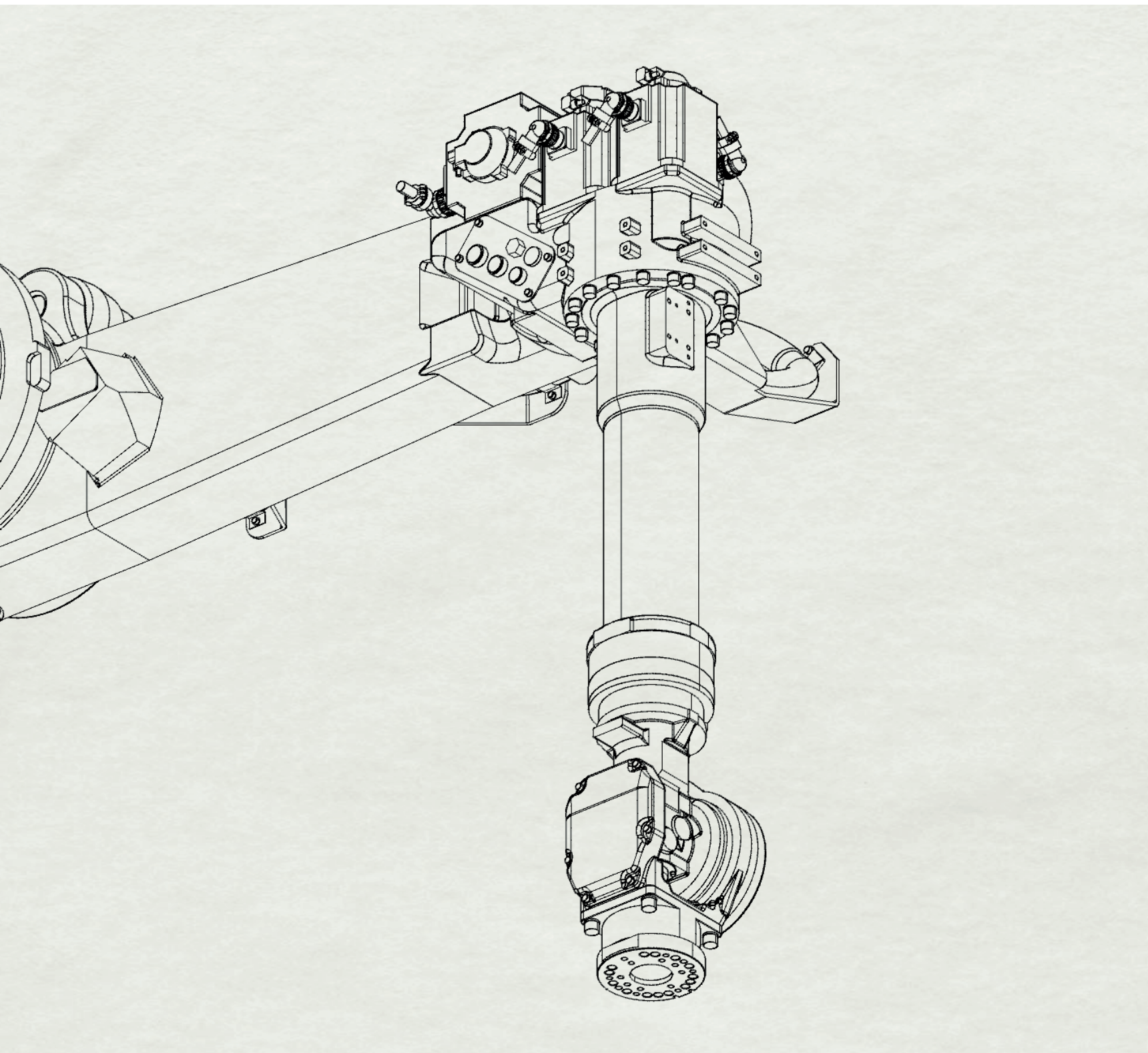


EXPLORING THE POSSIBILITIES OF LARGE-SCALE ADDITIVE MANUFACTURING WITH WOOD-PLASTIC COMPOSITES



MASTER THESIS BY LORENZO HOORN
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**EXPLORING THE POSSIBILITIES OF
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WITH WOOD-PLASTIC COMPOSITES**

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JULI, 2021

GLOSSARY

LSAM	Large scale additive manufacturing
BAAM	Big area additive manufacturing
WPC	Wood plastic composite
NFC	Natural fibre composite
WFPP	Wood fibre reinforced polypropylene
CFPP	Cellulose fibre reinforced polypropylene
GFPP	Glass fibre reinforced polypropylene
wt%	weight percentage
PCW	Post consumer waste
PIW	Post industrial waste
MDD	Material driven design
LCA	Life cycle assesment
GWP	Global warming potential

PREFACE

Dear reader,

This document you are about to read is my thesis project for the Masters Integrated Product Design. It contains the work of six months exploring 3D printing with wood plastic composites at the company 10XL. Although the pandemic was a challenging time to do a graduation project, I am very happy with the result of my work. Of course, you can never achieve great work alone and therefore I would like to thank the following people.

First, I would like to thank Gerbert Smits, Joep Grapperhaus and the rest of team 10XL for the opportunity of using their resources and helping me with my project. They gave me the trust of working on their research project and bringing it to the next stage. They provided a very open working environment for me to explore my interest and curiosity.

Secondly, I would like to thank my outstanding supervisory team for guiding me towards the end. Jeremy Faludi, for helping me with his expertise on sustainability and the support when creating the life cycle assessment. And Tessa Essers, for assisting me through the material exploration and writing this thesis. It was a pleasure working with them and I hope to have the chance to collaborate with them once again.

Furthermore, I would also like to thank two peer students. Prateek Jain, who is a material engineer from TU Delft, who developed the first wood compounds and helped me with technical questions about the material. And Justè Motuzaité, who is also an IPD student and collaborated with me on the life cycle assessment.

This project was a great experience and I hope the result is inspiring.

Enjoy!

Lorenzo

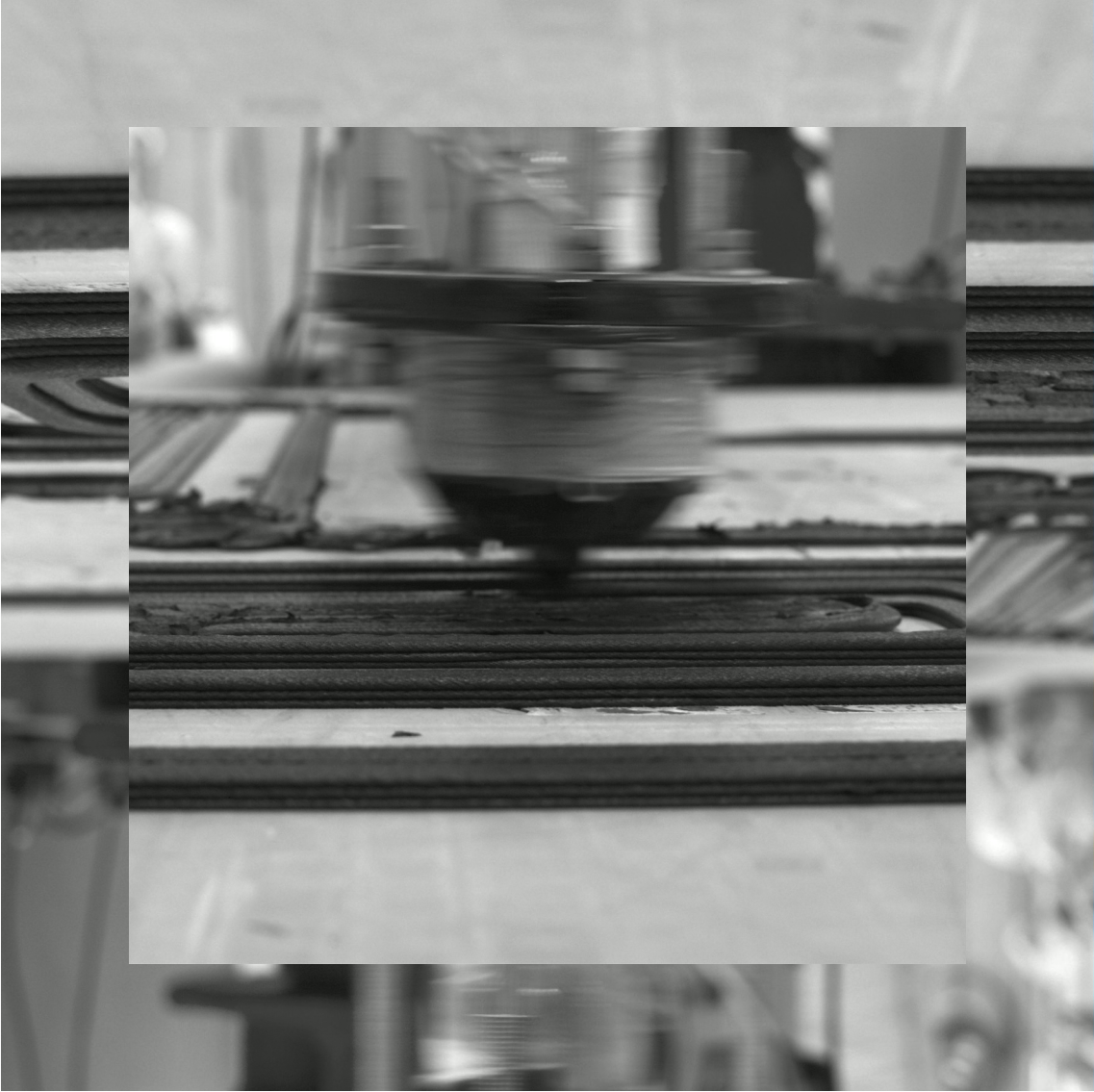


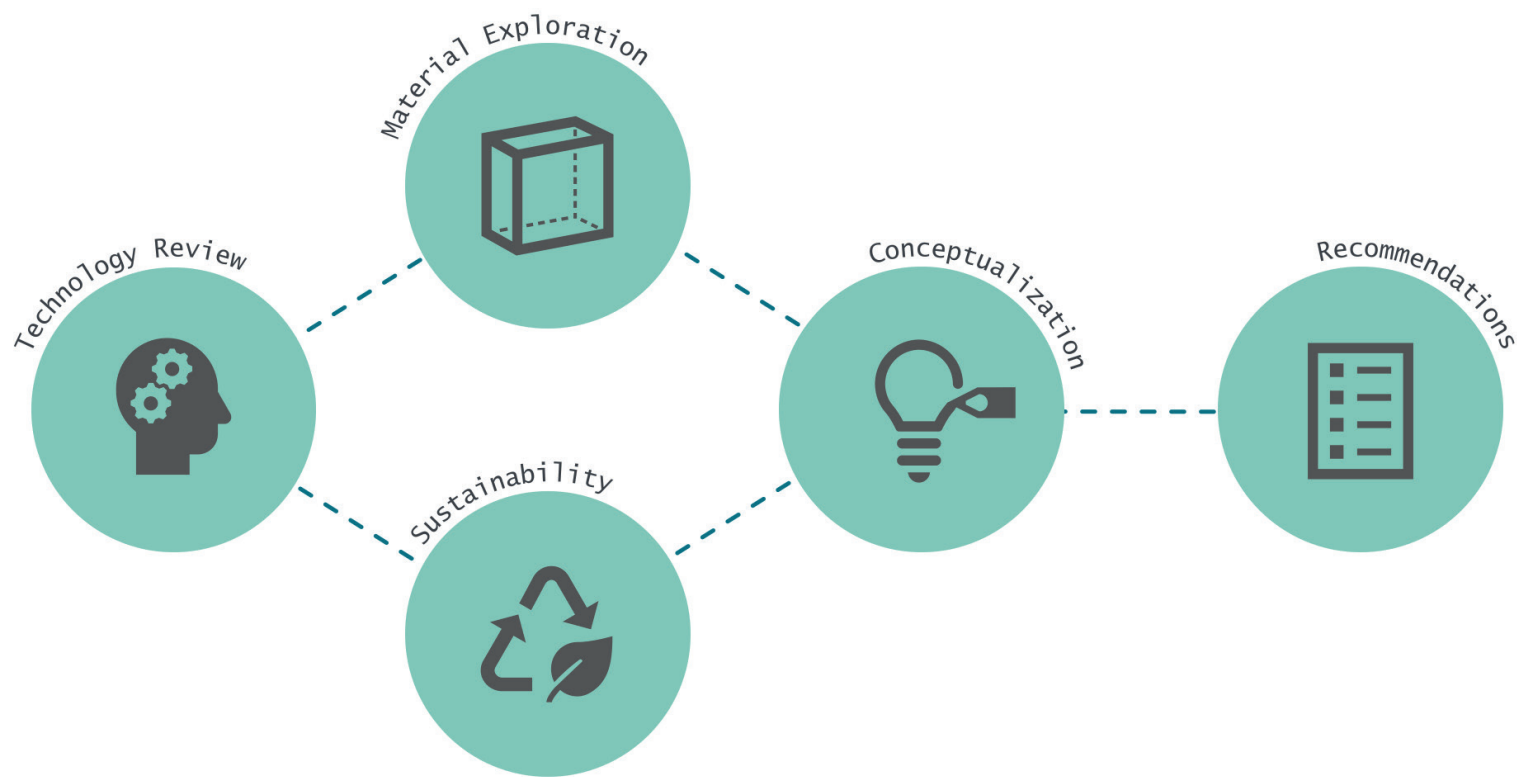
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INTRODUCTION

In the pursuit to a circular materials economy, turning waste into products is an important step in closing the material cycle. Currently, in the field of design and manufacturing, circularity is one of the most important focus areas. The ambition is to create products that are made of non-virgin materials and can be reused or recycled at their end-of-life. This way of creating products will help to decrease the resource depletion, waste generation and emissions from raw material produciton. To get to this circular material economy, it is important to improve the material technology and design in a better way (Ashby, 2016).



▲ **Figure 1: Report overview/**
Structure of the different
chapters.

When talking about waste material, it can often be separated into two categories: post-consumer waste (PCW) and post-industrial waste (PIW). Where PCW is in need of separation and cleaning processes, PIW is easier to work with since it is a clean stream of material. If collected properly, it can directly cycle back into new products. The focus of this thesis is to use waste of the wood processing industries. The interest of this research is in the application of this waste stream as a fibre reinforcement in wood-plastic composites (WPC) and the ability to use this compound for large scale additive manufacturing (LSAM). This study is conducted in assignment of the company 10XL, which is a design and manufacturing business, creating products made of fibre reinforced waste plastics. Furthermore, they are also developing circular materials for large scale 3D printing, including WPC. Their research and development of this wood fibre reinforced thermoplastic is the starting point of this Master thesis. 10XL successfully managed to compound their own sample batches, which will be used for exploring the possibilities of 3D printing with a WPC. The goal is to use the 60% wood-based materials and define the sustainable advantages over alternative fibres.

For desktop printers, WPC filament with 20%-30% wood fibre is already implemented in a wide range. However, what is novel to this research, is the combination of scaling up the printing process and using high percentages of wood material (60%-70%). To research the potential of using this bio composite in large scale 3D printing design and manufacturing, together with the company the following criteria were defined:

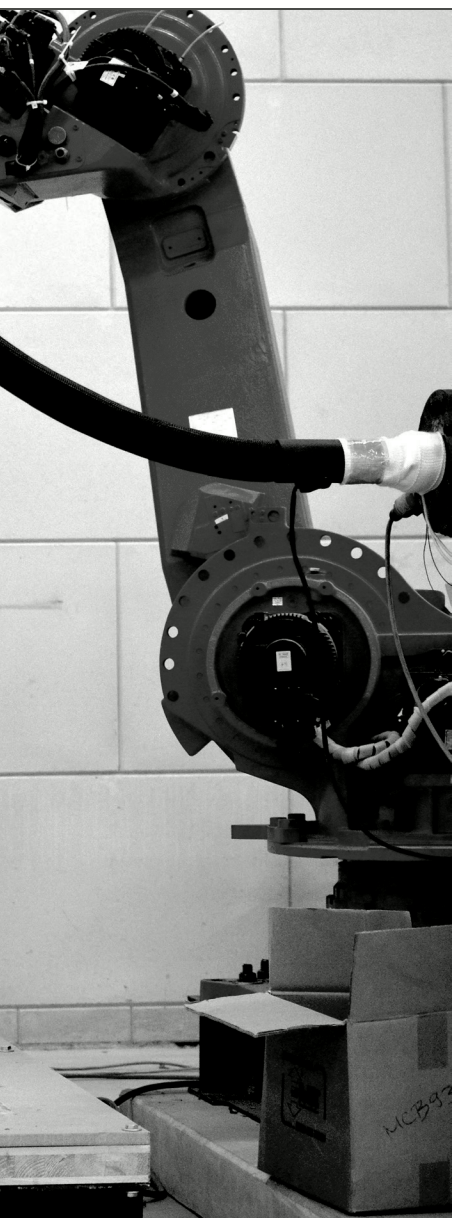
1. Obtaining a wood look/feeling from the printed material
2. Sufficient mechanical properties needed for 3D printing
3. Possess meaningful applications
4. Low environmental impact compared to other plastic composites
5. Circularity and end-of-life potential

Testing these criteria is done with the guidance of two different methods/tools. For point 1-3, the material driven design (MDD) method was used and for point 4-5 a life cycle analysis (LCA) was performed. These two processes run parallel to each other during the project and are combined in the end to define the concept direction. The thesis is structured based on these two methods (see figure 1). In the chapter 'Technology review', some essential pre-knowledge about LSAM and WPC is explained. After this brief introduction to the technology, the 'Material Exploration' chapter will include the MDD research. The LCA study is explained in the 'Sustainability' chapter. The conclusions of these two methods and the reflection on the criteria are discussed in the chapter 'Conceptualization', which functions as a concluding chapter that will bring all the results together. It will also explain the process of designing a final concept that will be prototyped. This prototype will be a physical representation of the research outcome and a showcase for the potential. It will be an addition to all the findings and the 'Final recommendations'.



TECHNOLOGY REVIEW

This chapter will explain the essential knowledge needed for this research. It starts off with an introduction to the process of large scale 3D printing. The paragraphs 'design', 'print engineering' and '3D printing' will illustrate the steps and essential knowledge needed for this manufacturing process. In the next section, the existing knowledge about WPC will be reviewed. It will define the material and the different compounds that will be used in this research. Finally, the last section will be about the state-of-the-art of product design with WPC.



02.1/ LARGE SCALE ADDITIVE MANUFACTURING (LSAM)

3D printing with large industrial robots, also known as BAAM/LSAM (short for 'big area' or 'large scale additive manufacturing'), is a form of fused granulate printing, where a continuous extrudate of molten plastic is extruded in a layer-on-layer manner, producing a 3D shape. 3D printing in general is a prototyping and production method that is vastly growing in the field of industrial product development. Advantages of this method are the versatility in forms that can be produced with one machine, rapid design-to-production cycles, the iterative process and a minimum stream of production waste. All these

factors combined contribute to a fast and flexible product development process, which consists of the phases design, engineering and production.

DESIGN

The process of LSAM starts with the development of a 3D computer aided design (CAD) model. There are some important design rules, as described by Cuevas & Pugliese (2020), to make sure the modelled shape can be printed. First off, it needs to be 'watertight', meaning that there can be no openings or holes (often referred to as naked edges) in the model. This could otherwise form an issue later on in the slicing process. Secondly, not every shape can be printed (yet). While technology is evolving, it is best to keep in mind that surfaces with an overhang over the ground plane smaller than 45° cannot be printed. Support structures can not be printed with these printers. Because of the continuous flow, the material can not be retracted. Therefore, the printer can not travel without extruding any material. Compared to other (desktop) 3D printers, printing openings and structures is extremely challenging. Furthermore, because of the larger nozzle diameters used, very small details will also be muted or even invisible due to the bigger printing lines and faster speeds.

PRINT ENGINEERING

When the design is ready, it can be engineered for printing. This step consists of adapting, exporting and slicing the CAD model to create the best printing path for a successful print. Exporting the final model is done by saving it as a .STL file, so it can be used by different slicing software. Slicing the model is literally cutting up the object in thin sheets. These represent the layers of the print, which are used to extract the coordinates in a 3D space. The text file of all these ordered points and other commands for the machine is called a G-Code. There are different kinds of software out there that can do the slicing, like Cura or Simplify3D. These programs will help to set the desired printing settings like print speed (feedrate 'F') and layer height and make the CAD model readable for the robot. Getting more advanced, it is also possible to use algorithm aided design tools like

- ◀ **.STL/** A file type representing a N.U.R.B.S. or Mesh surface from the CAD model in triangular connected tiles
- ▲ **N.U.R.B.S./** Mathematical representation of a 3D object with very high precision.
- ▲ **Mesh/** A representation of a surface based on edges and points creating small faces.

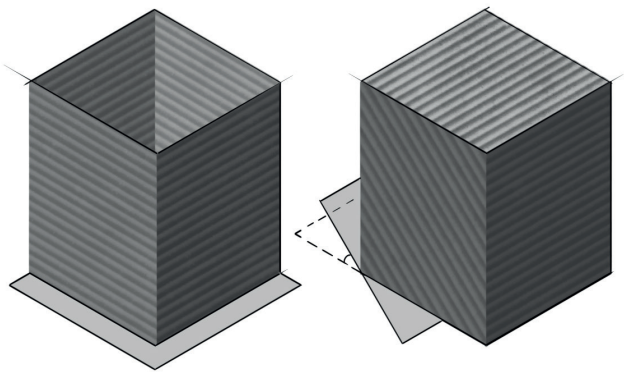


Figure 2: Printing Direction/
Printing in a horizontal or in a
45° angled plane.

Grasshopper to get more control over the printing paths. This way it is possible to extract G-code directly from the CAD modelling environment. No additional slicing software is needed and the printing path can be extracted directly from the modelling software. Additionally, every G-Code file needs to be translated for the robot in post-process software. Dependent on the robot that is used, it needs its own kind of language to move accordingly.

Printing in flat layers is called planar printing, which is done in the slicing software. The direction of the layers can be either in the horizontal or in a 45° angled plane (see figure 2). Horizontal plane printing will create an open shape by only printing the side surfaces of the model without a top or bottom. When printing in a 45° angle, it is possible to produce completely enclosed objects, just like the object was shown in the computer model. When the building plate is even mounted on a track, the print can become much longer.

The layer height setting for the print is dependant on the nozzle diameter that is used. Small nozzles with a thin layer height will result in more detail, especially if the feedrate is lower. Large nozzles and thicker layers will give a more robust print with rounder corners. Higher feedrates will also give rounder edges and less detail to the print.

The extrusion settings are controlled manually on the extruder, accordingly to the speed of the layer. If layer length differs a lot in the print, a ratio needs to be set to the feedrate, to make sure there is less under- or overextrusion.

PRINTING

The critical element that will make 3D printing a success is the material behaviour. The temperature profile and the extrusion rate on the machines need to be tweaked according to the material that is used. Printing consisting layers strongly depends on the viscosity, crystallisation, layer adhesion, extrusion behaviour, and shrinkage of the material (leading to warping). If one or more of these properties is not good enough, it is destined to end up with a failed print.

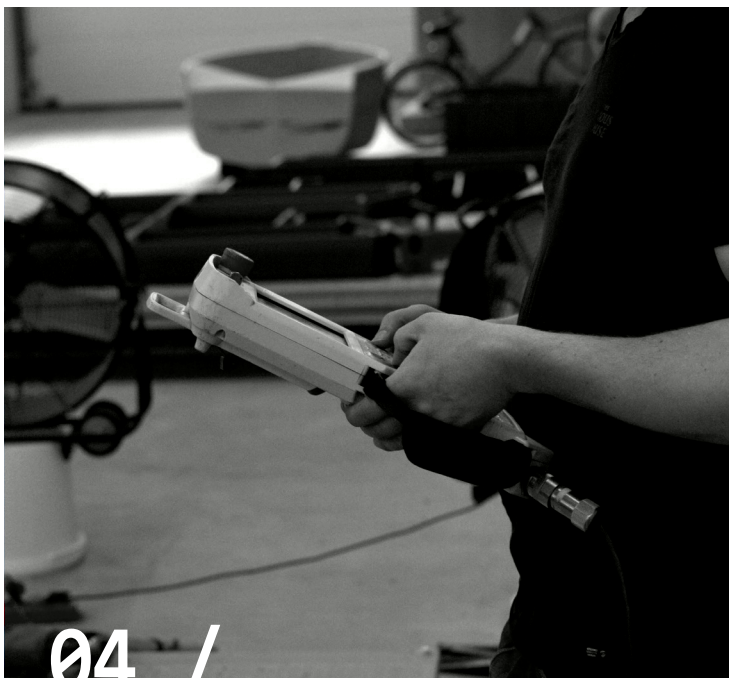
The standard material for LSAM is fibre reinforced thermoplastic. The material is heated just above the glass transition temperature to get to a fluid state, so it can be extruded and joined in a layer-by-layer production process. Each layer crystallizes to create the shape which the tool path follows. Which fibre-plastic combination is used depends on the criteria for the product. In most of the cases, 10XL will use 30% glass fibre reinforced polypropylene (GFPP), but other thermoplastics or fibres can also be used.

For LSAM, the printer setup consist of a large scale extruder, heated hose, large nozzles and an industrial robot. The extruder consists of a single screw within a heated barrel and a large hopper on top. This machine is roughly 2 meters long with different heating zones to melt the plastic. Where these heating elements help to keep a steady temperature profile, most of the melting is actually done by the screw. The design of this screw is made in such a way that the friction and pressure will increase towards the end and melting the plastic pellets. The outlet of the extruder is connected to a heated hose. It has a length of around 4 meters with a heated nozzle element at the end. The nozzle is fixed to the T-axis of the robot, which is controlled by the robot controller unit. The print is made on a bed, which is either fixed to the ground with the dimensions of 2x2x2 meter, or one that is mounted on a track that can move to print very long objects (up to 8 meters now). To fix the print, the first layer is welded to the bed by melting it together.

As a final processing step, it is also possible to post-process the print. This can be done with CNC-milling to get a smooth finish or cut off areas depending on the design. This can also be done by hand, like sawing or sanding. A downside of doing this, is that the material will melt if there is too much friction and it will start to clot together.



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- ▶ **Figure 3: Print head/** The heated nozzle, which is connected to the T-axis of the robot.
- ◀ **Figure 4: Control interface/** The print file is imported to the robot computer and initiated with the control interface.
- ▲ **Figure 5: Glass Fibre PP/** Granulate that is used for printing the objects.
- ▲ **Figure 6: Industrial Extruder/** The extrusion machine which is connected to the hose.



02.2/ WOOD PLASTIC COMPOSITES (WPC)

Figure 7: Different Material Samples/ Different raw materials or compounds used in this explorative research.

In natural reading order:

- _Arbocel C100
- _Borealis PP
- _Stora Enso DuraSence
- _Epolene (MAPP)
- _UPM Formi 3D
- _UPM Formi WB40
- _10XL/WUR Batch-I
- _10XL/WUR Batch-II
- _10XL/WUR Batch-IV
- _UPM Formi WB60
- _Rettenmaier Best Oak chips
- _Rettenmaier Lignocel 9S
- _Rettenmaier Lignocel FS14
- _Rettenmaier Lignocel HBK 700/2000
- _Sappi Lignex (lignin)
- _10XL/WUR Batch-III
- _Jeluplast H60-500-14
- _30% PIW GFPP
- _Sappi Symbio PP20
- _Sappi Symbio PP20 MI
- _Sappi Symbio PP30
- _Sappi Symbio PP40
- _UPM BioPiva Kraft Lignin
- _VolkerWessel wood waste
- _Weidmann Celova C500 (Cellulose fibre)
- _10XL/WUR Batch-V

A wood plastic composite (WPC) is a compound made of wood particles/fibres and a thermoplastic matrix. It is a type of natural fibre composite (NFC) with plant based natural fibres. Table 1 shows the taxonomy of natural fibres. This material can be seen as a bio composite, because the fibres are from a renewable and natural source. The fibres also make for a lightweight composite and increase the mechanical properties of the thermoplastic that is used. The plastics matrix functions as a binder and barrier for the fibres. It protects the wood from moisture, lowering the swell, shrinkage and the wear of the wood fibres. On the downside, adding wood to the plastic will make it a more brittle material (Wolcott & Englund, 1999).

In this project, the WPCs used are with fibres from a wood source, which is the material extracted from hard and fibrous substance inside the trunk and branches of a tree. Wood material comes in the form of a lot of different species, which are shaped in various forms and sizes. The largest

processed form it is known in, is lumber, directly sawn from the trunk of a tree. Going down in size, the taxonomical particle sizes of wood that are used in a WPCs are wood fibres, wood particle (also known as wood flour) and to the molecular level (nano)cellulose. Fibres and flour are often generated and captured in the processing of wood (like milling and sawing), but the cellulose needs to be extracted with mechanical/chemical extraction (like done in the paper processing industry).

To get a better understanding about WPCs, it is important to understand more about wood as a material. Wood is a type of lignocellulosic fibre/material, which is the structural substance produced by all kind of plants. As described by Douglas et al. (2021), this is the generic term for all vegetable material that is made out of cellulose, hemi-cellulose and lignin (see figure 8). When breaking down any part of a plant, these are the main building blocks that make up plant cell walls. The most important structural element of



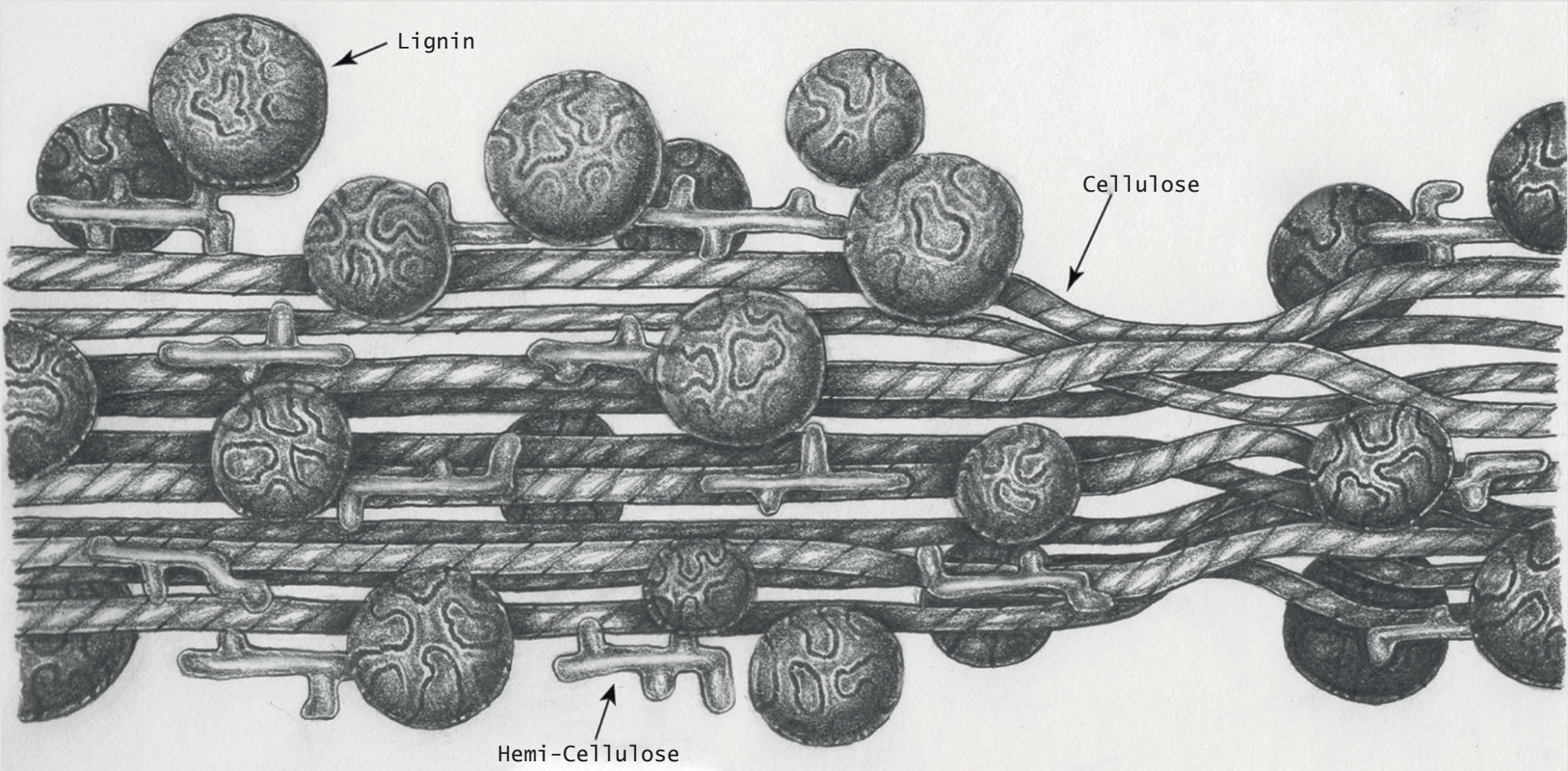
these three is cellulose, which is a material build up from long, unbranched molecular chains (see image 9). The long polymer has a lot of hydrogen groups on the sides of the chain. These groups attract water molecules and function hydrogen bondings between different chains. Cellulose is the most abundant organic polymer in the world and has a wide range of implementations.

The second structural element, hemicellulose, is located on the side branches of the cellulose. These are build up from different carbohydrate monomers and are much shorter and less densely packed. Lignin is the third most important element. Unlike cellulose and hemicellulose, lignin is an amorphous molecule structure, not consisting of long chains but forming a free structure (see image 9). Only cellulose and lignin extracts from the wood play an explicit role in the compounding, therefore the hemicellulose is rarely mentioned. But without the use of a binding agent, these additives do not blend well with a

plastic polymer like PP. Because the plastic is hydrophobic from nature, a binding material like maleic anhydride polypropylene (MAPP) needs to be added. It helps to bind the fibres with the hydrogen groups to attach to the polymer chains (see figure 10).

