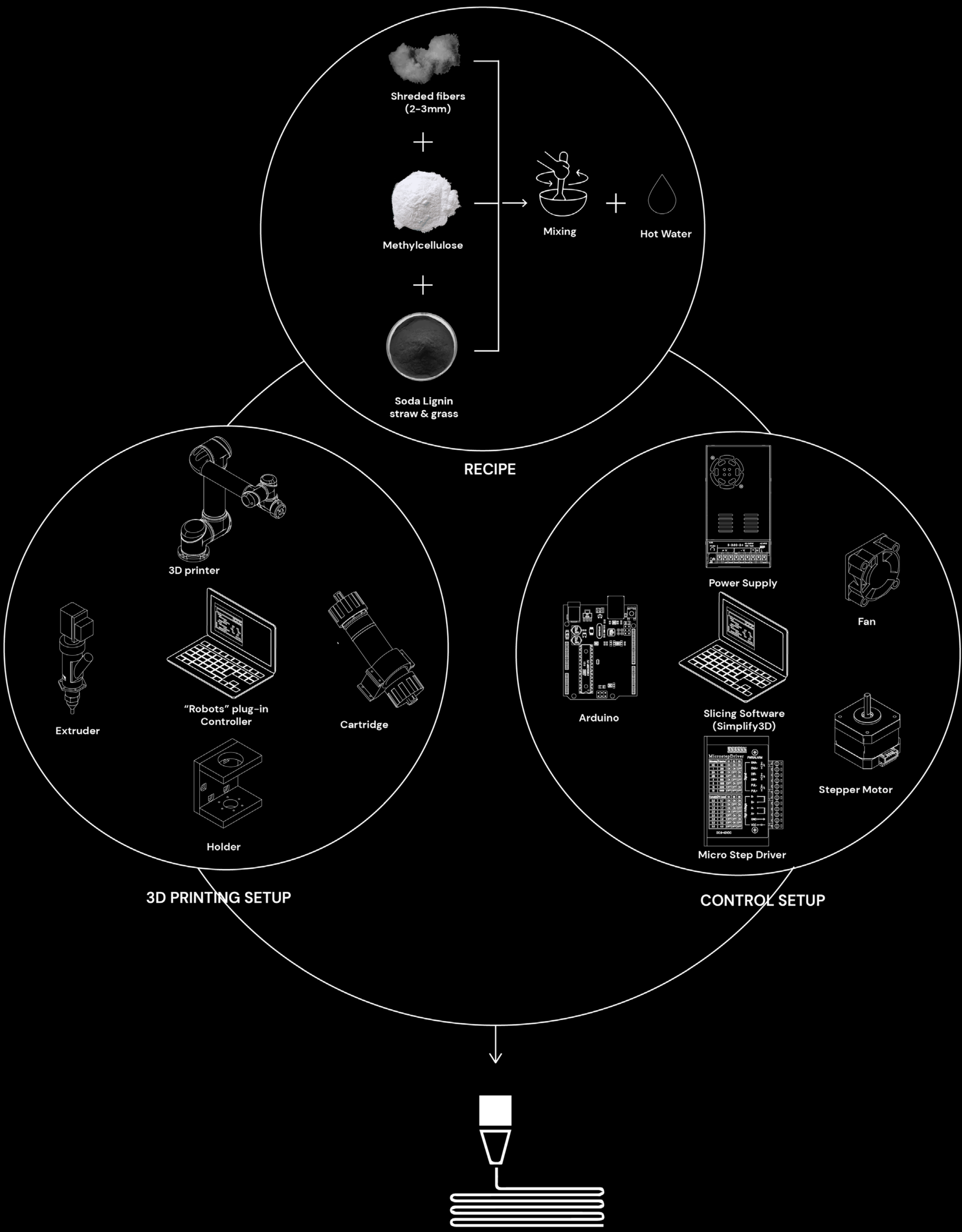


Figure 50: Diagram describing the full process to print paste 9
Source: own

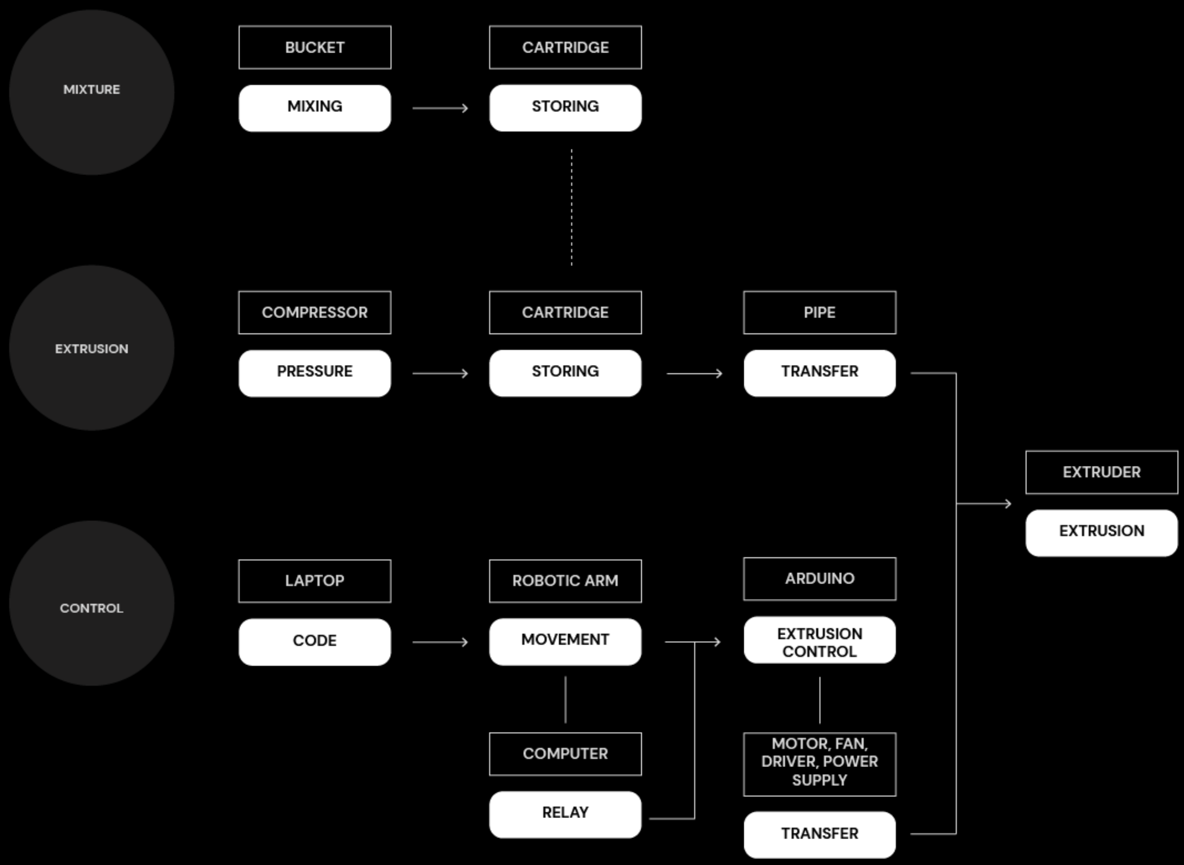


Figure 51 : Diagram to describe the workflow of entire process to print
Source: own

05 | 2 Machine exploration

05 | 2 | 1 Firmware Setup

The setup for the printing tests was based on a cold extrusion process. Therefore, Paul de Ruiter who is the head of the IAMA lab purchased an LDM WASP extruder XL 3.0 to ease the printing process. As the WASP extruder is only compatible with the Delta WASP 40100 Clay, a custom connection was necessary to set up. Thanks to the WASP team and Massimo Visonà, the connector pinout and the stepper motor datasheet of the WASP extruder were given. The initial setup was instrumented by the thesis of Athanasios Rodiftsis in 2020 who explains the wiring connection between a clay extruder and an Arduino board. Therefore, following the instructions that were given by Athanasios Rodiftsis eased the assembly of the wiring connection (Figure 5.2). After connecting the entire setup to a computer, the Arduino file (.INO) that was also written by Athanasios Rodiftsis was read, checked, and uploaded with the Arduino software to the Arduino hardware to validate if the stepping motor was properly connected and rotating. The setup did function, but the rotation of the stepping motor was inconsistent. The cause of this may be related to the power output of the Arduino controller which can't handle a certain level of amperage when the torque of the stepping motor is too high. As the chances of heating the motors are high, pulling too much current will activate the safety settings of the engine. Therefore, the stepper's motor torque would automatically switch to a lower amperage. Also, the

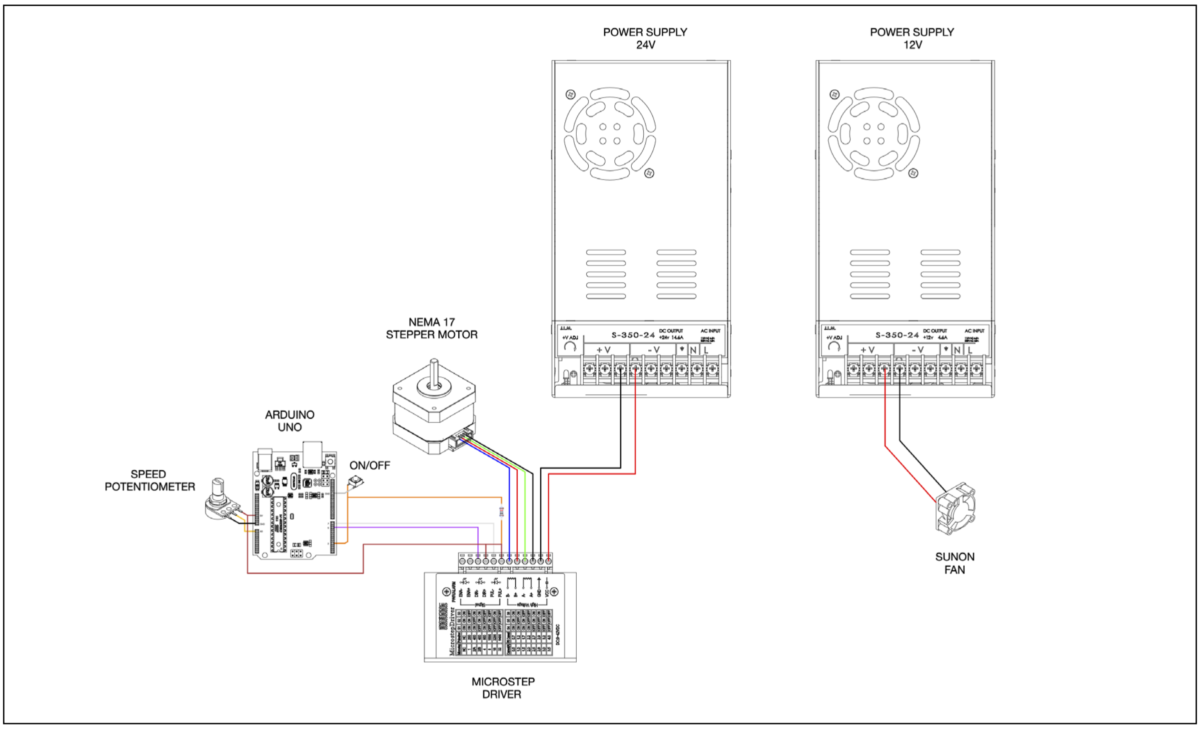


Figure 5.2: Diagram that describes the wiring setup for an LDM printing process made by Athanasios Rodiftsis in 2020
Source: own

setup that was made by Athanasios has many separate parts with intermediate drivers connected to an Arduino setup which has a separate driver and power supply. As the Arduino setup is suitable but not robust and accurate, the setup was changed to a duet 3 mainboard 6HC. The Duet board is based on an Arduino board but is extensive with many advantages. It is used for milling, laser cutting machines, and printers as you can incorporate multiple high-current stepper motors and has a lot of extension options. This means that there is the possibility to plug an extension board and then add additional engines which allow adding many functionalities such as stepper motors, activators, switches to end stops, etc. Also, the LAMA lab acquired these boards as they have a 32-bit processor which means a higher stepper rating. A low-end Arduino board would run at 16 steps, but these boards can go to 254 micro-stepping. Therefore, the motor is more silent, and the movement is smoother. The duet 3 mainboard 6HC has a higher ram which means a higher internal memory. The mother drivers and hardware drivers on the duet 3 motherboards are rated to 6.6 amps, which means that it is capable to add bigger motors like a 23 NEMA. Lastly, the duet 3 board fully integrates the drivers compared to an Arduino which has intermediate drivers. Thus, the new setup has a duet 3 mainboard 6HC that is only connected to a 24V power supply, cooling fans for the motherboard driver, and the stepper motor (17hs24-2104s-p5g). A USB cable is then used to connect the entire setup to a computer. To connect the motherboard to the computer it is necessary to follow the duet instruction on their website:https://docs.duet3d.com/en/How_to_guides/Getting_connected/Getting_connected_to_your_Duet, to properly connect the Duet via USB onto a computer (Figure 5.3). Once the wiring setup is established, the stepper motor's

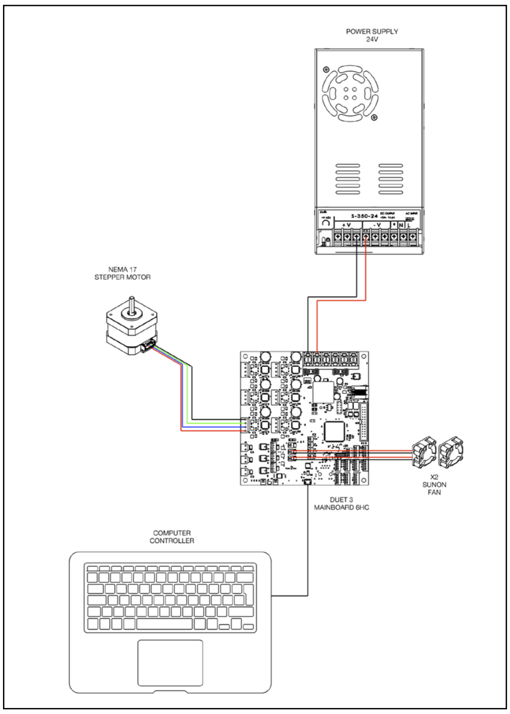


Figure 5.3: Diagram that describes the new wiring setup for an LDM printing process
Source: own

torque rotation is necessary to check. Therefore, following the survey or wizard made by RepRap firmware on the website of duet3D: https://configtool.reprapfirmware.org/Start, allows a simple and quick setup to generate a config. g file to safely configure the engine, the fans of the motherboard, and stepper motor. Once the survey is finished, the config. g file is exported onto a micro-SD card that is inserted into the motherboard driver.
The custom configuration bundle is safely configured by following these steps:

Start: only check "Custom configuration"
General: under-general preferences-board check- "Duet 3 MB 6HC"
I/o mapping: The motherboard has 6 entrances which means it can implement 6 stepper motors. As we have 1 engine the other 5 pins are ignored with no input. Therefore, the pin set of the engine E is assigned to the pin-set 0. Moreover, the end stops which are used to limit the machine are not activated.
Motors: The E motor speed settings are set higher than what is given because of the gears of the extruder (1:5 gear ratio). Since the extruder works around a spiral rod and not a filament, it is clear that we need higher settings. Therefore, the motor current is set to 900mA instead of 800mA (the motor current can be calculated by the amount of material extruder from the spiral rod. This can be understood by how much the spiral rod will turn downwards with 1 turn).
End stops: none
Heaters: All the temperature controls are switched off.
Fans: add 4 fans with a speed of 75% and frequency of 500 Hz with no thermostatic control
Tools: It is required to deactivate this setting as the minimum temperature safety slot in the firmware is based on a cold extrusion
Compensation: none
Network: none
Finish: To generate the whole set of driver information, the config. g which is considered to be the settings of the file is required to be saved onto the SD card. The other given files are only related to the end and beginning of the file.

