LAPIN AMK
Lapland University of Applied Sciences

Filament production and application for wood based PLA

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Abstract of Thesis

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3D printing as an alternative to conventional manufacturing methods, and its advantages in design freedom, customization options and ease of use, experienced a rise in popularity in the last decade. With fused filament fabrication (FFF) as one of the most commonly used methods and polylactic acid (PLA) as a frequently used material option, new innovations and opportunities in this sector are not uncommon.

The use of filler materials to increase the properties of the final product or lower the impact on the environment has been the subject of several studies. Two different kinds of wood based filament with a diameter of 1.75 mm were produced in the course of this thesis. Filament with a wood content of 5% for each pine and spruce wood was extruded and tested with a 3D printer. The two different wood types used showed no significant differences in their pre-processing or influences on the outcome. The inclusion of recycled PLA further emphasizes the benefits of a circular economy in 3D printing.

The wood material usable for the selected extrusion method only amounted to a fraction of the initial residue material, optimal parameters for the filament making process were found for the single extrusion, but not for the double extrusion experiments. The 3D printing tests were successful and led to satisfying results.

The acquired findings provide a solid foundation for future projects at the Lapland University of Applied Sciences.

Key words 3D printing, PLA, wood, filament, recycling

CONTENTS

FOREWORD

I want to thank all the staff members and colleagues at the Lapland University of Applied Sciences for their help and encouragement throughout the work of this thesis and in general during my stay in Finland. And also, a great thank you to my family, who are supporting me in achieving my dreams and life choices.

SYMBOLS AND ABBREVIATIONS

ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
CAD	Computer-aided design
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
MEX	Material Extrusion
PLA	Polylactic Acid
SDG	Sustainable Development Goal
STL	Standard Triangle Language
UAS	University of Applied Sciences

1 INTRODUCTION

3D printing has experienced an increase in popularity for manufacturing products with high geometrical complexity in the last two decades and is getting more available and affordable in the non-commercial sector. Following this trend, it is not surprising to see a rise in interest in developing sustainable and environmentally friendly printing materials.

There exist a variety of 3D printing technologies, with Fused Filament Fabrication (FFF) as one of the most widely used one. The ease of use makes it a great tool for educational purposes and allow for quick and uncomplicated production of prototypes.

Recycling the materials at the end of the life cycle of a product is a first step in reducing the usage of natural resources. By adding waste material from other processes, this effect can be further improved. These methods also hold educational value, as they help to understand the concept of sustainability and circular economy, which allow for a shift away from non-renewable resources.

Using the right method and filler material, it is even possible to improve the physical and mechanical properties of polylactic acid (PLA) and broaden their area of application.

Since having a composite material instead of only PLA changes the properties of the produced filament, there are a few factors to be considered. The properties should not significantly deviate or impair from the original material. There will be a turning point at which the disadvantages of the filler material overweight the gains. Considering the results already undertaken by previous research in this field, a concluded optimal approach will be followed, and the outcome analysed.

1.1 Motivation

This thesis should be seen as an opportunity to improve longevity of materials used in a closed and educational environment. As the mechanical engineering degree 3D printing laboratory of the Lapland University of Applied Sciences

(Lapland UAS) is primarily for educational purposes, it is practical for the material used for printing to be recyclable or reusable.

By going a step further and introducing waste material into the process, an even better result can be produced. Combining these two practices, an environmentally friendly and economical alternative will be achieved. Especially, when a massive amount of prototyping is involved, a concept for minimizing waste materials, e.g. closed-loop-recycling, is a task worthy of pursuing.

1.2 Scope

This thesis aims to produce a functional wood filled PLA filament ready for use in the Lapland UAS 3D printing laboratory. It should be able to be used with the FFF printers at the university. The spruce and pine wood were provided by local Vaara company as a residue from log production for the filament producing process. Each will be mixed with virgin PLA material and processed into filament spools. The printability of the new filament will be tested and compared between the two wood types.

The same procedure will be carried out with a composite material consisting of wood dust and recycled PLA. This thesis tries to answer the questions on how to prepare the given resources for the production method and what the best ratio between PLA and wood dust is. The specific methods utilized as well as the used equipment will be described in detail.