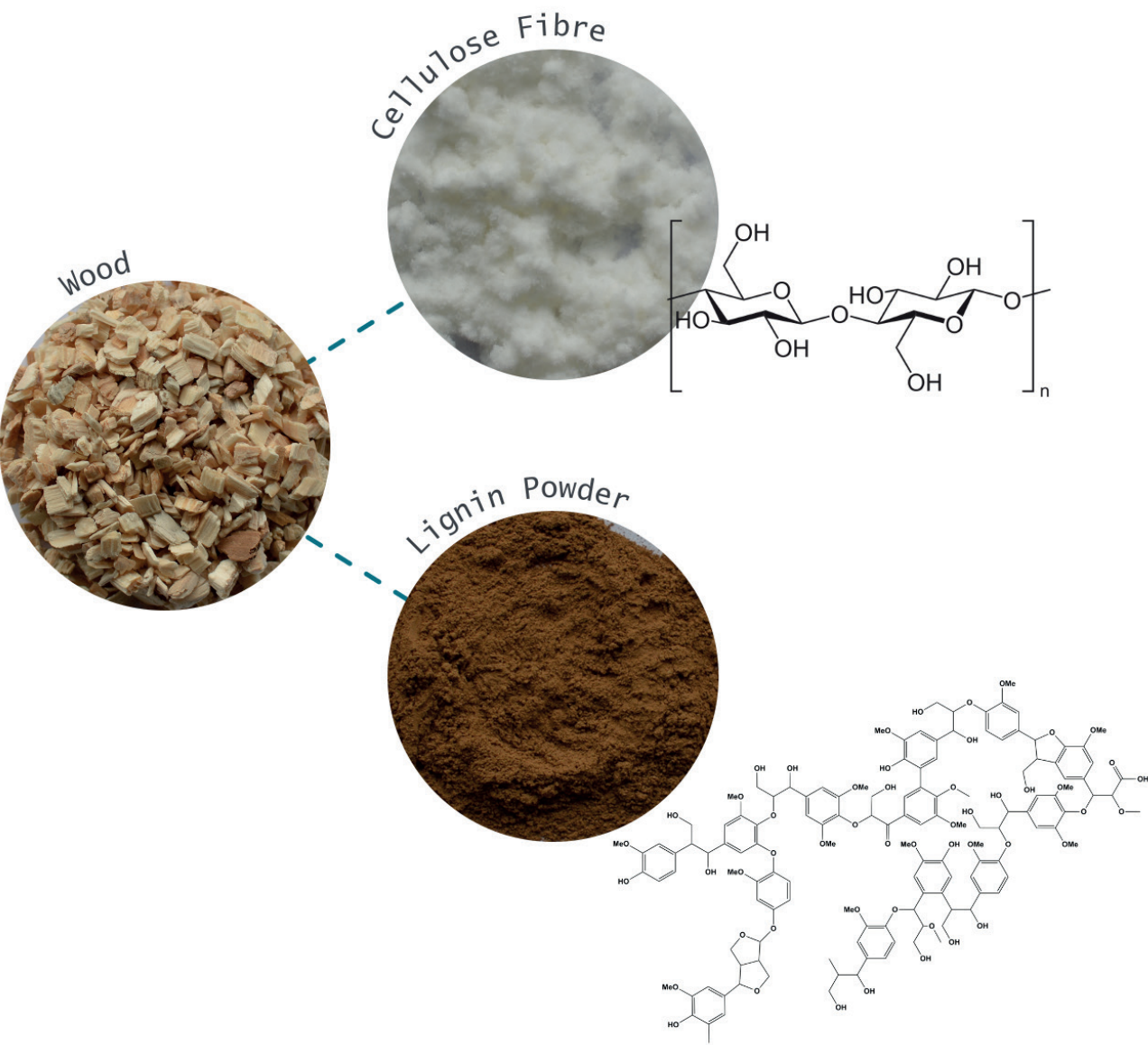
So, the different compounds that will be explored consist of wood and/or cellulose fibres with possibly lignin added to the PP matrix. A clear distinction can be made between wood fibre (WFPP) and cellulose fibre (CFPP) polypropylene mixtures. These will be further explored in this thesis.

Figure 8: Chemical Structure Wood ▼
A representation of the woody material structure with cellulose, hemi-cellulose and lignin materials.
(Source: Douglas et al., 2021)

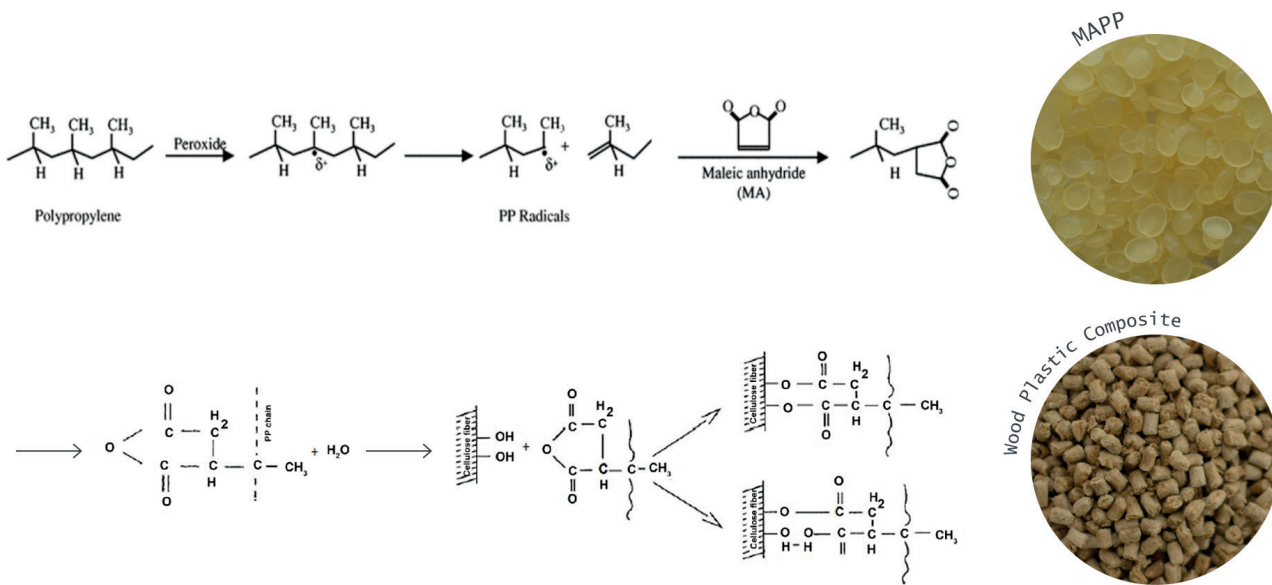


Natural Fibres									
Plant Based (cellulose or lignocellulose)							Animal (protein)		Mineral
Seed	Fruit	Bast (or stem)	Leaf (or hard)	Wood	Stalk	Cane,grass and reed	Wool/Hair	Silk	Asbestos
Cotton	Coir (coconut)	Flax	Pineapple (PALF)	Softwood	Wheat	Bamboo	Lamb's wool	Tussah silk	Fibrous brucite
Kapok		Hemp	Abaca (Manilla hemp)	Hardwood	Maize	Bagasse	Goat hair	Mulberry silk	Wollastonite
Milkweed		Jute	Henequen		Barley	Esparto	Angora wool		
		Ramie	Sisal		Rye	Sabei	Cashmere		
		Kenaf			Oat	Phragmites	Yak		
					Rice	Communis	etc.		

Table 1: Types of Natural Fibres ▲
A classificaton of different types of natural fibres.
(Source: Douglas et al., 2021)



◀ **Figure 9: Materials in wood/**
The two most important materials extracted from wood that are used in WPCs.



◀ **Figure 10: Chemical process/**
The process of combining wood fibres with a PP matrix using MAPP binder.
Source: Zhang et al. (2016) and Akonda & El-Dessouky (2019)

Figure 11: Flotsam & Jetsam/ ▶
3D printed bar and benches from
bamboo reinforced PLA.
(Produced by: Oak Ridge
National Laboratory)



02.3/ 3D PRINTING AND PRODUCT DESIGN WITH WPC

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WPC has already a wide use in the form of decking and fencing, where it combines the warm feeling of wood and the water resistance from the plastic. Also other fields of implementations are explored, for example furniture or (in combination with) 3D printing. Large companies like IKEA are looking at using recycled plastic with natural fibres (see figure 13). Transit companies want to take advantage of the light weight fibres in their interior. Other 3D printing companies are also testing with different types of NFCs, printing with cellulose fibre PP (figure 12) or bamboo reinforced PLA (figure 11). The market for WPC is still much smaller compared to other non renewable fibre reinforced plastics, but the (re)search for bio based material implementations is growing.

In this project, exploring the use of WPC in LSAM is the main goal. What is new, is the use of a large weight percentage (wt%) of fibres that will be printed. In the extrusion of decking, this is already done. But what kind of material character does the printed material or objects have and what are the sensorial design aspects? Combining WPC with the unique opportunities in 3D printing could potentially produce unique designs we are looking for as designers.

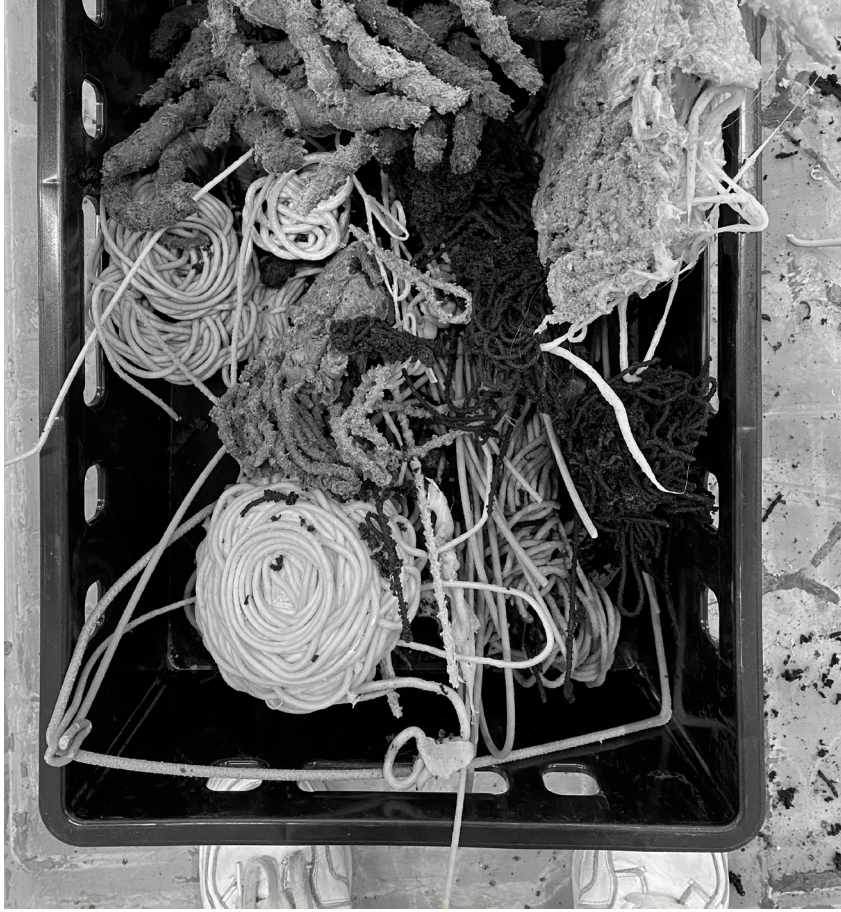




▲ **Figure 12: 3D Printed chair/**
Chair printed out of UPM Formi 3D
granulate.
(Work by: The Wood Region)

◀ **Figure 13: IKEA ODGER/**
Injection moulded chair from
recycled PP and wood chips.
(Design by: From us with love)





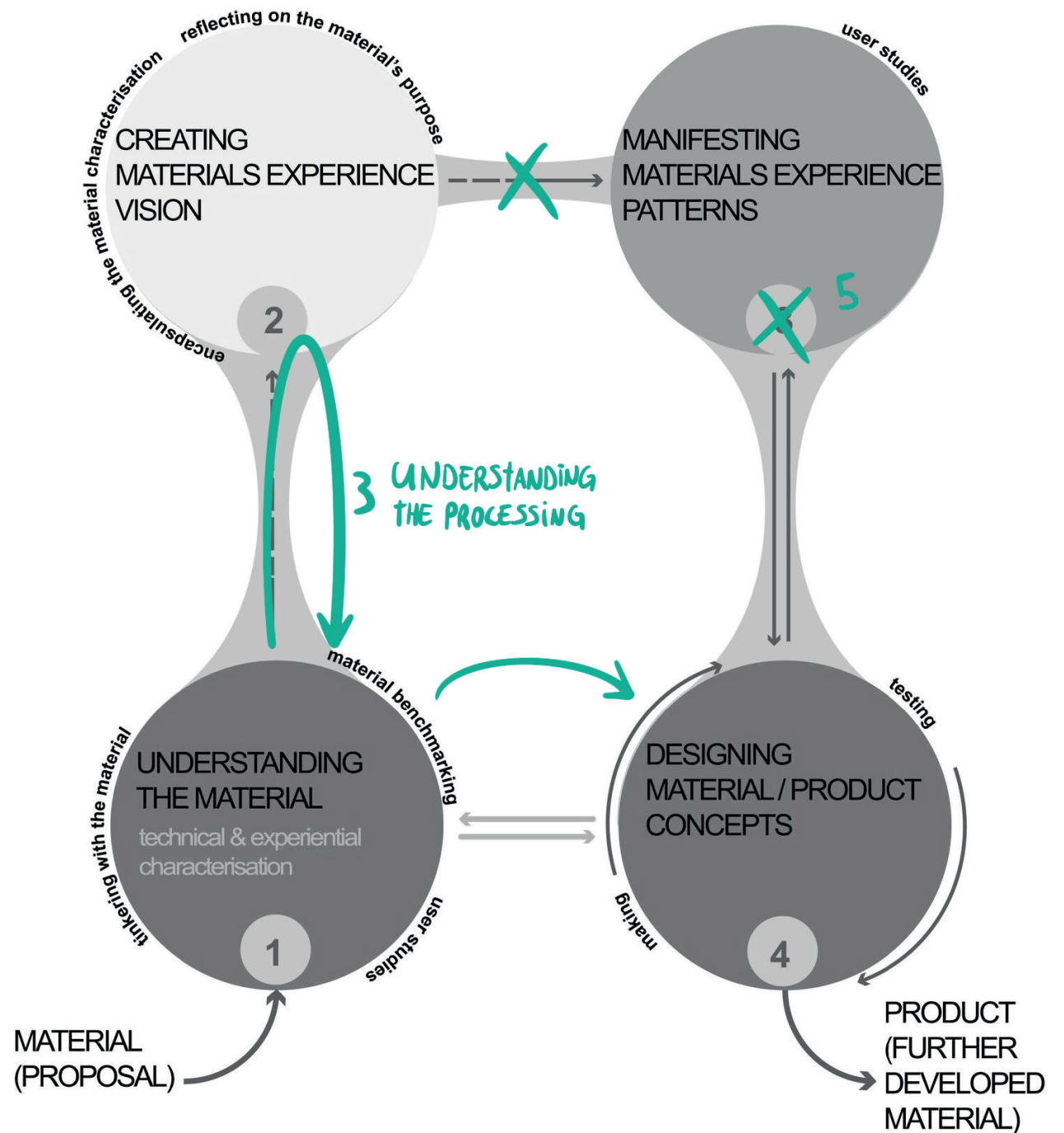


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MATERIAL EXPLORATION

In this chapter, the process and the results of the material driven design (MDD) method will be presented. There will be different chapters for each step/phase of the method. Initially, there is a short explanation of the approach of this methodology and the alterations to it. This is followed by the results and discussion. The order of the chapters, is like the process, in an iterative way. All gained knowledge and experiences from the exploitative research are taken into each next research step.

Figure 14: MDD method overview/ ►
The altered work flow of the material driven design method used in this project.



03.1/ METHOD: MATERIAL DRIVEN DESIGN

The first three criteria points that were mentioned in the introduction that will be researched are:

1. Obtaining a wood look/feeling from the printed material
2. Sufficient mechanical properties needed for 3D printing
3. Possess meaningful applications

The material driven design (MDD) method is used as a guide (Karana et al., 2015)

This method's design process starts with the material, unlike other design methods which usually starts with a problem/need for a product. The goal for the MDD method is to find the best implementation that fits a material based on its mechanical and experiential characterization. This is normally done by going through 4 steps, but because this project has different boundaries (the production process and different materials to test), the steps are not directly followed as intended but slightly altered (see figure 14).

STEP 1_UNDERSTANDING THE MATERIAL

The first step of this project is to understand the material and experiment with it in different ways (called material tinkering). Due to the fact that there is not one material but different compounds and a production technique to stick to, the freedom of the MDD method's tinkering process is lessened. Still, different experimentations and test can be preformed (see figure 15). The goal is to explore what the effects of different percentages of wood and/or cellulose in the biocomposite are. For the experimentation, all the different materials need to be heat treated in order to create samples. These samples will be used to explore the mechanical and experiential characterization of printed WPC.

To do so, 12 different compounds were extruded on a small lab extruder (Filabot EX6) at the 'Duurzaamheidsfabriek'. Starting small helps to add more flexibility into the material tinkering, because the large extruder needs long rinsing times and large quantities of granulate. On the small extruder, rinsing time is significantly smaller and changes to the settings can be observed directly. Therefore, more could be tested in a shorter time frame and still provide useful results. To test the strength of all the compounds and give an initial idea of the strength and stiffness, straight extrudates were made with a nozzle of 3mm. Five specimens were chosen to be tested in the tensile testing machine.

Other tests performed with the remaining specimens are a horizontal burning test and a water absorption test. The burning test is done by marking a fixed length on each of the different specimens and measure the time it takes for it to burn up while the extrudate is positioned horizontally. The flame is extinguished before the first mark with a lighter. The water absorption test

is performed by first drying the specimens at 115° for 3 hours and cooling them down in an airtight bag. When at room temperature, the specimens are weighed and then emerged in water. The water is at room temperature and the specimens will be submerged for 24 hours. Finally, after patted dry, the weight will be measured again, where the difference represents the water uptake.

For testing the material experience, two different shapes have been used in a user test. One shape is a cylinder, made with the lab extruder by whirling the extrudate around a cup and push the layer together by hand. The other is a small plate, created with the use of a heated press. Both objects were used in a user test to explore the sensorial properties for the material experience. The test performed consists of two parts. In the first part, 5 different cylinders are handed to the participant, initially not being able to see it. This will keep the focus on the other sensorial aspects feel and sound at first, without being influenced by the looks. In second instance, the visual and aromatic characteristics are evaluated by the user. Taste is left out from this research. In the second part, the participants are asked to rate all the different material plates on a matrix, which display opposite aesthetic properties on the axis. The samples include all the different WPCs and some reference materials (different types of wood and PPGF).

The following matrices were shown to the users:

	X axis	Y axis
1	<i>Fresh-Filthy</i>	<i>Plastic-Natural</i>
2	<i>Firm-Fragile</i>	<i>Rough-Soft</i>
3	<i>Luxurious-Cheap</i>	<i>Warm-Cold</i>

Finally, the same materials were rated from 1-10 to see which material was most associated with wood and which material was liked most.

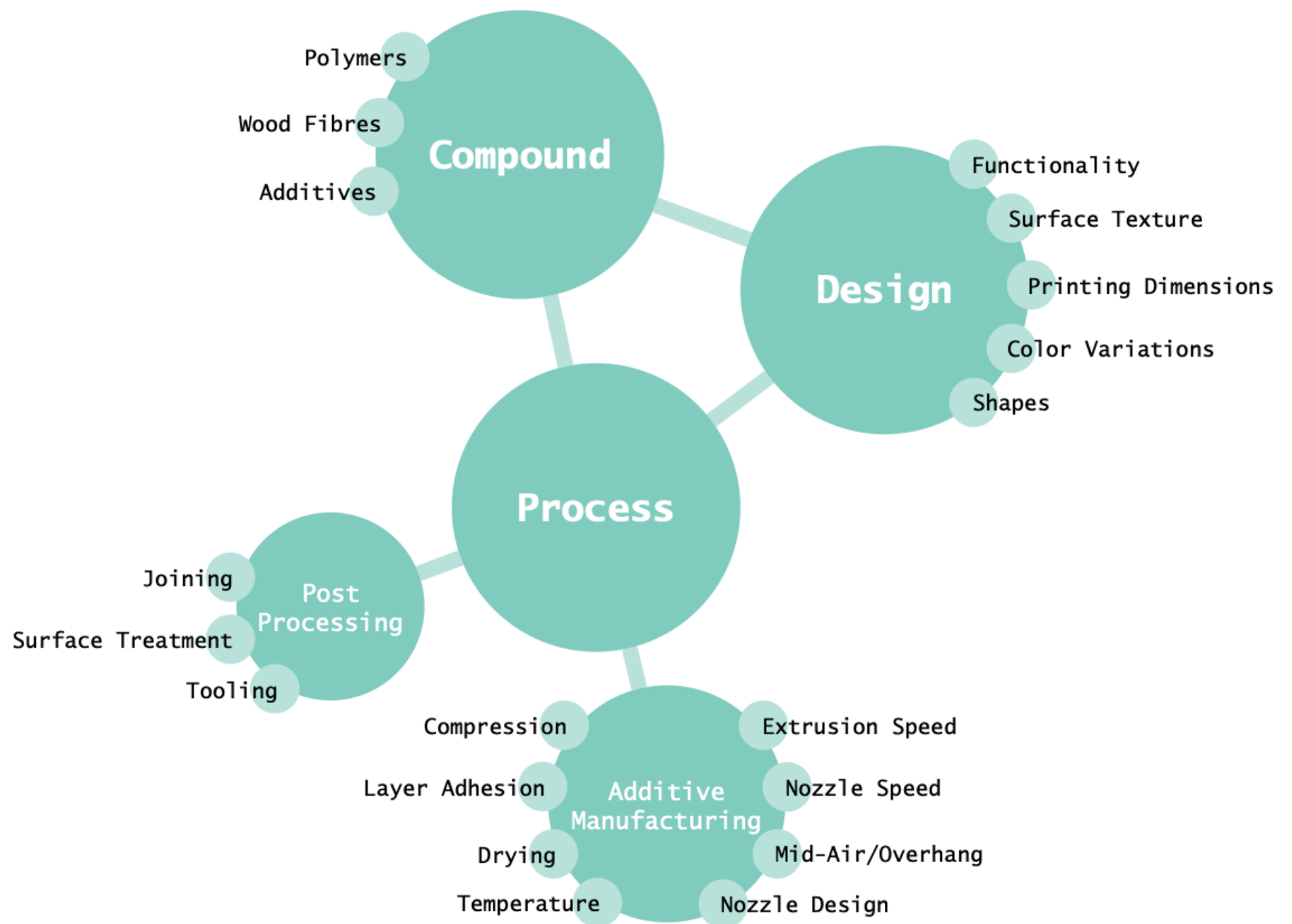


Figure 15: MDD Research Areas/ ▲
Different areas to explore in the tinkering phase.

STEP 2_CREATING MATERIALS EXPERIENCE VISION
The next step of the MDD method is to create a material experience vision for 3D printed WPC. The outcome of the previous step will help to define a point of view on the material characterization. This material experience vision will give purpose to the material and how it should be interpreted by the user. It is a guide for the designer help with questions like what can be printed with a wood-based biocomposites? Therefore, this vision will help the initiation of the concept phase in step 4. While the manufacturing process on the large extruder still needs to be explored, an extra step is needed in order to be able to print objects that fit the vision. This will be done in step 3, by using a smaller extruder that is mounted on a robot. This machine is able to print smaller objects and test in a more iterative way.

STEP 3_UNDERSTANDING THE PROCESSING

This third step of the MDD method will be a print tinkering phase. During this process tinkering, the WPC will be used to try printing cubes, shapes and patterns and evaluating different settings, techniques, nozzles and additives. Being able to print a tight cube is a good indication if the extrusion is constant, if the layer adhesion is good, if the warping of the material is within limits and test different post-processing treatments.

Printing settings to experiment with, are temperature, extrusion speed, print speed or feedrate and layer height. Different techniques of printing that can be tested is printing in the length, printing low on a high surface area, printing in a 45° rotated plane and printing non-planar. The different techniques can offer different product qualities, which can be used in the final concept phase in step 4. Furthermore, the printing technique also include bed adhesion and different additives to use. Adhesion to the print bed is important, since warping is always present due to the layer-on-layer technique. It is important to find out what the best way is to keep the print fixed to the bed to make sure the print will not fail. 3 things that will be tested is preheating and welding the plastic bed to the first layer, using different materials for the bed or fixing the first layers mechanically.

Analysing different nozzles is a meaningful test, since this is the crucial element of the printing process. The nozzle functions as the die of the extrusion process, defining the output of the extrudate. In combination with the initial settings

for speed, layer height and feed rate, it highly effects the outcome of the print. Furthermore, it can also affect the rheology and fibre alignment of the composite, since the nozzle is a transition in the path flow of the material.

With the test prints, it is also necessary to evaluate the experiential goal, if the printed material can achieve a natural and wood-like experience to the user. This is normally the 3rd step in the MDD method, to manifest the material experience. However, since this step is useful for designing a product with a specific material implementation, this is not yet useful for this study case. The goal of this project is more directed to validate the technique and find a minimum viable product that shows the potential of LSAM with WPC. When the production of WPC objects will be further developed into a final product, only then the step of confirming the correct material meaning is useful. For this reason, this 5th step of the method is not implemented yet in this thesis.

STEP 4_DESIGNING MATERIAL/PRODUCT CONCEPTS

The final step, step 4, is about putting all findings into the embodiment or a concept. Although the initial goal was not to design a final product, it is still meaningful to explore possible applications for the material based on the research. This way, the material potential is demonstrated in a realistic way, being able to show in which kind of design area it can succeed. In this phase, several design tools like how-to's, brainstorming, benchmarking and collage making can help to come up with a concept to prototype. This prototype needs to present the outcomes of MDD design research.

03.2/ UNDERSTANDING THE MATERIAL: TINKERING

-

Tinkering is the iterative process of getting familiar with the material. It is about doing small tests and just 'playing' with the material. Guided by the results, insights were gathered and used to characterize the mechanical and experiential properties of WPC. Based on the LSAM, process the results are divided in three different sections: Liquefying, Pressurizing and Printing.

LIQUEFYING

For a material to be printed, it needs to be able to become liquid so it can be transformed into the desired shape. The first tinkering outcomes were from heating different materials in an oven to get insight in the melt behaviour. What is notable, is that not all material behaves in the same way when exposed to hot air (see figures 16-19).

The polypropylene pellets with a high melt flow index (MFI) that were used for the WPC test compounds was put in the oven and mixed with some wood chips. When heated, the material coalesced and became very sticky. The wood chips submerged into the plastic, but this was very rough. The WPC however did not coalesce. It only transformed and mixed (slightly) when kneaded. It behaves similar as a dry clay, crumbling apart when touched. The cellulose based compounds showed better flowing behaviour, but still not as much as the PP material.

Where wood particles don't melt but burn when exposed to high temperatures, the WPC compounds showed the same characteristic. When exposed to the hot air of the heat gun, the material turned black instead of changing to a liquid state.





◀ **Figure 16: PP with softwood/**
Polypropylene with MFI 50 mixed
with softwood chips.

◀ **Figure 17: Cellulose WPC/**
Sappi Symbio PP40 granulate after
it was put in the oven.



◀ **Figure 18: PP with hardwood/**
Polypropylene with MFI 50 mixed
with hardwood chips.

◀ **Figure 19: Cellulose WPC/**
Sappi Symbio PP40 granulate after
it was kneaded together.

Figure 20: Noztek Pro Extruder/ ▶
Small lab extruder used for
initial extrusion tests.



Figure 21: Heat Pressure Plates/ ▶
Press with heated plates to
produce flat sheets from the
granulate.



Figure 22: Filabot EX6 Estruder/ ▶
Lab extruder with more power and
multiple heating zones for better
extrusion performance.



PRESSURIZING

Since only heat was not enough to manipulate the material, pressure was added to the equation. This was done by using small lab extruders and an heat press (figures 20-22) to merge the granulate together and creating more compact shapes. These outcomes could be used for further mechanical and experiential characterization of the material. The smallest lab extruder that was used to produce the first extrudates, a Noztek pro, resulted already good indication of the different compound process abilities. Tinkering with the machine on such a small scale helped to quickly try and learn about different machine settings and their outcomes. What was already seen from this first test, was that the compound UPM Formi 3D (with 20 wt% cellulose fibre) was extruded very easy. Changing to the compound with wood fibres however, caused more difficulty for the machine. Temperatures had to be cranked up, because it had trouble of extruding the material. The string of material coming out of the nozzle also started to show a rough surface and crumbled apart more easily. The Stora Enso DuraSence compound still had a smooth surface, but the 10XL/WUR Batch-I showed cracks and rough edges on the extrudate.

Taking a closer look at the three different materials under a microscope (see figure 23), it shows that the cellulose fibre compound has a very smooth an consistent surface. With this magnification it is not possible to see any of the fibres. On the other hand however, the 10XL/WUR Batch-I, which has 40 wt% unprocessed wood fibres, the surface is very rough and inconsistent. It looks like it is almost possible to see the wood dust in the matrix. Scaling up to the more powerful Filabot EX6 lab



▲ **Figure 23: First WPC extrudates/**
UPM formi 3D, StoraEnso Durasence
and 10XL/WUR Batch-I compounds
extruded on the Noztek Pro.

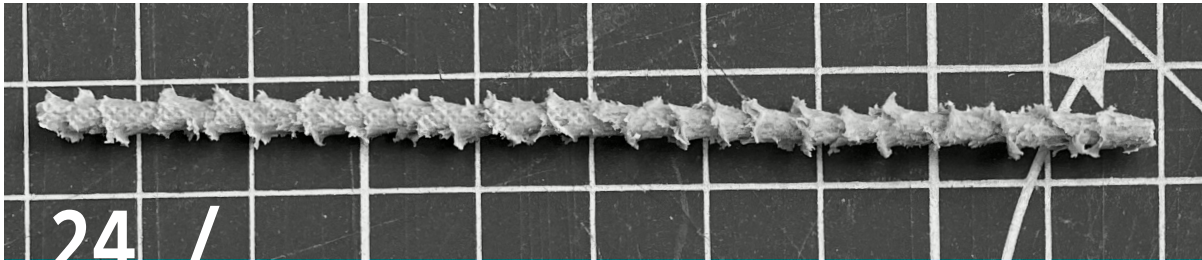


Figure 24: Extrudate Failure/▲
Stora Enso Durasence extrudate showing cracked surface in specific frequency.

Figure 25: Smooth Extrudate/►
10XL/WUR Batch-III showing a smooth and fluid extrudate coming out of the nozzle.



Figure 26: Cylinder and Sticks/►
The granulate was extruded into different specimens.





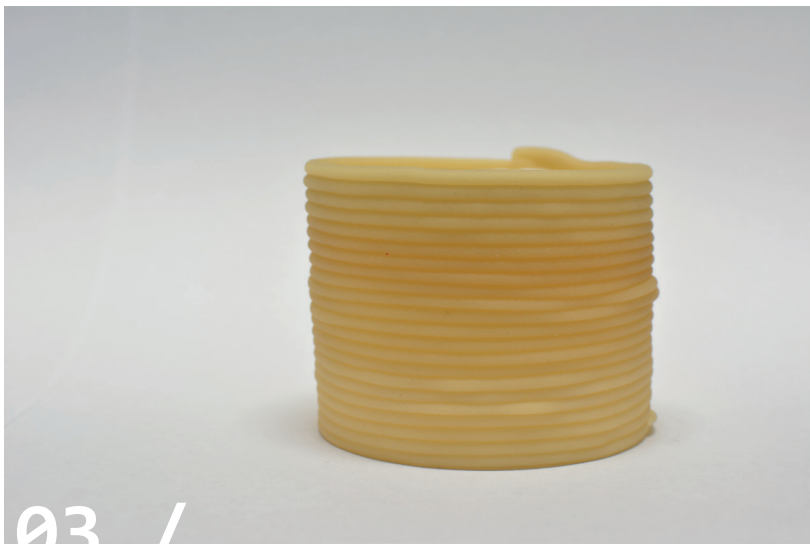
▲ **Figure 27: Temperature Profile/**
Temperature profile used to
extrude the different materials
on the 'Filabot EX6'.
169°C_180°C_160°C_40°C

extruder contributed to the processing capability and quality of the different material extrudates. Overall, the surface of all the different compounds was somewhere between smooth and some cracks with rough edges (figure 25). Only the StoraEnso Durasence compound, which extruded well on the first test, looked entirely different (figure 24). The outside of the string showed a 'palm tree' kind of skin, where it looked like the material was sticking to the nozzle. Changing speeds did not have any noticeable effect, the cracks just formed faster and in the same frequency. When doing a second test where the material was dried first, the phenomena still returned. This time it was in a lesser degree, but still very prominent. This type of failure was also perceived in other materials which contained wood fibres, but not as clearly.

Another noticeable feature was the adhesion of cellulose fibre versus wood fibre. The CFPP compound behaved just like regular GFPP that was extruded on this machine, having a low

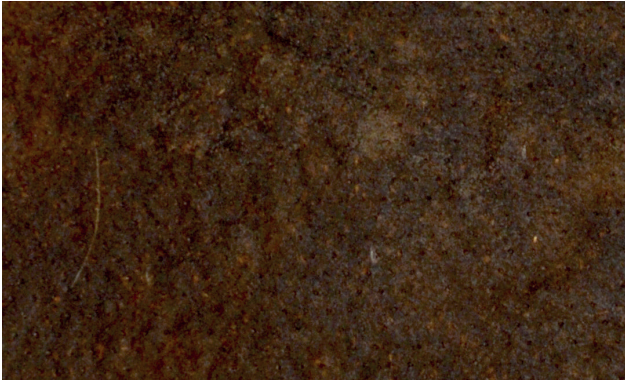
viscosity and being very sticky. Compounds with a high wood fibre content did the opposite. The adhesion was significantly lower and the viscosity was so high, no flowing behaviour was perceived. It was also very hard to roll the extruded string of material around the cup without breaking it. Where the WFPP crumbled apart when it was pulled to much, the CFPP and GFPP compounds showed some elastic behaviour and thinning out the string of extrudate when pulling too hard.

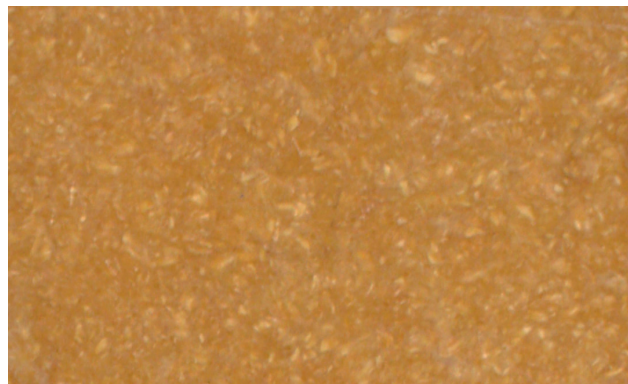
When the samples were crystalized, most of the materials were very brittle. Only the cellulose based compounds (UPM 3D and Sappi PP40) and the Durasence showed some flexibility. The others broke almost instantly when they started to bend. The cylindrical form (figure 28 next page) of the samples produced gave extra strength, but in this case almost all WFPP compounds failed on the layer adhesion when pulled apart. Of course this was all still done by hand.





▲ **Figure 28: Cylinder Samples/**
 Extruded material samples on
 the Filabot EX6.
 Compound used:
 1./GFPP
 2./UPM Formi 3D
 3./Sappi Symbio PP40
 4./Stora Enso DuraSence
 5./UPM Formi WB60
 6./10XL/WUR BB-I
 7./10XL/WUR BB-II
 8./10XL/WUR BB-III
 9./10XL/WUR BB-IV
 10./10XL/WUR BB-V





Using a heated press to manipulate the different materials proved to be a successful method, since all of the compound showed similar qualities. They were all coalesced into a compact, homogeneous and strong disk. The difference was mainly in the visual and sensorial appearance, showing different colours, grains and texture. These homogenous samples will be used for the user tests, since they are easy to handle and are a good representation of the different aesthetics with similar mechanical properties.