05 | 2 | 2 Hardware Setup

Once the wiring setup is configured, it is important to place the tool onto the robotic arm. Therefore, a connecting element was designed, and CNC milled to accurately hold the tool onto the robotic arm. It is important to take into consideration the total payload of the installation including the material to avoid unsafe operations and protective stops from the robotic arm, which can in the long run damage the robot. Fortunately, the total amount of the entire installation is 4.0kg which is less than the maximum load for both available robotic arms. Once the installation of the extruder is set on the robotic arm, a printing bed has to be placed. The reach of the robot must be taken into consideration to avoid any damage to the robot or the prints (Figure 5.4).

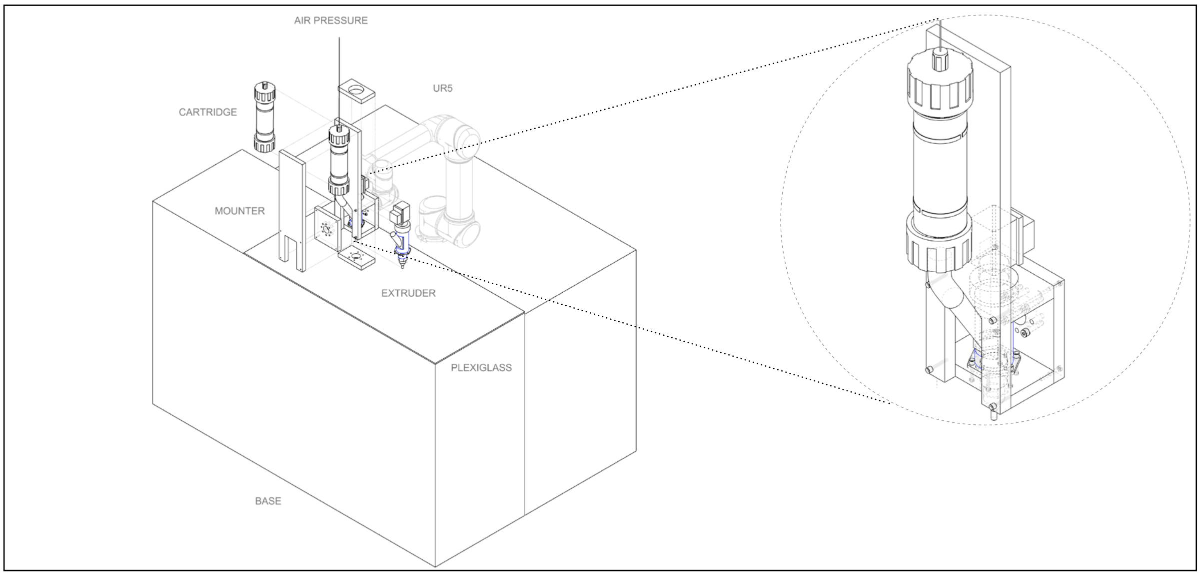


Figure 5.4: Axonometric view of robotic setup for a UR5 and zoom-in of the mounter + WASP extruder
Source: own

<u>To install the extruder onto a small 6-axis robotic arm such as a UR5 you need to:</u>
1: Screw the wooden plate to the flange with 4 internal hex screws (M6).
2: Rotate the motor including its body and ABS spiral screw feeder to the remaining wooden parts
3: Screw the extruder to the bottom wood part with 6 other internal hex screws and bolts (M4)
4: Screw 4 internal hex screws (M4) to the extruder including its vertical wood elements to the horizontal element that is already connected to the robot
5: rotate the ring nut including its nozzle (either 4,6,8mm) to the extruder
6: Screw the wooden plate to hold the cartridge to the connecting element with 4 internal hex screws (M2.5).
7: Place cartridge & hold it with a Velcro tape
8: Clean the equipment once done (All parts must be removed in the opposite order)

The robotic arm already had an installed base. However, it was necessary to extend its base as the workspace was split with another student (maximum reach = 0.850 meters). Again, a plexiglass printing bed was added on top of the base and taped to avoid any movements. In the case of mix 9, plexiglass was used as a printing bed to easily remove the prints, easily clean the bed, and not interfere with the curing process of the prints. The printing bed must also be designed in a 3D modeling software (Rhino/GH) to avoid any collisions or damages. The large robotic arm did not have a printing bed. Therefore, two wooden boxes were placed with heavy sandbags to avoid any movements of the base. A heavy metal plate was then added to have a flat surface to print on. The base was set in front of the arm at a 2-meter distance for a safe reach (maximum reach = 2.258 meters). It is important to measure the distance from the center of the base to the printing bed. Also, the dimensions of the plexiglass sheet were taken into account in the 3D modeling software (Figure 5.5).

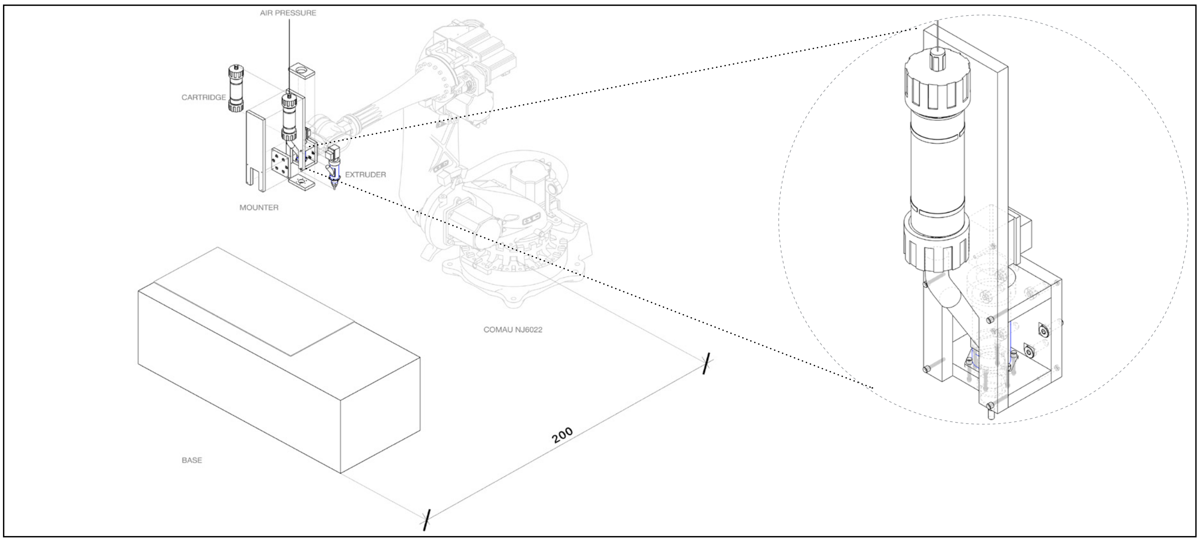


Figure 5.5: Axonometric view of robotic setup for a COMAU and zoom-in of the mounter + WASP extruder
Source: own

<u>To install the extruder onto a large 6-axis robotic arm such as a COMAU NJ-60-2.2 you need to:</u>

1: rotate the motor inside the connecting element

2: add vertical wood board and screw it to the horizontal element with 2 internal hex screws (M4).

3: Screw the extruder to the connecting element with 6 other internal hex screws (M4)

4: add ring nut including its nozzle (4,6,8mm) to the extruder

5: screw the connecting element with the extruder to the flange of the robotic arm with 3 to 6 internal hex screws (M8)

6: Screw the wooden plate to hold the cartridge to the connecting element with 4 internal hex screws (M2.5).

7: Place cartridge & hold it with a Velcro tape

05 | 2 | 3 Software Setup

Before introducing a movement to both of the robotic arms, it is important to use a slicing software to calibrate the speed of the stepper motor and pressure according to the consistency of the paste and nozzle diameter. Once the calibration of the extruder is settled, a workflow is established either in RoboDK or in Grasshopper to direct the movements of the robotic arm and activate the given tool. As the motherboard duet3D is currently not supported by Grasshopper or RoboDK it is necessary to simultaneously use a slicing software such as Simpligy3D to rotate the extruder, push the material with a pressurized system and manipulate the movement of the robotic arm separately (Figure 5.6). It is important to send a code to the slicing sotware to activate the rotation of the stepping motor (G0 E100.00 F250).

G0 (run motor)
E (extruder motor)
100.00 (amount of extrusion)
F (speed)
250 speed number

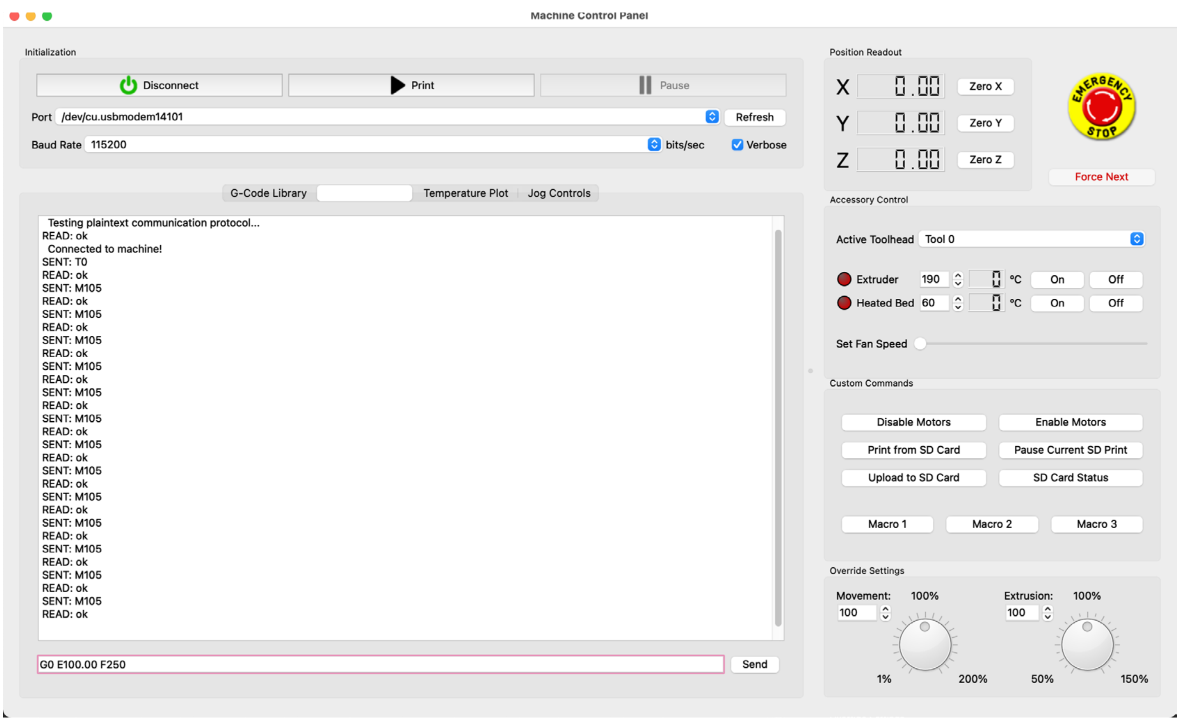


Figure 5.6: Screenshot to describe the connection with Simplify3D to connect to the stepper motor
Source: own

To use the COMAU NJ 60-2.2, a program is generated via RoboDK. It is necessary to export a 3D model of the printing bed, the tool, the geometry, and the type of robot which is found in the library of RoboDK. Regarding a 3D printing process, it is necessary to slice the given geometry with a certain height (E.g., 3mm). Therefore, the curvatures can either be imported from a 3D modeling software such as Rhino or with a slicing software. Slic3R is a great software to operate as it can be incorporated within RoboDK. A simulation is then established to check if there are no collisions between the printing bed and the arm as well as with itself. Once the setup satisfies the safety measures of the arm and the shape of the print, a code is generated and saved as a PDL. file. (Figure 5.7). The file is then exported onto a USB stick and inserted into the teaching pendant. Within the teaching pendant, the PDL. file is translated into a COD. file to generate a legible language that is understood by the robotic arm. However, there were some issues regarding the translation of the code. For this reason, the workflow was moved to another 6-axis robotic arm such as a UR which is more universal to further produce and test the printability of Mix 9 (Methylcellulose).