2 CIRCULAR ECONOMY

The concept of circular economy functions as the basis for this thesis, as it reflects the benefits of adding residue material to an already established manufacturing process. This chapter explains circular economy and furthermore describes how 3D printing can be integrated into circular economy.

2.1 Concept and goal

Circular economy is a concept, which aims to extend the life cycle of products. It is a shift from the linear economic model, where the raw material is gathered, processed, used or consumed, and at the end of its life being thrown away. In practice, circular economy would reduce waste to a minimum. It can achieve this, by reusing, repairing, and recycling of the otherwise disposed of material. (Circular economy: definition, importance and benefits 2023.) These methods result in an extended product life, closing resource loops and rising resource efficiency (Fischer et al. 2023, 129–130).

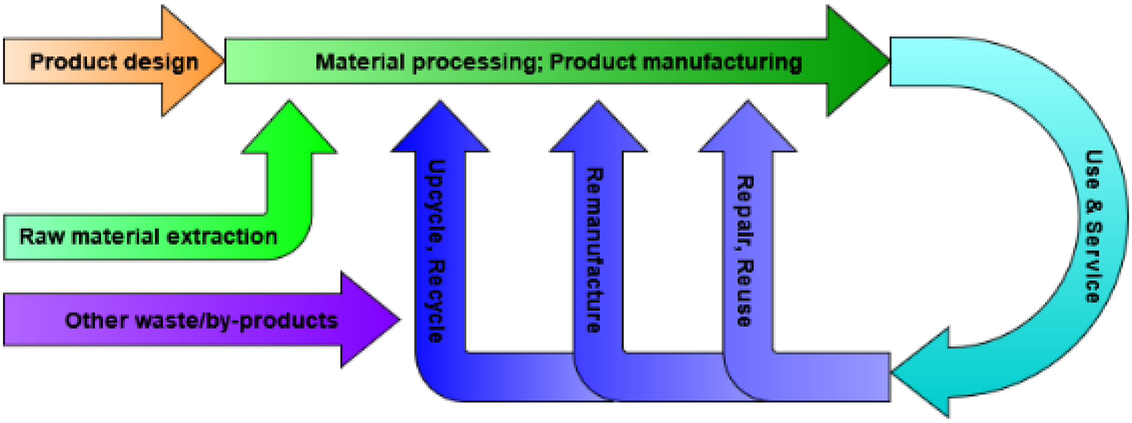

Figure 1. Circular economy model adapted from (Despeisse et al. 2017, 77)

Figure 1 illustrates the life cycle of a product in a circular economy, starting from the product design and raw material extraction. After the material processing and product manufacturing follows the use and service step and the loop is closed back to material processing and manufacturing through either repairing, remanufacturing, or recycling.

The benefits of this concept are primarily to protect the environment. It slows down the usage of natural resources. Starting the product design with circular economy in mind would also help to reduce the energy and resource consumption of a product. Especially, a reduction in critical raw material dependencies is a desirable incentive for the EU, as these materials are essential for achieving the climate goals. (Circular economy: definition, importance and benefits 2023.)

Circular economy profits from technology changes in the industry. The environmental impact comes primarily from the consumers, which uses those technologies. These technologies can range from reduction in resources and waste materials to lower energy consumptions in manufacturing or material innovations. (Fischer et al. 2023, 44.) While macro level circular economy focuses on the whole material cycle in the economy, on the micro level smaller innovations along the entire production process are more prevalent. This includes efficiencies, closing material loops (up-/downcycling) and extending product life. (Fischer et al. 2023, 133–134.)

2.2 Circular economy in 3D printing

3D printing can easily implement the concepts of circular economy with its design freedoms and mass customization, which will be discussed in detail in chapter 3. Other than subtractive processes, where large amounts of waste are produced, 3D printing is an additive process, which only adds material where it is needed. (Diegel, Nordin & Motte 2019, 1–2.)