▲ **Figure 29: Flat Sheet Samples/** Different areas that can be explored for material tinkering.

PRINTING

When scaling up to the large extruder, the two following steps were carried out. First, a consistent string of material must be extruded out of the nozzle to find the right temperature and speed settings. Next, if the string of material looks good, a test cube can be printed. This cube is used to get insight in the quality of the layers printed, the bed adhesion and warping of the print. Furthermore, these faces can also be used for testing post processing like sawing and sanding. If both steps are carried out successfully, the material can be used to print a final shape in the final phase of the project.

First, getting to the right extruder settings. The first tests were carried out with the compounds Sappi Symbio PP40, UPM Formi WB60 and a 50/50 mixture of both of them. These compounds were chosen because they were most available. The temperature profile for the heating elements in the hopper to nozzle (that are located in the extruder [5], coupling [1], hose [1], nozzle [1]), was set to extrude both materials was respectively 170°C-170°C-175°C-175°C-190°C-195°C-190°C-195°C (see figure 30). This was based on the earlier test and the fact that above 200°C the wood material will degrade. The nozzle used was from steel with a 6mm diameter.

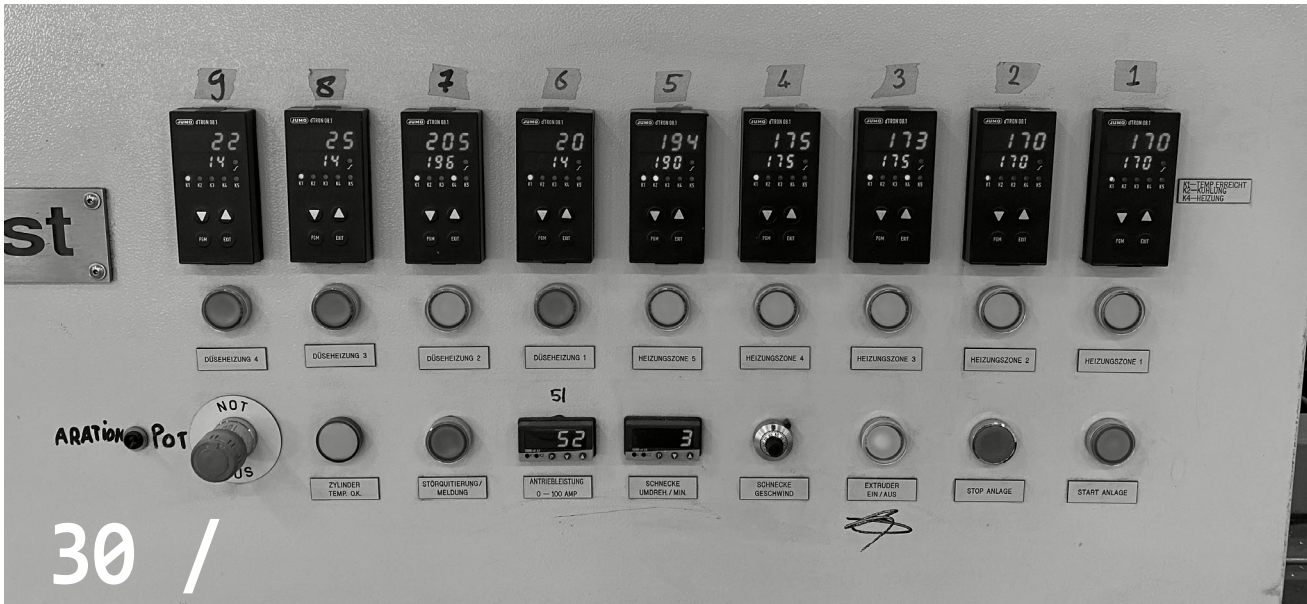
The CFPP compound showed no issues to produce a homogeneous and clean string of material (see figure 31). It extrudes almost identical to GFPP without any surface failures or distortions. When extruding the WFPP compound however, the printer failed to extrude a clean and consistent string of material. What happened with the Durasence compound on the small extruder in earlier tests, now also happened with the UPM Formi WB60 compound on a large scale. Observing closely, it seemed like the material was sticking to the end of the nozzle and then released. This happened sequentially, leaving a rough and torn surface on the outside of the extrudate as can be seen in figure 32. Gradually changing the extrusion speed to the maximum RPM the extruder could handle with WPC seemed to have no influence.

When changing the temperature profile with +5° to see if it reduced this effect, another phenomenon was observed. Higher temperatures and longer heating times lead to a strong discolouration of the material (see figure 33 and 34), where hotter conditions were correlating to darker (charred) colours. Something remarkable with the higher temperatures, was that when the extrusion started after a short stop, the extrudate appeared dark but

Figure 31: Sappi Symbio PP40/ ▼
Different areas that can be explored for material tinkering.

Figure 32: UPM Formi WB60/ ▲
Extrudate showing a rough and inconsistent surface.





◀ **Figure 30: Temperature Profile/** Temperature settings on the large extruder for first tests.

much smoother and consistent like seen in figure 34. Presumably, the darker (almost black) colour is because the material is heated through much longer. Higher temperatures also appear to have some effects on the smoothness of the extrudate, but a more plausible explanation is the time the material has to relax in the nozzle. Because of this, the chains of polymer and the fibres have the ability to restore a degree of elasticity (Inn et al., 1998). Therefore, the internal stresses are less when the material is pushed out of the nozzle.

Another issue when increasing the temperature was the production of a lot of steam, which made printing even impossible. At some points the extruded material was popping and spurting out of the nozzle. Too high temperature will detach the water molecules that are attached to the wood fibres. For this reason, it is also important to dry the granulate first. This is done a special dehumidifier, which takes out most of the water from the compound. This will decrease the amount of steam coming out and increase the extrudate quality.

▶ **Figure 33: UPM Formi WB60/** Heated at higher temperatures resulting in darker colour.

▼ **Figure 34: UPM Formi WB60/** Heated too much, starting to char but showing a smooth surface.



Figure 35: Printed WFPP Cube/ ▶
The surface of the print showed a lot of imperfections creating a rough feeling.



Figure 36: Printed CFPP Cube/ ▶
The cellulose fibre material producing smooth printing lines.



Figure 37: Rough Surface/ ▼
Representation of the fracturing of the surface for different materials when printing (50/50 mixture and WB60).



When printing the cubes from the WFPP form UPM, the roughness from the extrudate and the discolouration from the temperatures were seen back in the surface of the print (see figure 35). A unique effect from this, is that the layers are kind of blending. This could be an useful feature in the design stage. Printing the CFPP form Sappi seemed to work perfect (figure 36). However, after some layers of printing, the warping started to become a huge issue. The print detached from the printing bed and this affected the layers, resulting in an ugly print. The mixture of the two compounds was easier for the extruder to extrude without to much issues, but it still had the rough surfacing. Also the warping in this print was more of an issue compared to only the WFPP. The final box was curved up in the corners and because of that, some over extrusion was seen in the layers above. For all the boxes printed with the WFPP and the 50/50 mixture, see figure 38.

POST - PROCESSING

From the printed cubes, the sides were sawn apart to test how it behaves when tooling. Where GFPP is hard to saw or sand down, the WPC materials don't melt when using tools. It is almost like working with normal wood if not easier. Sanding the samples with very fine grain paper will give the material a smooth surface finish. However, because of the inconsistent extrudate, there are some holes that can seen. For the results, see images 39-44 on the next page.

▼ **Figure 38: Printed Cubes/**
Top box is from the 50/50
mixture, the others from UPM
Formi WB60, showing strong
discolouration.

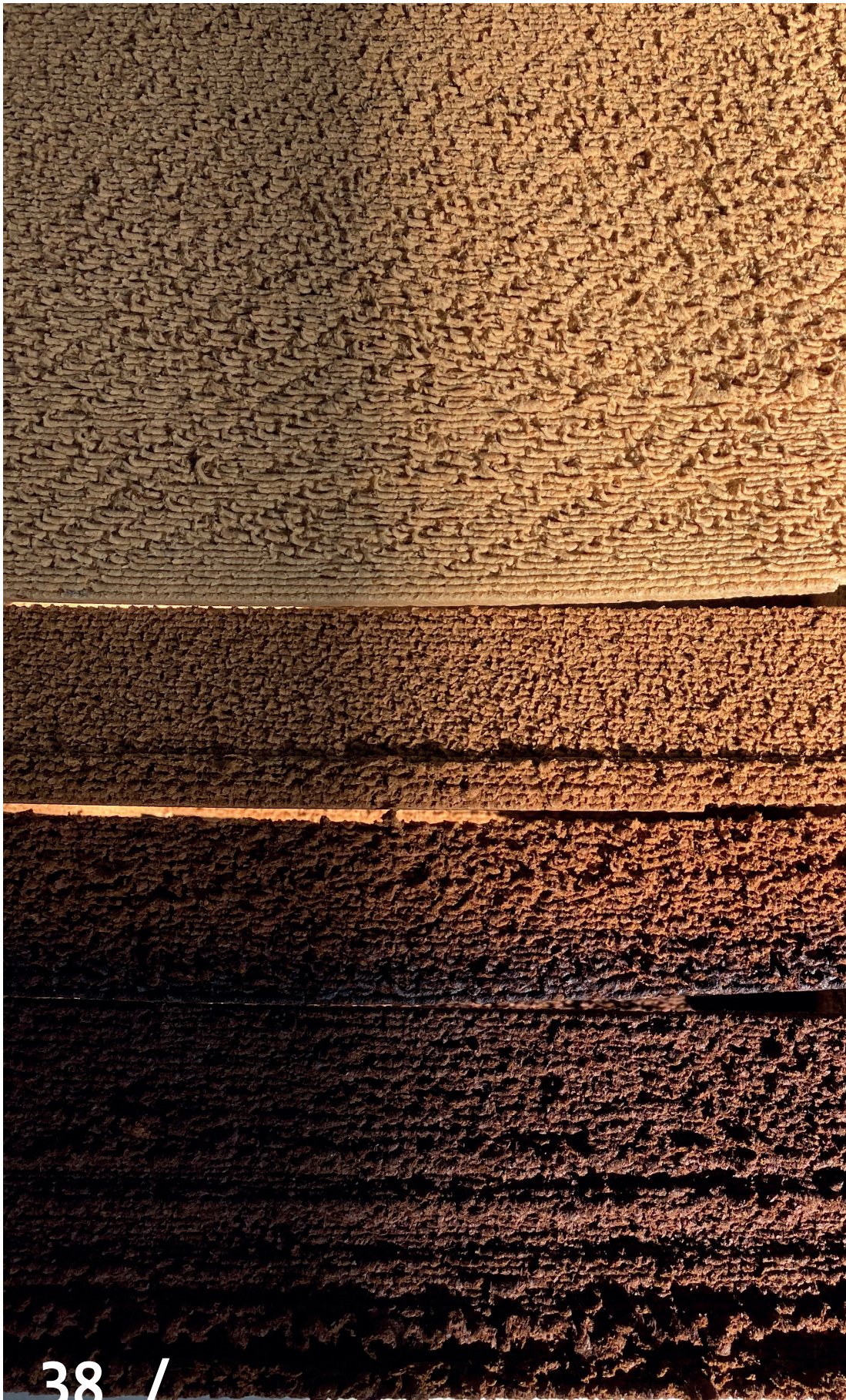


Figure 39: Rough Printed Surface/ ►
Close up from the surface of WFPP
that was printed.



Figure 40: Smooth Surface Print/ ►
WFPP sanded down with an
eccentric sander and grain P800.



Figure 41: Smooth Surface Print/ ►
CFPP sanded down with an
eccentric sander and grain P800.

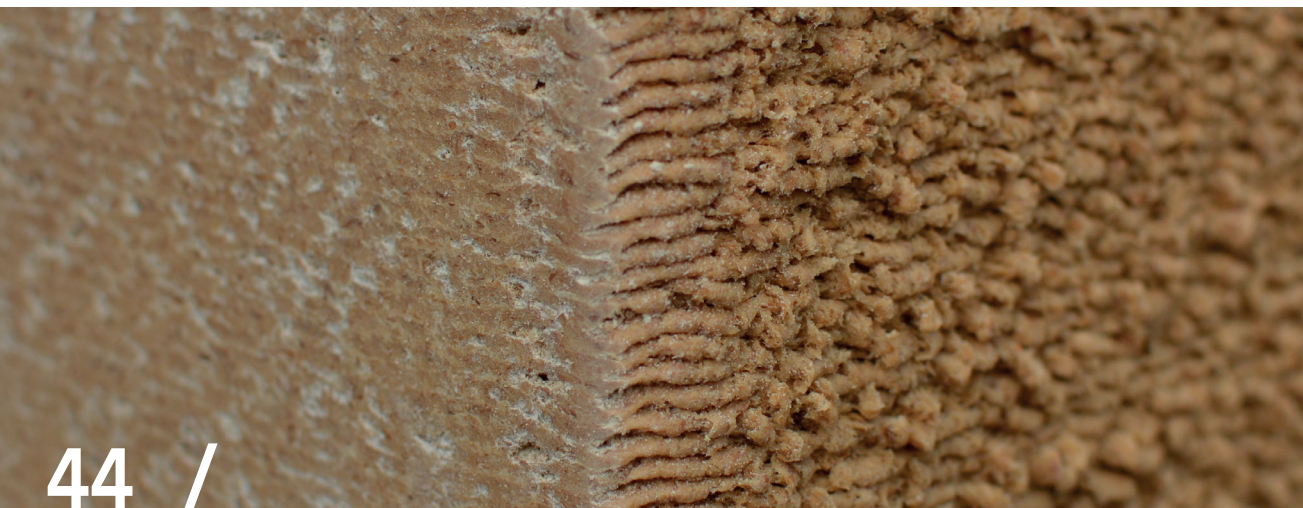




◀ **Figure 42: Smooth Surface Print/**
50/50 mixture sanded down with an
eccentric sander and grain P800.



◀ **Figure 43: Smooth Surface Print/**
WFPP partly sanded down with an
eccentric sander and grain P800.



◀ **Figure 44: Smooth Surface Print/**
Close up of 50/50 mixture one
side sanded and one side not.

03.3/ UNDERSTANDING THE MATERIAL: MECHANICAL PROPERTIES

All the other properties from material test results are presented in this chapter. The three tests that have been conducted with the extrudates from the lab extruder are tested to characterize the tensile strength, moisture uptake and burning speed.

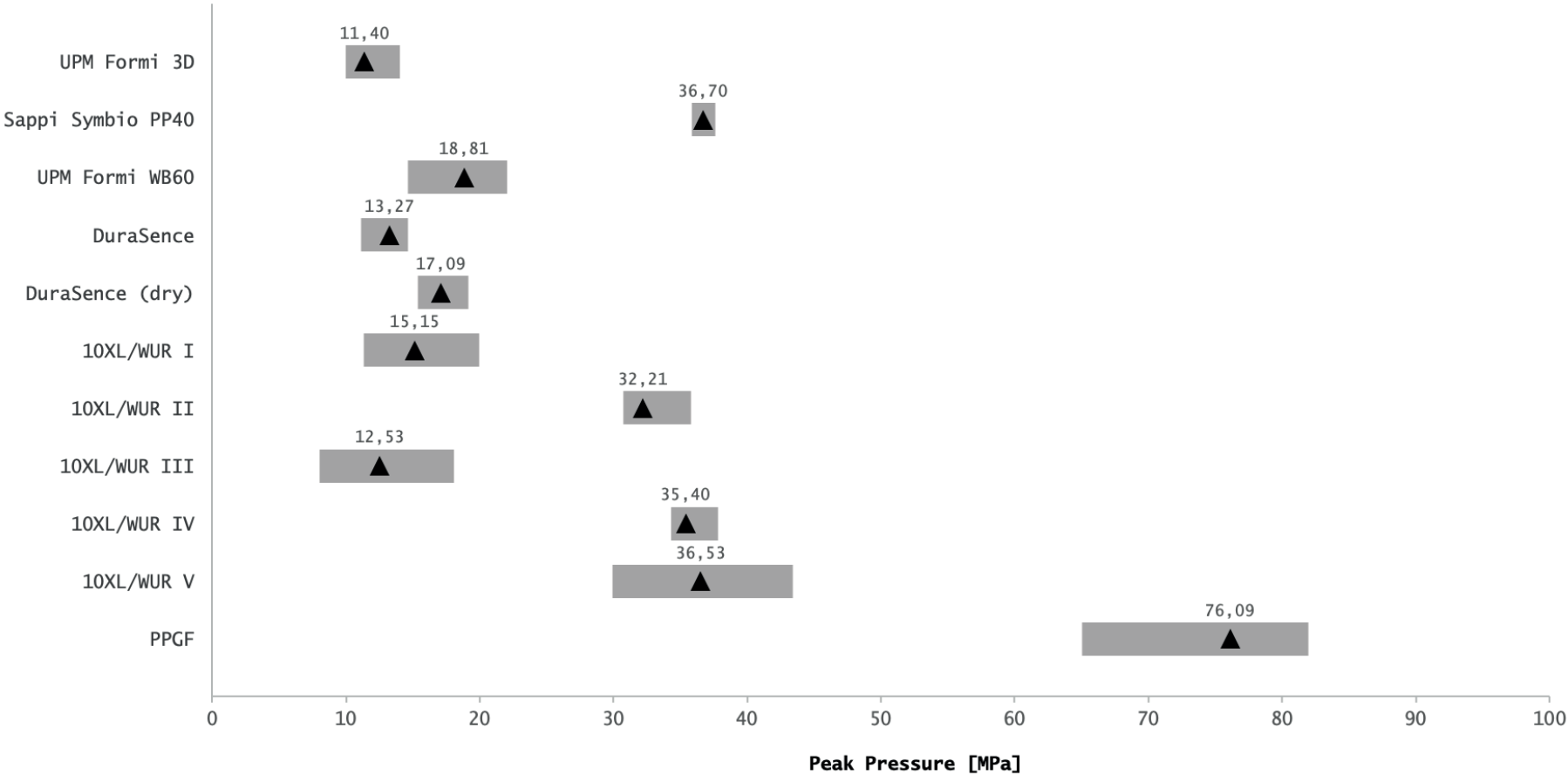
TENSILE STRENGTH & STIFFNESS

The measurements from the tensile test bench are shown in figure 45, displaying a range from all the peak forces that were detected for five different specimens of each compound tested. The black triangle is the average score of the five values. The GFPP that is normally used by 10XL is measured as a reference. From the results, it can be seen that all the different materials score significantly lower than the GFPP, but that some materials do

not perform too poor. There is a clear group of materials that show a notable strength, being the compounds Sappi Symbio PP40 and The 10XL/WUR batches number II,IV and V. With the UPM WB60 compound scoring around average for all compounds, the other materials all have a low maximum peak force.

The result that stands out, is the one from the CFPP. It shows the same strength in the elongated direction as the WFPP compounds. Looking further into the material composition of all the batches that were tested, figure 46 shows the composition of all the raw materials in the compounds. The material is ordered from strong to weak, based on the measurements in figure 45.

Figure 45: Material strength/ Strength calculated from peak force detections on the tensile bench for each compound shown on the y-axis.

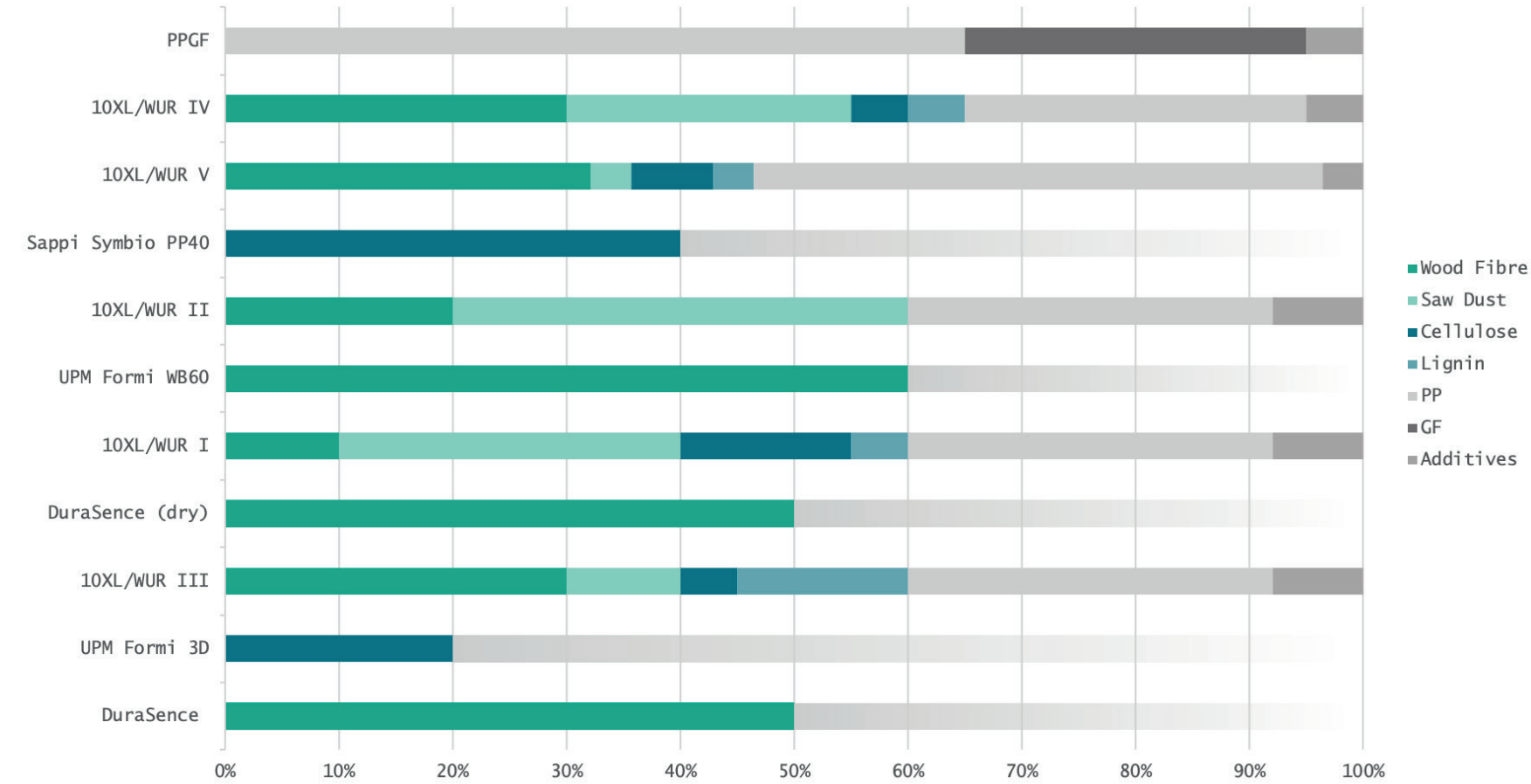


What can be seen in this table, is that there is no correlation between tensile strength and the type of raw material used. As mentioned, Sappi Symbio PP40 with only cellulose fibres shows the same range of values as the specimens with wood fibres. Also there is not a clear difference that shows that a mixture of wood fibre/cellulose fibre/lignin and different proportions have any correlating effect to the strength of the compound.

To get a better view of the mechanical behaviour, a stress-strain curve can be extracted from the measurements. Mapping out the stress (which is the peak force divided by the cross sectional area of the cylindrical specimen) to the strain (which is the distance the specimen was elongated until

it broke divided by its initial length, will result in the graph shown figure 47. Form this graph, different stages of deformation can be seen for the compounds. Comparing it to the peak force values, the same four WPC compounds come out to be the strongest in the elongated direction. However, figure 47 now shows that the WFPP materials are very brittle, but the the CFPP compound is much more ductile. It has more elastic behaviour while still withstanding the same stresses. The materials that performed the least are Durasence, UPM 3D and 10XL/WUR batches I and II. It is worth mentioning that the Durasence compounds produced inconsistent extrudate, resulting in a variable sectional area along the specimen. This presumably influenced the test results.

Figure 46: Compound Compositions/ Compounds ordered from strong to weak and displaying the composition of the raw materials.



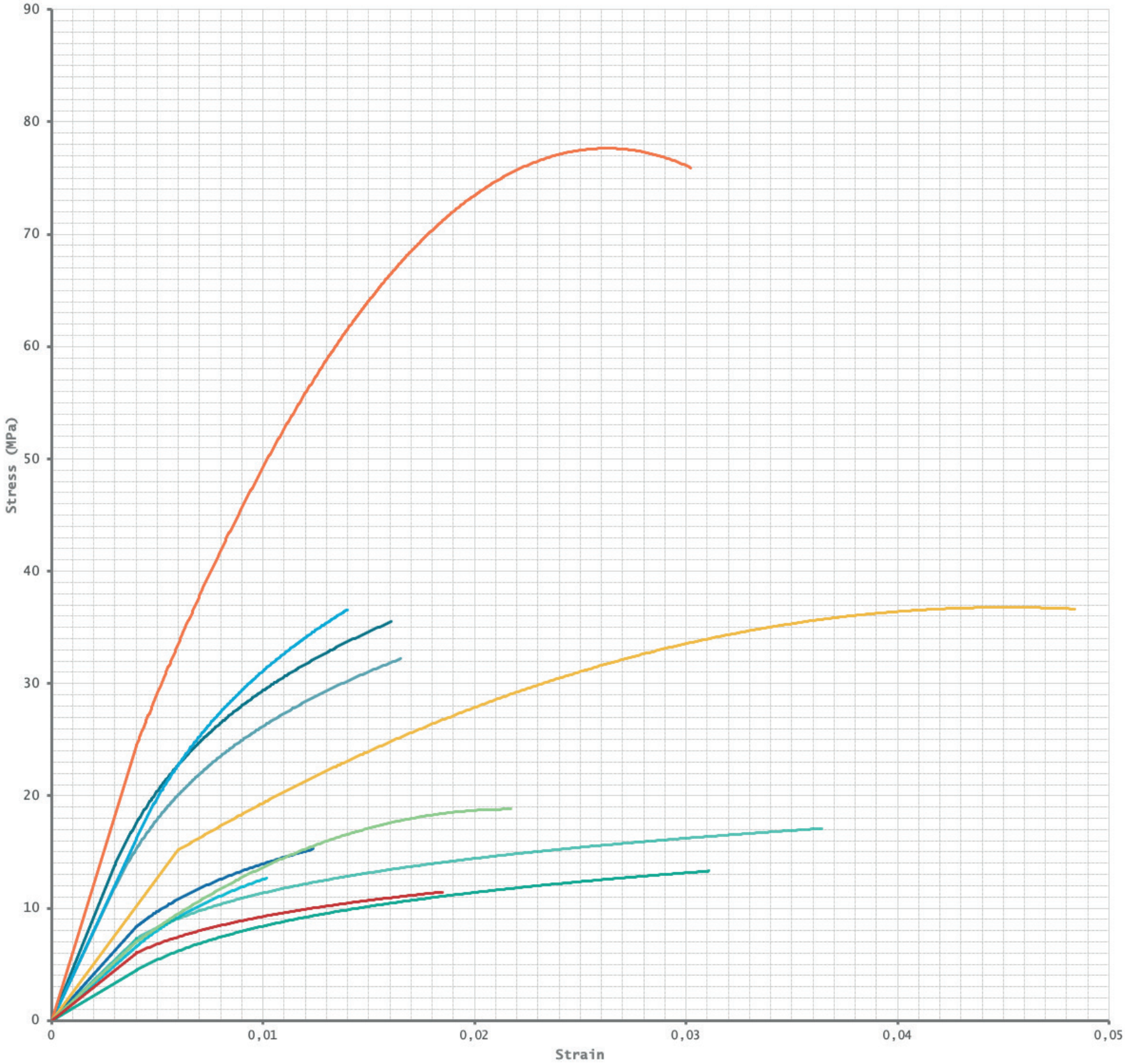
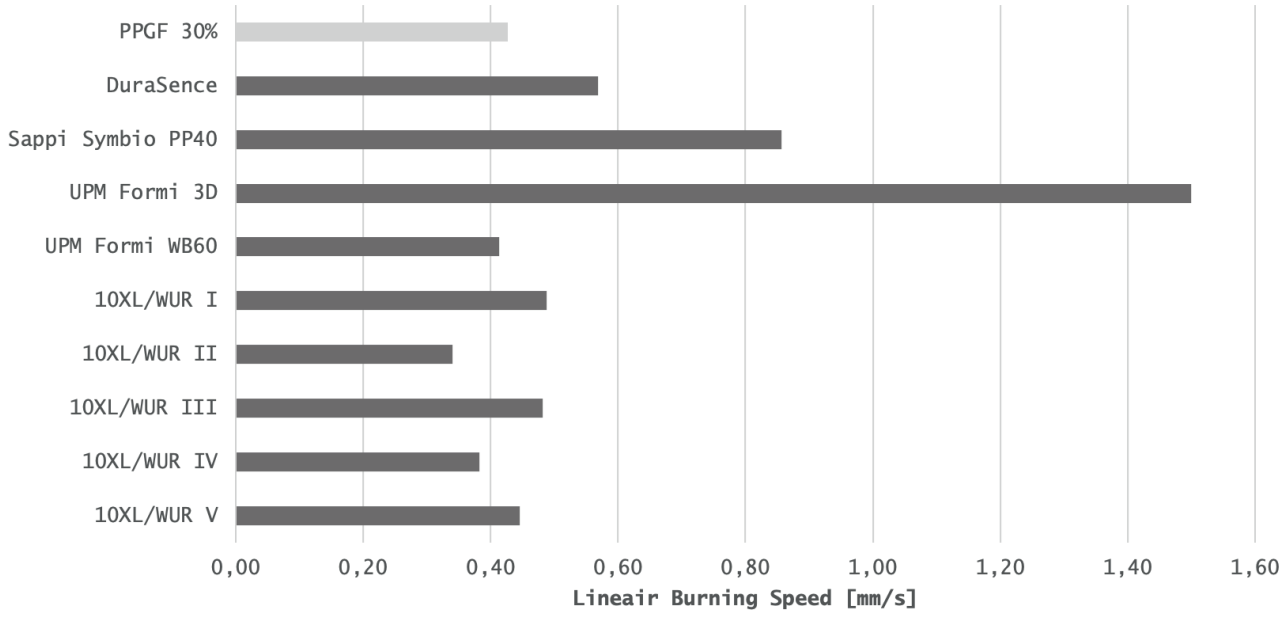


Figure 47: Stress/Strain Curves/ ▲
Calculated stress plotted to
the calculated strain from the
measurements.



◀ **Figure 48: Moisture Intake/**
Measured difference in weight
after submersion in water of
different samples.



◀ **Figure 49: Horizontal Burning speed/**
Measured speeds of specimens when
set on fire.

MOISTURE INTAKE

The absorption of moisture into the extrudate appeared to be very low after submerging under water. Figure 48 shows that on average the moisture intake is around 10 Wt%. Only UPM WB60 and 10XL/WUR batch I showed now measurable differences. It needs to be noted that these experiments were conducted without precise lab equipment, so the precision of the data is not accurate. Still, it gives insight if there are noticeable difference between the materials.

BURNING SPEED

Looking at the results of the horizontal burning test in figure 49, it can be seen that all the 10XL/WUR batches and the UPM WB60 compound score roughly the same. These burning speeds are comparable to that of the GFPP. All batches do not have any commercial flame retardants added. The slowest burning speed was seen in the compound with only wood fibre. The material that burned the fastest was the CFPP UPM 3D, which burned more than 4x faster. Clearly, the cellulose compounds have the worst flame retardancy.

Figure 50: Samples in User Test/ 5 Different samples used for sensory user tests.

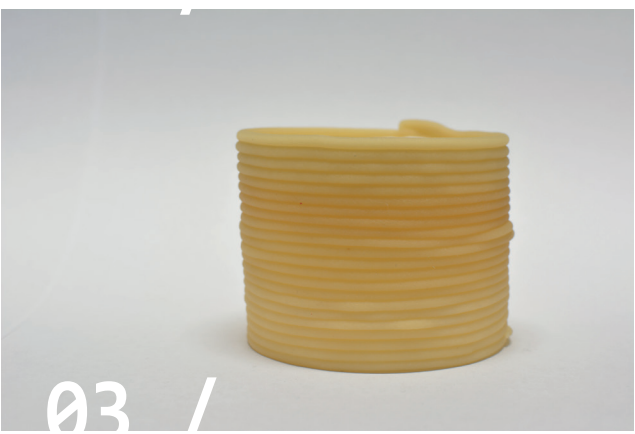
Touch: Hard & some texture
Sound: Hard & Plastic
Aesthetic: Pleasing & woody



Touch: Rough
Sound: Hard & Plastic
Aesthetic: Nice deep colour



Touch: Smooth but some grain
Sound: Hard & Plastic
Aesthetic: Old & Ugly



Touch: Rough & Unpleasant
Sound: Soft & Dull
Aesthetic: Hairy & Rope like



Touch: Sleek & Hard
Sound: Hard & Plastic
Aesthetic: Plastic



03.4/ UNDERSTANDING THE MATERIAL: EXPERIENTIAL PROPERTIES

-

The samples produced from tinkering were used to define some of the experiential properties of the different compounds. The results of this research are divided into two parts. The first part is about the sensorial aspects of the extruded samples like touch, sound, smell and aesthetics. All users (n=5) were handed 5 different samples which are shown in figure 50. The users were first blindfolded to touch and hear the objects and after shown the objects again to describe the look of the samples. The compounds used as shown in figure 49 are:

1. 10XL/WUR Batch II
2. 10XL/WUR Batch III
3. Sappi Symbio PP40
4. StoraEnso Durasence
5. PPGF 30%

The second part of the user test was only about the aesthetics of the flat pressed samples and the meaning/emotion users give to it. As explained in 'Step 1' of chapter 3.1, the users were asked to place the samples in a matrix with defining axis (figure 51) and on a scale from 1-10 (figure 52).

SENSORIAL EXPERIENCE

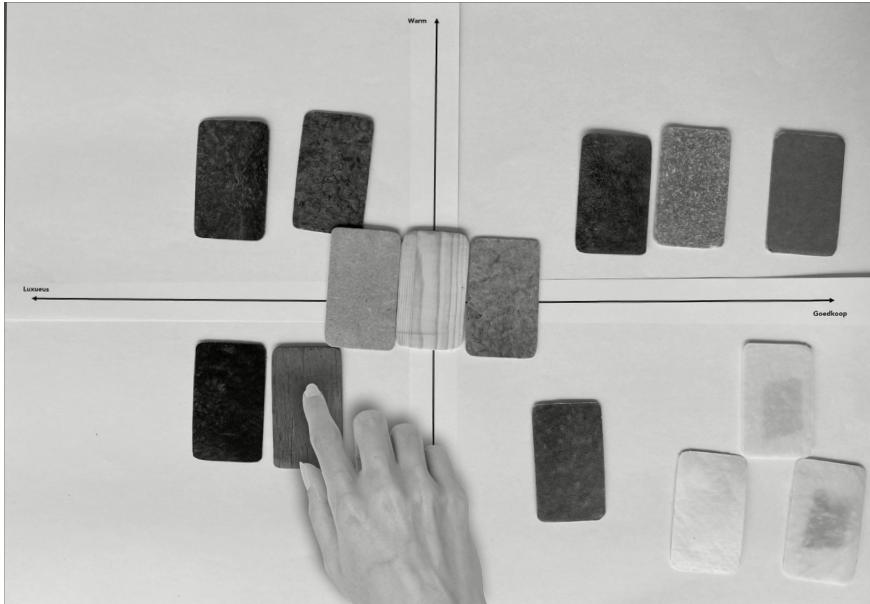
From the interview conducted, the most common answers are shown in figure 50. From the results it is noticeable that all kinds of WPC were perceived with some level of rough surface. More roughness increased the unpleasant feeling for the users. From sample number 4, the test subjects all reacted to it with a sense of disgust. In combination with the soft sound it made, people compared it to hairy rope. The other samples all sounded hard and plastic like.