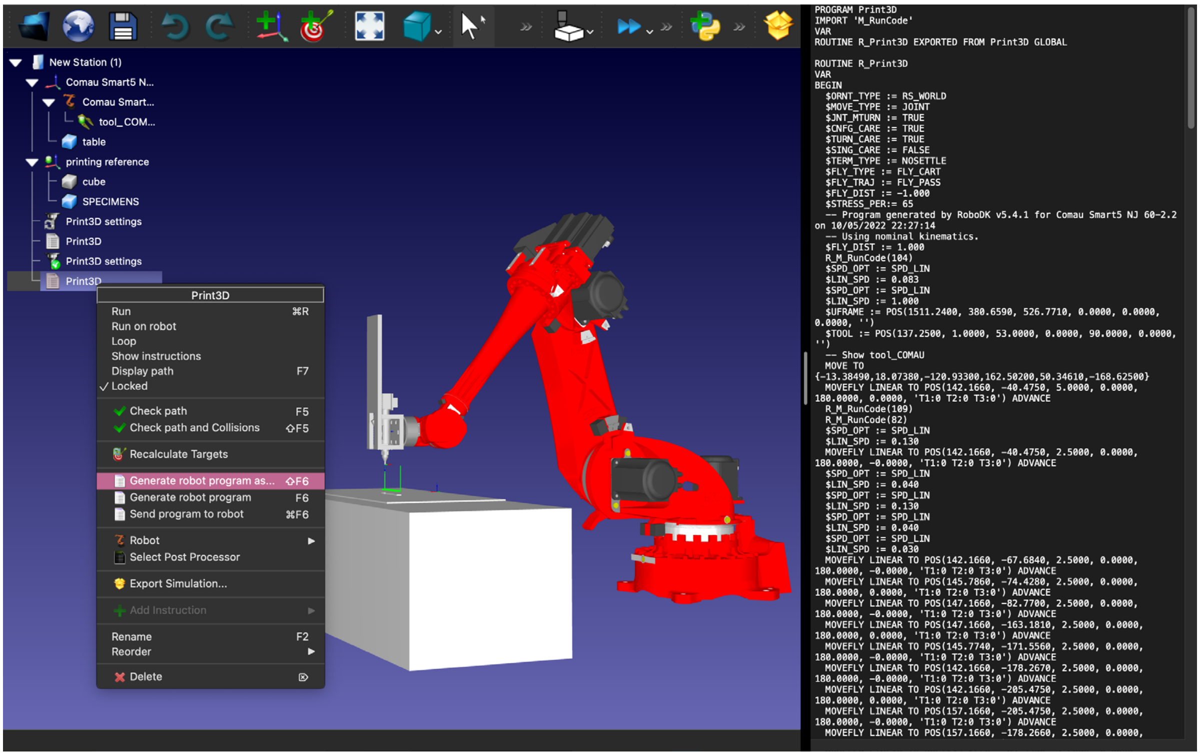


Figure 5.7: Screenshot of RoboDK to describe the generation of a code (PDL. file) using an incorporated slicing software (Slic3R)
Source: own

To use the UR5, a program is generated via the plug-in "Robot" in Grasshopper. It is necessary to first load the robot system from its library. It is important to mention that the plug-in is only compatible with ABB, KUKA, and UR robots. Moreover, a tool or end effector must be included by taking into account the tool's payload and TCP position. Also, the speed of the printing process and the position of the robot must be blended to smoothly move at a constant speed. Therefore, a zone parameter that blends the radius of the waypoint to avoid the robot to stop at each point and speed parameters are added to the program. Lastly, the contoured geometry is divided into control points and target planes to inform the direction and movements of the arm. All is then simulated digitally and later physically (Figure 5.8). To simulate the movements of the robot with the plug-in "Robots", a direct connection to a router via an ethernet cable to the computer and the control box of the UR can be made. The IP address of the router must be given to the plug-in. Once the set-up is connected, the movement of the robot can be dictated by the computer that is acting as a controller. More information can be found here: [https://github.com/visose/Robots/wiki#upgrading-from-an-older-version.](https://github.com/visose/Robots/wiki#upgrading-from-an-older-version)

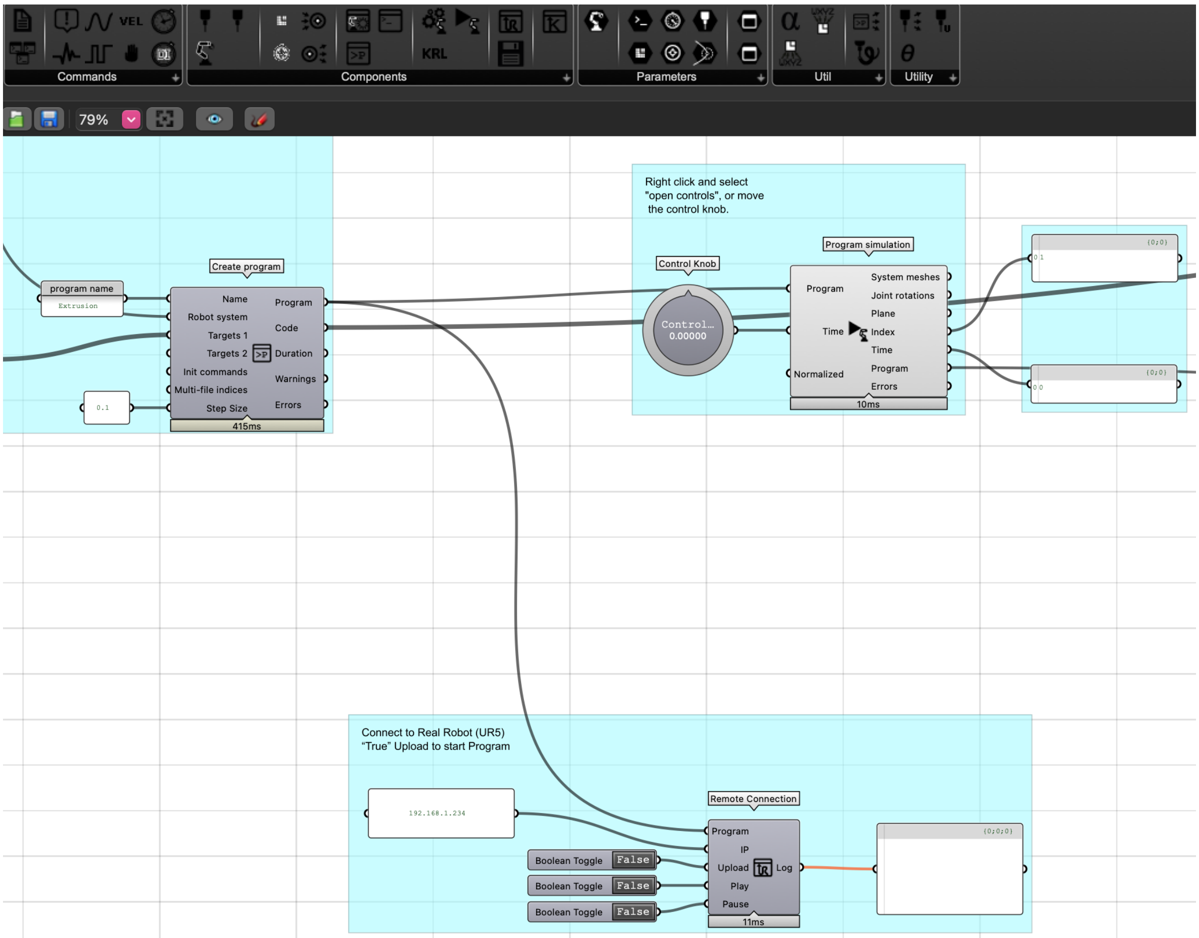


Figure 5.8: Screenshot of Grasshoper script using the Robots plug-in showing the envrionment and controlling device using a remote connection

Source: own

05 | 3 Conclusion

Firmware

A full connection between the UR5, the tool, and the controller would ease the printing setup. Running the motherboard duet3 from Grasshopper to synchronize the movements of the robotic arm with the extruder's options (end stops, retractions, z-lift) would allow a better and easier workflow. Therefore, a new wiring setup must be thought of to connect the motherboard to the pin connection of the UR5 (digital output 0).

Hardware

The design of a new connecting element between the robotic arm and the extruder should be rethought to ease the assembly and disassembly process. At the end of each job, the installation requires a clean-up to avoid any damage to the extruder. Therefore, as the process is based on the repetitive task to install and remove the wooden parts, metallic sleeve anchors must be included for a stronger connection and avoid tearing the wood. A Japanese joinery system can be a great way to easily and safely remove the parts.

Software

The translation of the code file given by RoboDK as a PDL. to a COD. file inside the teaching pendant must be better studied to scale up the printing process. Moreover, in the plug-in "Robots" a moveP is not possible. A UR5 can either be assigned to do a joint path (MoveJ), linear path (MoveL), or a circular path (MoveP). However, linear and circular movements are essential to print any type of curve (line, polyline, circle, ellipse, arc, NURBS, polycurve). Therefore, Konrad Jünger who is an industrial and product designer modified the text output of "Robots" to generate a moveP (https://github.com/visose/Robots/discussions/121). His addition was added to the plug-in. Also, there were some initial issues in regard to the smoothness of the path. Therefore, the reduction of the step size to 0.1 mm/s allowed a more accurate motion of the arm. Once all of these parameters are changed, the freedom to move the robot in any direction at a constant speed with a smooth path is feasible.

06 ROBOT: PRINTING PARAMETERS

06 | 1 Overview

Once the extruder is connected to the flange of the arm and the stepper's motor is rotating at a constant speed expelling a smooth paste on a reachable printing bed, the next step is to test the geometrical possibilities of Mix 9 (Methylcellulose). Therefore, a series of tests in regard to overhang, overlapping of layers, geometrical influences, infills, and nozzle diameters were tested to further understand the limitations and advantages of designing a window frame. After P4 the design of a window frame will be prototyped concerning these discoveries (Figure 6.1).

06 | 2 Printing Exploration

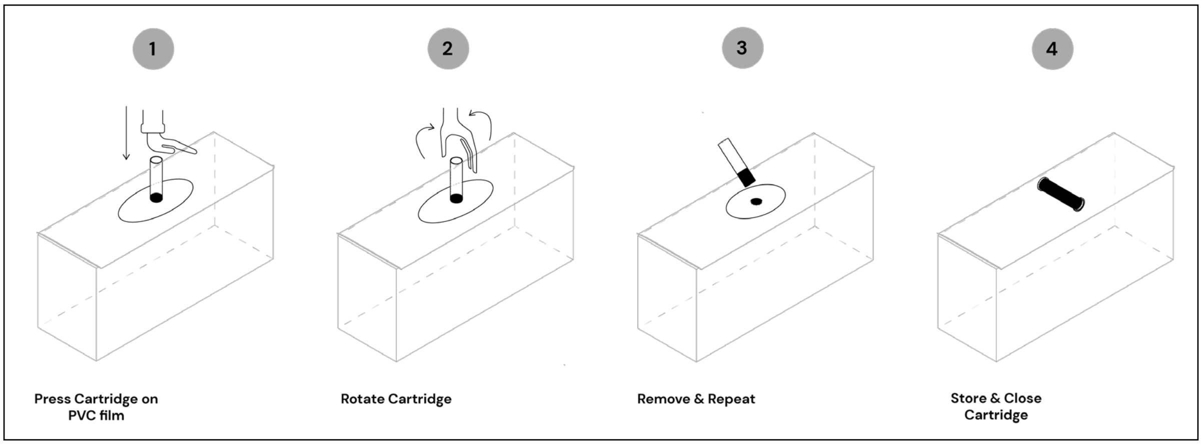


Figure 6.0: Diagram to describe how the material recipe mix 9 is inserted into the cartridge
Source: own

Before extruding, it is important to correctly fill in the cartridge to avoid any air bubbles and further damage to the printed shapes. Therefore, once the recipe is mixed into a paste it is required to flatten the paste onto a PVC film, press, and rotate it into the container. The process is repeated until the container is filled. To make one full cartridge of a 700cc dimension: https://vormvrij.nl/lutum/shop/#!/Clay-Cartridge-S/p/137376028/category=47484151, it is necessary to use cellulose = 16.4g, lignin = 164.3g, water = 356.0g, mc = 27.4g. (check the weight of cartridge with material 850g) and let the material cool down for 24 hours in PVC film before use. Also, if excess material remains in the cartridge, the material does not need to be removed if it is not in contact with air (Figure 6.0). As the maximum payload of the UR5 is 5kg. large prototypes can only be printed in separate parts. So, it is important to take into consideration the printing length of the model to

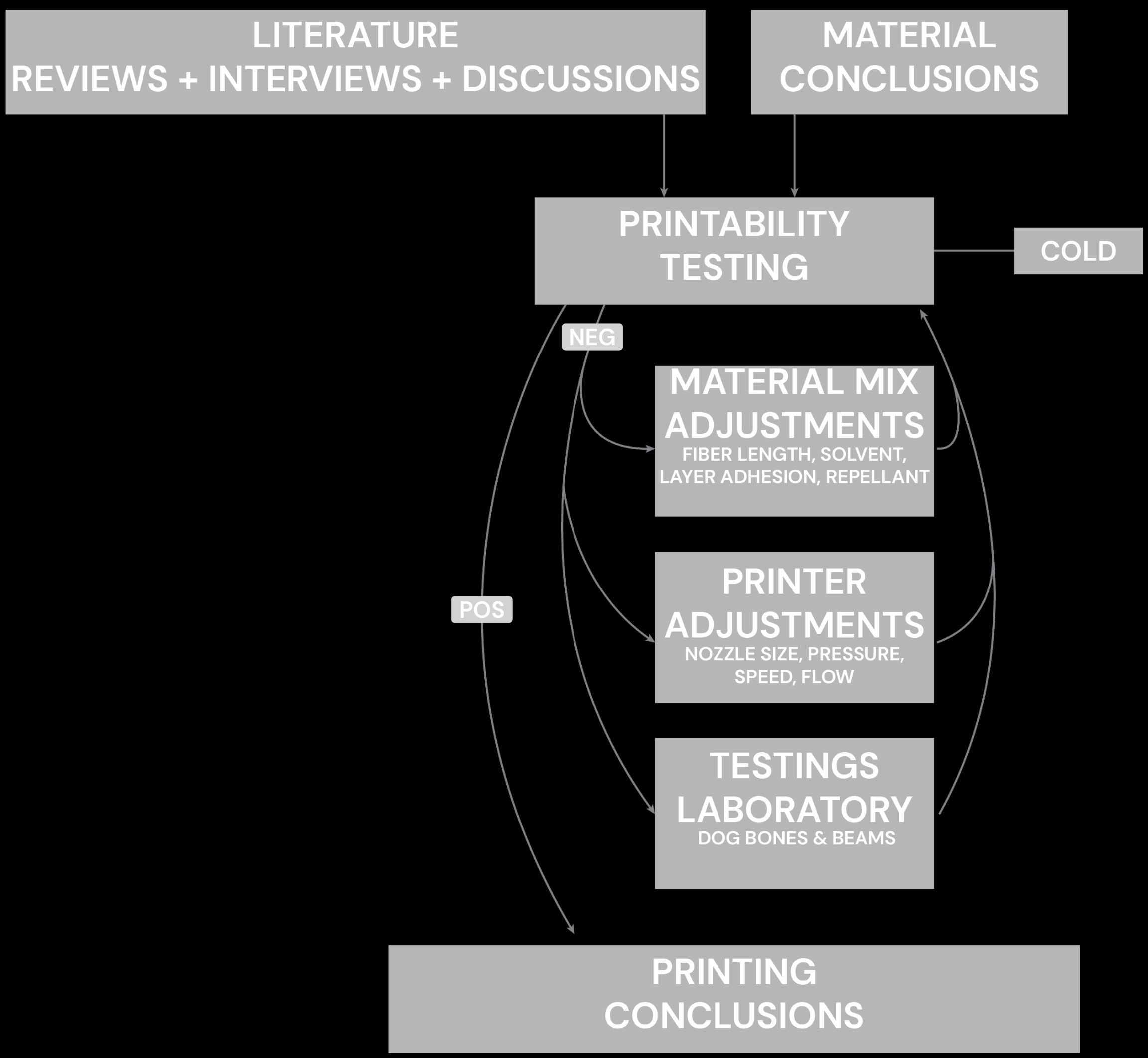


Figure 6.1: Overall worflow to test the printability

Source: own

avoid any damage to the print (with a 4mm nozzle, 21 meters can be continuously printed). Before testing the possibilities of mix 9, it is necessary to check if the nozzle is correctly positioned according to the height of the printing bed. It is also important to take into account the z-height of the contouring to allow a perfect adhesion between each layer. Depending on the extruder's diameter, the layer height will be adjusted (E.g., layer height = 3mm for a 4mm nozzle diameter). Moreover, it is essential to understand how the robotic arm can travel from one curve to the next, building a continuous trail for a fast and smooth print. Therefore, depending on how the contouring is constructed, a spiral vase mode can be established by flipping the alternate line to align the end and the start of the edge or corner of each curve (Figure 6.2). Once these general settings are checked in a simulation environment, simple geometrical shapes overhangs at different angles, infill shapes, and overlapping of the geometrical shapes are tested to further understand how the material behaves. These tests are crucial to understanding the limitations and advantages of printing a window frame. These tests will lead to an understanding of prototyping the final shape of the window frame.