When the samples were shown to the test subjects, everyone immediately identified the sample with the rough touch. Their idea of rope was combined to the process of weaving (like woven baskets). The samples used in this study were chosen because they were all very different. This was also perceived as such. The users all had their own taste on which they liked or disliked, but an overall conclusion that sample 3 was the most unattractive material. Because of the yellow tone and plastic feeling, it was described as ugly and old. Something that should be thrown away. The brown colours however were pleasant to look at.

A side note to this study is that the user subjects do not have any background in product design or material related. Therefore, most people had difficulties finding words to describe all the materials. It is suggested to do further research if a specific product direction is defined and check if these findings correspond to that of printed concepts.

Figure 51: Samples on Matrix/ ▼
All the material samples placed on one of the matrices to explore the material meaning.

Figure 52: Samples on Scale/ ▼
Samples scale from 1-10 on different scales.



MATERIAL MEANING

To explore the emotion and meaning of WPC, all compound samples were used in this test. Also benchmark materials dark wood, light wood, cardboard and MDF were used (figure 53). The goal of this part of the research is to explore if the WPC evokes some significant emotions or meanings.

The most significant result of the user test about the aesthetics and meaning are shown in figure 54. It shows a clear distinguishing between the CFPP and the WFPP compounds. The darker coloured material are seen as warm and more luxurious. The test subjects even compared it to leather. The lighter plastics were disliked the most, especially because of their yellowish tint. They were clearly identified as disgusting. Similar to the white GFPP, these compounds were seen as chilly and cheap. The CFPP were also seen as plastic material, but the WFPP was not significantly evaluated as plastic or natural material. It was scored somewhere in the middle, but over a wide range.

About the link to a wood-like material, it can be said that the CFPP compounds do not have any association to wood (figure 55). People do identify MDF as a wood-like material. Compound 10XL/ WUR Batch II scored even a little higher, being the compound material being associated the most to wood. For the other compounds it is hard to say if people associate it as wood. There were some users who mentioned that the darker compounds have something away from the bark of the tree. Furthermore, the colour and matte appearance of the WPC gives some natural feeling to it, but it does not give a significant wood feeling to everyone.

When rating the material that is most liked, the dark coloured compounds were scoring the highest (figure 56). The darkest one, 10XL/ WUR Batch III was even liked the most. It is also safe to say that the CFPP materials were disliked the most. Presumably, when printed the material will have some better appearance and are liked better.



▲ **Figure 53: Material Samples/**
Materials used in the user test.

◀ **Figure 54: Scores from Rating/**
Most significant outcomes for the
material scoring.

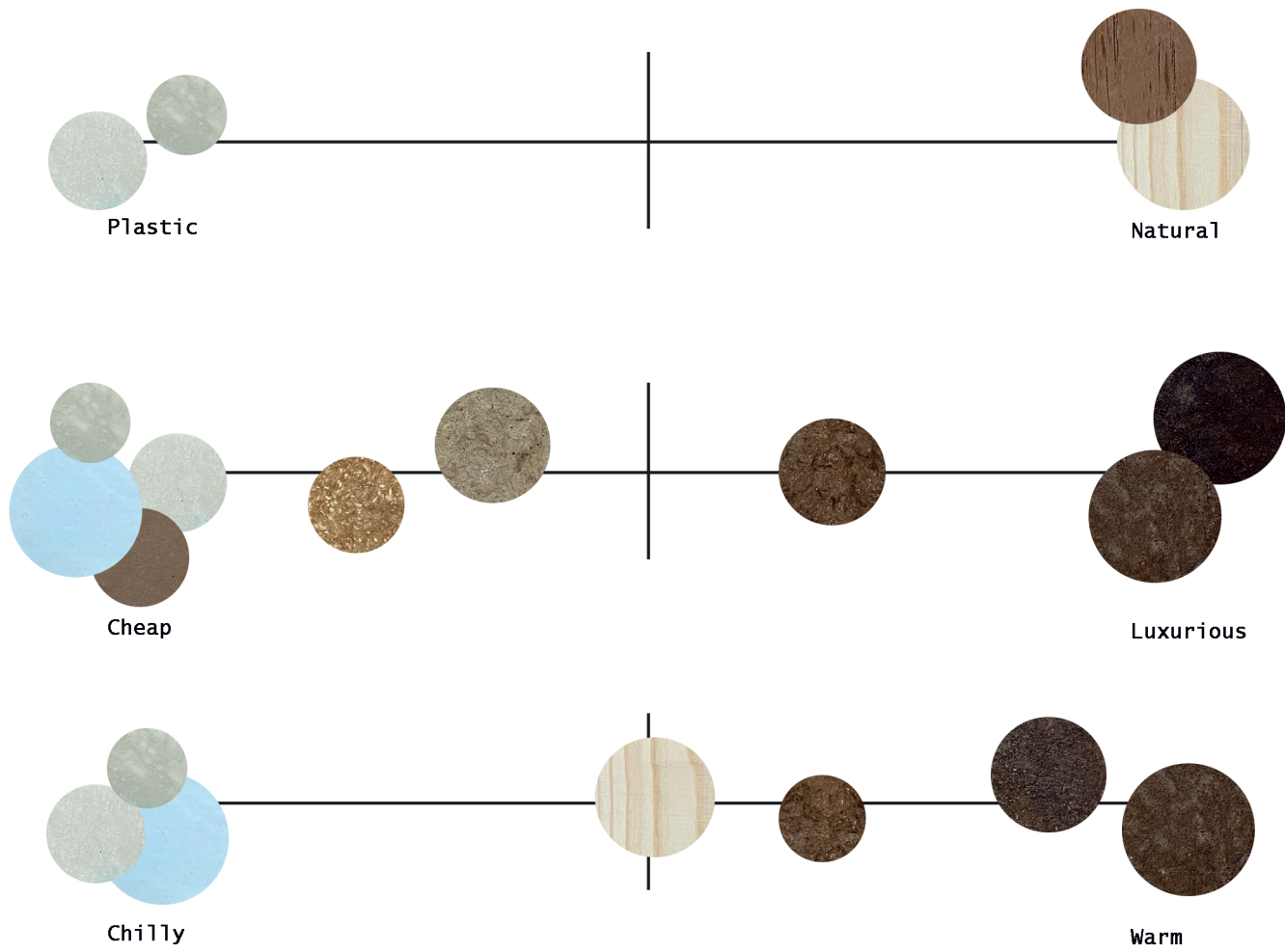


Figure 55: Scoring of Materials/
Scale of 1-10, 1 being least associated to wood and 10 being the most.

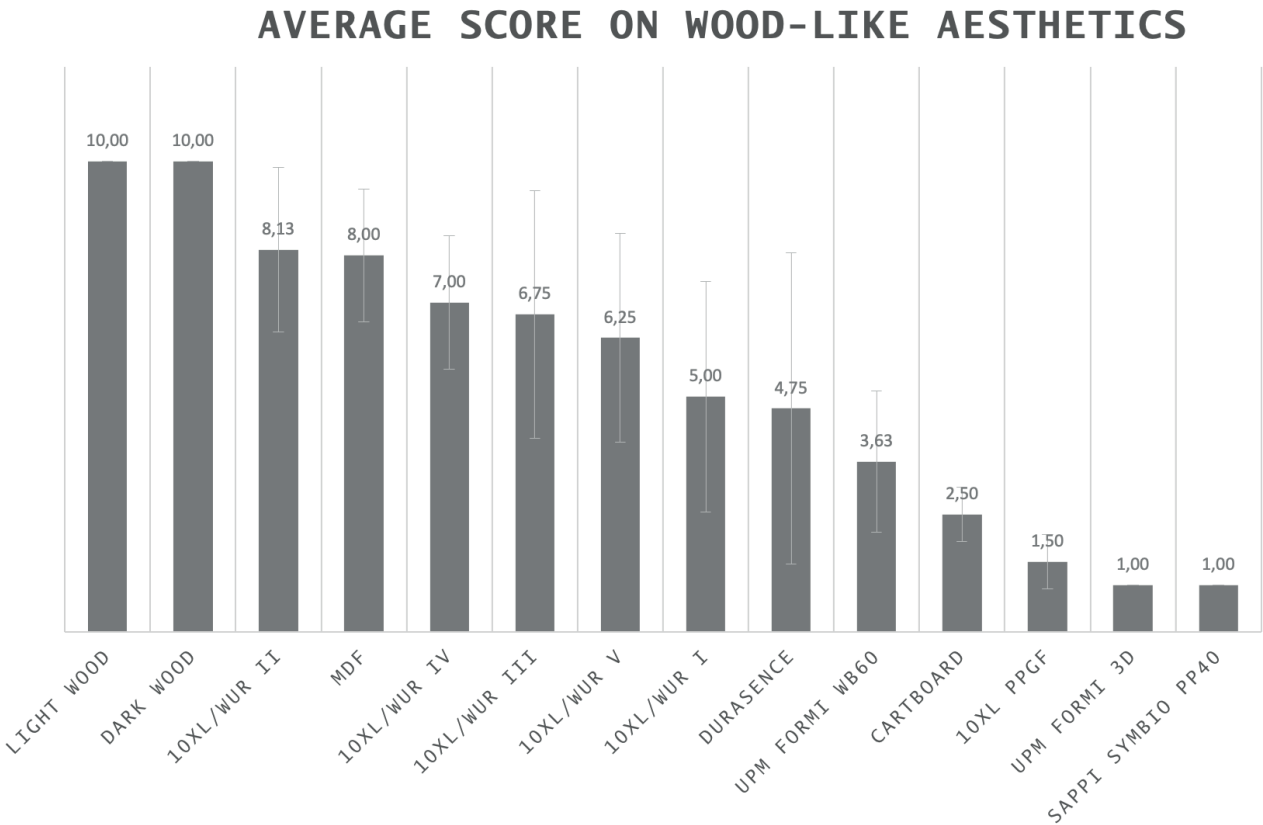
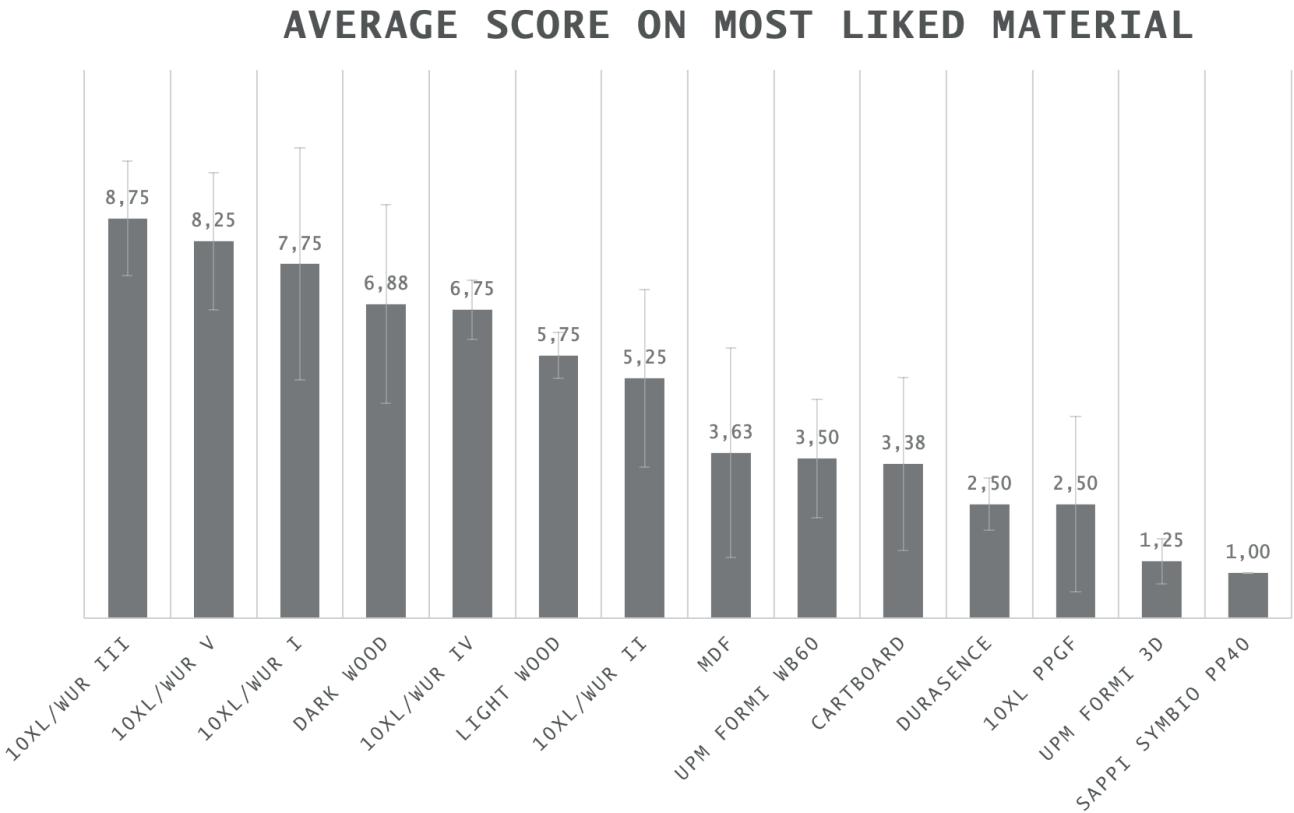


Figure 56: Scoring of Materials/
Scale of 1-10, 1 being least liked and 10 being liked the most.



03.5/ OUTCOME MDD STEP I

-

The goal of the material tinkering phase was to get insight in the character of WPC. The two most important outcomes from the different experimentations are:

1_Processing: WPC compounds with wood fibres are hard to process. They need to be handled at low temperatures at around 200 °C and need drying in advance to reduce the formation of steam while extruding. The material appears to have a very high viscosity compared to GFPP. When extruded, the extrudate is loose, brittle and shows a rough and damaged surface. This rough surface effect is characteristic of the printed material, which is disliked to touch.

2_Aesthetics & Feel: The aesthetics of printed WPC is natural, warm and unique, giving it some reference to real wood. Using only wood fibres, the colours are beige and light and adding lignin will bring out a dark brown. Using only cellulose fibres in the compound will give a white-yellowish tint, which is not very appealing. However, cellulose fibre compounds have better characteristics on the sensorial aspects, having a smoother finish and in feels much stronger and compact. Overall, all WPC feel much lighter than GFPP prints.

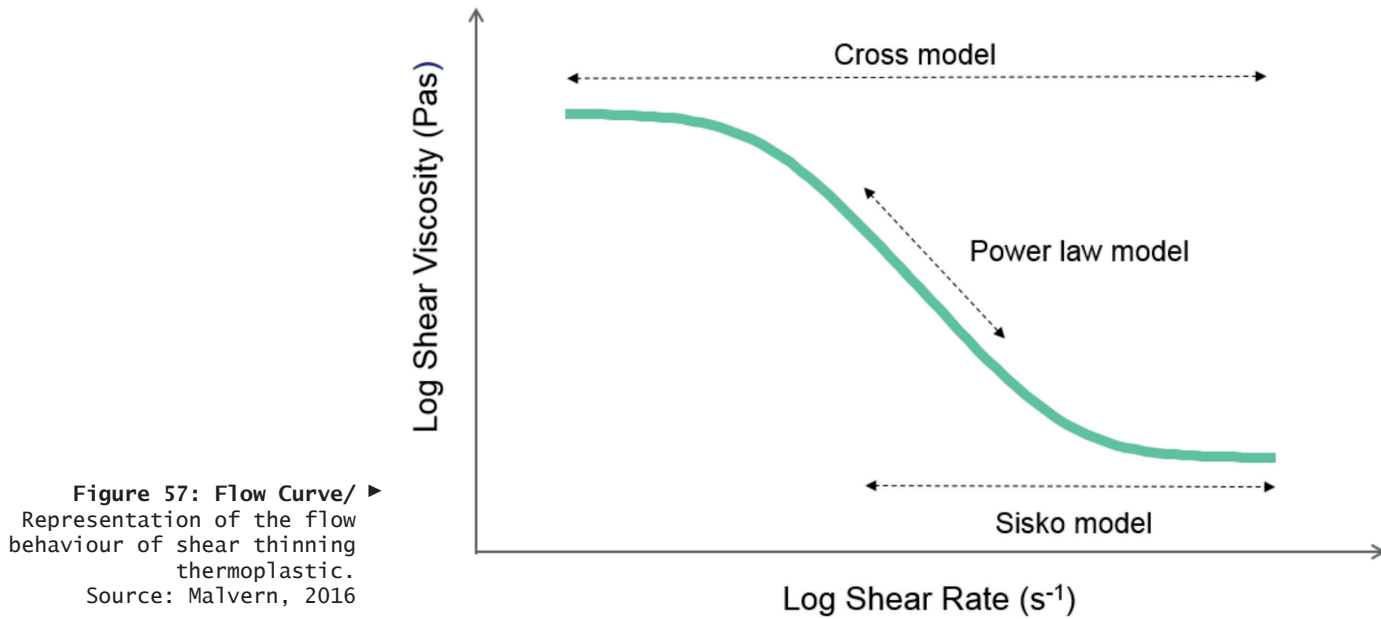
Outcome 1 will be explored further in the next tinkering step of the MDD method: exploring the printing process. All previous findings will help to direct the next exploration. First, this chapter will get into the WPC processing and the phenomenons that were observed. This conclusion will help directing the processing tinkering. The results from point 2 will be used in the following chapter, setting up a material Experience vision.

RHEOLOGY

The melt behavior and fluid dynamics of plastic compounds is called rheology. This was already explored in the first step of material tinkering. To be able to 3D print with any material, its flow and deformation behavior needs to be suited for the process. What was observed in different explorations with WPC was that the compounds from wood fibres did not show any liquid behaviour. Instead, they preserved their palletized form when exposed to hot air. Only when applying force/pressure to it, deformation and some kind of coalescing was observed. Still, in most cases the mixture was not lumped together and was easily pulled apart. It can be implied that WPC from wood fibres do not easily flow. It can be compared to a very crumbly paste like dry clay. Compared to CFPP and GFPP, the wood fibres will produce a compound which has a very high viscosity.

Simply increasing the extruding temperatures is not possible, since maximum processing temperature of lignocellulosic material is already at 200 °C. Higher temperatures resulted in darker extrudate that appeared to have charred and more steam was generated. This can be explained with a chemical transformation for wood fibre degradation. Because the wood does not melt but char at temperatures above 200 °C, the chemical reaction will release the gasses $\text{CO}_2 + \text{H}_2\text{O}$ and the forming of a cellulose chain with a lot of carbon groups giving it a darker colour (vtt, n.d.).

To make it easier to process the wood fibre plastic composites and minimize the extrudate failure, the flow needs to be improved. The fluid dynamics is a very complicated field of engineering, especially



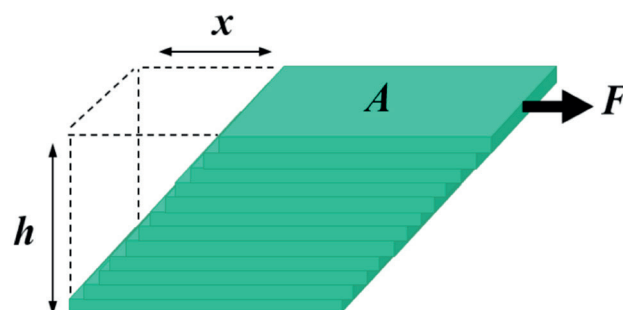
for composites. The thermoplastic materials in the compounds are known to be non-Newtonian, or pseudoplastic fluids (Malvern, 2016). This means the material will show shear thinning behavior, which makes the processing of plastics even more complicated. With a simplified explanation of the theory, some of the issues observed in the material tinkering can be explained.

SHEAR THINNING

The shear thinning fluid behaviour of plastics is the phenomenon of viscosity decrease when the shear (generated by the extruder) increases. For this shear flow, three different sections can be described for the relations between shear stress, shear rate and shear viscosity (see figure 57). This shows that melted plastic has critical window of shear rate at which the flow will improve, which is called the 'Power law model'.

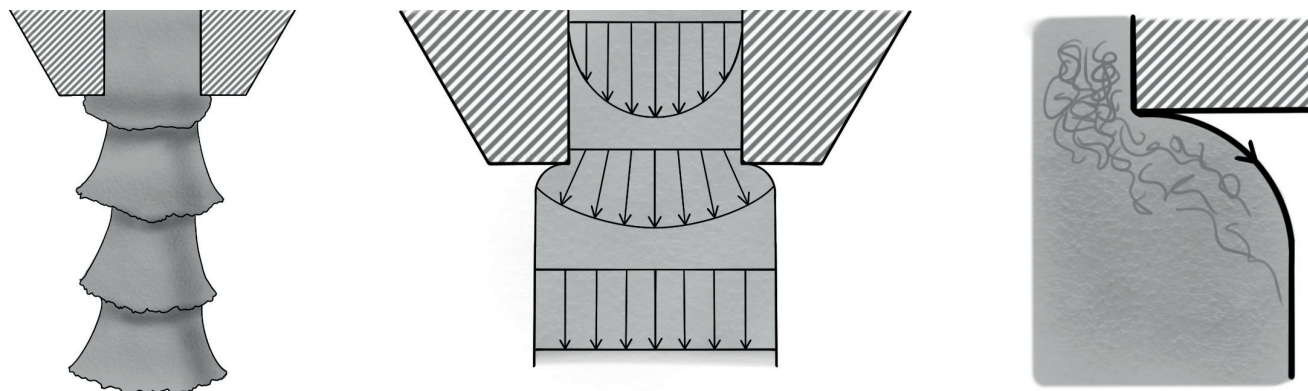
The shear rate in a fluid is the proportion of change in strain within time. The shear flow is

Figure 58: Layer of fluid/ Representation of fluid material sliding over each other when shear is applied. Source: Malvern, 2016



often explained as the sliding of fluid layers over one another with increasing speeds. This gives a visual model shown in figure 58, where the bottom plate is stationary and the top layer is at maximum speed. Now imaging the stationary plane to be a cylinder and being the inside of a pipe. This will create a velocity profile for fluid in a pipe (see figure 59b). It shows the velocity, thus the shear rate and stress, to be maximum in the centre and zero at the wall. The viscosity of the material determines the curvature of the profile. Materials that have little resistance will have a flat curve and the WPC that show high resistance will have a very strong curve. However, due to the shear thinning behavior, this curve will flatten at certain shear rates. Also, the friction to the wall has an influence on this velocity profile. More resistance will also lead to a higher shear rate.

Looking into the rough surface of the extrudate, this phenomenon is called melt fracture. It appears at the nozzle, the die exit of the printer. It is caused due to irregular flow and die swell (Ebnesajjad et Al., 2003). The fracture occurs in a regular sequence, at both slow and fast extrusion rates. Visually, it can be described as a bamboo or palm tree skin (figure 59a). This is called stick-slip behavior at the outlet (Wang & Drda, 1997). By way of explanation, the stress and shear rate between the melt and nozzle wall exit osculates, where the extrudate fluctuates between sticking



◀ **Figure 59: Pipe Flow Behaviour/**
Representation of fluid material
in a pipe coming out of a nozzle.
a) Stick-slip melt fracture.
b) Fluid velocity profiles.
c) High stress at die exit.
Source: Miller & Rothstein, 2014
and Inn et al., 1998

and ripping and a spurt of slipping. The main reason for this is the stress singularity at the die exit, as explained by Miller & Rothstein (2014). The polymer chains and fibres are under higher stresses than they can handle (see figure 59c).

To tackle this problem, the compound can be improved by using polymers with a high melt flow index (MFI) or decreasing the elasticity of the resin (e.g., by adding a small percentage of PE through the compound) (Hendess, 1996). Using a matrix with a high MFI will help the composite the flow more easily and lowering the elasticity will increase the critical shear rate of what the extrudate can handle. As shown already, the WPC materials are very brittle and have almost no elastic region.

Mechanically, there are also a number of changes that can reduce melt fracture, mainly of which is at the nozzle. It needs to be noted, that the long pathway of the melt, going through a long hose and multiple passageways, also has a negative effect on the flowing characteristics. Nevertheless, changing the design of the nozzle by increasing the L/D ratio, with a more conical shape to make it more streamlined, changing the material or coating (like PTFE) on the inside, increasing the temperature in the nozzle region and using ultrasonic waves on the nozzle are all options for improvement.

Another important factor for the flow of the material is the addition of natural fibres. Extensive studies show that the volume fraction of the fibres in the compound have a significant effect on ratio between viscosity of the compound (Vlachopoulos & Polychronopoulos, 2018).

Up until now, it is hard to pick out one single compound that is best. At least, mixing cellulose and wood fibres together does not have any beneficial impact. Therefore, the focus will be on either WFPP or CFPP as a composite material. The lignin powder can be seen as a polymer additive, since it is not a fibre. From these two different types of WPC, both have their unique properties. The CFPP is easier to process, but has a lot of warping and the colour is disliked. The WFPP is much more appealing, but the hard processing and brittle outcome are a big issue.



Colours of WPC/ ▶

03.6/ MATERIAL EXPERIENCE VISION

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To set a direction for further exploration and the design implementation, the material experience vision is the link between the conclusion of the material exploration and the next steps in the MDD process. This second step of the MDD method, as described by Karana et al. (2015), will "express how a designer envisions a material's role in creating/contributing to functional superiority (performance) and a unique user experience when embodied in a product, as well as its purpose in relation to other products, people, and a broader context (i.e., society and planet)".

The outcome of the material tinkering is the base to build this vision on. Looking back at the results, already a few explicit outcomes could be used for



variance



ramification



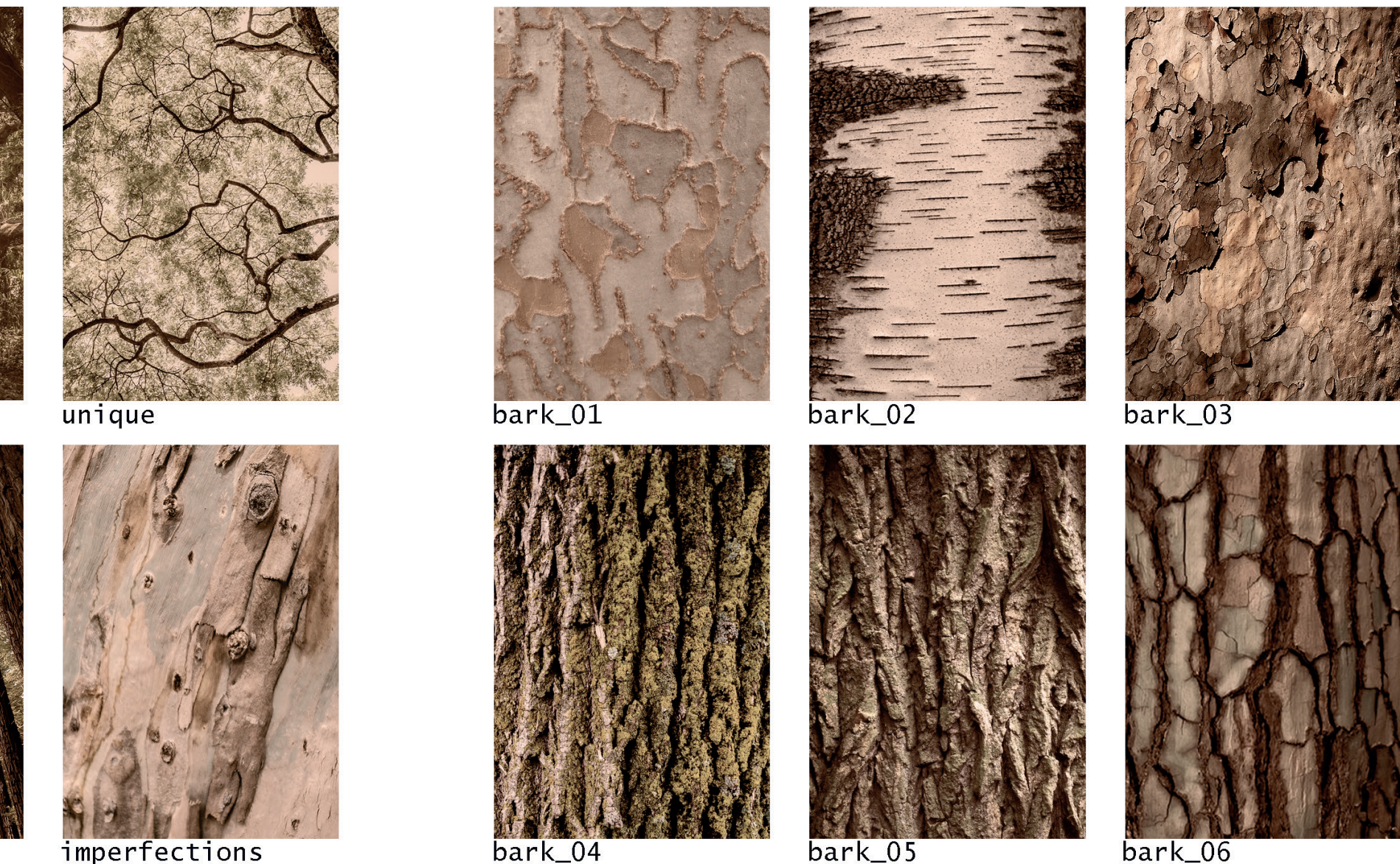
repetatance



lines

the material experience vision. First off, a clear distinguish can be made between the WPCs with cellulose fibres, wood fibres and lignin added to it. On the processing level, CFPP is smooth and compact, but WFPP extrudate is rough and more loose. Aesthetically, adding only cellulose to the PP give it a white-yellowish plastic look that feels smooth, using only wood fibres will give it a dark beige colour with visible fibres in it. The extruded material will also become very rough and unpleasant to touch. Adding lignin will colour it to a very dark brown.

The combination of the natural colour, surface finish, sensorial aspects and the characteristics from the printed material already come close to



unique

bark_01

bark_02

bark_03

imperfections

bark_04

bark_05

bark_06

the criteria of obtaining a wood look and feel. As an analogy, comparing wood and trees to additive manufacturing, some interesting resemblance can be seen (see figure 60). Looking from this perspective, the combination of technique and material is what will create the unique experiential features. Especially when using WFPP as a printing material, it is possible to manufacture one of a kind objects that with a unique character that can not be achieved with other fibre reinforced plastics.

Based on this metaphor to a tree, the vision is as followed: "As a derivative of wood, I want the 3D printed WPC to be seen as unique, imperfect and living material. With its unparalleled material

character and natural feeling, computational design and manufacturing can help to produce unique object with the printed layers reflecting the growth, just like seen in nature."

The Japanese philosophy of 'Wabi Sabi', which is about embracing imperfections, impermanence and incompleteness. This fits well to the printed WFPP composites, because the roughness and imperfectness is what gives the material it's unique character. Accepting this will be useful to find a meaningful implementation where the properties are embraced. These signature properties of the WFPP are moisture resistance (compared to wood), light weight, natural colour, rough printed surface and brittle.

▲ **Figure 60: Analogy for WPC/**
The characteristics of wood in nature and the resemblance of WPC to the bark of a tree.

03.7/ UNDERSTANDING THE PROCESSING

As discussed in the outcome of step 1 from the material driven design research, the processing of the material is very difficult. This directly affects the quality of the prints in terms of layer adhesion, under extrusion, smoothness and overall consistency of the print. The more difficult the extrusion process is, the more likely the print will fail. The two main indicators for the difficulty of printing are the high pressures reached in the extruder (compared to GFPP) and the melt fracture of the extrudate at the nozzle.

To solve these problems, it is either the material properties that need to change (like viscosity of the matrix and the properties of the fibre) or adjusting the execution of the print. Since material engineering is not in the scope of this project, the extrusion and printing was further explored. To put in context of the MDD method, this third step will be about process tinkering.

ELIMINATING MELT FRACTURE

The phenomenon of melt fracture is a well researched issue in the field of thermoplastic extrusion. As explained in chapter 3.5, this issue is caused due to the high shear rates at the exit of the nozzle wall. In the extrusion process, different parameters can be changed to bring down the effects of melt fracture. Some interesting options described by Hennies (n.d.) to test are the temperatures in the nozzle region, the streamline of the extrusion path and the shape and size of the nozzle. Furthermore, the addition of a lubricant in the form of coatings in the nozzle region (so called polymer processing additives

or PPA) that will improve the processing of the material.

The first step of iteration was the installation of a new nozzle. Based on the literature, the design of the nozzle should be more streamlined and have a higher length/diameter ratio to increase the uniformity of the flow. Furthermore, slightly increasing the melt temperature in the nozzle region will help to reduce the viscosity of the material and lowering the shear rates in the extrudate. The combination of these two adaptations was tested on the large extruder to see how it would effect the outcome. The test setup of the nozzle can be seen in figure 62. It is 135 mm long conical shape with a 4 mm diameter and a M22x1.5 adapter to fit on the printer (figure 61). The material it is made from is brass, which has a higher thermal conductivity coefficient compared to steel, so heating up this region will be faster. For the heating up, a heat tracing was wrapped around the nozzle and packed with glass fibre isolation tape. These extrusion tests were performed with the 50/50 compound mix of Sappi Symbio PP40 (40% CFPP) and UPM Formi WB60 (60% WFPP), because they mix well and are most abundant.

Using an increased temperature of 220 °C at the new nozzle, the extrudate still showed the melt fracture (figure 63). The level of rough surface was still the same as seen before. As the last thinner section of the nozzle was a straight section, which is called the land length of the die, it was decided to cut this part off. While this decreases the alignment

Figure 61: Brass Nozzle/ Shape of the nozzle used in the test setup.



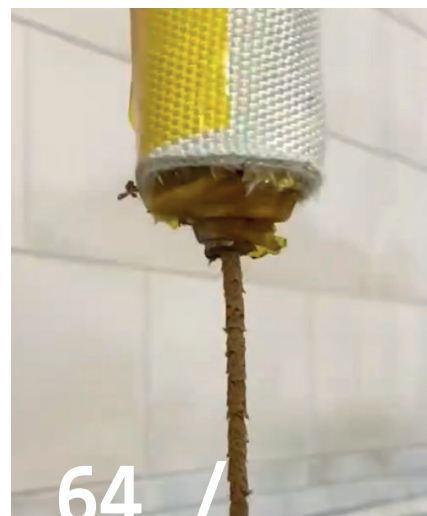


Figure 62: Heated Nozzle/
Nozzle wrapped in hot tracing and isolation band.