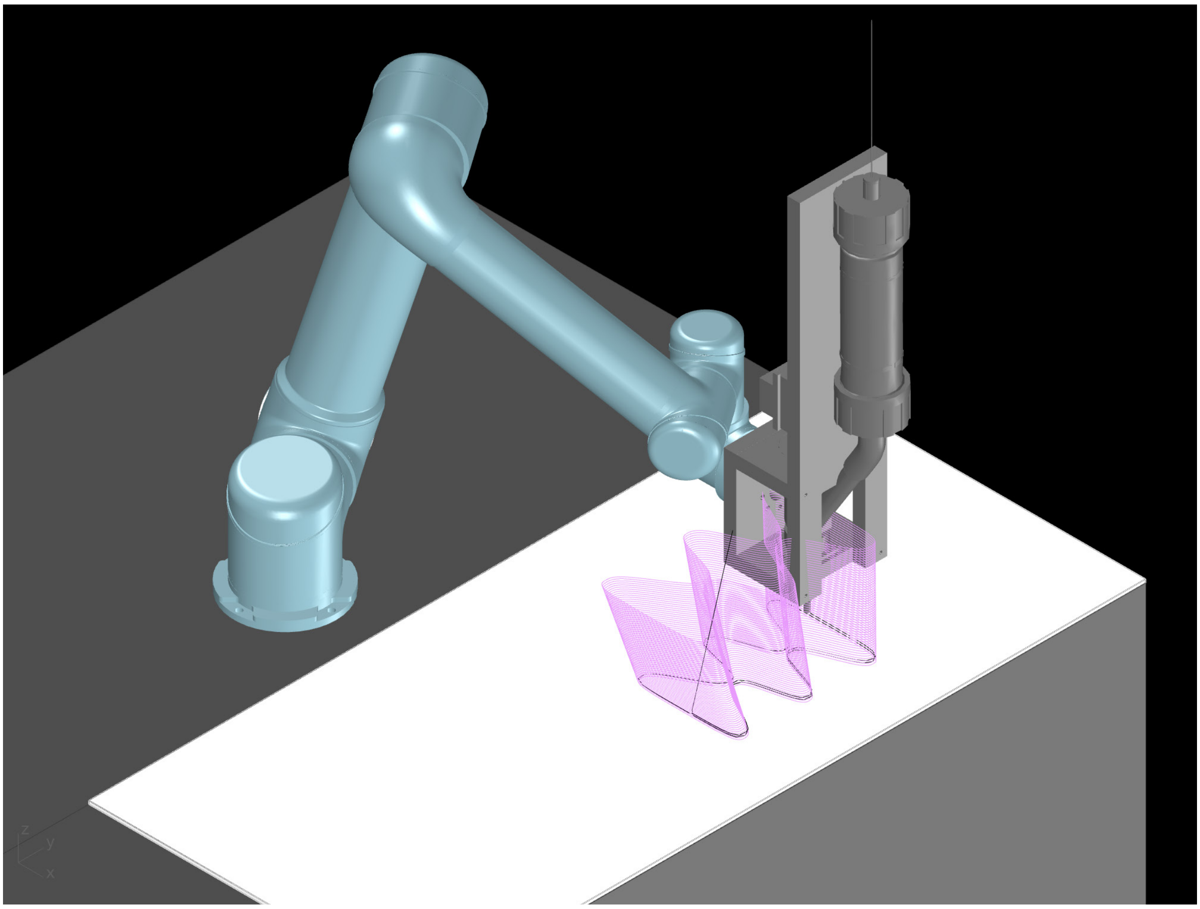


Figure 6.2: Workspace using the UR5 and Slicing of a tested overhang shape
Source: own

06 | 2 | 1 Geometrical Influence

A list of geometrical shapes from a square, circle, olive, diamond, and named "tangent" was tested as a straight extrusion with a height of 50mm (Figure 6.3). All were able to be printed until the end of the program. However, all of the shapes collapsed except for the circle and tangent (Figure 6.4). Therefore, during the printing process, curvatures do help in stabilizing the overall geometry. Also, during the printing process, the material was being pulled away from its underneath layer which will have a direct effect on the structure of the printed shape. It can be avoided by changing the speed of the print, changing the consistency of the material mixture, and/or using a larger nozzle.

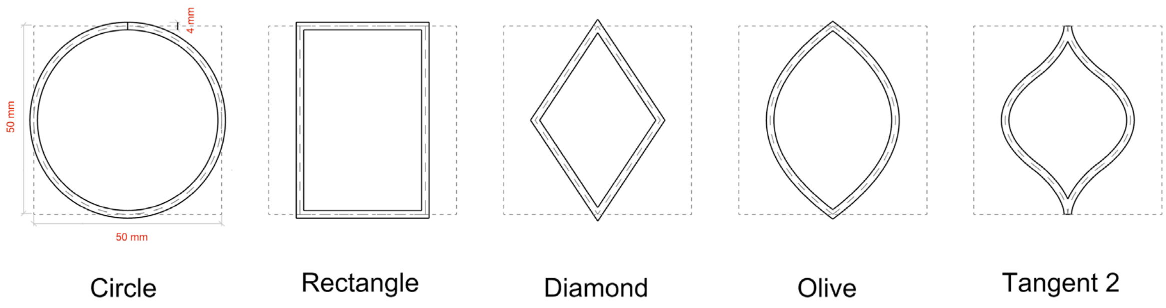


Figure 6.3: Plan of printed geometrical shapes
Source: own

Figure 6.4: Printed Circle, Figure 6.5: Printed rectangle, Figure 6.6: Printed Olive
Source: own

06 | 2 | 2 Infill & Toolpath

The percentage of infill required, and the shape of the infill are important aspects to take into account to further optimize a stable printed shape. the straight-line infill was initially tested with different distances. As a straight line will collapse after a certain height it is important to fully overlap the linear path (Figure 6.7). Therefore, to optimize the overall shape, reduce its weight, and be structurally stable, the infill must be curved. The toolpath must be continuous by always starting where the toolpath ends on the layer. If the toolpath is misunderstood, the printer will travel back to its starting point which will damage the print (figure 6.8-6.9-6.10).

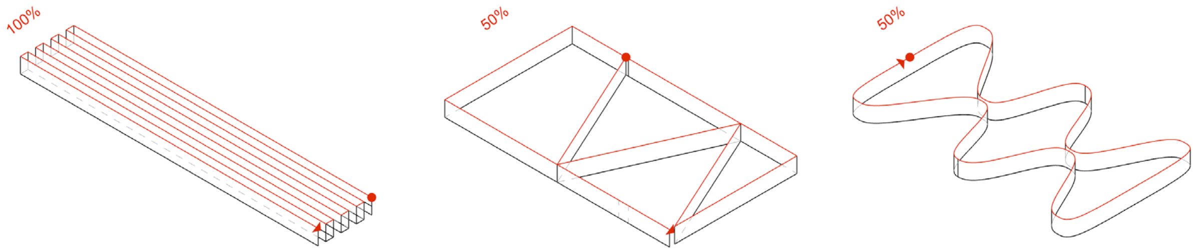


Figure 6.7: Axonometric view to describe the infill density & toolpath direction
Source: own

Figure 6.8: Printed 100% straight infill, Figure 6.9: Printed 50% straight infill, Figure 6.10: Printed 50% curved infill
Source: own

06 | 2 | 3 Overlap

The layer width given by the digital simulation is always different from the physical print as the given pressure, material consistency, inner nozzle diameter, and stepper's motor speed is not taken into account. Therefore, it is important to check the minimum and maximum overlapping between two curves or lines to avoid structural deficiencies during the job and after when drying. Therefore, a distance between connecting curves from 4mm-2mm-1mm was tested (Figure 6.11). The 1mm overlapping distance proved to be the best for the print to fully connect during the printing process and once dried (Figure 6.12-6.13-6.14).

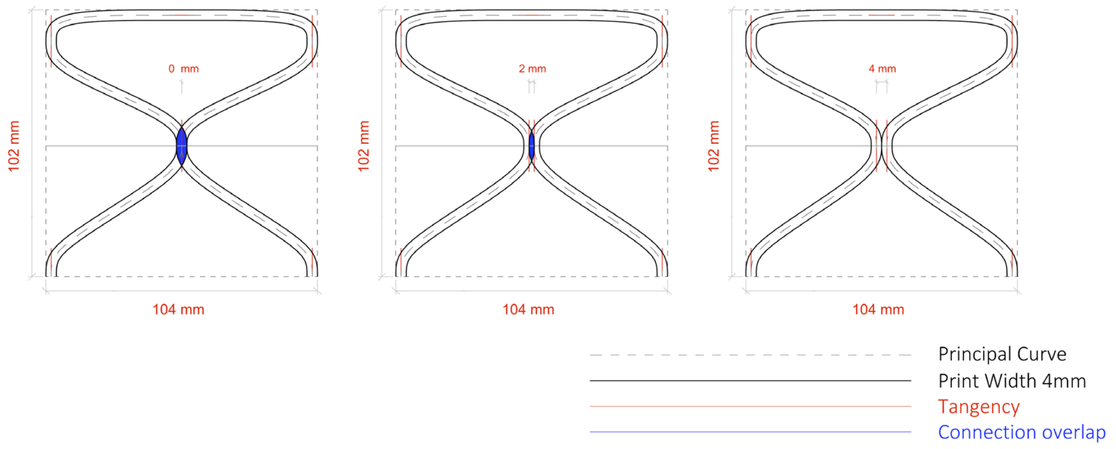


Figure 6.11: Plan of overlapping between layers
Source: own

Figure 6.12: Printed 4mm overlap, Figure 6.13: Printed 2mm overlap, Figure 6.14: Printed 1mm overlap
Source: own

06 | 2 | 4 Overhang

Before testing the maximum angle that the print can withhold, the nozzle diameter must match the dimension of the printed design. For example, with a 4mm nozzle diameter, a 50X70X50mm box is the correct dimension (Figure 6.15). The initial overhang was at a 20-degree inclination which collapsed after 50mm (Figure 6.16). The reason is related to the overall structure of the design as the geometry has straight edges. Therefore, an infill was added and reprinted. However, it did not help and collapsed again at 50mm (Figure 6.17). A curved overhang was then tested. Nevertheless, it also collapsed after 50mm (Figure 6.18). In this situation, the collapse of the shape was due to the consistency of the mixture as it was less viscous compared to the previous mixture. Thus, the recipe must cool down for 24 hours before use. Further tests should be implemented by printing in increments of 8 layers and a wait of 30 minutes in between to let the material cool down and print higher.

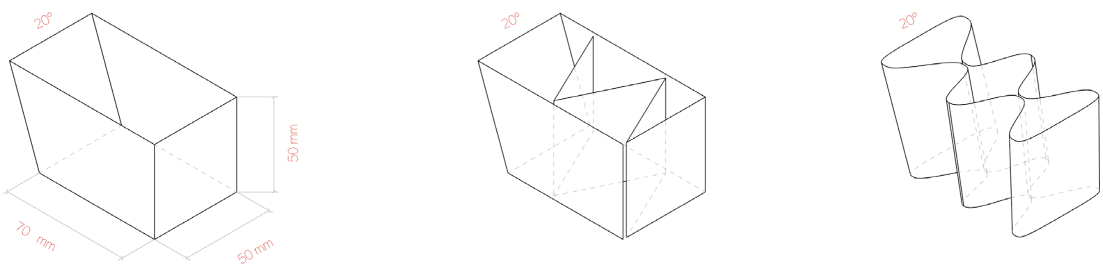


Figure 6.15: Axonometric view of overhangs
Source: own

Figure 6.16: Overhang 20 degree with straight infill, Figure 6.17: Overhang 20 degree with zigzag infill, Figure 6.18: Overhang 20 degree olive shape
Source: own

06 | 3 Conclusion

During the printing phase, many challenges and advantages were recognized for the future design of a window frame. The first challenge was to print a straight line after a certain height. It is important to understand the power of the curvature to stabilize the overall shape. Also, the infill and toolpath must be understood to print continuously for a faster and cleaner print. The minimum distance for two edges to connect is 1mm with a 4mm nozzle diameter for higher stability. To offer more geometrical freedom to design with mix 9 (Methylcellulose) overhangs were tested and failed. Moreover, during the printing phase, it was noticed that the viscosity of the material recipe differed when it was directly used to print. The recipe was revealed to have a higher viscosity rate when it was cooled down for 24 hours. Furthermore, the overall shape of the geometries did not shrink except in its height. The overall drying time depends on how much air is in contact with the print. Thus, if the infill of the design is full, the drying time will take longer than expected. In addition, with a 4mm nozzle diameter, 2 bar pressure and a stepper motor speed of 2000mm/s, the contouring of the geometry must be at a 3mm height for a smooth adhesion between each layer. After printing with different nozzle diameters, the nozzle width does affect the definition of the print. Therefore, to print a high-definition edge, a smaller nozzle diameter is necessary. For the moment the setup of the printing phase is established with a UR5. Thus, it is possible to use a popup command to stop the printer during the job to refill the cartridge and continue with the print. However, to ease the printing process with large objects, the setup must be switched to a larger robotic arm that can hold larger cartridges and even be connected to a pump system.

07 DESIGN: WINDOW FRAME

07 | 1 Overview

The use of advanced technologies such as 3D printing and milling presents a new vision and method to construct our built environment. 3D printing could potentially offer a larger spectrum to building elements in comparison to milling, as it can print entire elements without wasting any material. Now, many building elements could potentially be studied to be 3D printed. 3D printing window frames can be utilized in different areas of the construction industry such as in the heritage field by replacing or enhancing existing window frames. Also, 3D printed habitats are faced with an issue which is the interface between flat wooden elements and a curvy printed wall as they do not properly coincide. Therefore, 3D printing of wooden elements would not only help to replace existing mundane wooden window frames but improve the methods of 3D-printing buildings and offer a larger spectrum to print habitats (Figure 7.1-7.2-7.3). Nonetheless, after testing the mechanical performances of the discovered recipes, none can enter the construction industry. Thus, the design can either take two different directions. Either to replace existing elements of a window frame or showcase a new typology of its own. In this case, the design exploration will be guided by printing a corner of a wooden window frame according to the advantages and restrictions that were previously explored as a proof of concept to showcase the future vision of 3D printing wooden window frames (Figure 7.0).

Figure 7.1: Rotten wood at the corner of a window frame in my apartment
Source: own

Figure 7.2: Intersection between flat wooden frame and 3D printed Qatar pavilion, Floriade expo 2022
Source: own

Figure 7.3: Flat window frame connected to 3D printed concrete house, Eindhoven 2019
Source: https://www.3dprintedhouse.nl/en/project-info/project-milestone/

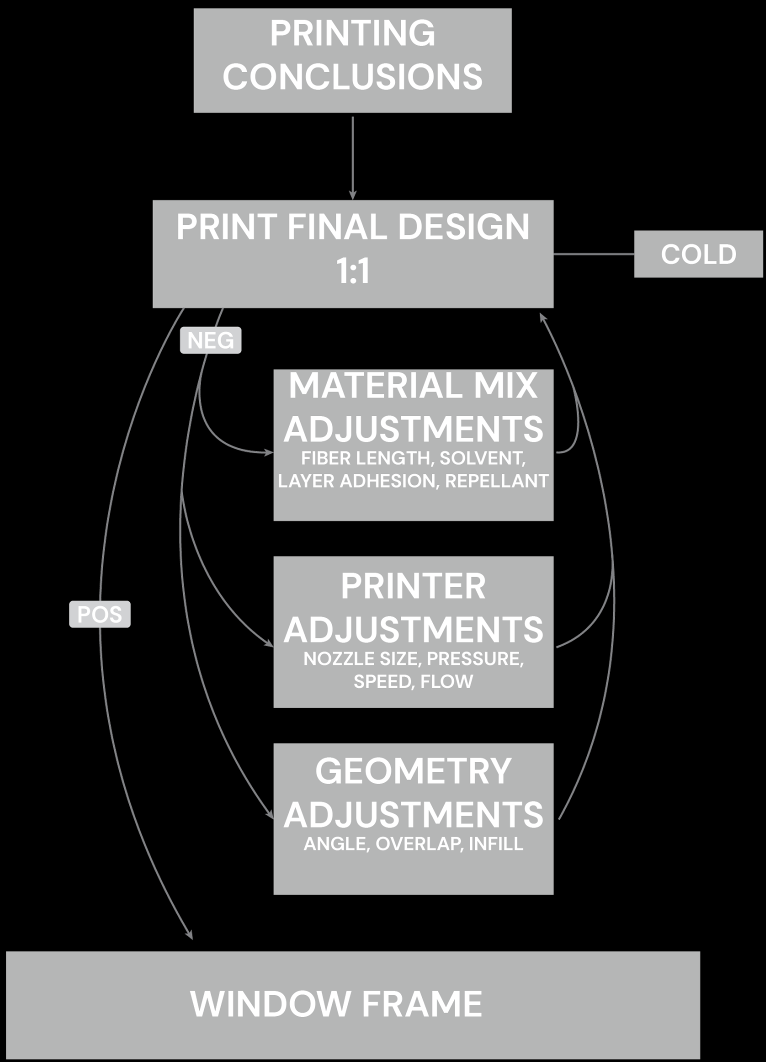


Figure 7.0 Overall worflow to design and print window frame

Source: own

07 | 2 Design Exploration

It is necessary to englobe the possibilities of what mix 9 (methylcellulose) and 3D printing technology can produce together. As the focus of the design is a window frame, the corner will be further studied and explored according to the advantages and limitations of the previous printability tests (Figure 7.4-7.5-7.6-7.7-7.8-7.9). A standard L-shape wooden window frame (Figure 7.10) will be investigated to further optimize its shape according to the discovered printing properties.

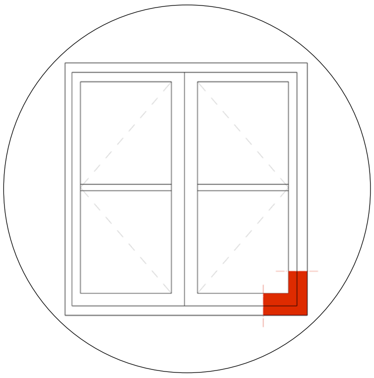


Figure 7.10: Typical L-shape wooden window frame
Source: own

Figure 7.4: Material Recipe, mix 9 (methylcellulose)
Source: own

Figure 7.5: Nozzle widths (4-6-8mm)
Source: https://www.3dwasp.shop/en/product/kit-of-stainless-nozzles-for-ldm-wasp-extruder-xl/

Figure 7.6: Geometrical influence, power of the curve
Source: own

Figure 7.7: Overlapping between layers (1mm distance)
Source : own

Figure 7.8: Overhang limitation
Source: own

Figure 7.9: Maximum height limitation (safe height = 4cm)
Source: own

07 | 2 | 1 Border Restriction

The first aspect to reconsider is the border of the wooden frame. As typical L-shape frames have straight edges and corners, it is necessary to redraw the borders of the frame into curved ones (Figure 7.11). After testing multiple geometrical shapes, it was identified that straight lines do not mingle well with the printed material, but curved geometries such as the circle proved to print the highest. Also, the corner of any given geometry would always be curved as the geometry of the acquired WASP nozzle is circular. Therefore, further study can be implemented by switching to a rectangular nozzle.

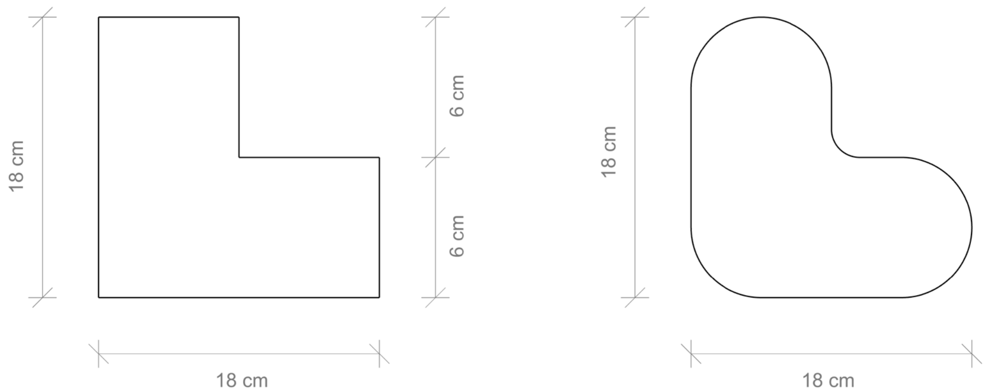


Figure 7.11: Plan view of straight vs curved edges
Source: own

07 | 2 | 2 Height & overhang restriction

The second aspect to reconsider is the total height of the printed shape. After testing multiple geometries, it was revealed that 4 cm was the maximum height before a collapse would occur (Figure 7.12). Thus, during the design of the window frame, it is important to split the overall piece into different parts and later assemble it into one piece. However, as the material shrinks once dried, the assembly of each piece would appear different and affect the overall shape of the design. Luckily, it was discovered that the material dries at a fast rate which implies that it is possible to print one single piece. The safest method to print a heigh geometry is in increments of 8 layers with a 30-minute wait in between each phase of print to avoid the material to buckle, which would result in misalignments of the toolpath and no adhesion between layers.

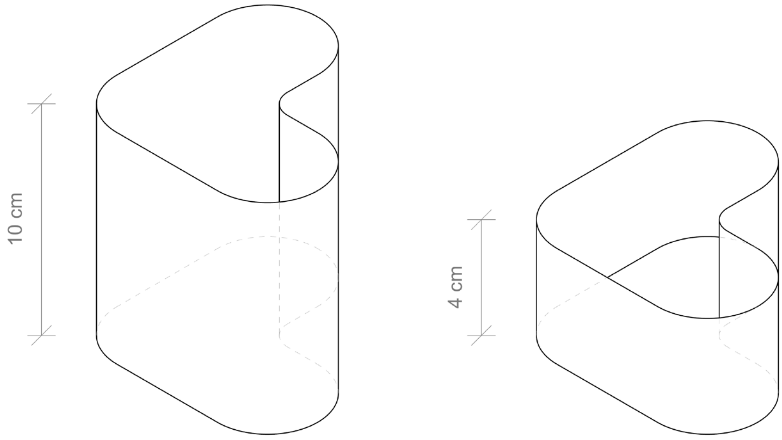


Figure 7.12: Axonometric view of non printable vs printable height
Source: own

07 | 2 | 3 Toolpath

The third aspect to reconsider is the weight of the overall geometry and unnecessary material loss. Window frames are solid pieces to avoid any water damage. However, the use of 3D printing technology would be illogical if we were to print a solid object. Therefore, it is important to study the optimization of the body of a frame to not only be lighter and faster to print, but to possibly create a new system of its own. Inserting other important aspects that a window frame requires such as a gasket becoming a seal as it must be thought of to implement a locking system through the use of an infill pattern. Thus, a study was further explored between straight, curved, and Voronoi shapes (Figure 7.13). The important aspects to consider are to first build a single toolpath that can be printed at once. The designed geometry should help the overall geometry to stand and therefore requires the path to overlap with itself. Lastly, as we already know, curved paths would offer higher stability while printing. Moreover, curved paths would allow inserting other printed elements without any external glues. Therefore, the final toolpath of the cavities would be curved.

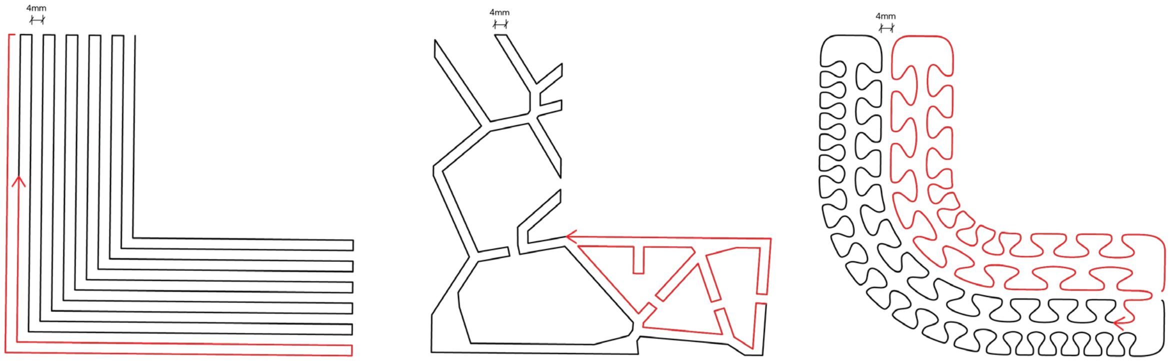


Figure 7.13: Axonometric view of non printable vs printable height
Source: own

07 | 2 | 4 Window Frame Typology

The last aspect to consider is the parts that constitute a window frame. Therefore, looking at a typical wooden frame, the sill, frame, sash, gasket, and glass must be considered in the design and printing method (Figure 7.14). When using a 3D printing method of construction, it is important to consider that the frame and sill can become one printed element. Also, the sash could be potentially removed as the gasket which can be directly inserted in the curved infill of the frame. Thus, the single frame and sill would be printed as one piece and the gasket would be printed with another material that is semi-flexible to easily insert and lock itself into the frame. The glass sheet could then be slotted and held by the gasket. Also, as window frames require precision between elements and are average size elements, the nozzle diameter must be taken into account. Therefore, a 4 mm nozzle will be utilized for a higher definition and accurate model.

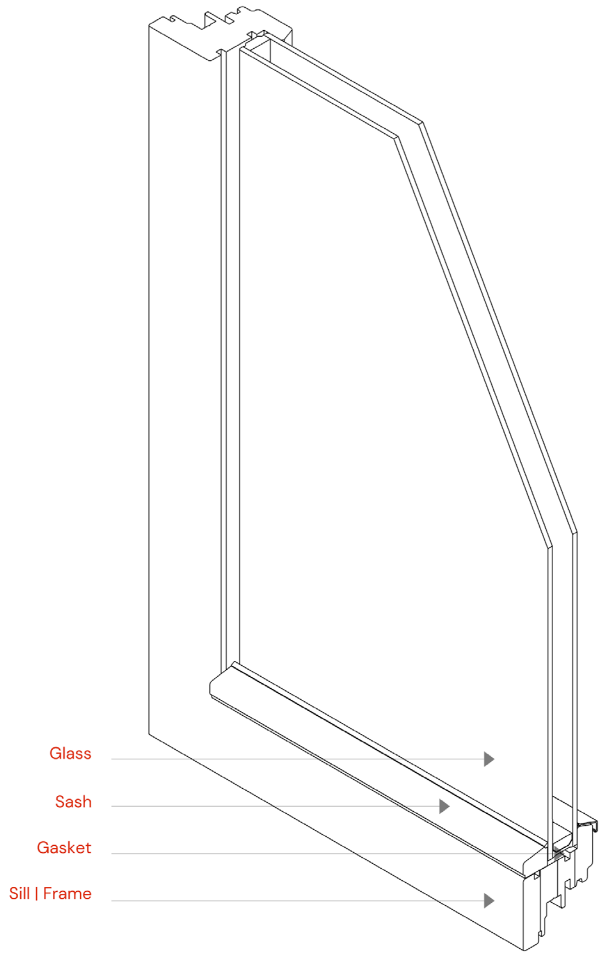


Figure 7.14: Axonometric view of typical wooden window frame
Source: own

07 | 3 Final Print

After understanding all of the parameters which enabled the design decision of the window frame, the printing phase was established (Figure 7.15). During this phase, multiple aspects were identified. As there was a limitation in regard to the total height of the printed shape, the final print was split into four parts. A single printed part would take approximately 40 minutes to print for a total of eight layers, one full cartridge, and 21 meters of material. However, during the printing time, the material was drying at a fast rate, which would imply that objects could be printed monolithically. Printing a single object, would not only allow to have a single element but also speed up the process and possibly integrate elements while printing. Also, during the printing phase, it was observed that the printed infill was too dense which would have consequences on the drying time of the pieces as air does not have space to flow inside the cavities. Thus, after one week, the elements were dry and shrunk by approximately 10 to 15 percent. Shrinkage is a serious issue in regard to 3D printing large objects. As the correct position between the nozzle and the previously printed layer is not aligned, it would cause misalignments between the previous and ongoing printed layer. Also, as the window frame incorporated a gasket, the design of the gasket had to be readjusted as it did not take into account any tolerances. After readjusting the design to compensate for the shrinkage of the material, it was detected that softening or curving the edges of the gasket would help to further seal and weathertight the connection between the gasket and frame.