Figure 63: Melt fracture/
Melt fracture still present with new nozzle installed.

Figure 64: Shorter Lead Length/
Straight tip of nozzle is removed and showing an improved surface.

Figure 65: High Speed Extrusion/
At high RPM and alarming pressures, the extrudate looks to be smooth.



of the fibres, it would decrease the shear rate in the extrudate (Kramer, 2019). What can be seen in figure 64, is that the melt fracture slightly reduced. Some rough edges and cracks were still seen, but taking off the nozzle tip was certainly an improvement. By varying the RPM and thus the pressure, the best range of values was explored. In the range of settings that is normally printed with (2 - 60 RPM), something curious was observed. At very slow speeds, the extrude appeared sufficient, but this was too slow to print with. Gradually increasing the RPM value did not show any improvements in the surface of the extrudate, it all looked similar. At higher speeds, the pressure at the end of the extruder reached values above 100 bars, where the machine will automatically switch off at 130 bar. But close to these maximum values, the extrudate showed a very smooth string of material, which came out of the nozzle at a very high speed (see figure 65). This phenomenon can be referred back to as slipping, as illustrated in figure 66 (Wagner et al, 2014). The shear stress in the nozzle will drastically drop at these settings and produce a smooth string of material.

▼ Figure 66: Shear stress and RPM/
Representing the effect of screw RPM on different types of flow regions.
Source: Wagner et al, 2014)

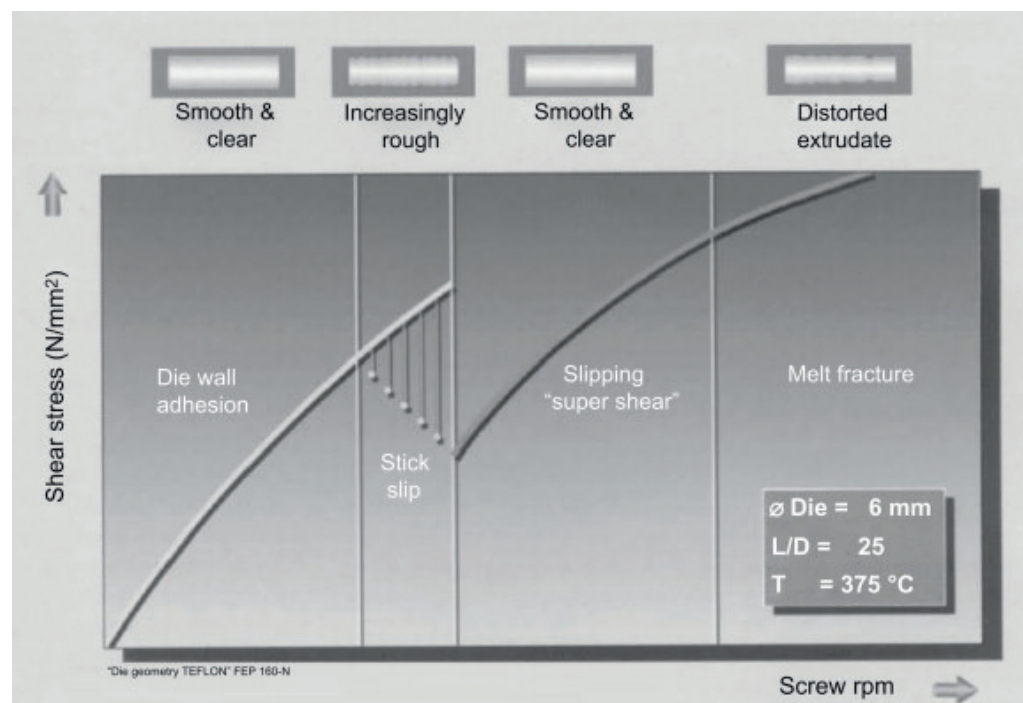


Figure 67: New Extruder (A3)/ ▼
Smaller extruder mounted on a
robot for test printing.



The tests with the new nozzle on the big extruder did not achieve the desired results. Only the adaptation of the nozzle was not enough to achieve a smoother extrudate. Looking back at the samples from chapter 3.2 that were created on the Filabot EX6 extruder and compare it to the results on the large printer, a big difference is the extrusion path distance and number flow obstacles in this path. Where the small extruder has a small nozzle directly at the end of the barrel, the large printer still has a coupling section, connecting to a $\pm 4\text{m}$ long hose and again a coupling section to the nozzle. This extrusion path is not very streamlined, what can increase the irregular flow of the material. For this reason, it was decided to purchase a smaller extruder and mount it directly on the head of the robot (see figure 67). The need for an extension from the extruder will therefore be eliminated. Because the dimensions of the extruder barrel are much smaller (430 mm in length and 25 mm in diameter), only small nozzles have been used (2-6 mm). The screw of the extruder was driven by a 1.5 kW motor with a 1:10 gearbox. The barrel is equipped with 4 heating units controlled by a single PID-control unit and at the nozzle screw another heating element is connected, which can be controlled separately. This last heating element will replace the one on the nozzle itself.

NOZZLE SIZE

The first extrudates on the machine with a 4 mm steel nozzle showed less melt fracture in the form of stick-and-slip, but the result was still comparable to that of the large extruder with the heated nozzle (see figure 68). Changing to a smaller nozzle (2 mm), the extrudate started to look smoother. To test how this would print, the first test cube was printed with the 10XL/WUR compound number II. This test object also had a texture on one side to see the effect of it. The result in figure 69 show however a lot of print failures. Some of them are in the design, since the textured surface had too much unsupported overhang. But on the plane sides there was also a lot of under extrusion and very bad layer adhesion (figure 71). The cooling down of the material was probably too fast for it to print well. The surface of all the prints were still rough as in previous results. Looking at figure 70, some of the layers did not print on top of each other. On these sections the extrudate reveals it was smooth when coming out of the nozzle. However when the layers were printed on top of each other they started to become rough and showing the melt fracture again. Presumably, when the layers are pushed together they are exposed to too much stress again. Printing with a 4 mm nozzle and compound batch IV from 10XL/WUR showed even rougher surfaces (see figure 72). But also when looking at the areas where the layers are not printed on top of each other, the extrudate looks smooth as well. Due to these observations, a larger layer height was tested in the next step.

Not only the wood fibre compounds were tested, also the cellulose fibre compound Sappi Symbio PP40 was tested again on this printer (see figure 75). The discolouration on the smaller extruder showed to be less, extruding a whiter material instead of yellow or caramel colour. To see how the CFPP would colour with pigment added, a blue colour was added for the second half. When printing, the same issues of warping proved to be an issue (figure 74). The forces were so great, the print even broke on the layers itself (figure 73).

LAYER HEIGHT

To make sure the layers don't fracture because they are pushed on top of each other, the layer height of the print was doubled from 1.2 mm to 2.4 mm. This way, the extrudate is more gently placed on top of each other. The extrusion rate is also increased for that, making sure enough material comes out of the nozzle and the printer does not pull on the material. This increase in RPM also showed some improvement flowing behaviour. Because more material needs to be extruded and the extrusion path that is heated is only short, the temperature of the heated elements is also increased (165 °C and 135 °C) to compensate for the heating time. One downside for these printing settings was that the motor was having performance issues. The new model of the test cube was printed with the 50/50 mixture (Sappi Symbio PP40 and UPM Formi WB60). The results in figures 76 & 77 show already a much neater print, but still some issues due to warping and under extrusion.



▲ **Figure 68: Extrudate on A3/**
The first extrudate on the new extruder (A3). Material: 50/50 mixture of WFPP and CFPP.



Figure 69: Test cube V_1/ ▲
First printed cube from 10XL/WUR
batch II compound material and
2mm nozzle.

Figure 70: Close up of layers/ ►
Printed layers showing a rough
surface, but the extrudate showed
to be smooth.



Figure 71: New Extruder (A3)/ ►
Smaller extruder mounted on a
robot for test printing.





◀ **Figure 72: Test cube V_1/**
Partly printed cube with 10XL/WUR
batch IV and a 4mm nozzle.

2 /



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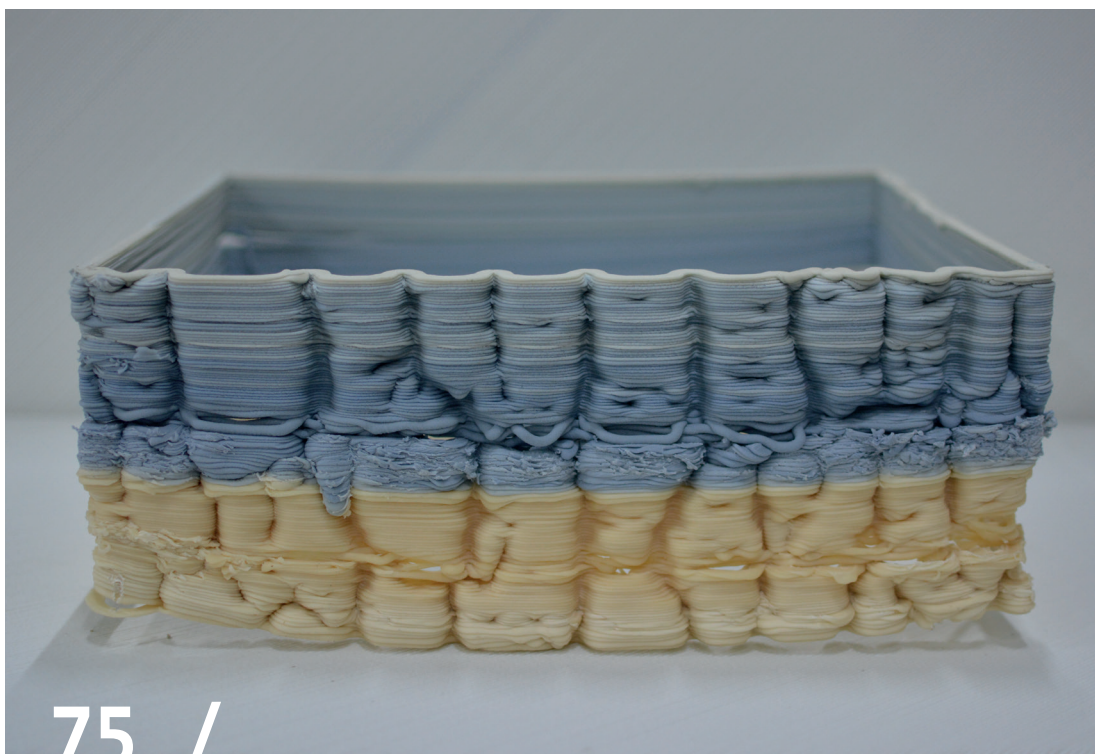


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◀ **Figure 73: Layer Detachment/**
Sappi Symbio PP40 failing due to
intense warping.

▶ **Figure 74: Print failure/**
Sappi Symbio PP40 warping issues.

▼ **Figure 75: Test cube V_1/**
Sappi Symbio PP40 partly printed
cube.



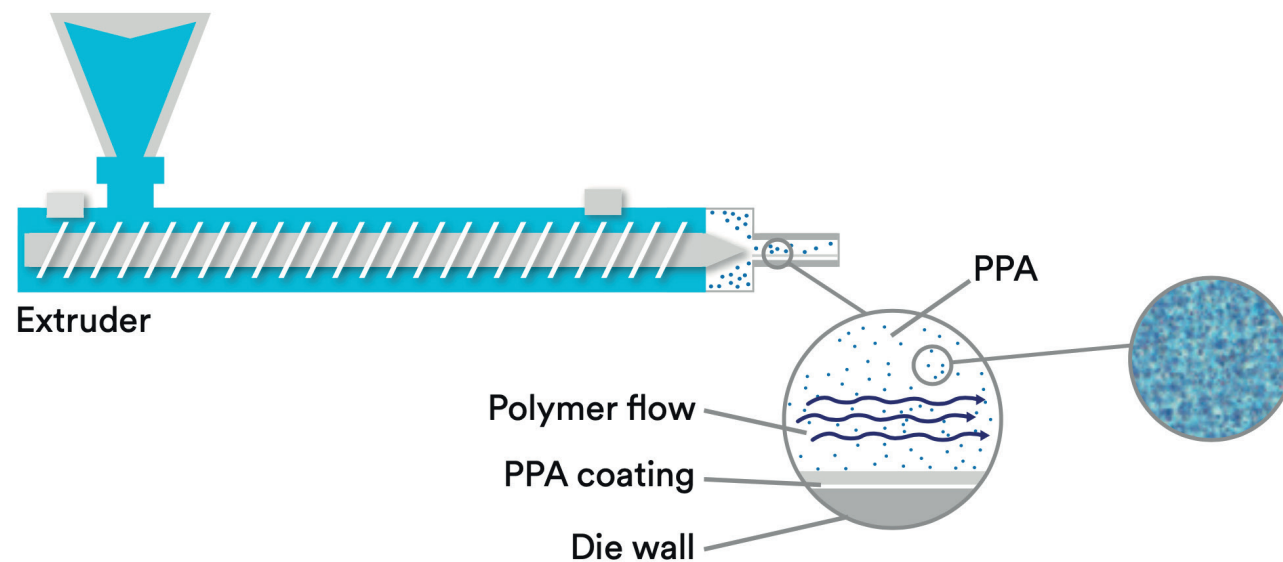
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Figure 76: Test cube V_2/ ►
New print with 50/50 Mixture
material of CFPP and WFPP,
printed with 4mm nozzle and
double layer height compared to
previous print.

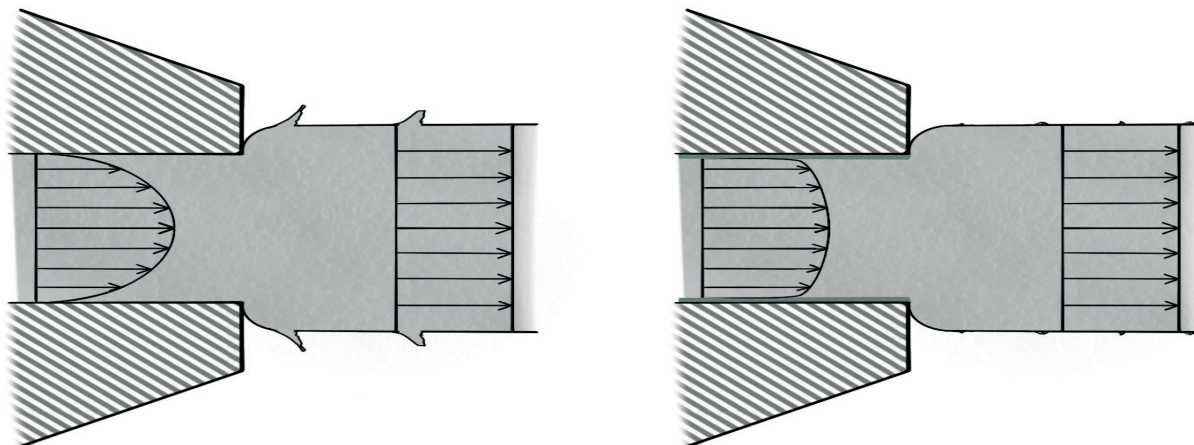


Figure 77: Flat wall of cube/ ►
Print failures still an issue
in this print, showing under
extrusion and warping.





◀ Figure 78: Working principle PPA/ Representation on the working of Dynamar PPA from 3M (source: 3M).



◀ Figure 79: Flow profile of melt/ Flow profile before and after adding PPA to the compound.

POLYMER PROCESSING ADDITIVES (PPA)

The last adaptation to the processing was the addition of the a polymer processing additive (PPA). For this project, Dynamar from 3M was used, which is a fluoropolymer based additive. This type of material helps to improve the manufacturing process of high viscous polymers and eliminate different types of melt fracture. The way this works is that the PPA will create a temporary coating on the metal walls of the extruder and nozzle (see figure 78). With this coating, the material that is extruded will flow more fluidly out of the nozzle. Because friction is decreased, the stick slip phenomenon can be eliminated and the stress from shear in the die is reduced.

Figure 79 shows the difference in flow velocity. To test the effect of adding Dynamar to WPC, 5 wt% was added to the 10XL/WUR compound batch I (which was also printed before the start of this project). The extruder was equipped with the 4 mm steel nozzle, the temperature settings were set to 165 °C - 135°C and the layer height was set to 2.4 mm. The outcome of the cube can be seen in figures 80-83. Compared to the initial cube from this material and other compounds, the layers appear to be much smoother and this resulted in a much better print. The layer adhesion was also good along the print and the cube felt strong and light weight.

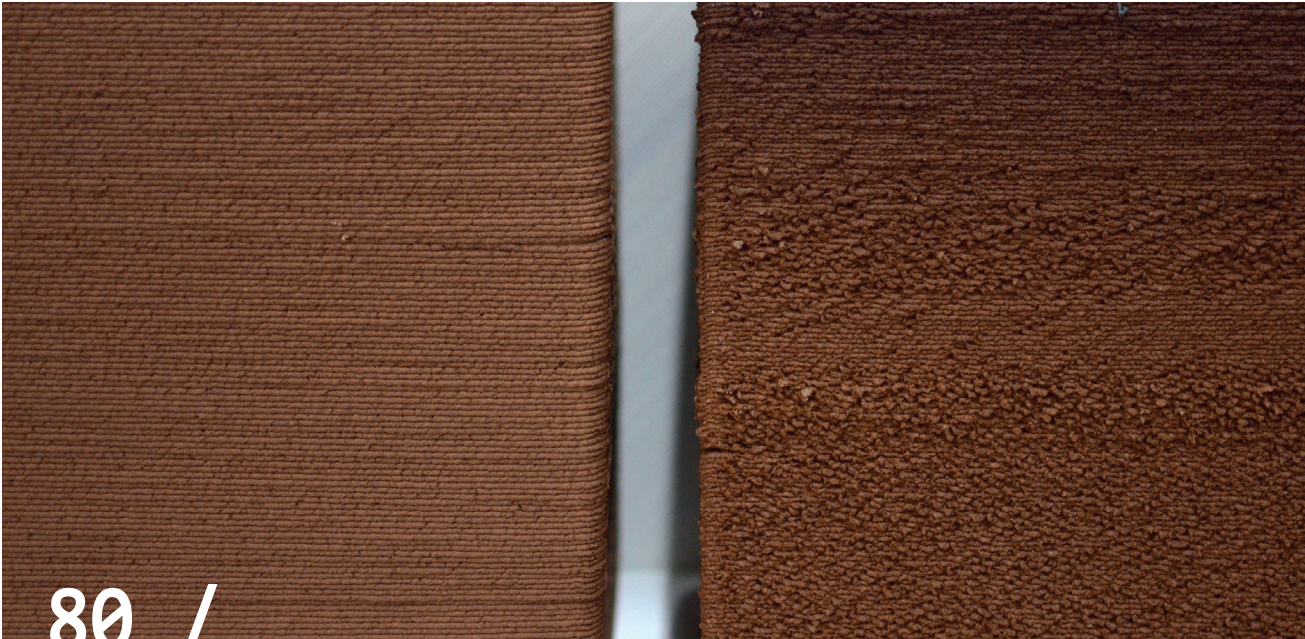
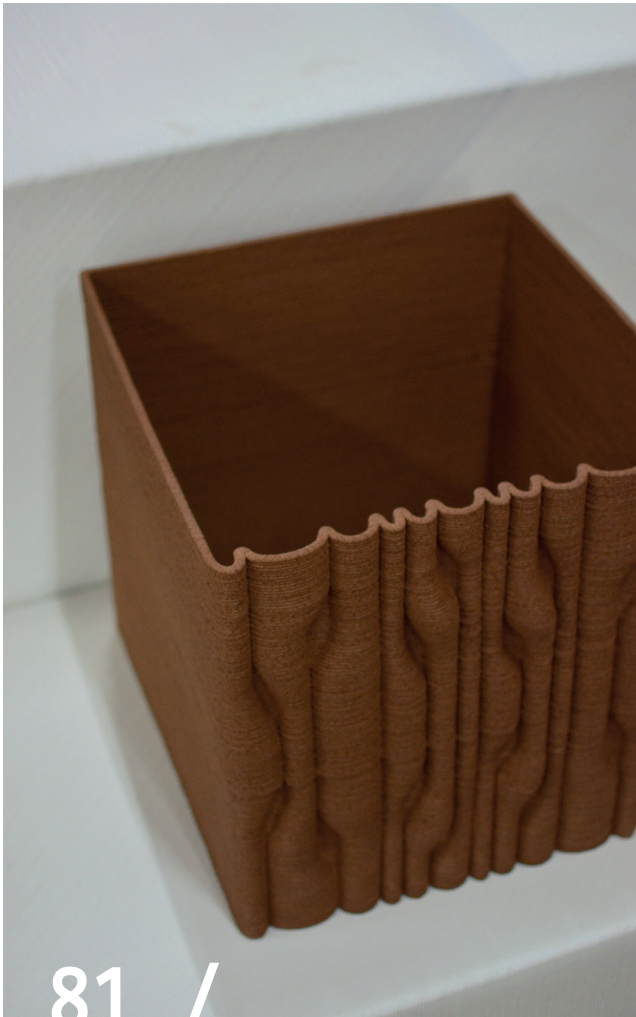


Figure 80: New vs old cube/ ▲
Left: 10XL/WUR Batch I with PPA and higher print layers.
Right: 10XL/WUR Batch I first test print on large Extruder.

Figure 81: Test Cube V_2/ ►
Consistent layers without any failures or warping.

Figure 82: Close up of layers/ ►
The layers are very consistent and much smoother compared to previous prints.



03.7/ OUTCOME MDD STEP III

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Based on the result from step III of the MDD method, the process tinkering, it can be concluded that the best way to print WPC (with wood fibres) is by adding a PPA to the granulate. The cellulose fibre compounds already have very good extruding properties, but showed other print failures like warping and consequently separation of the layers. Other parameters that lightly improve the printing process are the small diameter nozzles (4-6 mm), the increased heating of the nozzle region, the shorter extrusion path and high pressures.

A remark on the new test extruder that was used for printing the WPC is that the motor/gear reducer installed showed signs it was not powerful enough. The WFPP compounds tested all have a very high viscosity, so the motor needs to produce a lot of torque to push the material out. The current 1.5 kW motor used was simply not strong enough and overheated very quickly. Reducing the friction to the walls of the nozzle and extruder to improve the flow was therefore essential, so the extruder could still be used to 3D print smaller objects. Upgrading to a more powerful motor would be a logical step. To get feedback on the how much work is supplied by the motor, a pressure sensor at the end of the extruder would be a good indicator. This is already in use on the large printers, so adding it to the smaller extruder will be helpful.

Since material flow is such an important factor in the processing of wood fibre filled WPCs, changing the nozzle material or coating it to get a very low friction coefficient with the extrudate. These kind of nozzles are already implemented in desktop FDM printers (e.g. Zodiac Pro nozzle). It can be tested if using large scale nozzles with low friction materials will eliminate the necessity to add a PPA to the compound. This could presumably save on costs and extra environmental impact of the additive.

Another issue that needs further research is the adhesion to the bed. The WPC materials do not melt down to other materials or to wood. Melting the plastic bed of the printer to the extruded string works a little bit, but the connection of the first layer is not as strong as that of PPGE. The high content of wood fibre in the compound makes it resistant to melting and flowing. Heating it with too high temperatures will start the material to burn. As an alternative, two opportunities can be explored further. One is using a sticking agent, like wood glue for example, to hold the first layer to the bed. Another is to fix the print mechanically to the bed. Using multiple screws is an option, but this often breaks the first layers, increasing the chance for the print to detach from the bed. A better solution would spreading the forces on the first layers from warping on a larger surface area.





SUSTAINABILITY

The sustainability chapter consist of the research to the environmental impact of WPC compared to PPGF compounds. For this research, a life cycle assessment (LCA) was performed together with fellow IDE student Justè Motuzaitè. To estimate the impact of the different materials, a combination of research and measurements was conducted. The different sections in this chapter are based on the different steps of the LCA. It starts with the explanation of the method, continuing with the goal and scope, the life cycle inventory, the impact assessment and concluding with a final reflection on the LCA. The outcome of the research is an indication to find out if WPC is a better alternative for GFPP.

04.1/ METHOD: LIFE CYCLE ASSESSMENT

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For criteria 4 and 5 mentioned in the introduction, a Life Cycle Assessment (LCA) will be created to explore the sustainability aspects of WPC. The LCA will measure the environmental impacts of LSAM with different compounds. The impact of different WPC ingredient compositions will be compared to each other and to 30% GFPP from a post-industrial and post-consumer waste stream. The functional unit that will be used in all models is printing 'one CityGard that will last up to 10 years'. This is a print of a little over 3 hours and weighs 74,5 kg (including waste). The different machines used, which are collectively called the printer, are a 'Hubral' industrial extruder with a 30 kW 'Walt' motor. The robot used is a 'Yaskawa ES 165 with DX-100 unit'. In between is a thermo-heated hose connected to the extruder with a heated couple and at the robot heat to a heated nozzle. The database used for the calculations is the 'Idemat 2021' from Delft University of Technology (maintained by the 'Design for Sustainability group' from the faculty IDE. The impact calculations for the GFPP compounds and the machinery are done by peer student Justè Motuzaitè, who collaborated on this LCA.

Building a LCA consist of 4 steps, which are all iterative (see figure 83). To create a clear focus area of impact that will be assessed, defining a goal and scope will help to provide some boundaries to the research. Secondly, an inventory needs to be set up within these boundaries. In this step, all the data will be collected, which will be used in step 3. This step is to look at the different impacts categories global warming potential (GWP) and ReCiPe. The final step is the interpretation, which is actually important during all steps. LCA is a very iterative process, which develops based on the results found. The interpretation of all steps and choices need to be communicated clear to be able to present evident results.

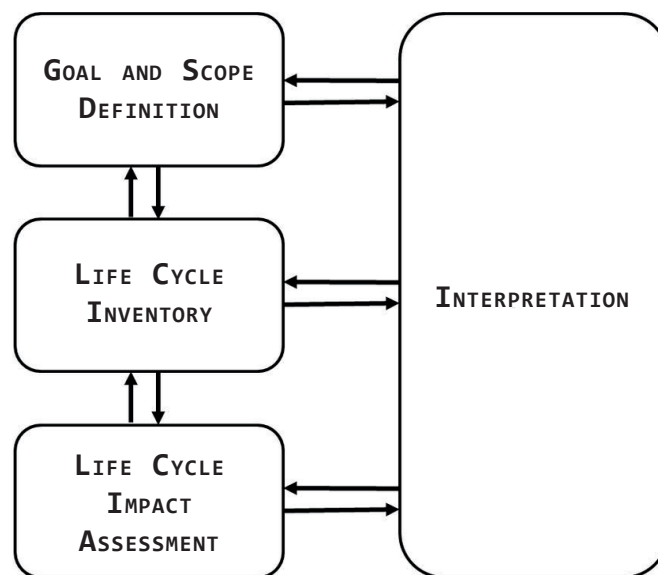
The first step is to define the goal and scope. The goal is to measure the impact of LSAM with WPC and compare it to GFPP, which is the most common printing material in the 10XL production line. This comparison will define what the change of impact is when using different wood compounds instead of using glass fibre polypropylene. To create an outline, a life cycle of the product is created based on the 5 stages (raw material extraction - manufacturing - transportation - use - end of life). From here, a meaningful scope can be defined which will help to set up the inventory. The impact factors that will be considered are the GWP and the ReCiPe endpoints.

Step two is to create the inventory. This is based on the elements that are within the scope of the life cycle. This inventory is divided into different groups: Raw materials (including the compounding of the granulate), transportation, machinery, energy and end-of-life. The eco-intensity of all the different elements of the inventory can be extracted from the 'Idemat 2021' database, or need to be defined with a sensitivity analysis. The value per item on the different groups need to be measured or defined. The masses per item are defined by the wt% of each raw material in the total weight of the print. For measuring the transportation distances, 'Google Maps' was used to draw the route from extraction site to compounding site and eventually the travelled distance of the compounded granulate to 10XL. The energy consumption of the printing process was measured in three different categories, which was base on their purpose but also on their type of power plug. The current for the extruder motor, which had a 63A 400V power connector, was measured from the 'Resotec Redis 310' screen connected to the extruder. The extracted numbers for the current were multiplied with 400V to get the power of the motor. The heating elements

were measured separately, because they connected to a 220V socket controlled by the extruder. The power used by the robot was measured with a 3-Phase energy meter, which was connected to a 32A 400V power plug. The readings from the meter were collected via an Arduino, measuring the time it took to consume 1 Wh. For measuring all the elements connected to a normal 220V power socket, a 'HM8115-2 Rohde & Schwarz power meter' was used. This included all the other heating elements (coupling, hose, nozzle, heat gun) and the cooling from the fans. This data will be collected in a separate file to extract the energy use in MJ. Furthermore, the impact of the machine itself will also be taken into consideration by looking at its build and the materials used for that.

The third step is the impact assessment, to define where in the life cycle the greatest impact will be. The impacts were scored on the global warming potential (in kg CO₂-equivalent) and with the ReCiPe (RIVM, 2011) endpoints methodology. Because not all data is directly in the database, it is necessary to define a comparable value from a sensitivity analysis. These numbers are an educated guess, based on research, reasoning, assumptions and with a high uncertainty in the LCA model. The lower the uncertainty per item, the smaller the range of impact. With the model, also other scenarios will be explored. Different compound formulas can be compared to see the differences in impact and different processing scenarios will be put next to each other.

In every step of the process there is a level of interpretation for the decisions and results of the LCA. These will be discussed for each step in the following chapters. It is important to take the interpretations into consideration in each steps, so it easier to understand where the flaws and inconsistencies are in this study.



▲ Figure 83: LCA steps/

▼ Image of the CityGard/
Source: WereIdvoormorgen.nl



04.2/ GOAL & SCOPE

The goal that was set for this LCA was to compare the impact of printing with WPC to GFPP. The scope of comparison are all the life cycle stages except the consumer use (see figure 85). This part will be excluded, because the 'CityGard' does not consume any energy while in use (which is the case of most printed products by 10XL). It is expected that there will be almost no impact from this part of the life cycle.

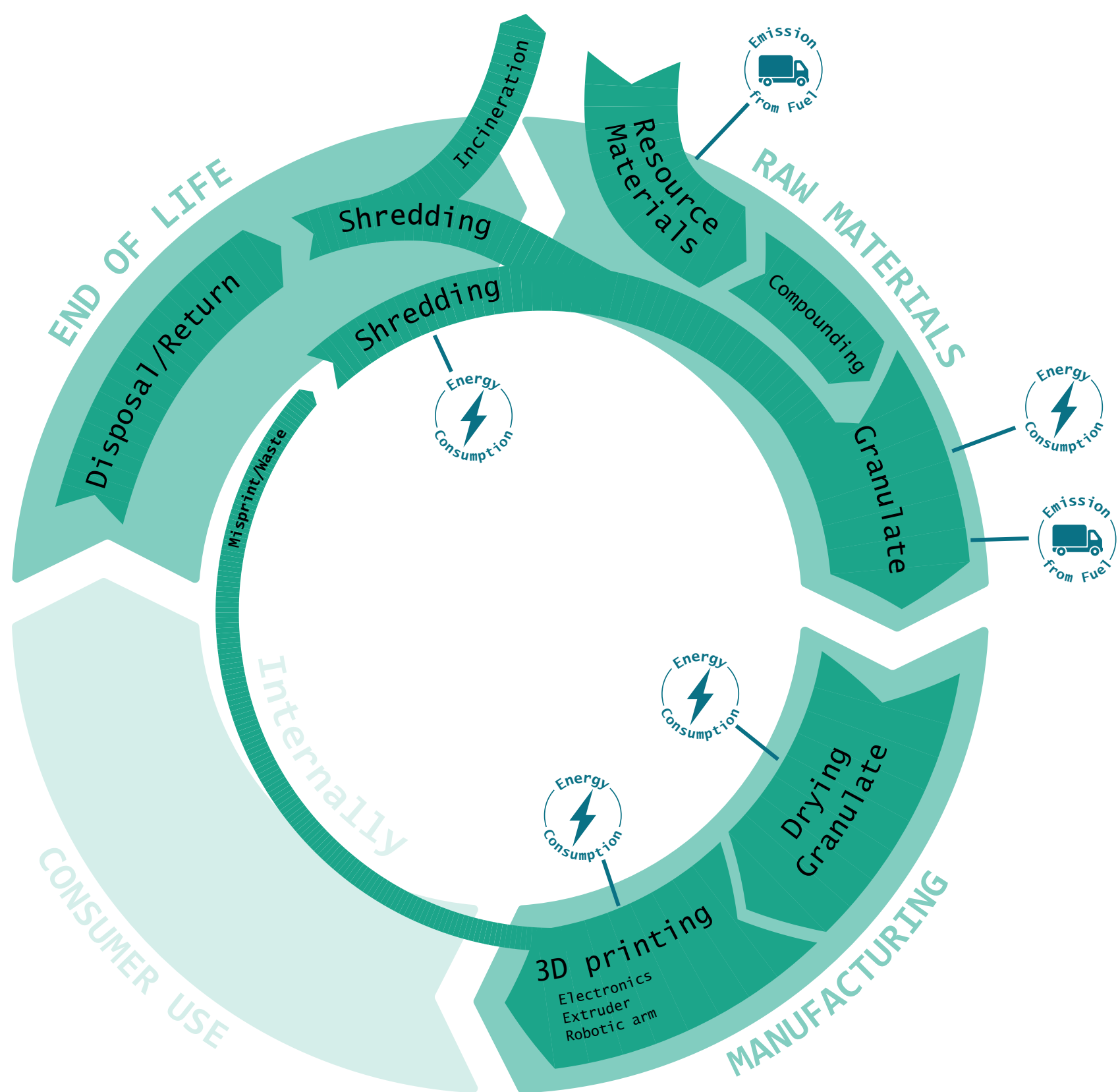
Looking at the sections that are included, the first part is the raw materials. This includes all the resources needed to make a fibre reinforced thermoplastic composite. The process of compounding the granulate is also included, because this is needed so it can be used for LSAM. The four different compounds that will be compared are shown in figure 84. These WPC materials were chosen, because batch I has all three used lignocellulosic materials (wood fibre, cellulose and lignin) and batch II has only wood fibres in it to compare). One important thing to notice is the origin of the raw materials. The different 10XL/WUR compounds were made with virgin PP for the initial tests, but the GFPP compounds are made from a type of downcycled PP. The opposite applies for the fibres, where the wood fibres are a waste source and the glass

fibres in are virgin. These two scenarios will be compared, but it can be argued later on what the comparison is when some compounds share the same resources, like a downcycled or waste PP. The specific compound compositions that will be used to compare is a WPC from virgin PP, compounded with only saw dust and one with a combination of saw dust, cellulose and lignin. From this model, different variations can be examined. These two recipes will be compared to GFPP, one that is post-industrial waste (PIW) and one that is compounded from post-consumer waste (PCW) PP. The biggest differences are the type of PP used (so virgin, post-industrial and post-consumer), the type of fibres and the fact that only PIW does not have to be compounded before it can be printed.