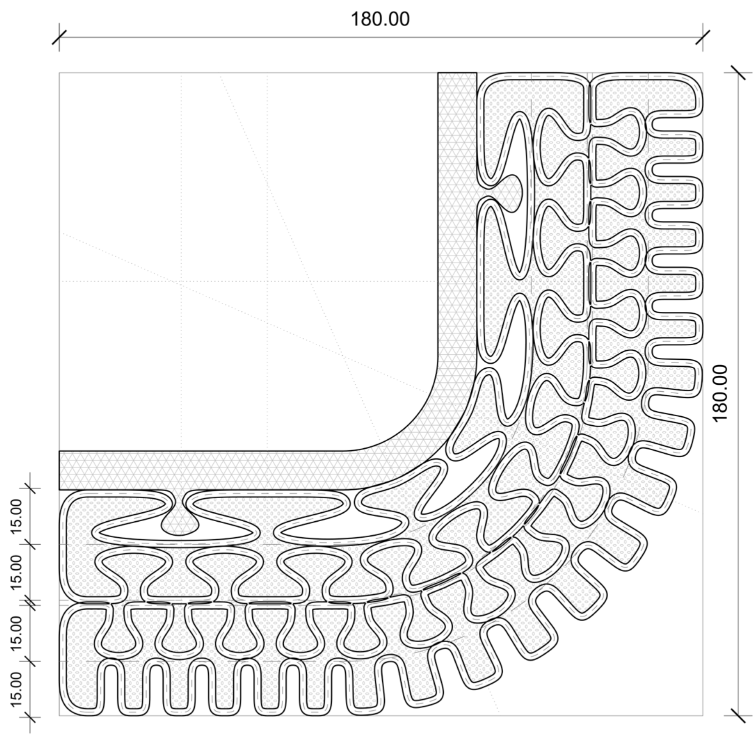


Figure 7.15: Final plan of optimized corner of window frame
Source: own

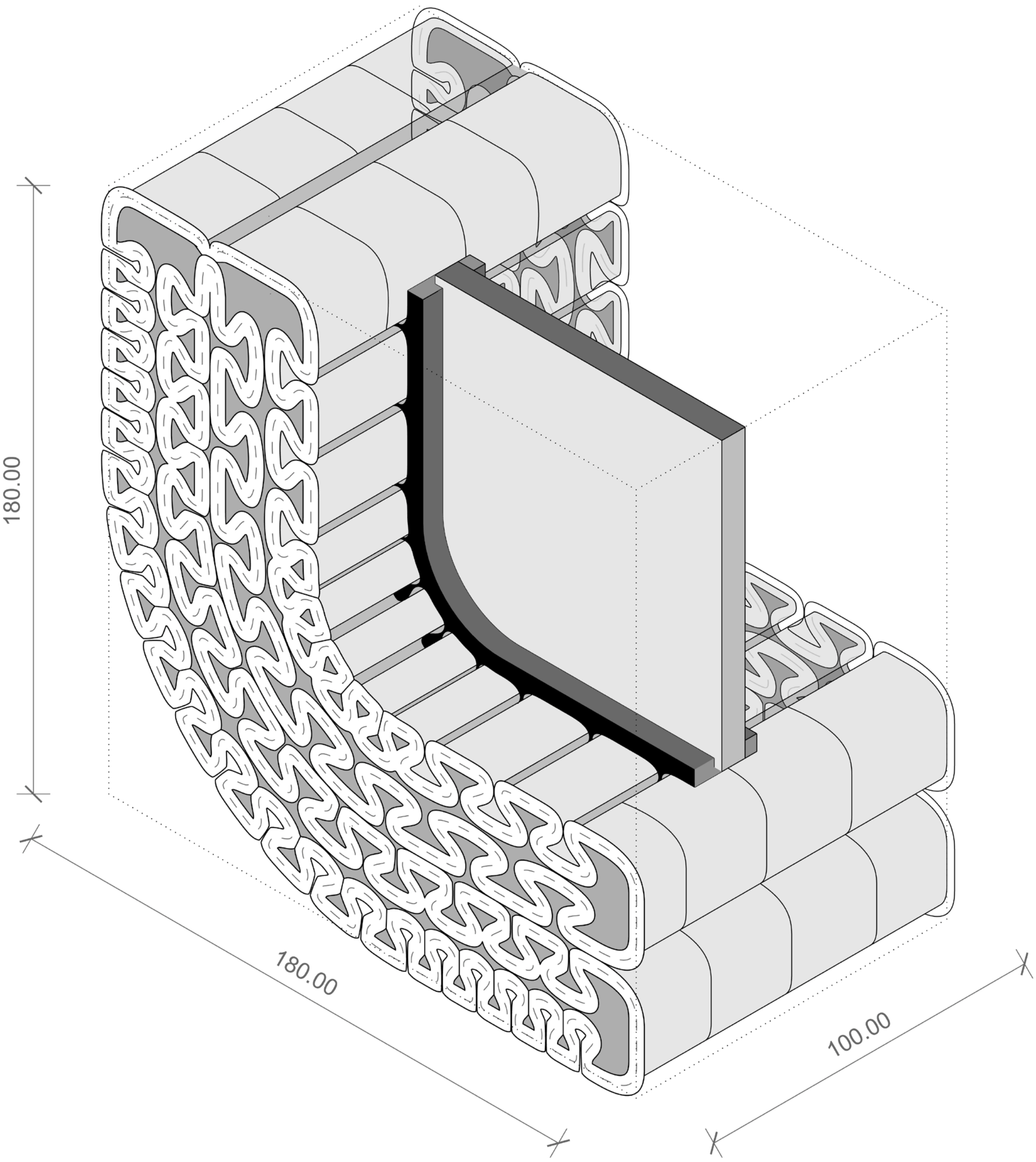


Figure 7.16: Final Axonometric view of optimized corner of window frame
Source: own

Figure 7.17 (left): Final Axonometric view of optimized corner of window frame
Figure 7.18 (top): Connection between 3D printed gasket and frame to showcase tolerances
Figure 7.19 (bottom): back of window to showcase the misalignements between parts
Source: own

07 | 4 Conclusions & Recommendations

Material Development

The current recipe mix 9 (Methylcellulose) is a promising foundation to 3D print with wood waste to either replace mundane elements in the current building industry or to offer 3D printed frames, allowing better connections between 3D printed houses and window frames. However, the current application of the discovered recipe can only be applied to design furniture, columns, or wind turbines (check FLAM). More research should be done based on the developed recipe to achieve higher structural performances and water resistance. Therefore, to enhance the material properties of the discovered recipe, exploring different binding agents in addition to lignin and cellulose such as nano cellulose, different additives such as bentonite, and larger fibers such as hemp or flux need further research to improve the discovered recipe.

Fabrication Development

The possibility to geometrical 3D print construction components such as a window frame is achievable. However, it is important to research on printing at higher inclinations and in different directions to enable a printing on-site setting. Also, more research can be elaborated on the drying speed of the components to avoid high levels of moisture content. Thus, printing bigger cavities, and on a mesh base that is elevated would allow air to flow homogeneously. Lastly, the drying time of the printed material is crucial to the total height of a print. Therefore, research in printing continuously at a faster rate should be improved by enhancing the material recipe to dry at a faster rate and shrinking no more than 1 to 5%.

07 | 5 Future Vision

Currently, mix 9 (Methylcellulose) is insufficient to enter the construction market because of its mechanical properties. However, its printability has shown that it is possible to 3D print a window frame to a certain degree. In the first case scenario, it could be used to replace parts of a wooden window frame (Figure 7.20). In the context of 3D printing one single printed window frame, two different scenarios occur, either to print on-site or in a factory. Printing in a factory would ease the printing phase as it is done in a controlled environment and would be simply plugged into the wall while or after the printing phase of the house (Figure 7.23). As it was previously discovered, printing multiple parts of a window frame to be staggered into one part would impact the overall quality of the frame. Thus, an integral printed part should be implemented. Also, 3D printing in a factory would allow better control over the shrinkage of the material, the geometrical complexity of the printed shapes, and to coat the frame. Nevertheless, the printed parts would be done on a flat surface and later flipped at a ninety-degree angle to be integrated into a wall (Figure 7.21-7.24). As the window frame would be oriented in a different direction, the cavities would face its surrounding environment, leading to thermal bridges. Thus, the cavities can be compensated by filling their cavities with additional material or 3D printed gaskets. However, the shape of the printed layers would not be air-tight between both elements.

Therefore, a second scenario is established with the logic of printing the frames on-site (Figure 7.25). As the frame can be printed on-site in parallel to a wall, it would allow more freedom to 3D printed habitats. If the current recipe is further elaborated into strengthening its printability capabilities, it may have the freedom to print higher and in different inclinations. In the best-case scenario, the wooden frame would act as a scaffolding to the wall while continuously and simultaneously printing with two different materials. The advantage to print on-site would allow a staggering between both materials allowing a perfect fit between components in a wet state (Figure 7.22-7.26). Therefore, further study should be implemented on the different printing directions of a 3D printed window frame as it may be affected by the total loads that it can take. Lastly, the cavities of the frame would be oriented in a z-direction, which would not allow any thermal bridging (Figure 2.27).

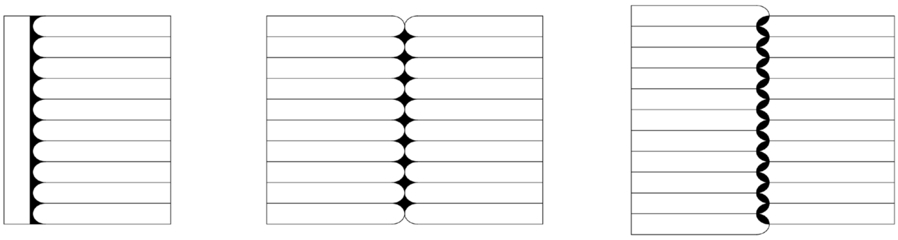


Figure 7.27: Diagram to describe the connection between flat and 3D printed elements to 3D printed elements when printed seperatly, and 3D printed elements when printed together
Source: own

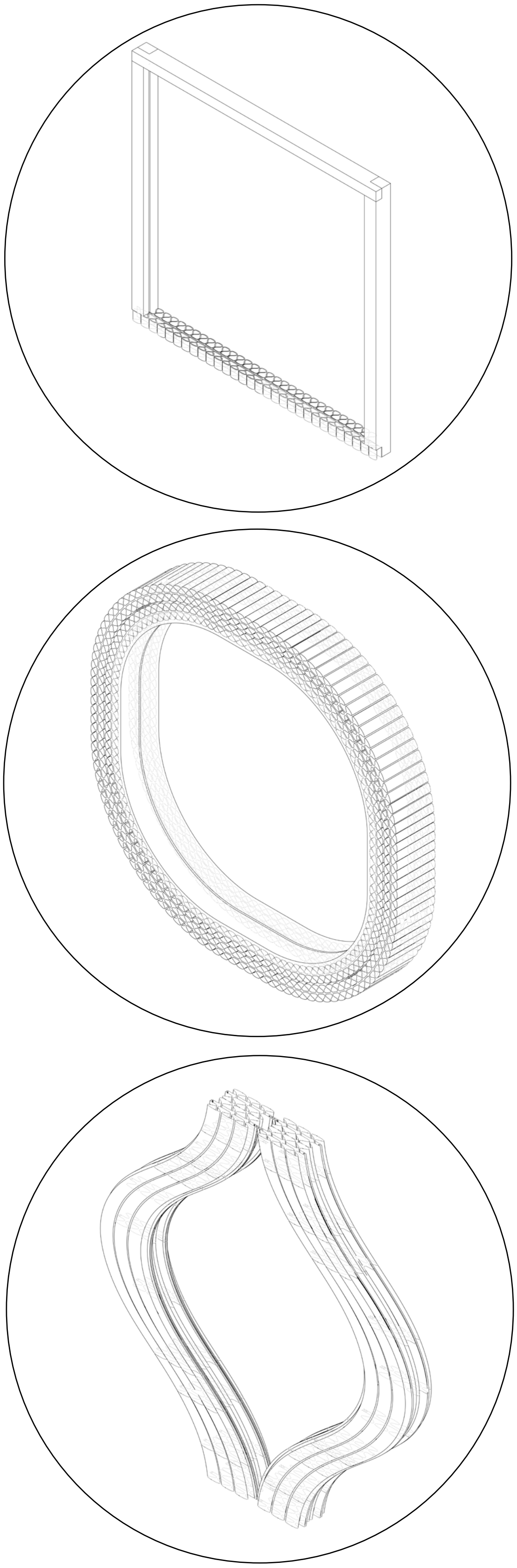
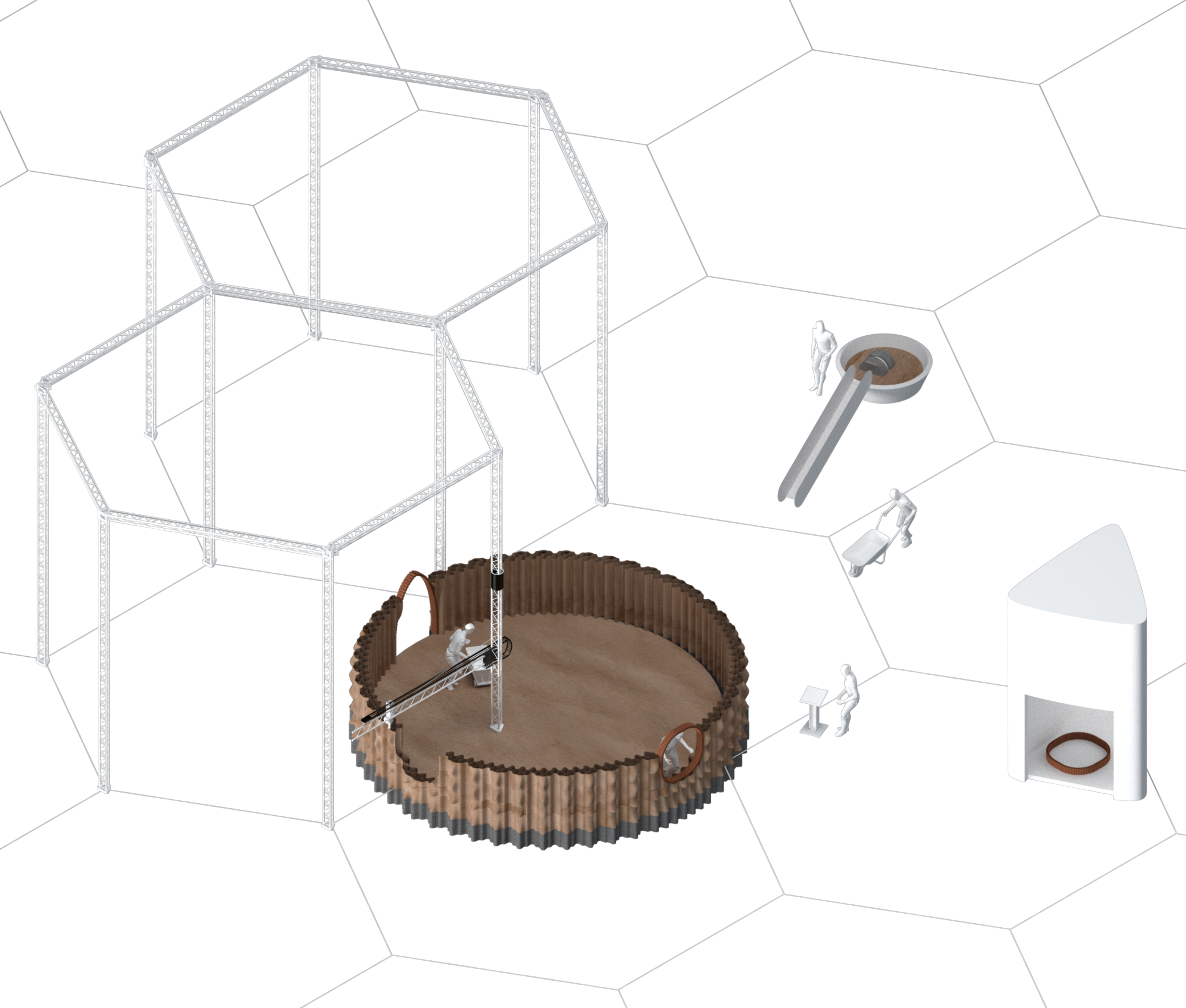