The second Part of the scope will be the manufacturing process of the prints. For WPC, it includes the drying of the granulate and the printing process. This section consist of the energy consumption of all the machines and the impact of the machinery itself. This gate-to-gate production site of 10XL will show where the company should focus on to improve. The focus will be on different utilizations of the printers and comparing different scenarios.

Figure 84: Four materials in LCA/ ▼
The four different compounds that will be assessed in this study.





▲ Figure 85: Life Cycle to review/
Overview of scope to explore in
this LCA, excluding the use.

04.3/ LIFE CYCLE INVENTORY

The inventory of the LCA is build up from five different sections, directly taken from the scope. These are the raw materials, transportation, machinery, energy consumption and end of life. For each section, the most relevant interpretations are discussed in the following chapters.

RAW MATERIALS

Initially, creating an inventory for the raw materials used in compounding the granulate is the most comprehensive part. Due to confidential information about material recipes and the wide range of products used in this industry, it is hard to find all figures in the material database. Not everything is included, so with extra research an educated guess needs to be made. Using this so called sensitivity analysis, a model that is close to the reality can be developed. It can give enough insight in the environmental impact, but it is never exact. The interpretation for the WPC recipe consist of the matrix material PP and wood fibres (wood dust and/or cellulose) with the possible addition of ligin. Neccesary additives are a binding agent and a flow enhancer.

The main ingrediens of a WPC are the PP and the wood material. For this model, virgin PP was used since all compounds used in this research did not include any rPP. The wood material consist of wood fibres, cellulose fibre and lignin powder, which all are not included in the 'Idemat 2021' database. Therefore, a sensitivity analysis is needed. For the wood fibres, saw dust that is collected at wood processing plants can be used for the compounding. Since this is a waste product, the impact of this material will be zero. The cellulose and lignin powder however, are extracted from wood through a chemical process. Therefore, these two ingredients do have a environmental impact. One of the raw materials that was used for the 10XL/WUR test compounds was from a company called Borregaard. This company conducted a LCA for the production plant at Sarpsborg (Ostfold Research, 2009 & 2016). This research concluded that the global warming potential (GWP) for cellulose production was 622 kg-CO2 eqv./ton dry matter and for powdered lignin 749 kg-CO2

eqv./ton dry matter. The data included was for the scenario of cradle-to-costumer. Since the unit needs to be in kg-CO2 eqv./kg, these numbers need to be divided by a factor of 1000. Using these values directly is possible, but doing a sensitivity analysis that is close will help to evaluate all the midpoint in the database. The extraction of lignin and cellulose is done at paper production plants (where they create chemical pulp from wood). The LCA flowchart for the production of consumer board at Borregaard, shows that around 90% of the impact comes from the pulp production. Looking at the 'Idemat 2021' database, two values are referable, with the assumption that the company borregaard uses sustainable foresting (as they state on their website). These are the 'Idemat2021 Paper, woodfree uncoated (virgin paper), FSC & FSC 80 gr/m2'. Taking the average of these values and using a 90% cut, it comes down to an impact of 0,65 kg-CO2 eqv./kg. For lignin, no good reference was found in the database. What is known, is tat the lignin powder is extracted later on in the process. The data from the Ostfold Research (20016) also shows that the GWP impact of liginin powder is greater than that of cellulose, so the values from the sensitivity analysis need a factor to represent this difference.

The additives used in the WPC inventory are the binding agent and the flow enhancer. Also these materials don't have a direct reference in the database. Based on their chemical composition and the processes for creating these materials, a sensitivity analysis was conducted. For the binding agent, the specific material that is used is maleated polypropylene. This is made by breaking down the PP polymer chain with the use of peroxide. In this mixture with free radicals, maleic acid is added to form the MaPP. Accordingly, looking at the database, values are given for polypropylene, hydrogen peroxide and maleic anhydride. Based on the patent of the MaPP used from Westlake chemicals (Roberts et al., 1994), which is called Epolene E-43, the chemicals used in the production are around 1wt% peroxide and 10wt% maleic acid. Based on this, the impact value of the binding agents was determined. Secondly, the

flow enhancer was analyzed in a similar way. The ingredient used in the compounding and thus this model is called Aerafin 35, produced by Eastman. It is a propylene-ethylene based amorphous polyolefin polymer, so an unstructured combination of propylene- and ethylene units. Similar to this, ethylene-propylene copolymer, also called EPDM, is a rubber polymer too build up from these same units. This material is included in the database. By using a high uncertainty, it can be added into the inventory of the LCA.

TRANSPORTATION

The transportation section includes the shipment of the raw materials to the location for compounding and the transport of the granulate itself to the 10XL production location. For each of the raw materials, a supplier has been chosen based on the 10XL/WUR test compounds I & II to define the locations. The company that will create the pellets is Transmare Compounding.

MACHINERY

The impact of the machine components is calculated by measuring all the parts and assigning a material to it (executed by Justè Motuzaitè). The 3D printer consist of multiple machines, primary being a Yaskawa ES 165 robotic arm and 100DX computer unit connected to a 30kW single screw extruder. The robot consist of the metal arm which is moved by 6 different motors. The 100DX unit houses all the electronics and PCB's. The extruder unit is build up from a screw and barrel, connected to a large gearbox with 30kW motor. It also houses some electronics in a steel plate box. Furthermore, the printing bed and all the wiring is included. The weight of all the parts has been assessed using SolidWorks. The manufacturing of all the parts is also taken into account.

ENERGY

To include the power consumption of the LSAM, the energy was measured during printing. Based on these measurements, each step of the process can be accessed to find where the biggest impact is. The different steps that were defined for printing with WPC and the corresponding

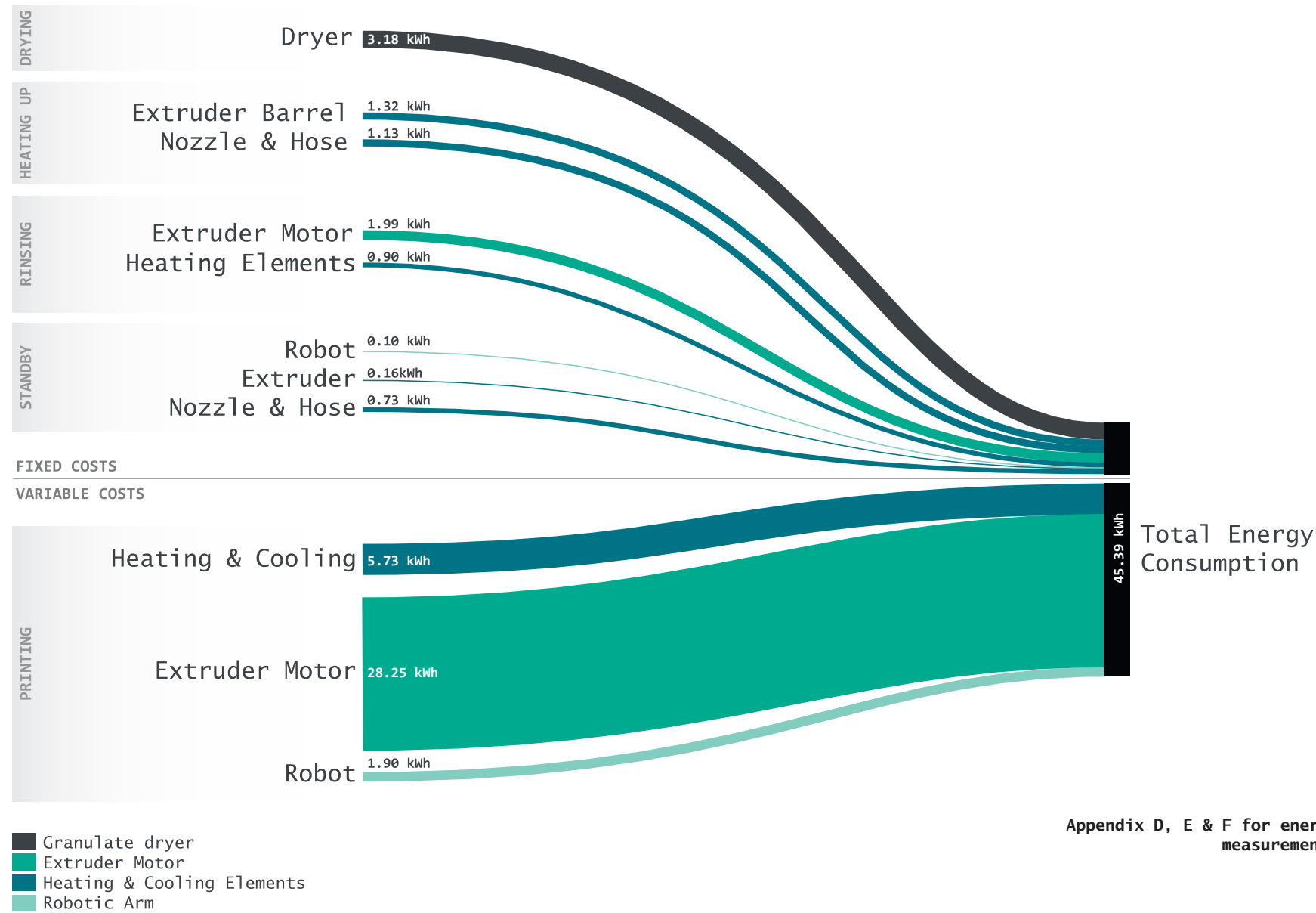
energy consumption can be seen in figure 86. It is divided in the different phases during printing. The drying, heating up of the machine, rinsing out other material and standing by are fixed costs that take almost the same amount of time. The variable costs are in the printing time them self.

What the results are showing, is that 81% of the total energy consumption is during the printing itself, especially extruding, which is a significant factor of 62%. The printing time for this test was 3.2 hours. Drying the compound for 3 hours also has a serious contribution of 7%. The steps of heating up, rinsing and standby all took 0.5 hours, but these are not very energy intensive. Especially when the print will take longer, this part will be negligible compared to the printing itself.

END OF LIFE
For the disposal of the print, the situation that will be assessed is that the CityGard will be incinerated for electricity. Because it is assumed that the print will be there for 10 years at least, it is not sure if the object will be returned to 10XL and the material can not go into a municipal recycling stream, recycling the CityGard will not be taken into consideration.

Looking into burning the material, two elements are included in the inventory. This because not every raw material can be found in the waste treatment section of the database. Therefore only burning PP and softwood (12% MC) is included. The PP is seen with all the additives included and for the softwood the same for all wood based materials.

▼ **Figure 86: Energy Consumption/**
Flow diagram of the energy
consumed by the printer for one
CityGard (3.5 hours of printing).



04.4/ IMPACT ASSESSMENT

With the inventory fixed, the impact of printing one 'CityGard' on a large printer can be assessed. The impact will be estimated for the global warming potential and scored with the ReCiPe method. Based on the outcomes, different scenarios and utilizations will be discussed for each life cycle or impact category.

GLOBAL WARMING POTENTIAL

The outcome of the LCA for WPC and GFPP (figures 87-90) shows that the material section is the most important factor for environmental impact. Presumably, because the printing volume is largely increased with LSAM, the impact of this stage becomes much more significant compared to FDM desktop printers (Faludi et al., 2015). A big influence for this outcome is the use of virgin PP as a matrix material. This material has a large CO2-equivalent footprint, even for this scenario where only 32 wt% of the compound is actually virgin plastic. The fibres have a much lower impact, or even none in the case of using collected saw dust. Independent from the specific compound recipe, a WPC with 60% wood based material will never exceed the impact of the virgin PP. Compared to 30 wt% glass fibre, using 60% cellulose fibre (which has the largest impact from all the wood fibres)

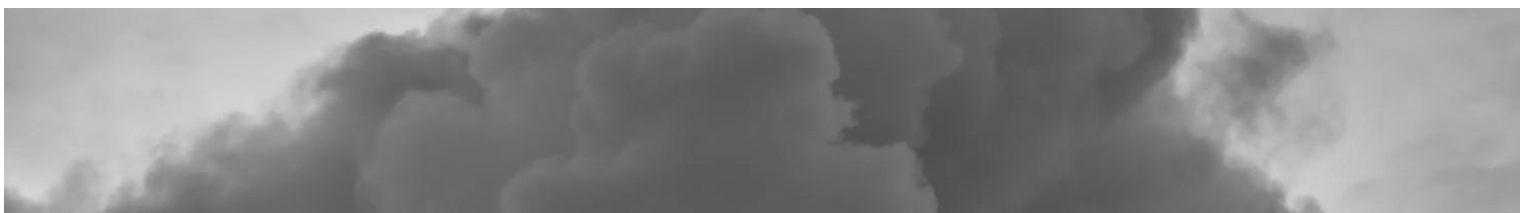
is a big improvement. Not only because the CO2 footprint of the fibres is smaller, but also because the amount of PP will decrease. The additives for binding and flow have the highest impact factors of all the raw materials. Still, because the weight percentage of these materials is low, the total impact is only a small portion. Due to the high uncertainty, it is also not sure how much the exact impact will be. What also is a significant factor in the material section, is the compounding process of the granulate. This needs to be done before it can be printed, so it is an inevitable step in the life cycle. The process happens in a twin screw extruder, where all the raw material are mixed together and then extruded and chopped up in small pieces, or a shear mixer, where all the raw materials are merged together.

The second biggest impact is from the energy consumption of the printer. The measurements showed that the primary element is the extruder, with the extruder motor in specific. During printing, there is an almost constant energy consumption measured for the extruder with only slight differences in for different printing speeds. The global warming impact of the print is therefore linear increasing with the printing time. Therefore, printing faster would reduce printing times,



without increasing the energy consumption. Due to the fact that thermoplastics like PP are shear thinning materials, higher pressures will decrease the viscosity of the material and therefore make it easier to extrude the material. This is also seen when comparing the measurements of printing with WPC and GFPP. The viscosity of the material is an important variable that effects the energy that is consumed by the extruder. The WPC have much more resistance to flow than the GFPP, this property reflected back in the current consumed by the extruder motor. Inevitably, this means that the wood fibre material has a higher energy intensity in the manufacturing section.

The impact of the end-of-life stage seems to be almost zero, but looking into the components, it appears that the incineration of PP is one of the biggest contributions in this model. Only because incinerating the wood scores as a saving effect, the total impact scores very low. Still, the fact that this single element in the end-of-life has a large effect, it can be very meaningful to look at different solutions like recollecting the disposed products and shred it so it can be used in new prints.



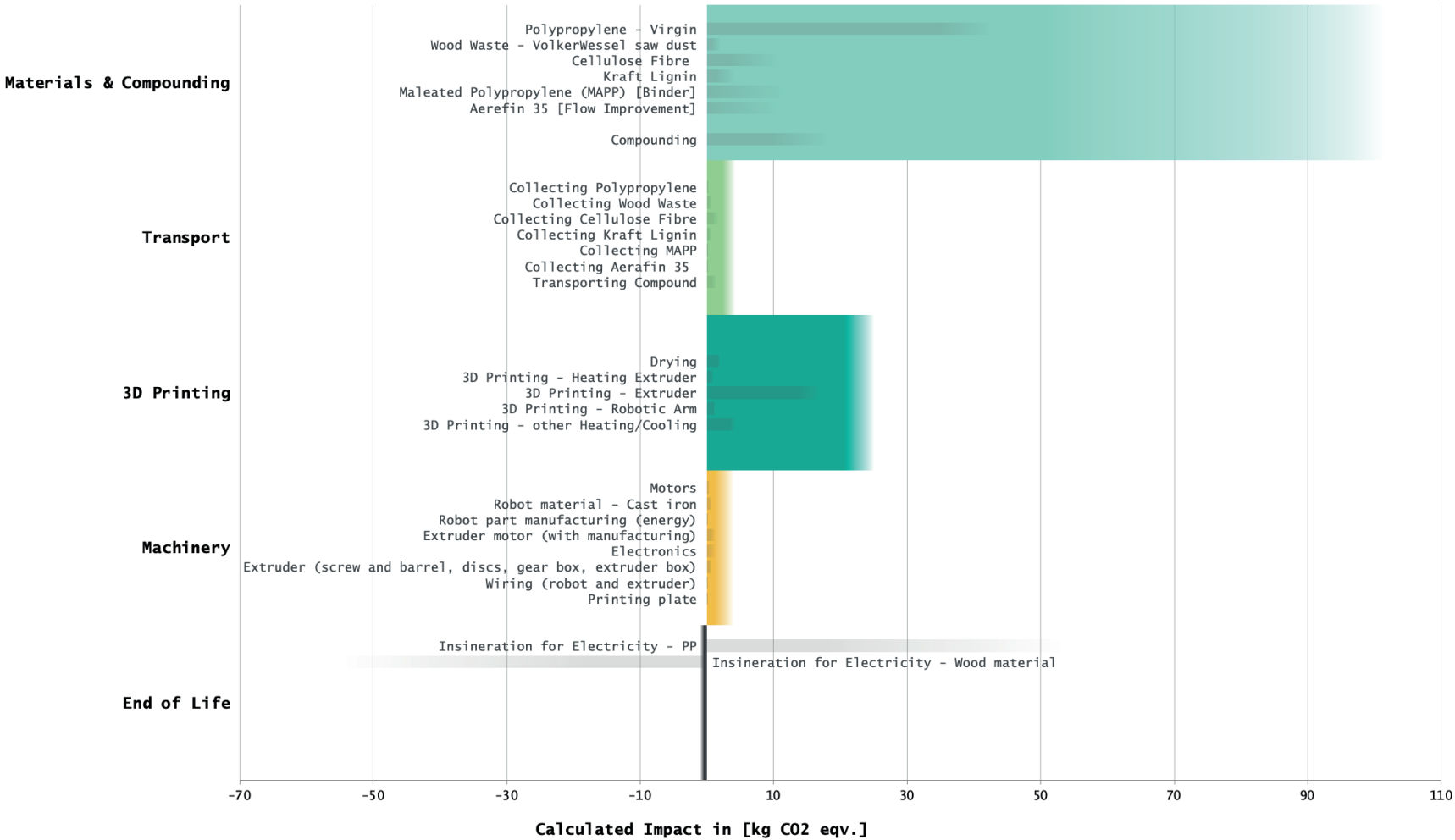


Figure 87: GWP of WPC I/▲
Impact assessment for 10XL/WUR
Batch I compound.

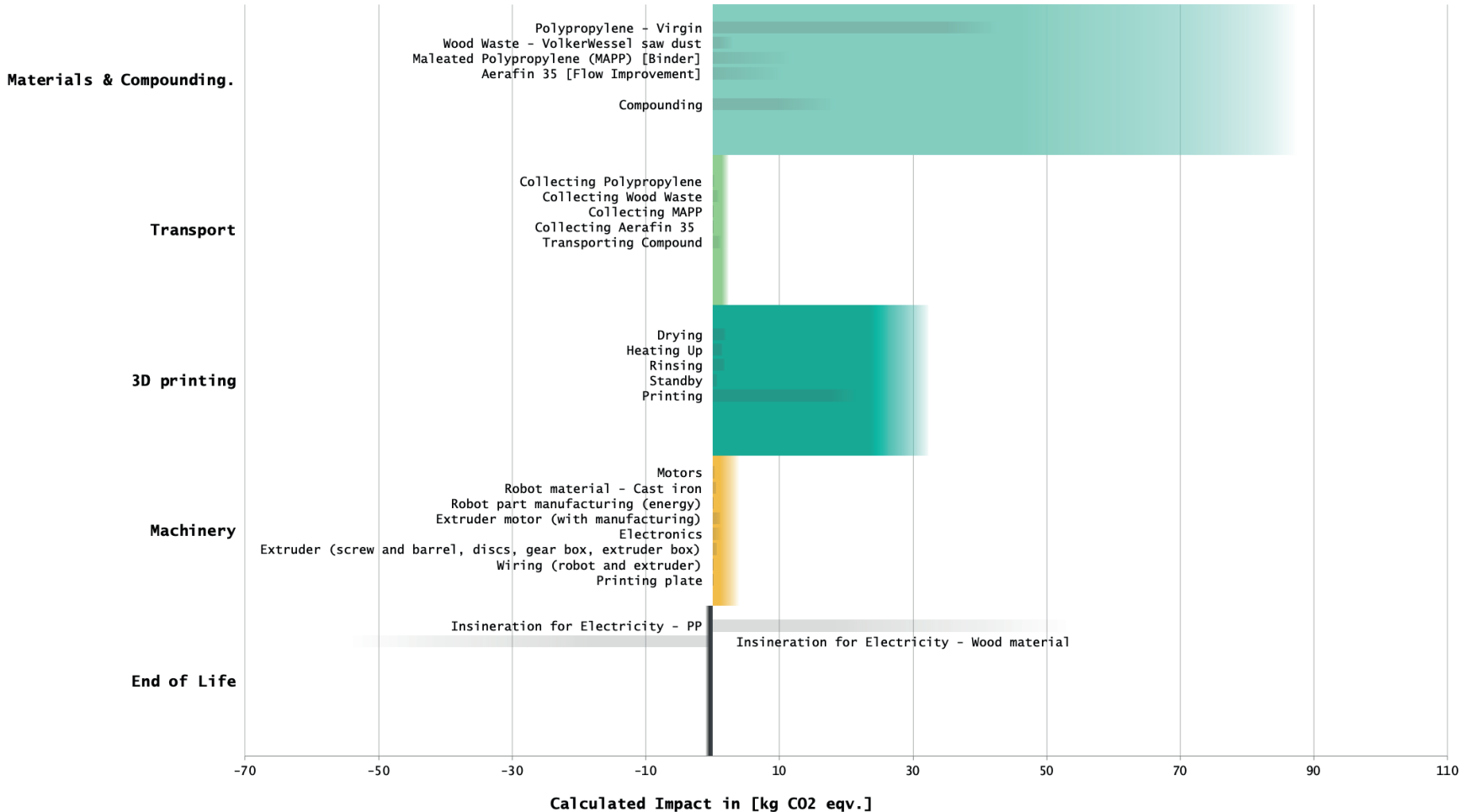
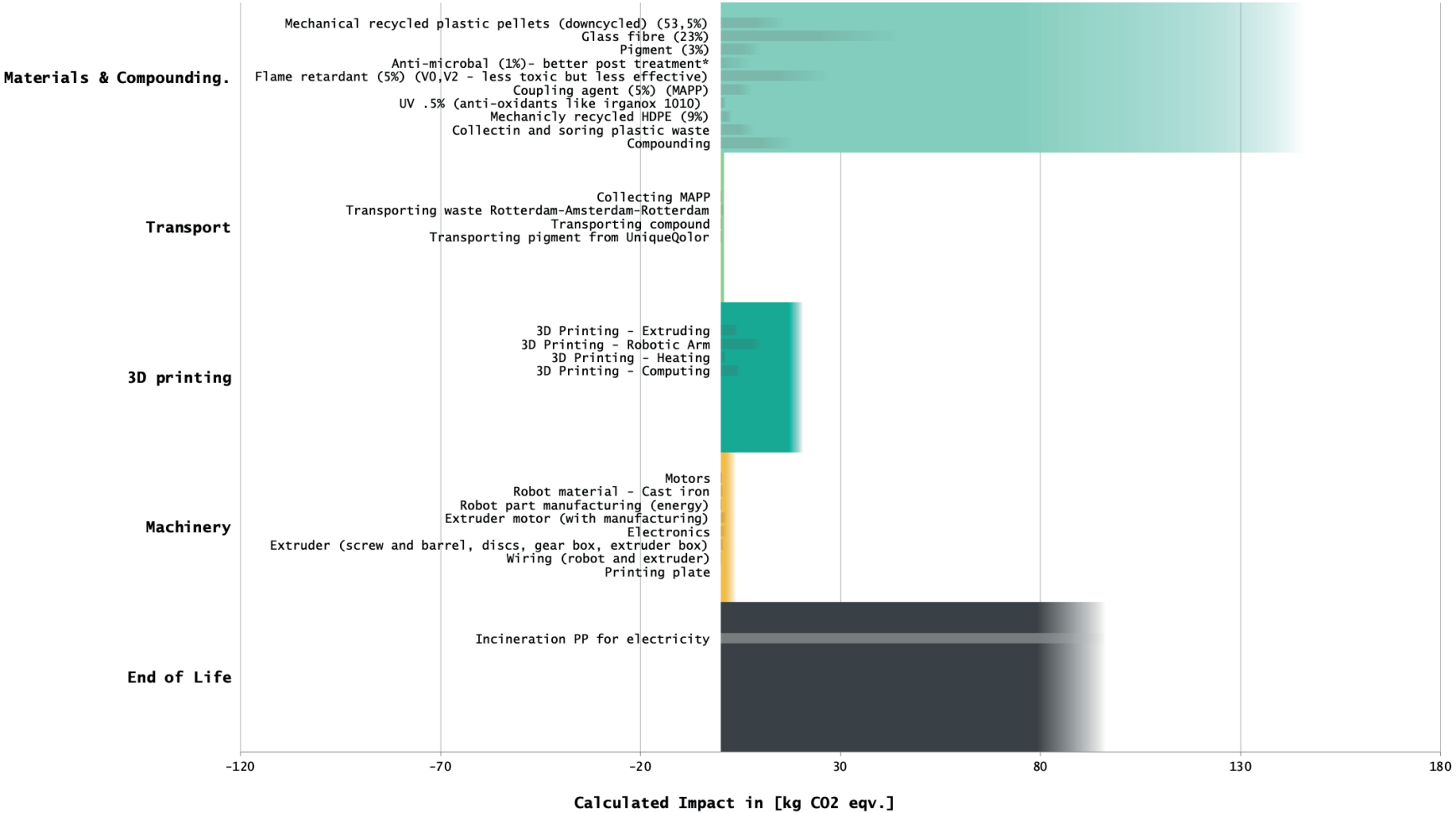
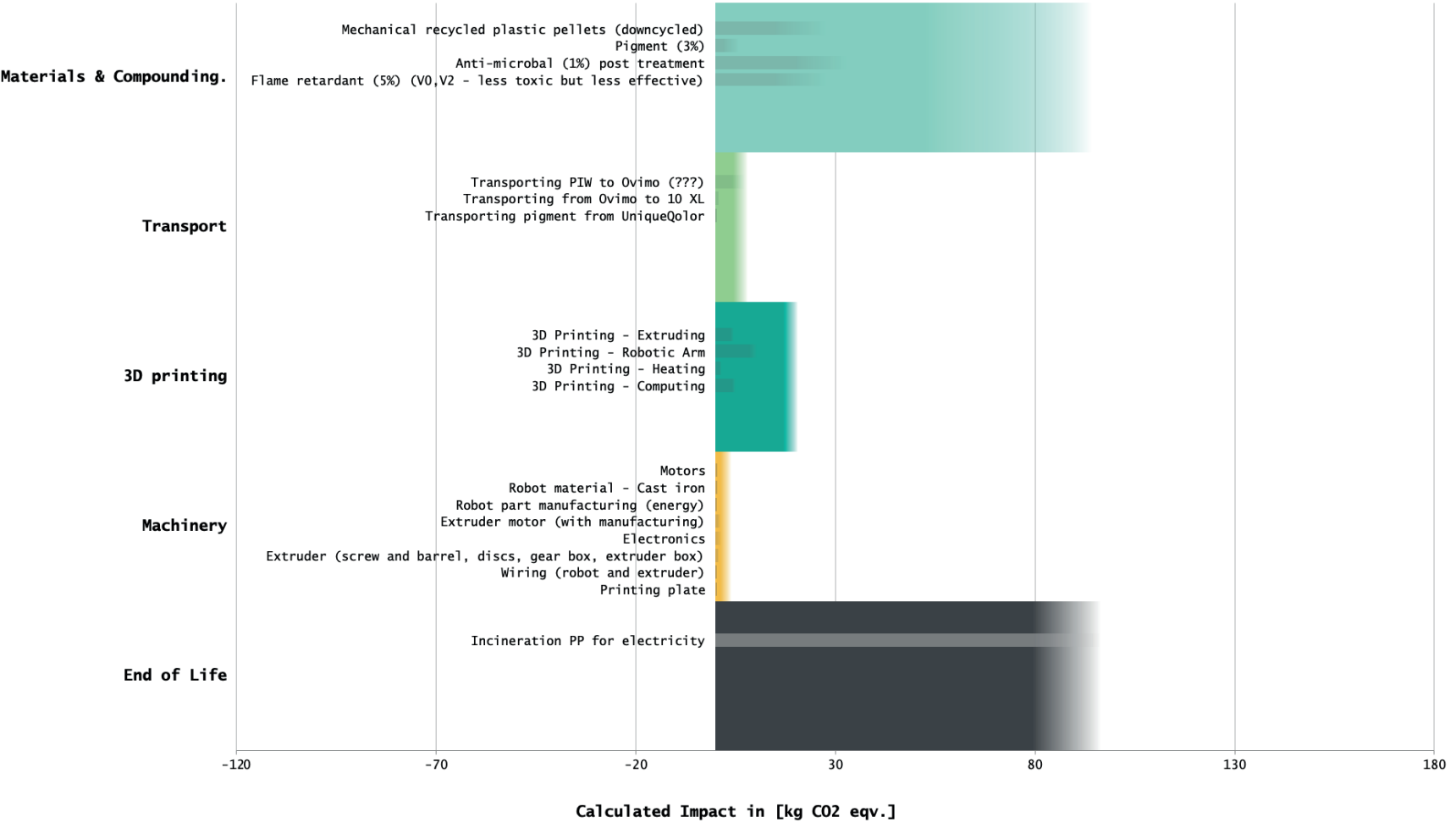


Figure 88: GWP of WPC II/▲
Impact assessment for 10XL/WUR
Batch II compound.

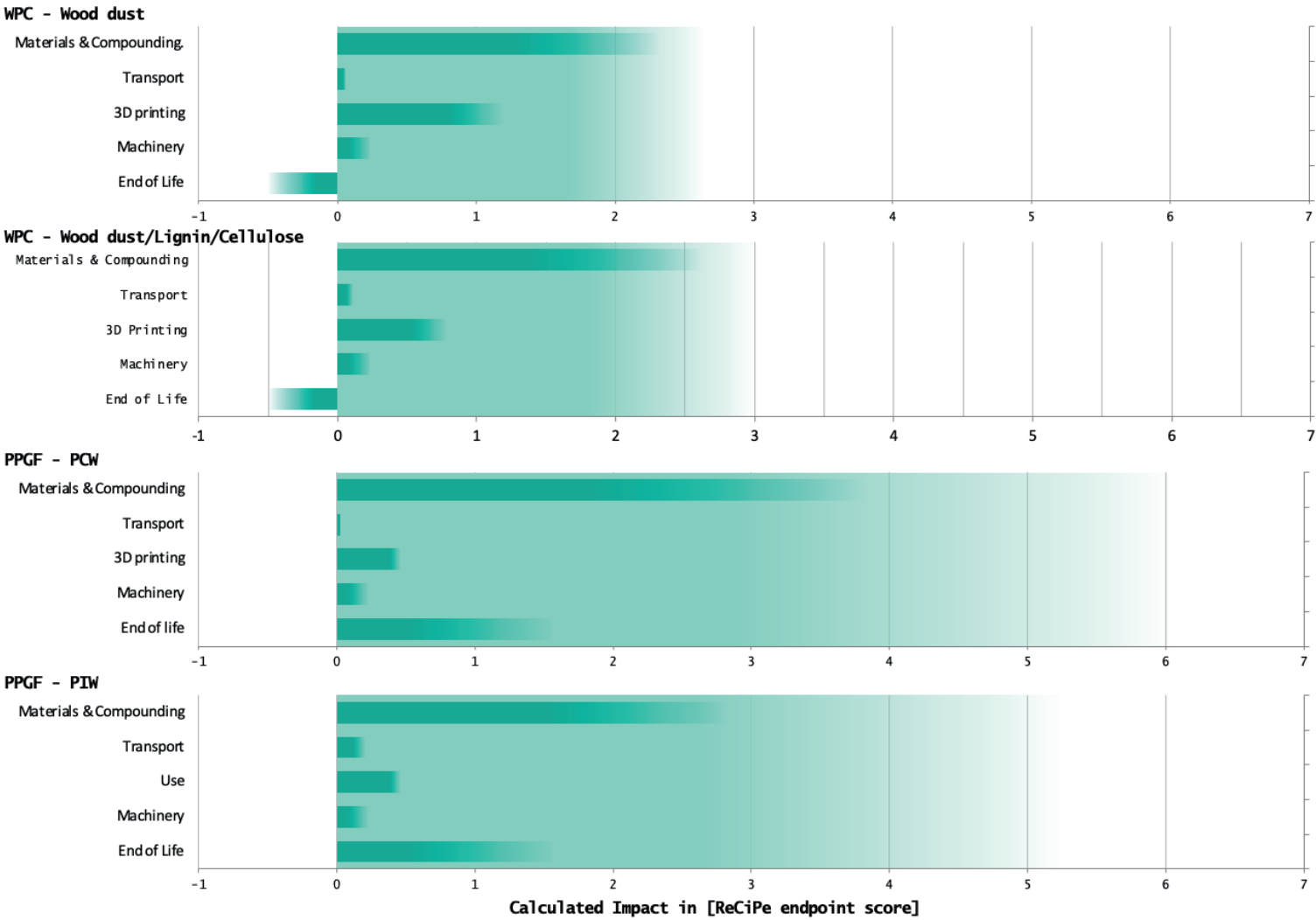


▲ Figure 89: GWP of PCW PPGF/ Impact assessment for post consumer waste PPGF compound.



▲ Figure 90: GWP of PIW PPGF/ Impact assessment for post industrial waste PPGF compound.

Figure 91: ReCiPe Endpoints/ ▼
Endpoint score for the four compounds for each life cycle stage and total score.