Figure 7.20: Replace part of existing window frame with 3D printed wood
Figure 7.21: 3D print window frame horizontally in factory
Figure 7.22: 3D print window frame vertically on site
Source: own



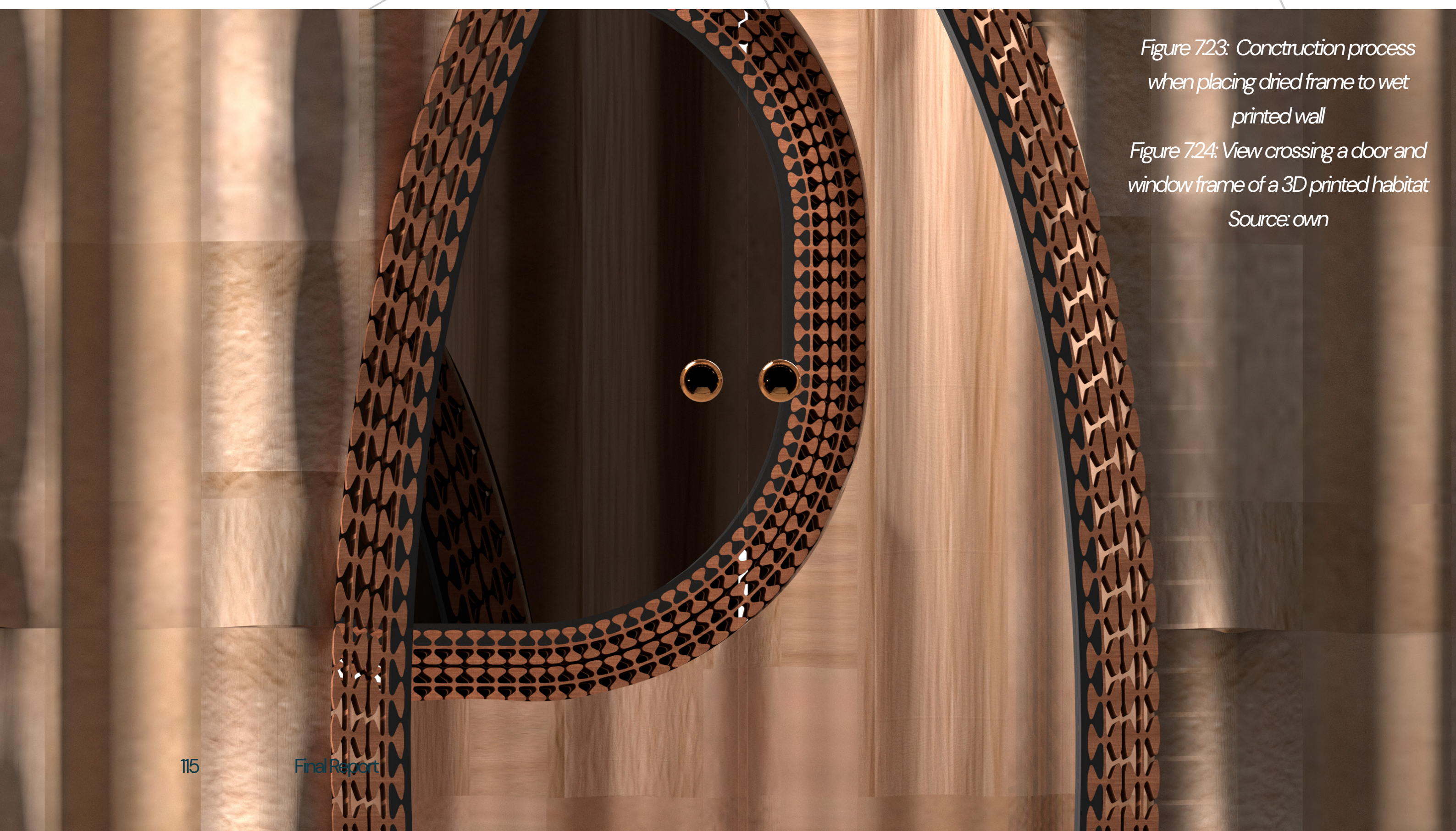


Figure 7.23: Conctruction process when placing dried frame to wet printed wall
Figure 7.24: View crossing a door and window frame of a 3D printed habitat
Source: own

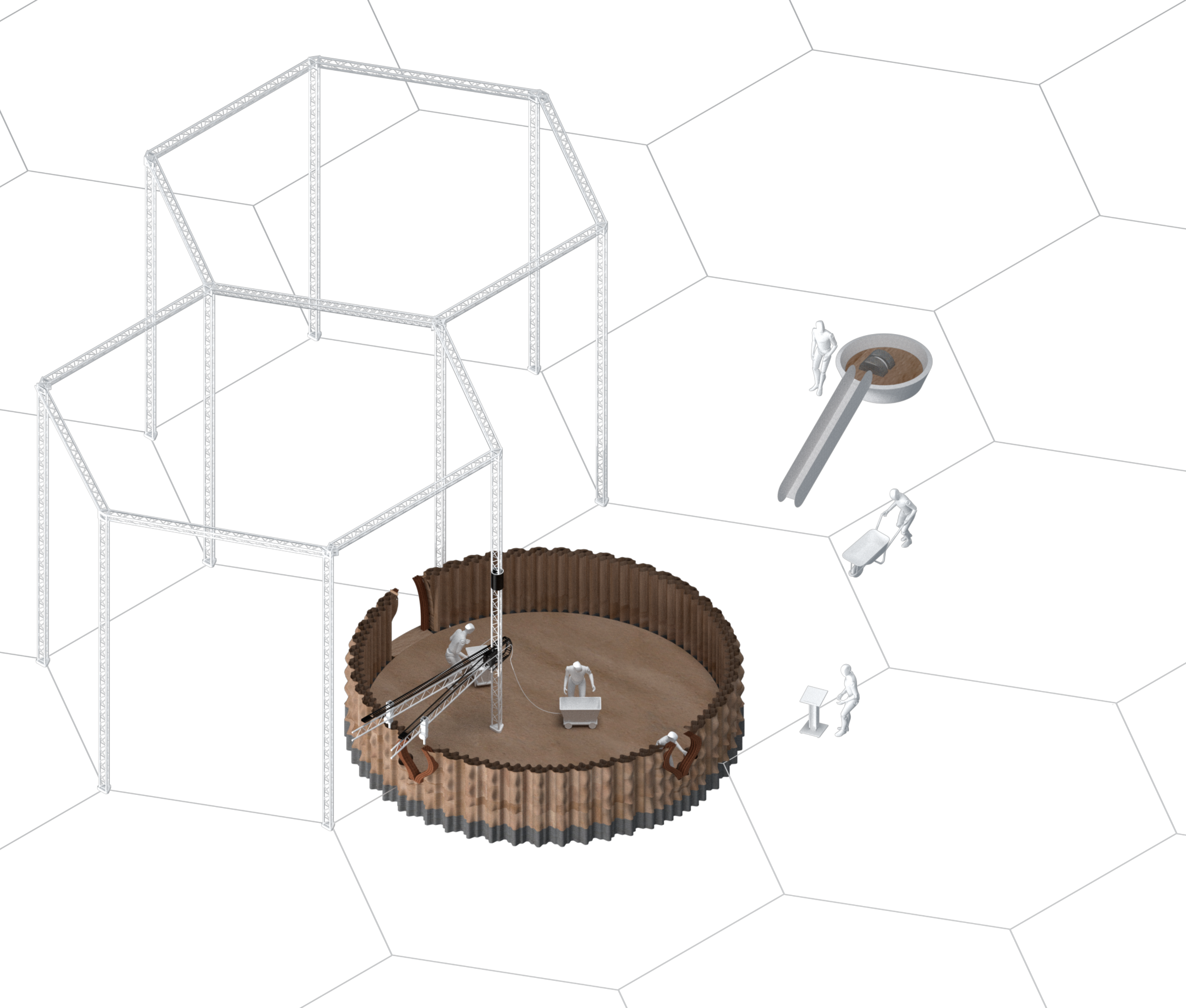


Figure 7.25: Conctruction process, printing wooden window frame and 3D printed clay wall simultaneously
Figure 7.26: View crossing a door and window frame of a 3D printed habitat
Source: own

08 OVERALL CONCLUSION

An additive manufacturing process in combination with wood waste has shown the interest and research of many universities and companies around the globe. From sawdust that is generated through the harvest of trees to the paper industry which extracts large amounts of lignin. All of these inert substances can be rethought, reimagined, and upcycled into innovative artifacts for a variety of professions. The target of this research paper was to understand if 3D printing with lignin can potentially become part of the construction industry. Upcycling wood waste into a functional component for the building industry is an excellent start towards sustainability and circularity. However, the creator must reevaluate his relationship with the built environment to fully work with nature. One way to re-establish the relationship with buildings is to maintain and preserve what is already constructed by using non-destructive techniques to replace mundane elements when necessary. Another is to use low-carbon construction techniques and natural materials which can be re-crushed and reused into a building material. Therefore, before offering a fully natural material that turns into a component for the construction industry, many steps and implementations were taken into account during this research. Wood has a variety of colors and qualities which will direct its use for different industries. Just in the construction industry, many tests such as fire resistance, moisture content, tensile, bending tests, etc. have to be validated to become part of the construction industry. Therefore, in the case of lignin, initial material experiments were conducted with my colleague Alexsander Coelho to find a recipe that can become a substance for use within an additive manufacturing process. Ten different recipes were further studied and four of them were promising. These four promising recipes were tested mechanically. At the moment, none of the recipes can enter the construction market. However, further research should be established involving 3D printing the specimens with additional fibers to strengthen the overall mix. Regarding the printability test, the acetone, DMSO, and wood glue mixture were not continued as they would either deteriorate the extruder or were not fully bio-based recipes. Therefore, mix 9 (Methylcellulose) was the final recipe to conduct the printability tests. A custom-built wiring system and tooling installation were designed and produced to establish an LDM 3D printing setup. After conducting a variety of printability tests such as geometrical shapes, overlapping, maximum height, maximum overhang, and infill density, the limitations of these tests guided the design of a printed window frame. Therefore, the corner of a window frame was designed and produced according to those known advantages and limitations. The final result showcases the possibility to produce and or replace window frames by the use of an additive manufacturing process or by enhancing a better connection between 3D printed houses and window frames.

09 REFLECTION

Graduation Process

Position of the graduation topic in the studio

This master thesis aimed to promote wood waste as an ecological contributor to the building industry through the use of additive manufacturing. Within the Building Technology track, the master thesis combines the discipline of design informatics and facade design. Both topics were selected for research and design on a sustainable and circular innovative facade component. In a time of environmental distress, the profession has the responsibility to act with new ideas and solutions to be handed to future generations. Therefore, my graduation topic integrated a 3D-printed custom-built window frame to marry the relationship between the graduation thesis, master 's track, and master 's program.

Looking back at the research methodology

The research strategy was based on "Research by design". Phase 1 was dedicated to the contextual background of my research topic based on literature papers and conducting multiple interviews with experts in the field of 3D printing with bio-based materials. Phase 2 was dedicated to the writing of the contextual background. Phase 3 was based on "practice" to experiment and evaluate different material recipes. Phase 4 was also based on "practice" to produce and prototype 3D printed components. Therefore, the "Research by design" approach was the correct methodology to follow as different mechanical tests and printed elements were successfully demonstrated. However, due to the limited time of a graduation thesis and many unexpected challenges that came along, phase 3 and phase 4 could have been implemented at an earlier stage of the thesis to ease the design process and scientific evaluation.

Research and design-related

After the state-of-the-art research manifested by Thomas Liebrand in 2018 by extruding pure lignin and cellulose with acetone, the aim of this research was based on changing the binding agent into a bio-based one. Therefore, the initial research was based on literature reviews and interviews to test different natural binding agents with cellulose and lignin. Once the exploratory phase of the findings was conclusive, the design of a final product was only achievable by understanding the limitations and advantages of 3D printing them. Therefore, a series of printing tests were conducted to further guide the final shape of a 3D printed window frame.

Dilemma during the process & how it was dealt with

As the initial phase of the graduation topic relates to the explorations of bio-based recipes, a regular collaboration between the faculty of civil engineering & geosciences with the faculty of architecture and the built environment should be implemented. It would ease the fabrication and testing of the explored recipes to collect additional information to further produce a product that could potentially enter the building industry. Fortunately, thanks to our mentors and Prof.dr.ir. P.C. Christian Louter, we were able to find a collaboration between both faculties to further test the final recipes. Lastly, it was hard to foresee the time it would take to install and equip the 3D printers. With the help of Serdar Asut, Paul de Ruiter, and full access to the LAMA lab, the process to purchase the necessary tools and installing the equipment was achievable between P3 and P4.

Societal Impact

Applicability of results

Thanks to the collaboration made with Alexsander Alberts Coelho who chose the same research topic, two types of results were achievable. After exploring a material research phase together, Alexsander Alberts Coelho conducted the mechanical testing of our findings with the focus to design a structural node and I conducted the printability of our findings to design a window frame. Given the current results of the mechanical properties and printability of our final recipe, it is possible to 3D print building components in a cold extrusion process (liquid deposit modeling) with lignin and cellulose in combination with water and methylcellulose.

Further improvements

More research is necessary to improve the printing workflow and material properties of the recipe to become a fully integrated facade component. The final recipe and fabrication process need further study in regard to the printing process and scientific testing to improve the reliability of our recipe and offer a larger range of geometrical freedom. Thus, scaling up the process and improving the material's viscosity, shrinkage, and reduction of its water content should be further studied. Lastly, the structural properties of the final recipe should be improved by adding different lengths and types of fibers while 3D printing.

Sustainability & Social Relevance

The possibility of 3D printing with a wholly bio-based material coming from waste is a great accomplishment. Also, the final paste could potentially become circular if crushed into a powder that can be reprinted. By implementing a fully sustainable and possibly circular recipe with the implementation of sustainable technology, the impact of such harmless and natural innovation will reduce the construction industry 's carbon footprint and lead to a healthier environment. I am a true believer that the use of robotic manufacturing processes in combination with bio-based and waste materials will lead to a fully sustainable, circular, and the unique built environment.

Professional Relevance

3D printing window frames can be utilized in different areas of the construction industry such as in the heritage field by replacing or enhancing existing window frames. It can also be beneficial to large-scale 3D printing companies. During my interview with Marijn Bruurs, Witteveen+Bos, he has elaborated his interest in my graduation topic. Marijn Bruurs described that the interface between window frames and 3D printed concrete buildings is still traditional. Therefore, the freedom to 3D print complex elements such as window frames can be utilized to enhance the uniqueness of custom habitats.
Also, the connection between window frames and 3D printed habitats leaves room for improvement, as they are not completely flush with each other. As both materials utilize a different manufacturing process, a perfect fit could only be established by 3D printing a window frame as well as the surrounding structure.

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11 | APPENDIX

Linseed Oil Coating

		Weight (g)				Water Absorption			Water Retention (after 1h)			Water Retention (after 3h)		
		Initial	After 24h	After 1h	After 3h	Quantity (g)	Weight Ratio	Average	Quantity (g)	Weight Ratio	Average	Quantity (g)	Weight Ratio	Average
Methylcellulose	C1.7	2,43	4,42	4,05	3,24	1,99	81,89%	70,89%	1,62	66,67%	58,64%	0,81	33,33%	30,52%
	C1.8	3,14	5,20	4,86	4,07	2,06	65,61%		1,72	54,78%		0,93	29,62%	
	C1.9	2,90	4,79	4,48	3,73	1,89	65,17%		1,58	54,48%		0,83	28,62%	
Wood Glue	C2.7	5,39	5,81	5,69	5,60	0,42	7,79%	8,27%	0,30	5,57%	5,73%	0,21	3,90%	3,91%
	C2.8	5,69	6,21	6,05	5,94	0,52	9,14%		0,36	6,33%		0,25	4,39%	
	C2.9	6,97	7,52	7,34	7,21	0,55	7,89%		0,37	5,31%		0,24	3,44%	
Acetone	C3.7	3,40	4,19	3,92	3,53	0,79	23,24%	20,74%	0,52	15,29%	14,57%	0,13	3,82%	3,48%
	C3.8	4,60	5,69	5,40	4,81	1,09	23,70%		0,80	17,39%		0,21	4,57%	
	C3.9	5,89	6,79	6,54	6,01	0,90	15,28%		0,65	11,04%		0,12	2,04%	
DMSO	C4.7	5,12	6,63	6,38	5,79	1,51	29,49%	30,80%	1,26	24,61%	26,06%	0,67	13,09%	14,85%
	C4.8	5,21	6,90	6,67	6,20	1,69	32,44%		1,46	28,02%		0,99	19,00%	
	C4.9	4,89	6,38	6,14	5,50	1,49	30,47%		1,25	25,56%		0,61	12,47%	

Bee Wax Coating

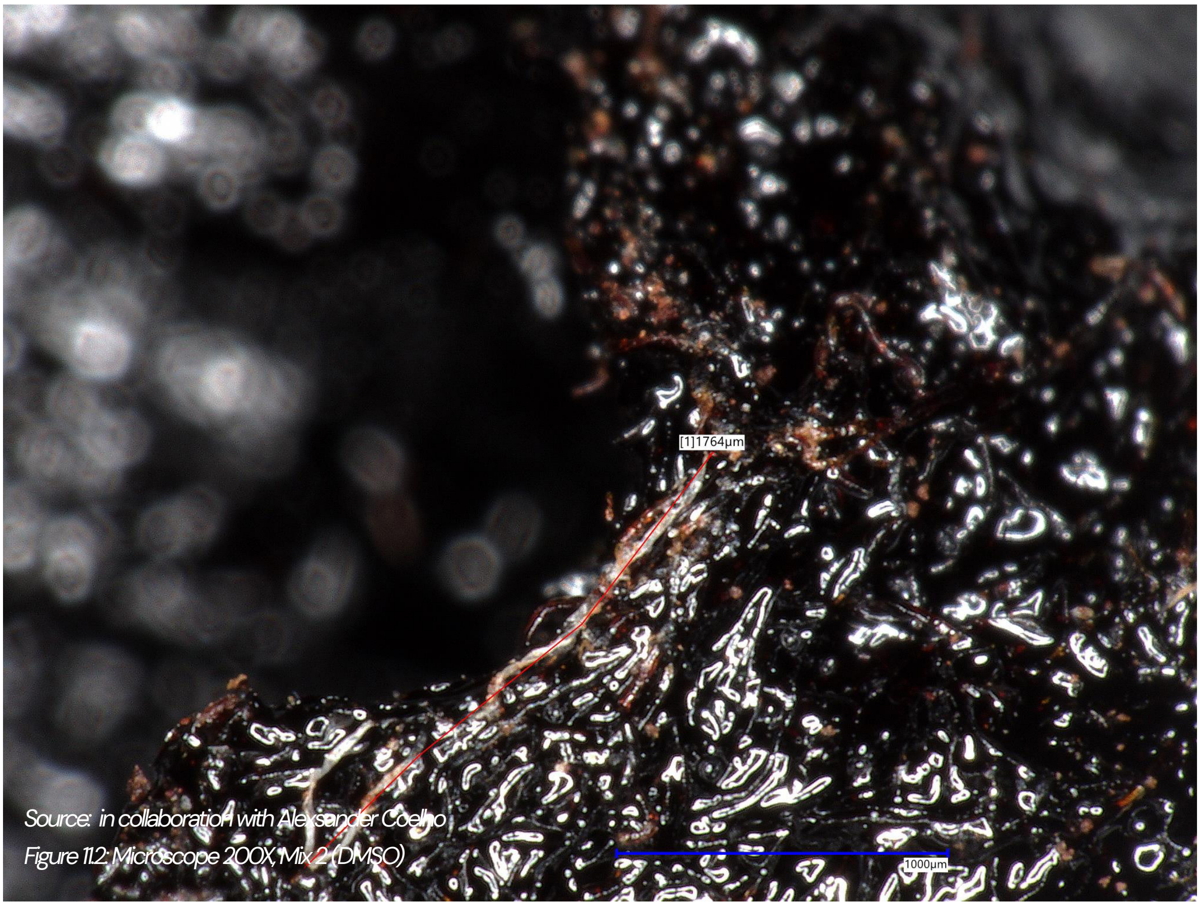
		Weight (g)				Water Absorption			Water Retention (after 1h)			Water Retention (after 3h)		
		Initial	After 24h	After 1h	After 3h	Quantity (g)	Weight Ratio	Average	Quantity (g)	Weight Ratio	Average	Quantity (g)	Weight Ratio	Average
Methylcellulose	C1.4	4,69	7,89	7,68	7,01	3,20	68,23%	69,61%	2,99	63,75%	64,40%	2,32	49,47%	46,75%
	C1.5	3,00	5,05	4,89	4,34	2,05	68,33%		1,89	63,00%		1,34	44,67%	
	C1.6	3,10	5,34	5,16	4,53	2,24	72,26%		2,06	66,45%		1,43	46,13%	
Wood Glue	C2.4	7,14	7,47	7,31	7,25	0,33	4,62%	3,60%	0,17	2,38%	1,41%	0,11	1,54%	0,98%
	C2.5	6,53	6,71	6,59	6,57	0,18	2,76%		0,06	0,92%		0,04	0,61%	
	C2.6	7,59	7,85	7,66	7,65	0,26	3,43%		0,07	0,92%		0,06	0,79%	
Acetone	C3.4	6,28	7,61	7,38	6,68	1,33	21,18%	20,35%	1,10	17,52%	17,52%	0,40	6,37%	7,13%
	C3.5	5,55	6,66	6,55	6,02	1,11	20,00%		1,00	18,02%		0,47	8,47%	
	C3.6	5,64	6,76	6,60	6,01	1,12	19,86%		0,96	17,02%		0,37	6,56%	
DMSO	C4.4	6,99	7,82	7,60	7,47	0,83	11,87%	10,44%	0,61	8,73%	7,83%	0,48	6,87%	6,15%
	C4.5	7,34	8,22	8,01	7,86	0,88	11,99%		0,67	9,13%		0,52	7,08%	
	C4.6	7,10	7,63	7,50	7,42	0,53	7,46%		0,40	5,63%		0,32	4,51%	

No Coating - Pure Material

		Weight (g)				Water Absorption			Water Retention (after 1h)			Water Retention (after 3h)		
		Initial	After 24h	After 1h	After 3h	Quantity (g)	Weight Ratio	Average	Quantity (g)	Weight Ratio	Average	Quantity (g)	Weight Ratio	Average
Methylcellulose	C1.1	2,00	4,90	4,40	3,22	2,90	145,00%	134,91%	2,40	120,00%	114,22%	1,22	61,00%	58,79%
	C1.2	2,41	5,45	4,99	3,87	3,04	126,14%		2,58	107,05%		1,46	60,58%	
	C1.3	2,50	5,84	5,39	3,87	3,34	133,60%		2,89	115,60%		1,37	54,80%	
Wood Glue	C2.1	6,50	7,15	6,96	6,81	0,65	10,00%	10,35%	0,46	7,08%	7,33%	0,31	4,77%	4,82%
	C2.2	5,78	6,37	6,21	6,06	0,59	10,21%		0,43	7,44%		0,28	4,84%	
	C2.3	5,35	5,93	5,75	5,61	0,58	10,84%		0,40	7,48%		0,26	4,86%	
Acetone	C3.1	3,46	4,34	4,13	3,48	0,88	25,43%	24,62%	0,67	19,36%	19,31%	0,02	0,58%	2,16%
	C3.2	5,38	6,66	6,39	5,55	1,28	23,79%		1,01	18,77%		0,17	3,16%	
	C3.3	6,21	7,74	7,44	6,38	1,53	24,64%		1,23	19,81%		0,17	2,74%	
DMSO	C4.1	4,37	5,54	5,34	4,43	1,17	26,77%	28,23%	0,97	22,20%	23,82%	0,06	1,37%	7,12%
	C4.2	6,58	8,55	8,26	7,36	1,97	29,94%		1,68	25,53%		0,78	11,85%	
	C4.3	5,90	7,55	7,30	6,38	1,65	27,97%		1,40	23,73%		0,48	8,14%	

Figure 11.0: Spreadsheet comparing water absorption and retention percentage of mix 1, mix 2, mix 8, mix 9
Source: own in collaboration with Alexsander Coelho

Source: own in collaboration with Alexsander Coelho
Figure 11.1: Microscope 200X, Mix 1 (Acetone)



Source: in collaboration with Alexsander Coelho
Figure 11.2: Microscope 200X, Mix 2 (DMSO)

Source: own in collaboration with Alexsander Coelho
Figure 11.3: Microscope, 200X, Mix 9 (MC)

Source: in collaboration with Alexsander Coelho
Figure 11.4: Microscope, 200X, Mix 8 (WG)

Acetone Mix					
	Specimens				
	B2.1	B2.2	B2.3	B2.4	B2.5
F Failure Load [N]	61,87	37,16	61,37	38,48	30,04
σ_{FS} Flexural Strength [Mpa]	9,37	6,86	9,74	5,70	4,77
E Flexural Modulus [Gpa]	0,15	0,22	0,20	0,37	0,33

Acetone Mix					
	Specimens				
	A2.1	A2.2	A2.3	A2.4	A2.5
σ_{UTS} Ultimate Tensile Strength [Mpa]	1,76	1,26	1,70	1,09	0,98
σ_{YS} Yield Strength [Mpa]	1,09	1,25	1,51	0,81	0,97
E Modulus of Elasticity [Gpa]	0,28	0,11	0,20	0,13	0,13

Wood Glue Mix					
	Specimens				
	B3.1	B3.2	B3.3	B3.4	B3.5
F Failure Load [N]	122,78	143,36	173,33	166,05	158,29
σ_{FS} Flexural Strength [Mpa]	20,67	23,89	28,89	27,28	27,06
E Flexural Modulus [Gpa]	0,67	0,64	0,79	0,90	0,79

Wood Glue Mix					
	Specimens				
	A3.1	A3.2	A3.3	A3.4	A3.5
σ_{UTS} Ultimate Tensile Strength [Mpa]	6,99	6,69	7,66	7,04	6,66
σ_{YS} Yield Strength [Mpa]	4,81	3,58	4,26	3,58	3,74
E Modulus of Elasticity [Gpa]	0,30	0,58	0,41	0,64	0,77

Methylcellulose Mix					
	Specimens				
	B1.1	B1.2	B1.3	B1.4	B1.5
F Failure Load [N]	30,37	27,99	22,91	28,26	28,57
σ_{FS} Flexural Strength [Mpa]	9,41	10,00	8,59	10,60	10,85
E Flexural Modulus [Gpa]	0,90	0,67	0,82	1,02	1,05

Methylcellulose Mix								
	Specimens							
	A1.1	A1.2	A1.3	A1.4	A1.5	A1.6	MC.01	MC.02
σ_{UTS} ltimate Tensile Strength [Mpa]	3,60	2,94	4,29	4,07	0,00	0,00	3,37	3,74
σ_{YS} Yield Strength [Mpa]	3,51	2,89	3,79	4,06	0,00	0,00	3,21	3,63
E Modulus of Elasticity [Gpa]	0,37	0,25	0,56	0,45	0,00	0,00	0,33	0,52

Methylcellulose Mix - EXTRUDED SPECIMENS					
	Specimens				
	A5.1	A5.2	A5.3	A5.4	A5.5
σ_{UTS} Ultimate Tensile Strength [Mpa]	3,14	3,45	3,23	2,43	2,64
σ_{YS} Yield Strength [Mpa]	2,58	3,10	2,98	2,38	2,51
E Modulus of Elasticity [Gpa]	0,42	0,46	0,52	0,44	0,40

Figure 11.5: Spreadsheet comparing mechanical properties of mix 1, mix 8, mix 9 in terms of their tensile strength, yield strenght, modulus of elasticity, and flexural modulus, flexural strength
Source: done by Alexsander Coelho