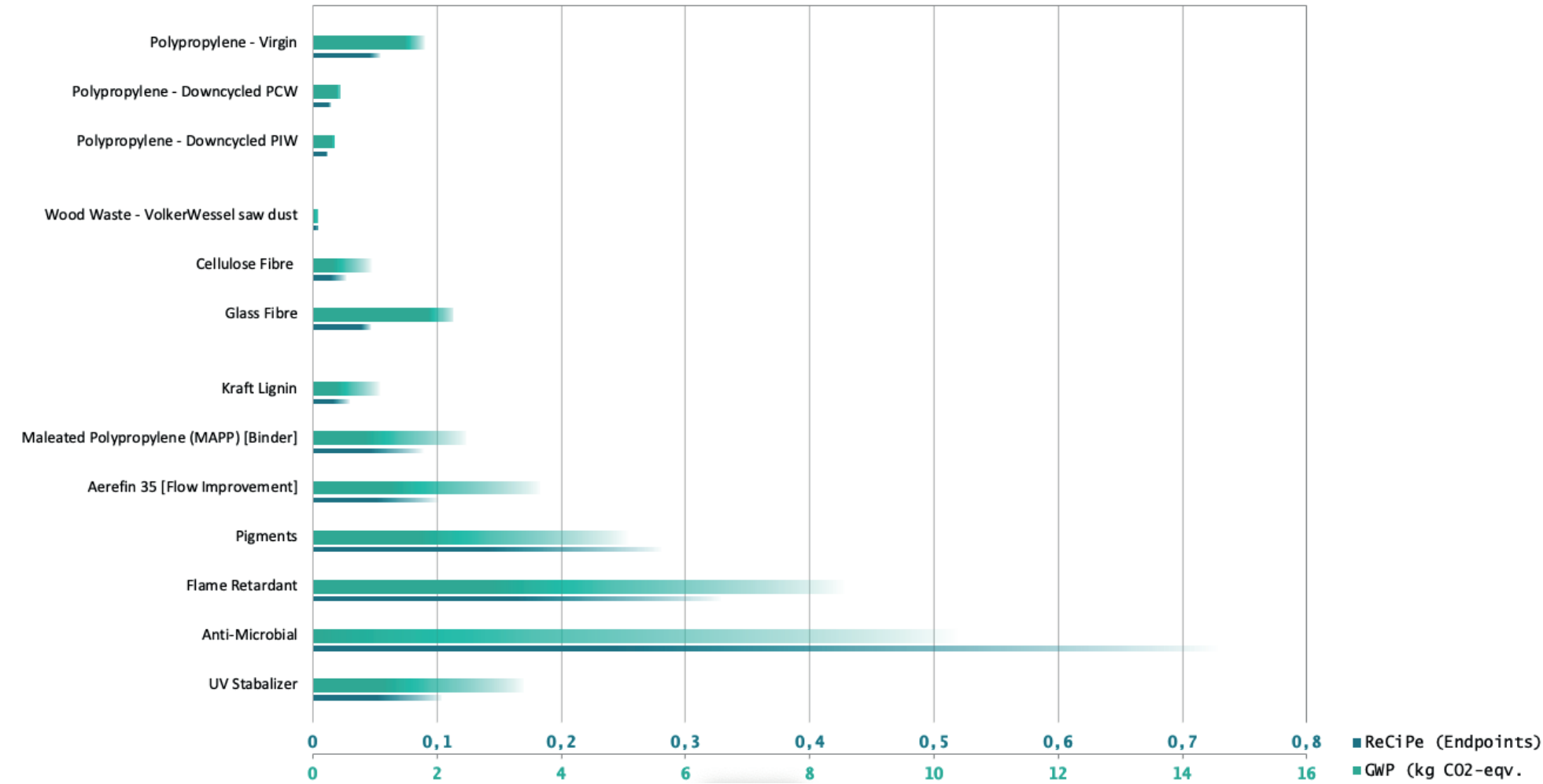
ReCiPe

Using the ReCiPe endpoint scoring system to measure the impact for LSAM, it also shows that raw material is the largest contributor to the environmental impact (figure 91). This is the case for both the WPC and GFPP materials. Other than the use of virgin PP and the incineration of it, there is no prominent component that has a high impact value. Except the incineration of the wood fibres, which has a very high negative value on the impact. Looking at the other life cycle stages, only one other factor seems to be significant, that of the energy consumption while 3D printing. This is the extruder motor and the energy needed for heating and cooling.

Comparing the wood to the glass fibre PP compounds, it is clear that the WPC scores much better. The biggest overall difference is in the end of life. The scenario that is compared, is the

incineration of the product when it is disposed. Where the WPC consist of roughly 1/3 out of PP, for GFPP this wt% is almost double. The incineration of the thermoplastic is particularly consequential for the global warming potential. Burning the wood for electricity on the other hand has no impact, it rather reduces the overall score because no extra CO2 gets emitted. Other differences can be seen in the fibres and the different additives that are needed. New glass fibres for post-consumer plastics has on of the highest impacts. Also the use of flame retardant scores high. For this reason, using lignocellulosic materials as an alternative for fibres and additives is a sustainable option. Both wood fibres and cellulose fibres enhance the strength (Wolcott & Englund, 1999) and lignin has been researched as a flame retardant in thermoplastics (De Chiroco et al, 2003).

▼ Figure 92: Impact per material/ GWP and ReCiPe Endpoint for each of the raw material used, each per 1KG.



SCENARIOS & UTILIZATIONS

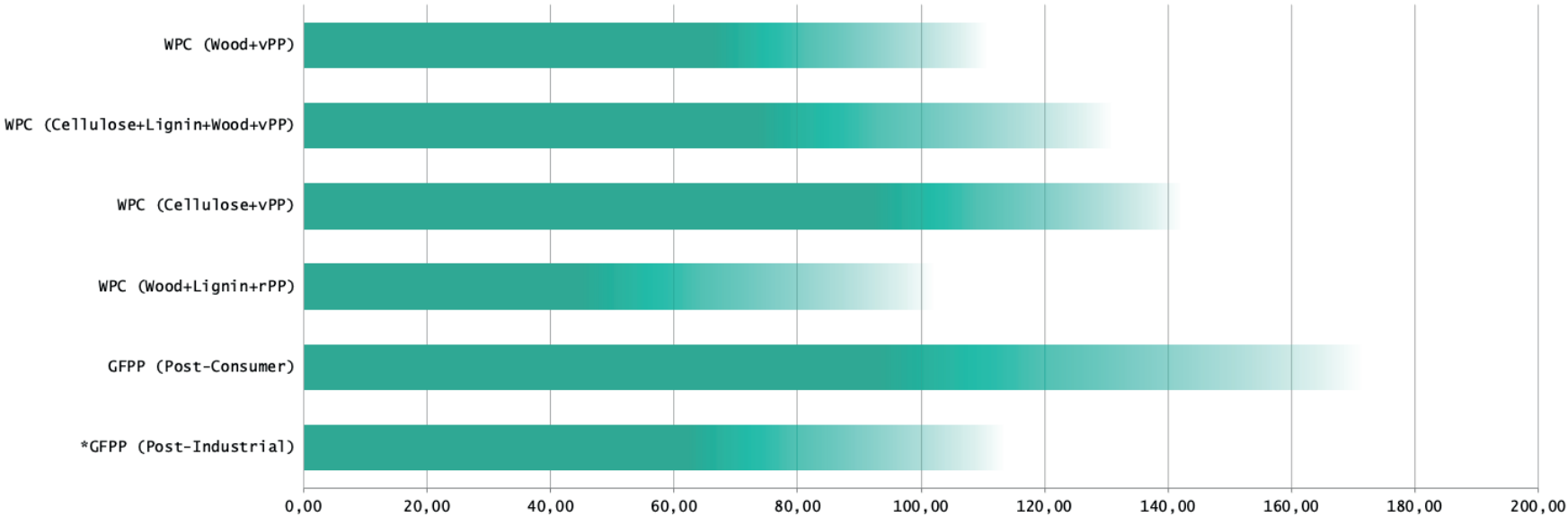
For this LCA, the two WPC compositions that have been researched were wood waste fibres compounded with virgin PP and a mixture of wood waste fibres, cellulose fibres, lignin and virgin PP. However, there are many more compositions that can be explored with this LCA model. There are two interesting compound recipes that will be compared to see how it will influence the environmental impact. The first one is a composition of 40% cellulose fibres with virgin PP, just like the Sappi Symbio PP40 compound used in this project. The other one being a potential further developed compound with 40% wood waste fibres, 20% lignin as additive alternative for UV degradation and fire retardant and a matrix of downcycled PP. For the comparison see figure 93.

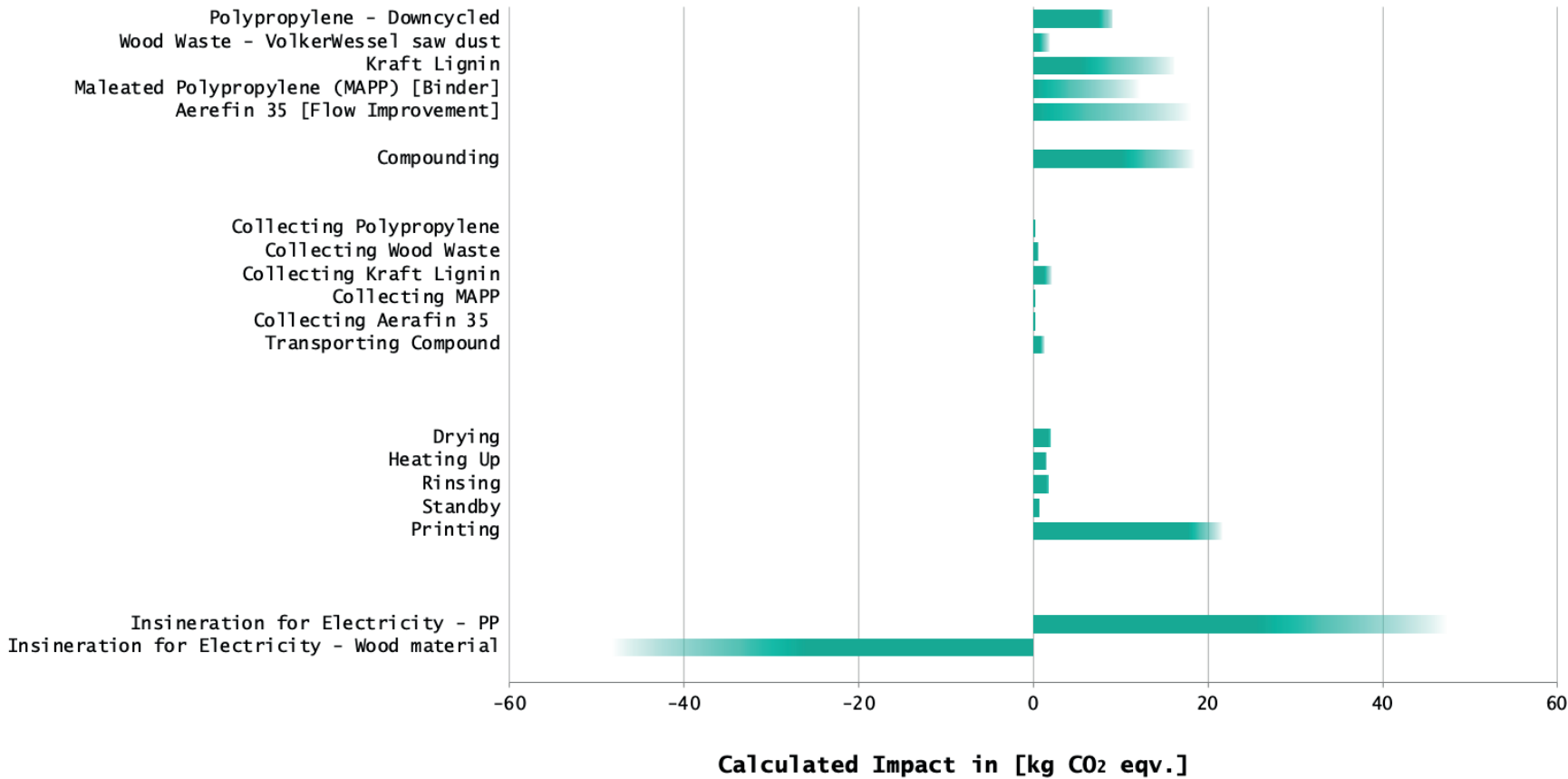
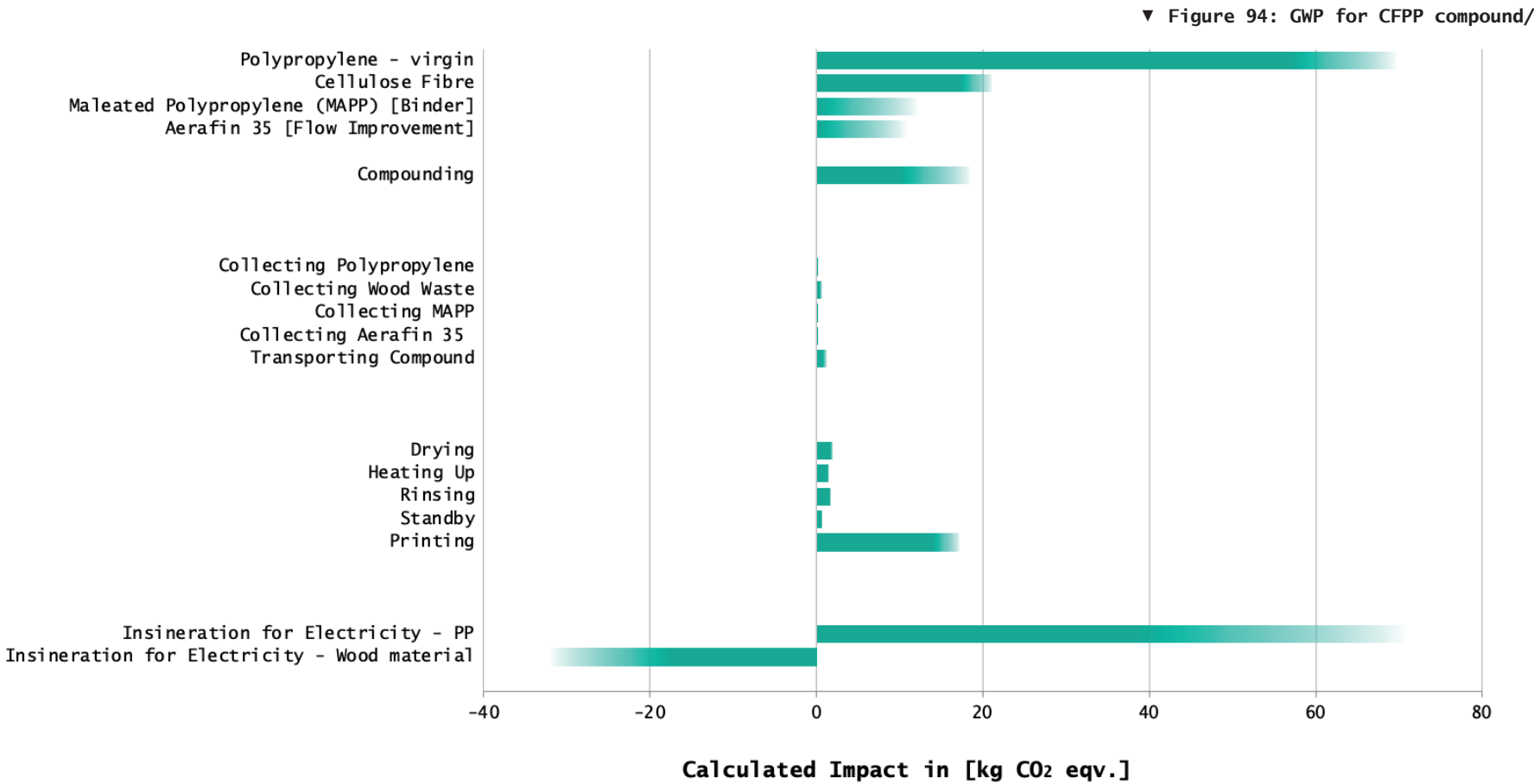
Looking at the GWP in figures 94 and 95, some significant changes can be seen. For the CFPP, the larger amount of virgin PP used in this compound clearly increases the impact drastically. In both the extraction of the raw material and the incineration in the end-of-life, the plastic is the biggest factor. On second place, the cellulose fibres contribute for a lot of the impact. Still, increasing the amount of cellulose fibres would be a good change, since it would save on the wt% of PP. Furthermore, the printing of CFPP was easier then printing the WFPP material, so the same energy use as for the GFPP was used in this model. The new potential compound with rPP shows that finding a more

sustainable solution for the virgin PP decreases the total impact drastically. With a 60 wt% of wood material, the thermoplastic is not even the biggest impact of the WPC anymore. This time, the processing of the material (including compounding) has a much higher share to the total impact.

The settings for the printing speed is an important factor for better utilization of the machine. As was shown in the energy measurements, the printing process and especially the extrusion has the largest share of impact in the manufacturing process. From the readings of the extruder, different printing speeds did not largely effect the energy consumption of the motor. Rather, very slow printing speed resulted in a larger amount of current drawn by the motor (see figure 96). This effect was seen in both the GFPP and the WPC. Presumably, this has to do with the shear thinning properties of the plastic material. When shear is low, the viscosity is high. If the shear rate is increased (by increasing the RPM of the extruder), the viscosity becomes lower and easier for the machine to extrude. Looking at the different feedrates of the printed object (figure 97), no significant difference in motor current was measured. Based on these observations, it can be concluded that printing faster (thus higher RPM) do not increase the energy consumption of the extruder, but does decrease the printing time, resulting in less energy used for the whole print.

Figure 93: GWP comparison compounds/ * does not include compounding process.





▲ Figure 95: GWP alternative WFPP/

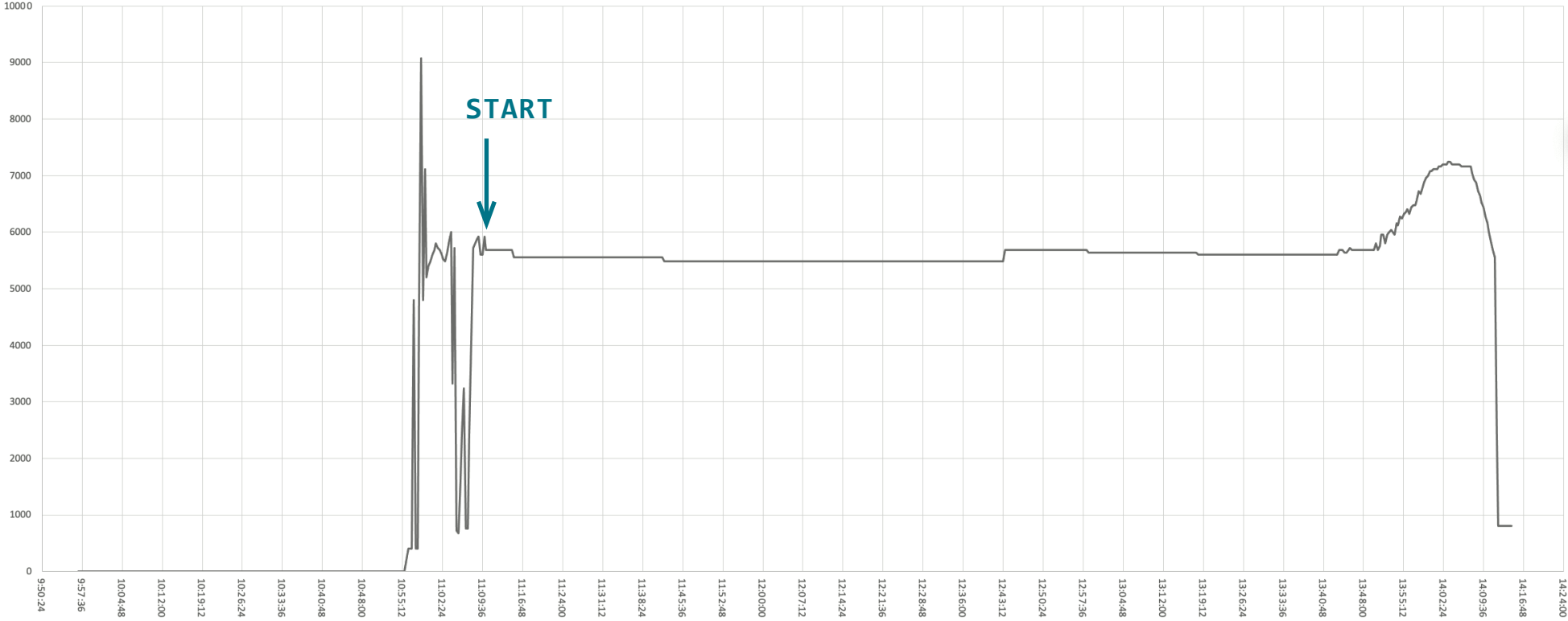
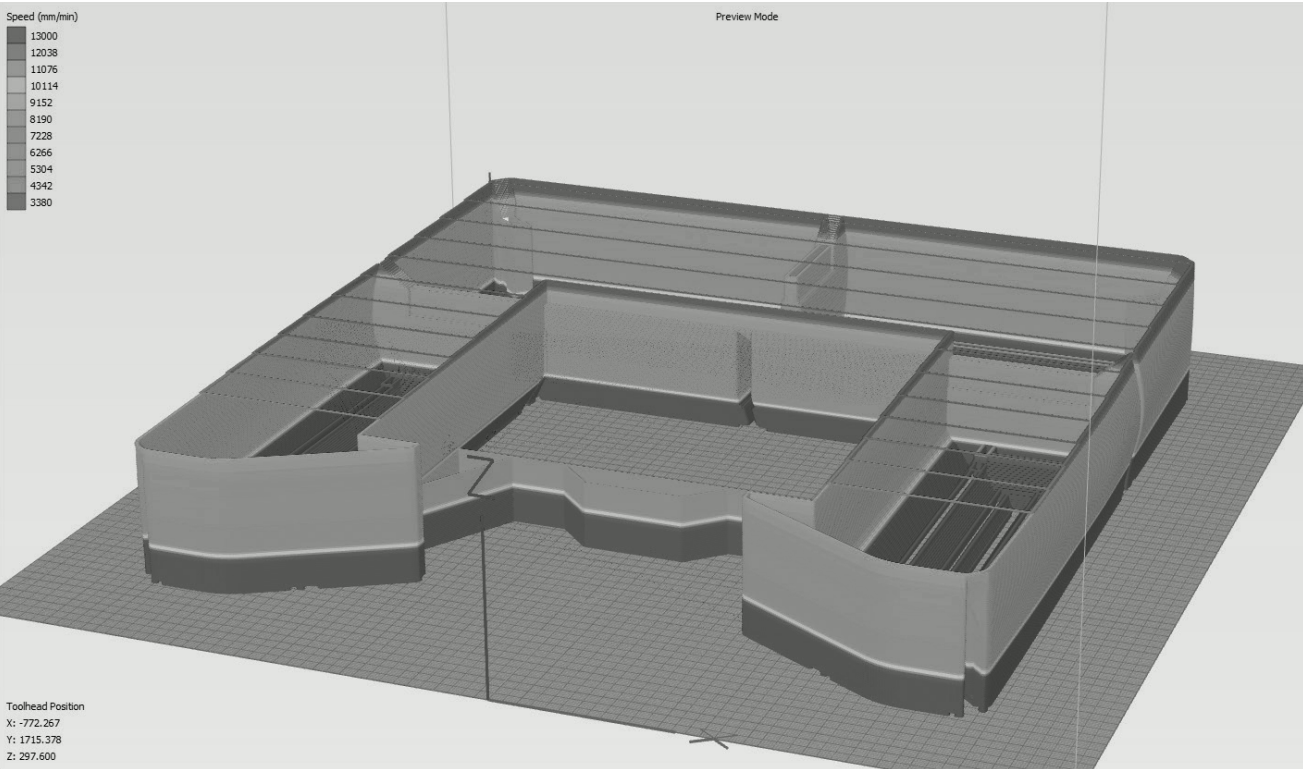


Figure 96: Energy use extruder/ ▲
Showing an consistent power usage
along the print, except for the
last layers of the print.

Figure 97: Layer speeds/ ►
Different speeds of the print,
shown in Simplify 3D.
Bottom (dark grey): 13000 mm/min
Middle (light grey): ±7000 mm/min
Top (grey): ±3380 mm/min



04.5/ REFLECTION OF THE LCA

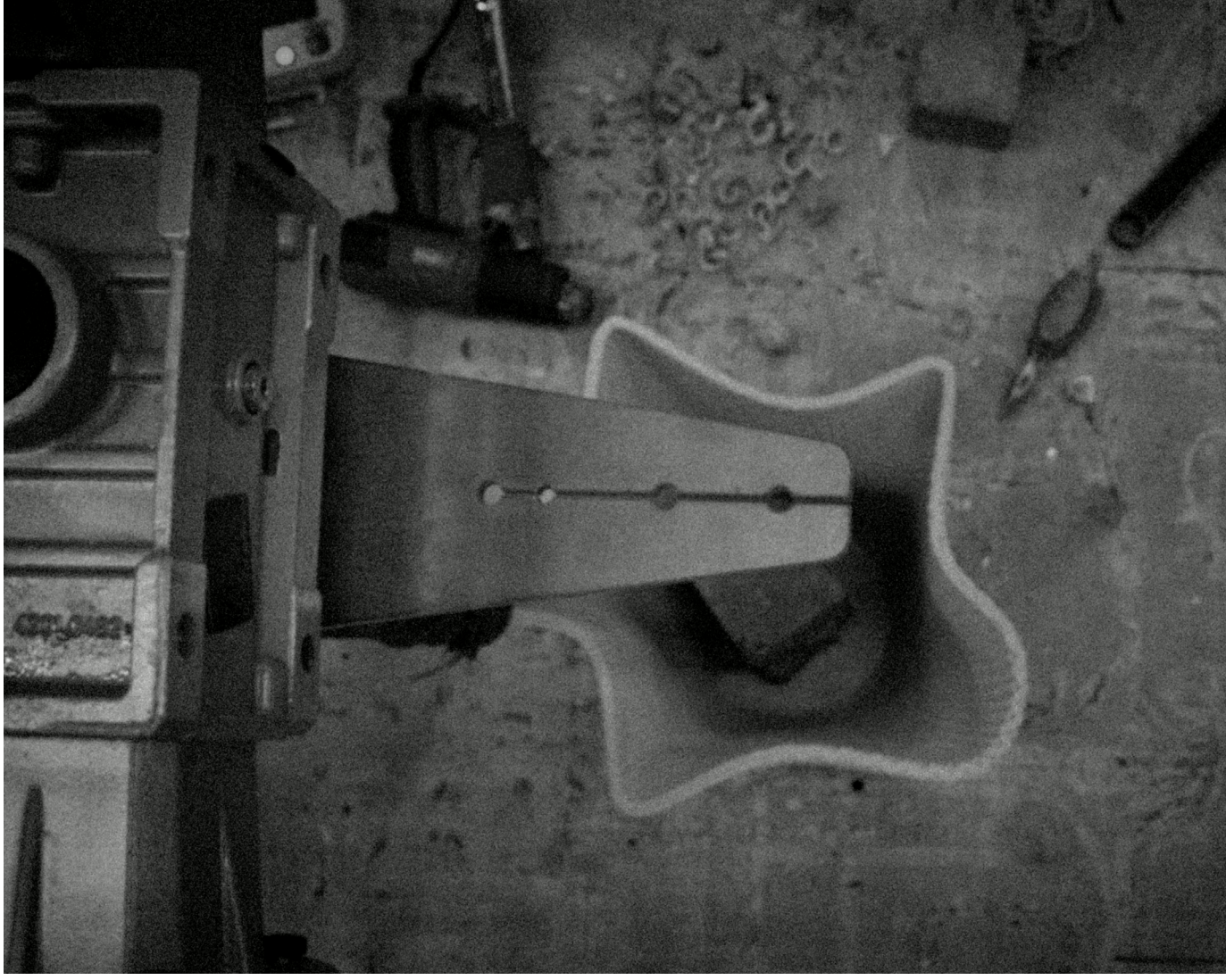
-

This LCA model that compares the impact of LSAM with different WPCs and GFPP compounds is a good indicator to see which section of the life cycle has the biggest impact. It also gives a good grasp on the impact of the different compounds and the printing process itself. However, the numbers shown in this model are not exact. Most of the values used in the calculation have a big uncertainty, mostly because of unknown impact of different materials. The sensitive analysis helps to get to a complete model, but the outcome can not be seen as defined. Also, the measuring of the energy consumption for printing with WPC was not as precise as intended. Due to processing issues at high feedrates, only the final 1/3 of the print could be measured and the total consumption was estimated based on these measurements and the outcome of printing with GFPP.

Nevertheless, some meaningful conclusion from this sustainability research are:

1. Using wood waste as an alternative for glass fibre is a very sustainable improvement. It has almost no impact and using high weight percentages also saves on plastic use. Using cellulose fibres is also a better alternative, but not as significant as wood waste fibres.
2. PIW plastic that does not need any compounding or additives and is therefore a very sustainable material with a low environmental footprint. For the WPC to get in the same range or even better, these compounds need to be made with downcycled PP instead of virgin PP. Using a waste stream as a source for the plastic is highly beneficial.
3. For the print manufacturing, using higher print speeds will cut down the energy consumption for the extruder, which has the largest share of impact for this life cycle stage. Due to the shear thinning effect of the plastic, higher extruder RPMs will decrease the viscosity and the current used by the motor will stay constant. Faster print speeds will cut down the printing time of an object and therefore save on energy. Especially for larger prints these savings will be very significant.
4. For the end-of-life of each print, the best scenario would be to collect discarded prints and reuse them as printing material. For WPC, incineration will not lead to extra emission, but for the GFPP, the incineration of the material will have a large contribution to the overall impact. Reusing old prints again for printing would therefore be meaningful.

CONCEPTUALIZATION



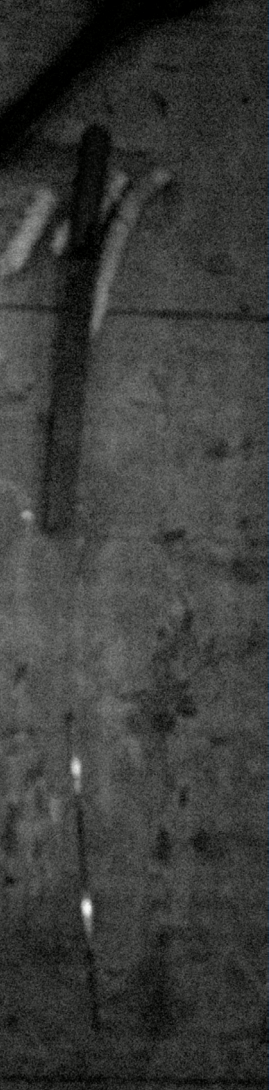
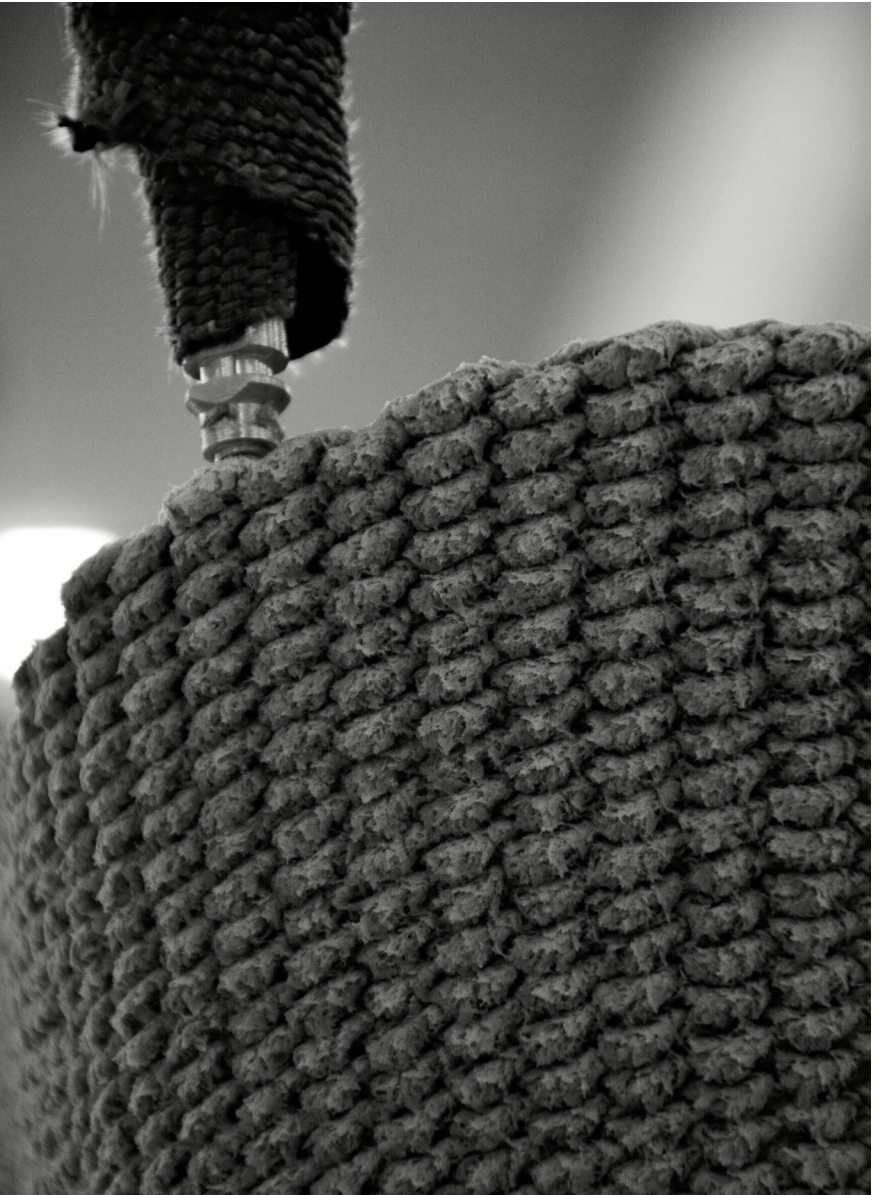




Figure 98: Wood samples/ ▲
Colours extracted from different
pictures of wood.

05.1/ COLOUR AND SENSORIAL DESIGN ASPECTS

The goal of printing was to obtain a wood look and feel from the material. But what is the feel and look of wood? Can this even be generalised? Wood material comes in a lot of different forms and the association of wood can also be different among people. To give an idea of what is meant with a material that looks and feels like wood, this colour and sensorial framework will purpose as a direction.

COLOUR PALETTE

As wood is a natural product that comes in different shapes and forms, there is not one colour that can be defined as a wood colour. It ranges from yellow to brown tints, but the bark of a tree can also be in the colour range of white to grey. Therefore, different wood

samples and parts of a tree have been used to create a colour palette (see figures 98 & 99). It includes some muted tones of brown and red from the woody material. Also the gloomy and the (dark) greys from weathering and burning of wood is in there.

SENSORIAL DESIGN

Based on the material vision from chapter 3.6, a collage has been created (figure 100). This helps to give an overview on what kind of design elements are strongly attached to LSAM with WPC materials. The most important element that defines the sensorial aspects for 3D printing with this material are the imperfect layers and the rough textured outcome of the print. The imperfection of the layers make for a unique objects. Combining



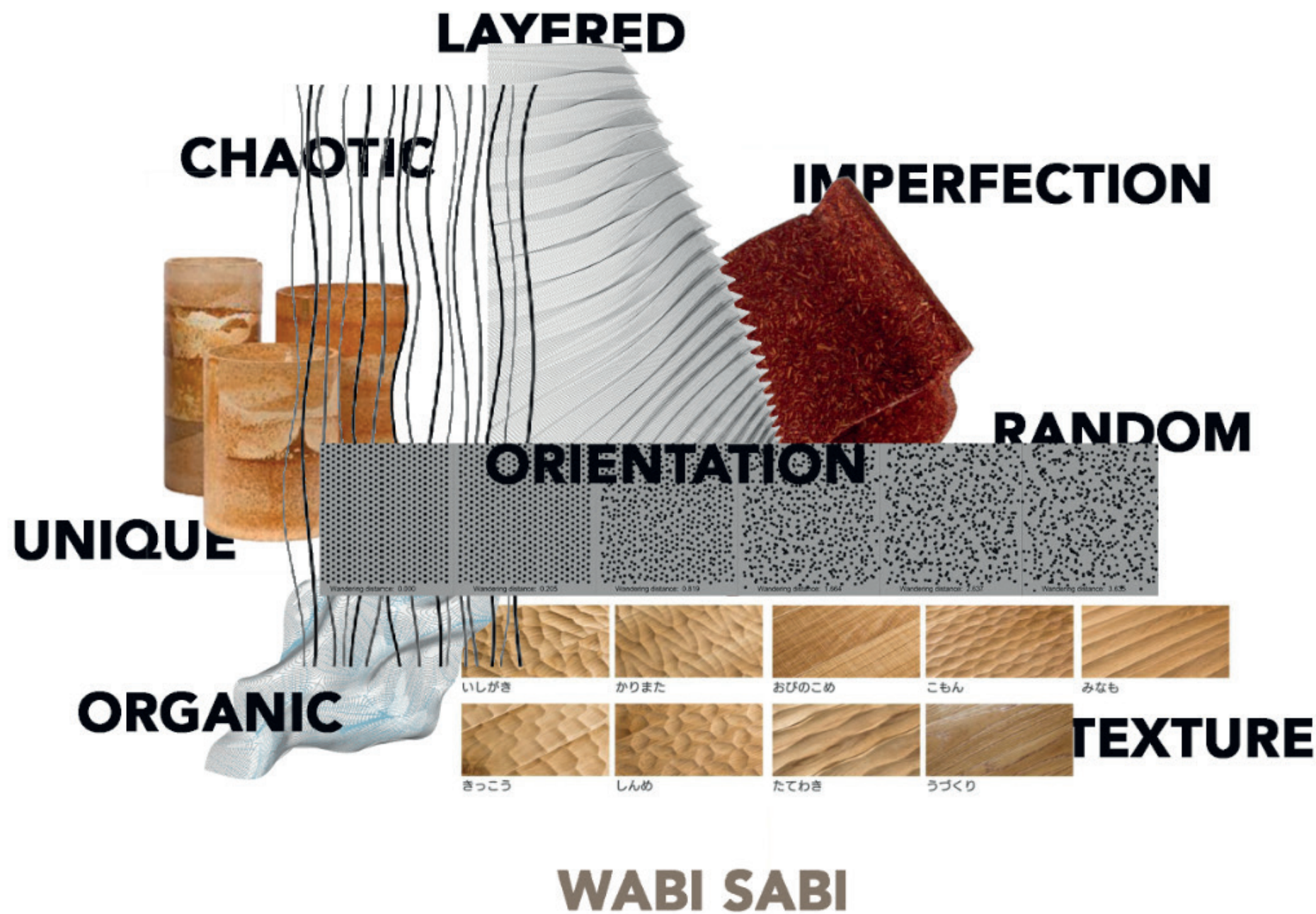
this with organic and nature inspired shapes or structures (biomorphism) can help to achieve a wood feeling of the print.

Based on the idea of biomorphism and the vision for WPC, the printed material has a strong resemblance to the bark of a tree (see figure 101). Both materials are rough and brittle. They both show cracks and imperfections which gives it a unique character. The bark of a tree functions as a protective skin, shielding it from different kind of outside exposures. It serves no structural purpose to the tree. This analogy of being the outside protective skin is the design direction which will be explored in the concept phase for implementation.

▼ Figure 99: Colour Palette/
Colour palette for wood.



Figure 100: Vision Collage/ ▼
Collage representation of the
material experience vision for
LSAM with WPC materials.





▲ **Figure 101: Biomorphhic analogy/**
The analogy for LSAM with WPC,
comparing the material to trees
and its bark.

05.2/ CONCEPT IDEATION

The concept development stage purpose is to give an idea for potential implementations of LSAM with WPC. The ideation starts with a brainstorm session to explore possible product directions. It was important that the ideas would fit or make use of the properties that came out of the exploration. From these ideas, three different concepts and printable shapes were created.

BRAINSTORM

Different properties of WPC that can be utilized are the light weight, the water resistance (compared to normal wood), the unique texture and natural appearance. For example printing a hull or a shell from it could be beneficial because it is very light. The printed WPC would still needs to be strengthened, because the material does not have very strong mechanical properties. But

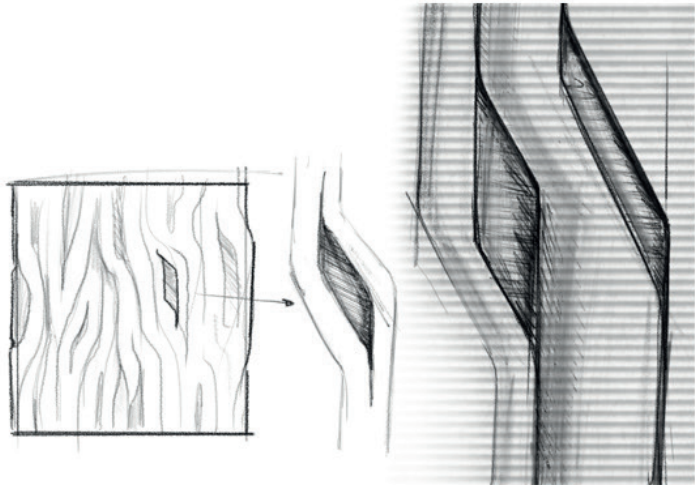
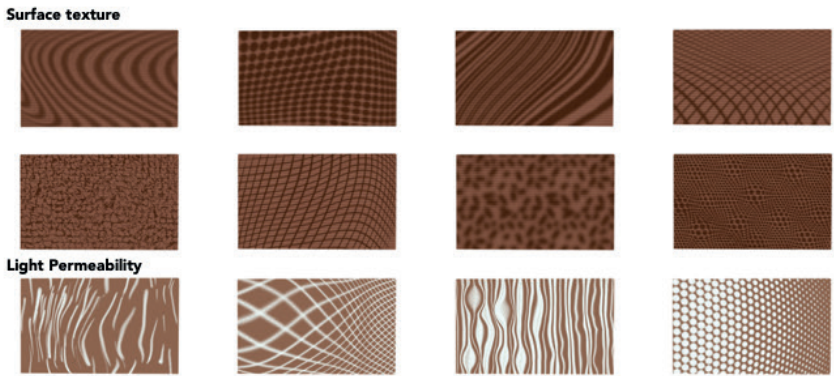
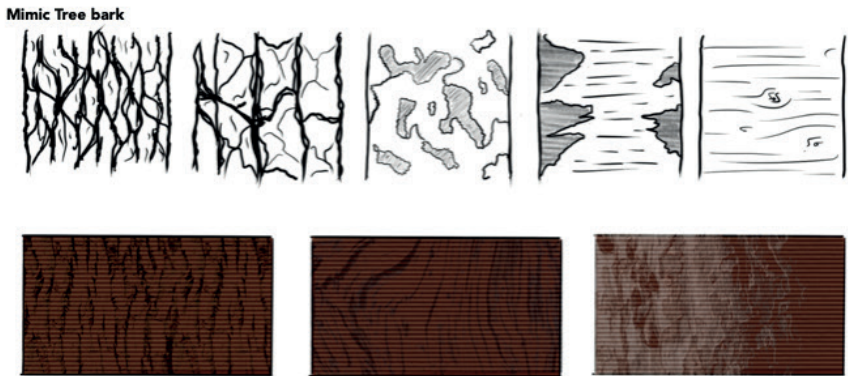
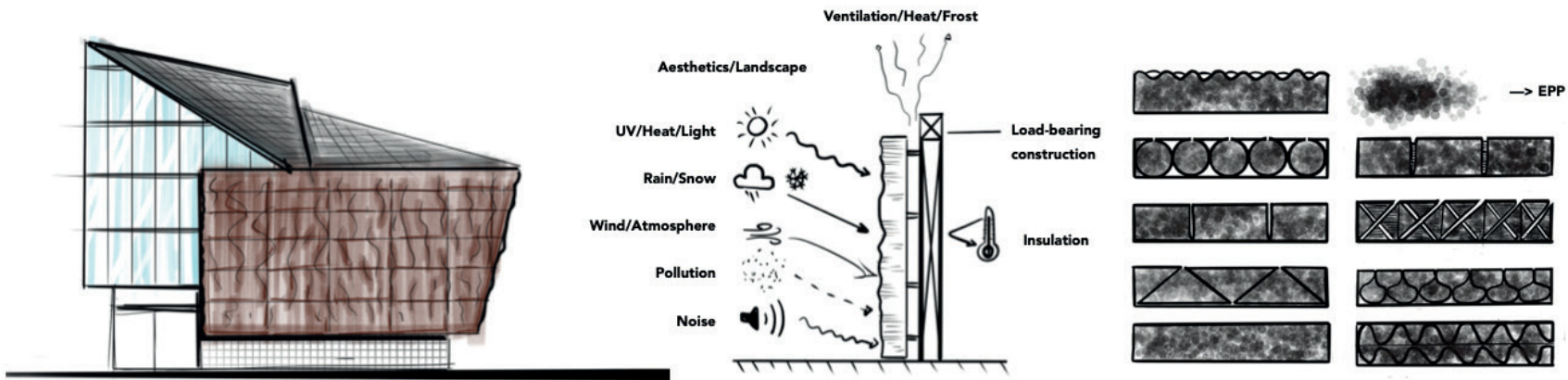
the rough surface might make it easy to stick sheets or fibrous on the outside. Because the material is brittle and rough, implementations that do not require any interaction or structural properties are much more suitable. It should mainly purpose as an aesthetic and protective product.

Based on the association of the printed material to bark, the same kind of use as a skin can be implemented in the concept. Taking the freedom and scale of the manufacturing process of 3D printing, a meaningful implementation of the WPC could be in pre-fabrication building panels, also called prefab facade elements. This concept is ideation can be seen in figure 102. The printed material will give an unique natural appearance, it is weather resistant, light weight, sustainable and does not have any structural purpose.

Wood is used in construction for centuries, but with the form freedom of 3D printing, organic and biomorphic structures can now be created out of wood.

Another use or addition to this concept is the integration of vegetation. Printing objects with planters or a place for greenery can strengthen the idea of naturalness. The material suits perfectly to be used to print vases or planters, but integrating this idea into the prefab facade elements will pick up on the trends of vertical gardening and green roofing of buildings. Some interesting element when further developing this concept would be to see how well the wood fibre material is protected from deteriorating and how the roots will interact with the rough surface of the material. Maybe the roots can strengthen the printed object rooting into it.

SKETCHING



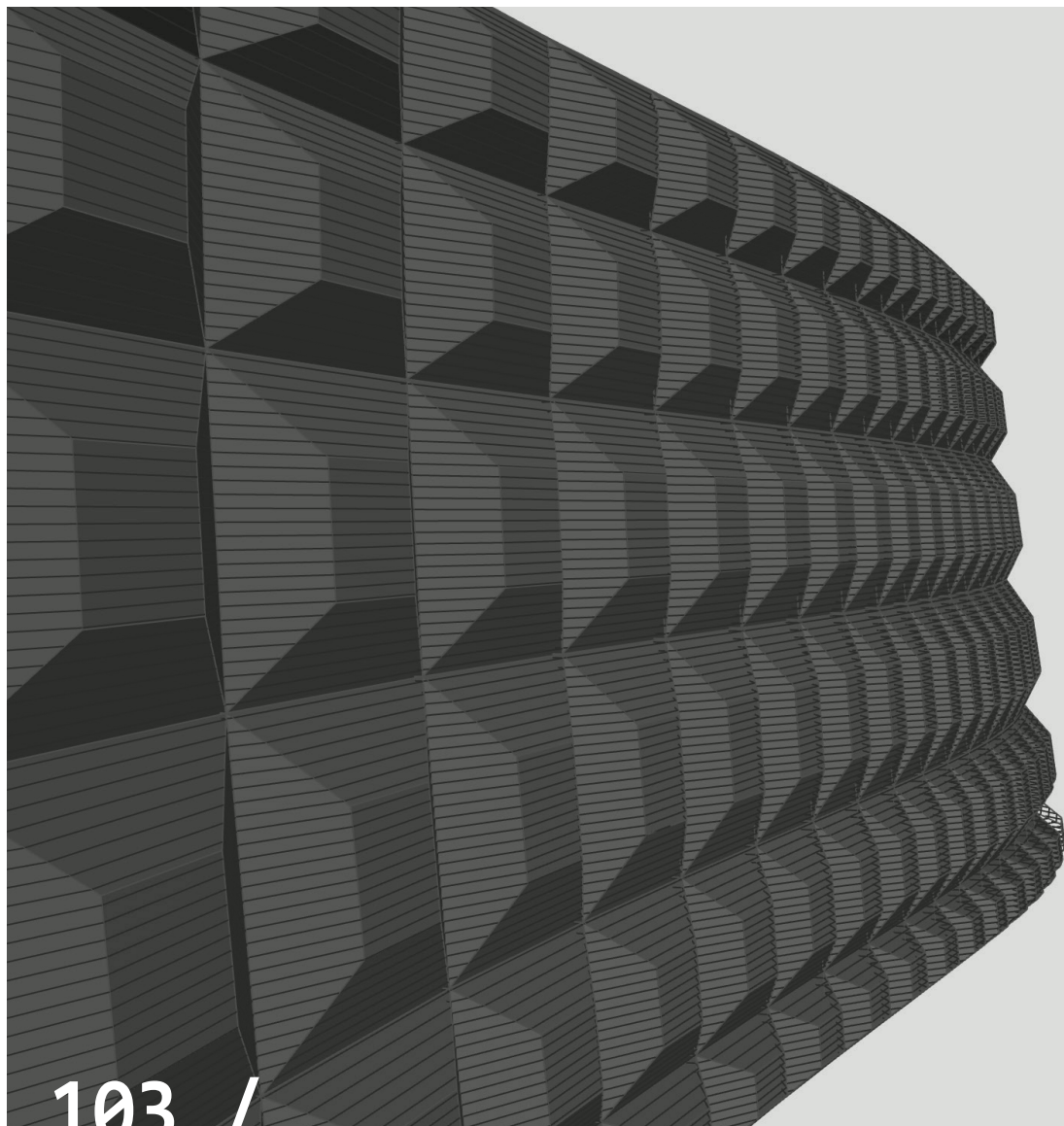
▲ Figure 102a: Ideation/ Sketches of the prefab facade elements and analogy to bark.

INSPIRATION



▲ **Figure 102b: Inspiration/**
Collage of building façades.

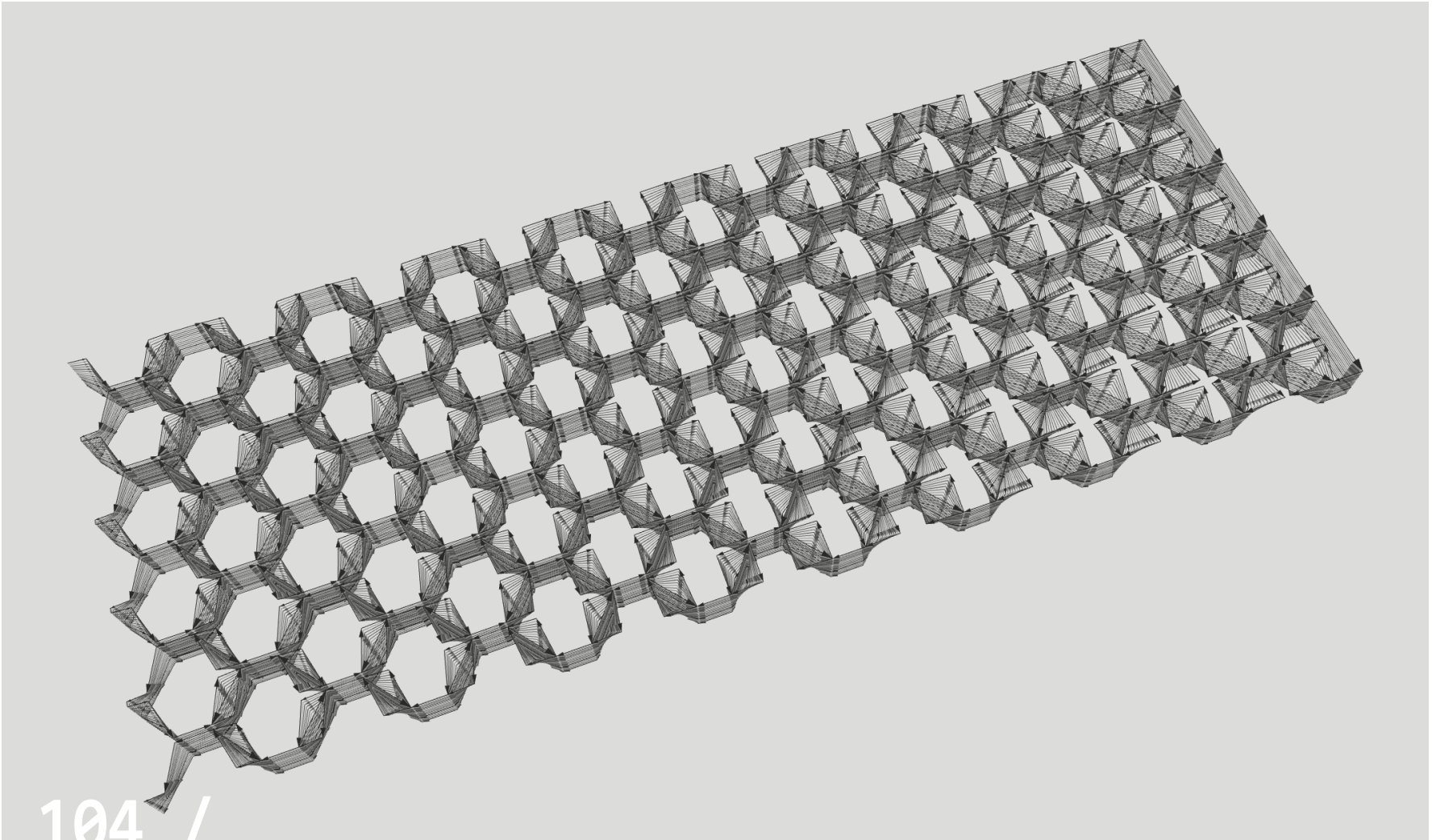
Figure 103: Wall Facade/ ▼
Textured wall that can be used
for cladding a building .



103 /

Three different strategies to print the pre-fab wall façades. The print can be made in the height, as shown in figure 103, printing a wall up to 2m in the z-direction of the printer. A large number of layers can also be printed in a 45° angle (figure 104), creating an enclosed box. The advantage of this printing technique is that the print can be enclosed and can be filled up with vegetation for example. The third option is shown in figure 105. This is a print of only a few layers tall, but spreading out over a large surface area of the printing bed. This will create light permeable structures which can also be used to guide plants or as shadings.

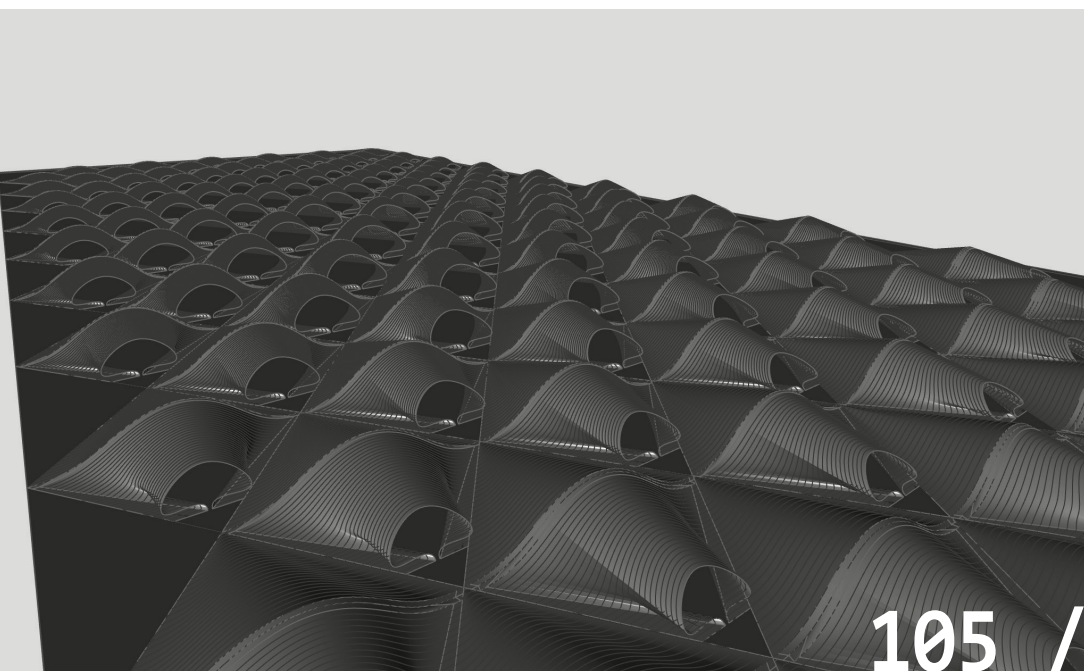
However, due to different issues and restrictions, these objects were not printed as a mean of representation and prototype. The availability of the material to test with and the amount of time needed to make a good representable print was limited. For this reason it was chosen to present the physical objects in the form of vases. This direction was also an interesting outcome of the brainstorm session, due to the fact that these objects mainly purpose an aesthetic purpose. These printed objects can later on be used again as inspiration for further development for the pre-fab façades. The final prints are shown in the following figures (106-114).



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▲ **Figure 104: Light Facade/**
Light permeable element with
varying openings for shading.

◀ **Figure 105: Planter facade/**
Facade with planters to grow
plants in.



105 /



Figure 106: Vase V_1/ ▲
10XL/WUR Batch III Printed as non planar vase.

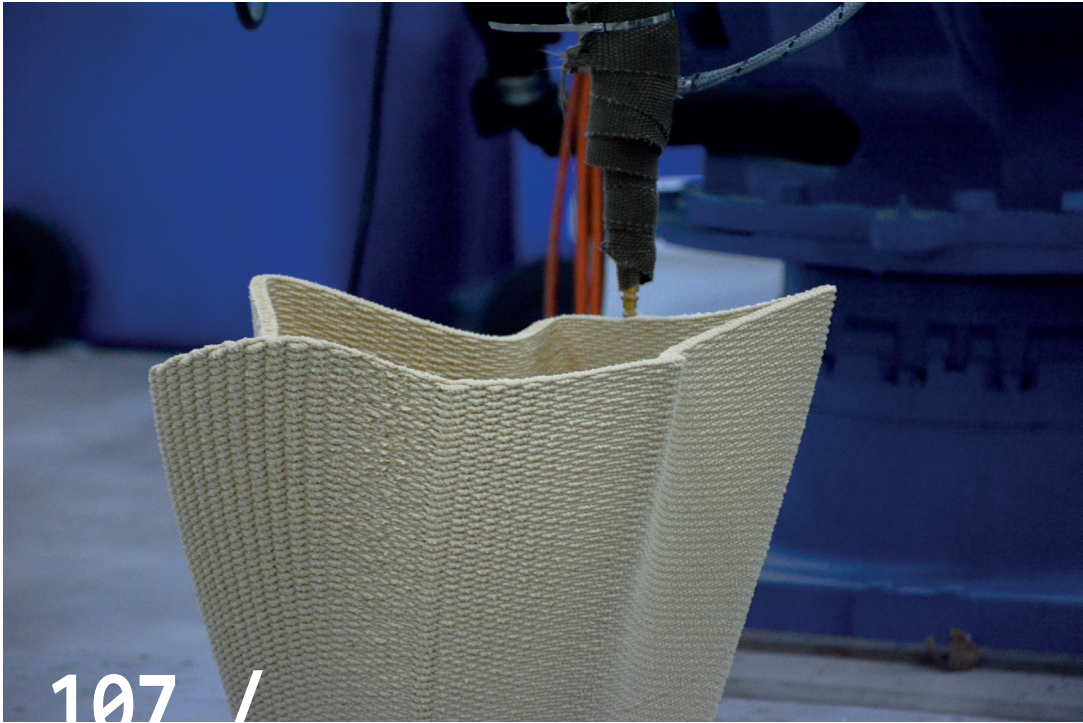


Figure 107: Vase V_2/ ▼
Sappi Symbio PP40 printed as non planar vase with texture.



Figure 108: Vase V_2/ ►
Sappi Symbio PP40 printed as non planar vase with texture.



- ◀ **Figure 109: Vase V_2/**
10XL/WUR Batch V printed as a non planar vase with texture.
- ▶ **Figure 110: Vase V_1/**
10XL/WUR Batch II printed as a non planar vase with texture.
- ▼ **Figure 111: Vase V_2/**
10XL/WUR Batch IV printed as a non planar vase with texture.



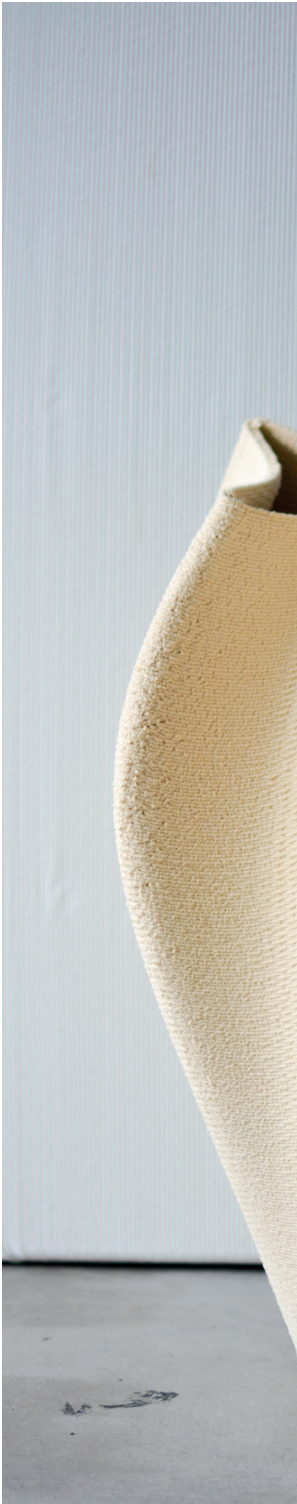
Figure 112: Overview/
Overview of all the printed vases
from WPC.



▲ 10XL/WUR Batch III



▲ 10XL/WUR Batch II





▲ Sappi Symbio PP40



▲ 10XL/WUR Batch IV

10XL/WUR Batch V ▼





Compound	Remarks
10XL/WUR Batch I + PPA	Extrudes good, some rough edges but consitant layers
10XL/WUR Batch II + PPA	Extruded well and has a old wood colour
10XL/WUR Batch III + PPA	Extrudes well and but has a very dark colour
10XL/WUR Batch IV + PPA	Extrudes difficult (due to fluffy pellets) and is very rough and loose, but looks natural
10XL/WUR Batch V + PPA	Extruders sufficient, but has more roughness than compounds I-III, also natural look
Sappi Symbio PP40	Extrudes good, but does not look natural and has a lot of warping

▲ **Table 2: Important notes/**
Important findings while printing
with all the materials.



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VASES

Overall, the results of the printed vases are very stunning (see table 2 for notes). Especially when using a weave like texture, the outcome is very appealing. These settings make it very pleasing to look at. The material itself gives already some unique texture of its own, but the addition of the pattern almost hides the fact that it is printed. It gives a very natural touch to it. In combination with the non planar printing, the shapes look very dynamic and natural. Because every material has its own colour, all object look unique and feel as one of a kind.



CONCLUSION & RECOMMENDATION

As an overall conclusion, it is safe to say that there is enough potential for WPC to become a successful and sustainable printing material. It has some unique experiential properties no other material has. Even within the group of WPC material there is a lot of variation in how the printed material appears. Figure 115 gives an overview of the most important properties for WFPP and CFPP (compared to GFPP) explored in this study.

From an experiential perspective the WPC is very unique, particularly the compounds made with wood fibres. On the mechanical level, the WPC needs to be further developed by adapting the PP matrix and the lignocellulosic fibers. Based on the LCA research, the use of a waste stream PP is proven to have a much lower impact. Therefore, searching for an alternative for virgin PP with a high MFI value would be highly beneficial.

Testing different sources and amounts of fibres is also recommended to do. A assumption that can be drawn from this study is that the

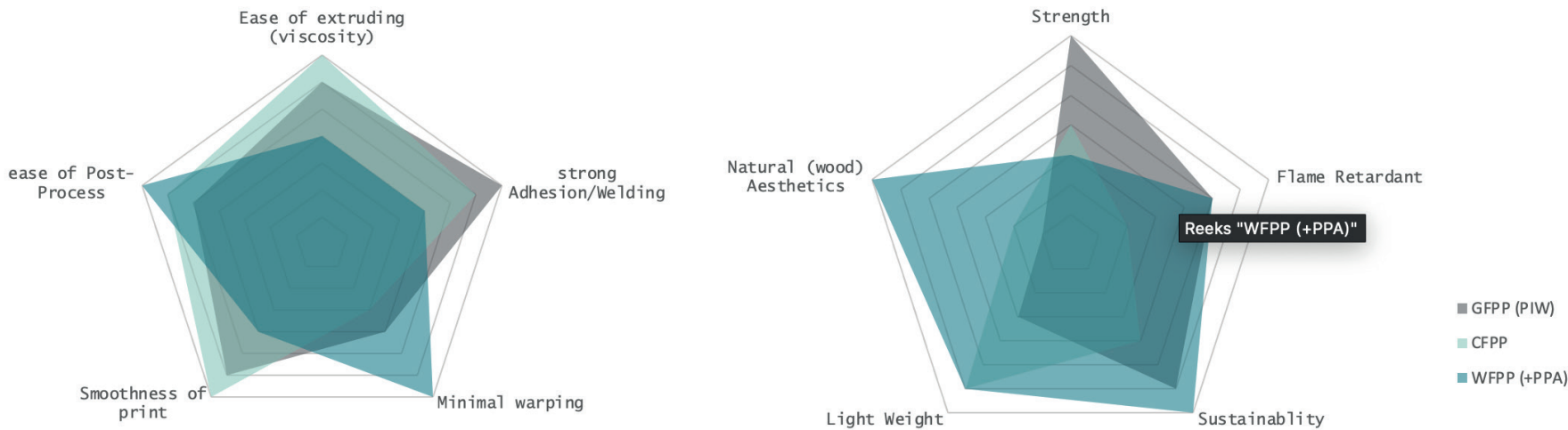
combination of cellulose and wood fibres does not have any beneficial effects. The addition of lignin however is strongly noticeable in colour. Based on research, it is also explored as an alternative polymer additive for UV degradation and fire retardants (De Chirico et al., 2003). Another factor that need to be further explored is the effect of different wt% of wood fibres. Vlachopoulos & Polychronopoulos (2018) showed that large percentages have a strong effect on the viscosity of the compound and Wolcott & Englund (1999) concluded with their study that high percentages of wood fibres do not increase the strength of the material. Therefore it is recommended to test different compositions with the same raw materials and define what works best for 3D printing.

On the mechanical part, the design of the nozzle will have a large influence on the quality of the print. Some important features need to get rid of the melt fracture is to have a coated surface that has a low friction coefficient with the WPC. The shape needs to be tapered to the end and the last section of

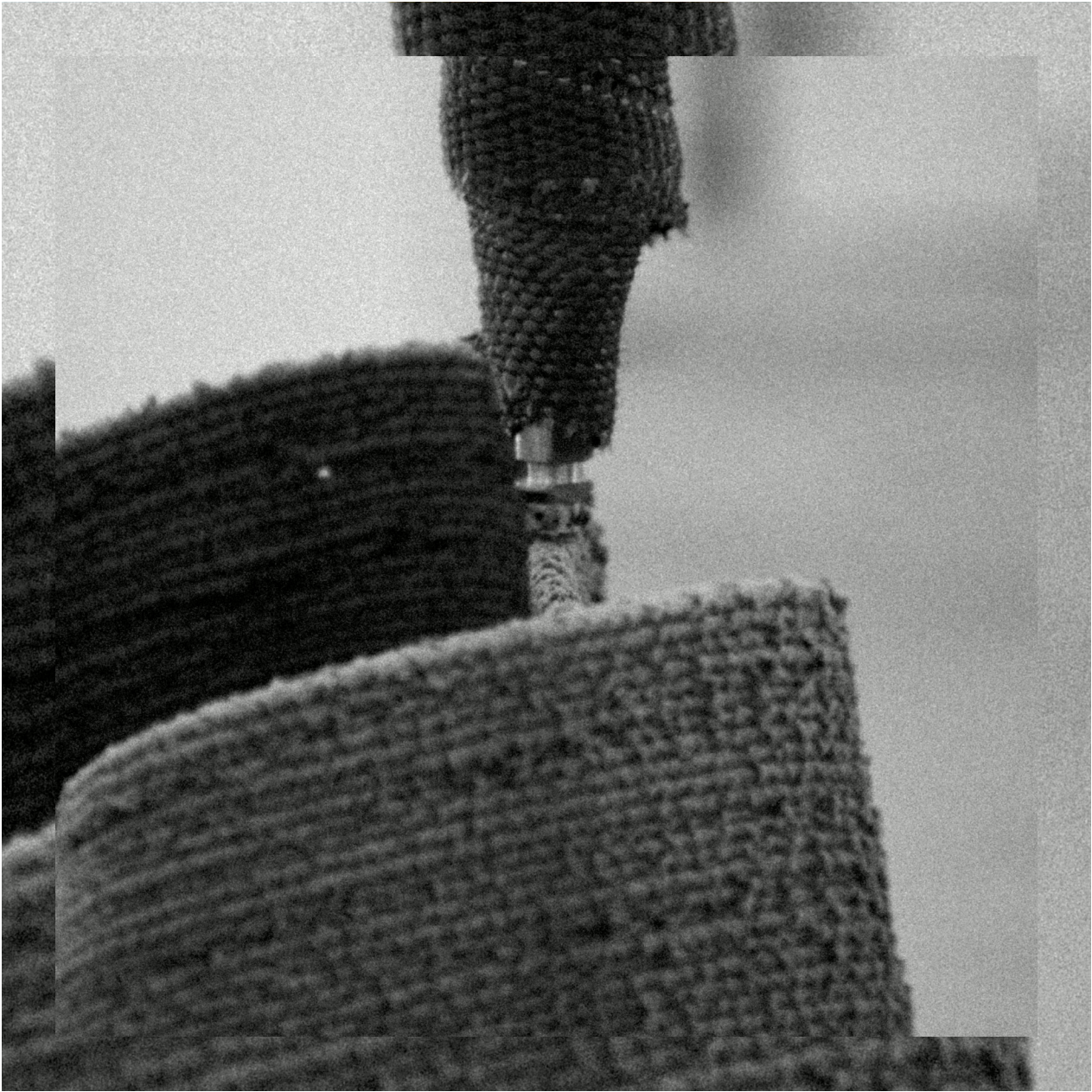
the nozzle needs a seperate heating element to increase the temperature in this section. Also the addition of a PPA is necessary, but it need to be further tested with a new nozzle.

For the implementation of WPC to products that can be printed by LSAM, the current direction would prefab facade elements or large objects with aesthetics purpose. Since the experiential properties are very good, but the printed WPC is very brittle, the best use for now is products that don't require any load baring. The façades are a good idea since it can give a natural feeling to the building and protecting the construction.

Because the compound is very light weight, it could potetnially also be used in constructions that benefit from lower masses. An example could be the hull of a boat that can be cladded afterwards. But to explore the best type of use, first the material needs to be refined.



▲ **Figure 115: Properties overview/** Different properties of GFPP, CFPP and WFPP scored and compared to each other.



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