The usage of sustainable materials as printing material is a contributor to circular economy in 3D printing. PLA for example is a bioplastic and has a low health and environmental impact compared to other commonly used printing material. Improving printer technologies and using materials with low melting temperatures reduces energy consumptions. (Faludi et al. 2015, 150.)

Material supply is another aspect of circular economy. While filament is produced by a range of both small and large companies, the feedstock material comes from a small amount of large polymer producers. In case of recycling, the material needs to be separated into single polymers to be considered applicable for reuse. A lack of information regarding the composition of the material can hinder an effective recycling cycle. (Despeisse et al. 2017, 77–78.)

Education and skill development regarding 3D printing can also be considered a huge factor in establishing a circular economy. With its wide range of technologies, applications in prototyping, tool development, and product manufacturing, it can influence the life cycle of a product as early as in its design stage. (Despeisse et al. 2017, 80–81.)

To further emphasize the advantages of recycling PLA, the transportation of the raw materials or even the produced filament has a huge impact on the environment, compared to recycling. Even if the production of the filament would be local, it only has a small positive impact in comparison. The used scenario assumes a PLA manufacturer located in the US and the consumer in France. (Caceres-Mendoza et al. 2023, 6, 9–10.)

The model of circular economy provides a possible solution for some of the Sustainable Development Goals (SDGs). The SDGs consist of 17 goals, which are trying to achieve a more sustainable future for all. Clean and affordable energy is one of the sustainable development goals which are profiting from circular economy. Sustainable cities, economic growth, as well as life below water (i.e. oceans), and life on land also benefit from circular economy. Circular economy projected on 3D printing would have its highest impact in the responsible consumption and production and climate action goals of the SDGs. (Fischer et al. 2023, 24, 136.)

3 3D PRINTING

This chapter gives an insight into the basic principles of 3D printing, lists the different categories, and highlights their advantages over conventional manufacturing processes.

3.1 Overview of 3D printing

3D printing or additive manufacturing (AM) is a production method which involves adding material, mostly layer-by-layer, to a product until it is finished. In its early days in the second half of the 1980s, it was mainly used for prototyping. This procedure, called rapid prototyping, was faster since it typically had a shorter preparation phase for manufacturing than conventional manufacturing methods at that time. One additional advantage of AM is that products can be manufactured directly out of a 3D CAD model without need for further fixtures or additional tools. (Godec et al. 2022, 1–2.) The CAD model needs to be converted into a format, which the AM machine can understand. The most commonly used file format is the STL file format, which stands for standard triangle language, stereolithography or standard tessellation language. The STL format converts the CAD model into a triangular based model as seen in Figure 2. The software of the AM machine slices the triangular model into thin layers, which height can be adjusted depending on level of detail. (Diegel et al. 2019, 4–6.)

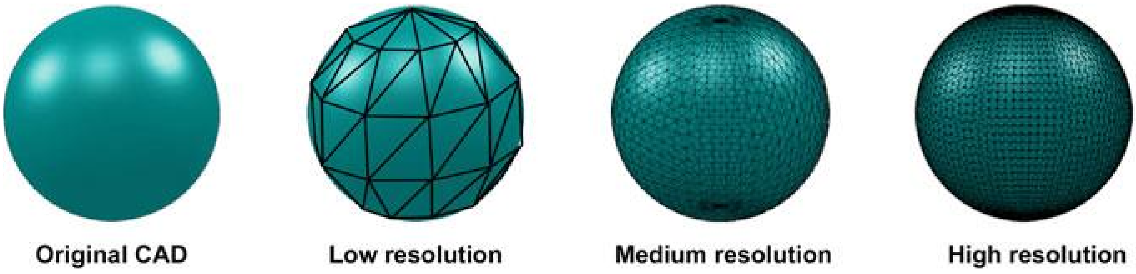

Figure 2. STL format example (Diegel et al. 2019, 5)

AM is divided into seven different categories. One of them is material extrusion (MEX), which will be disused in greater detail in the coming chapter. For Vat photopolymerization (VPP), a liquid photopolymer is selectively cured by light-activated polymerization. Material jetting (MJT) is a process, where droplets of build material are selectively deposited. Sheet lamination (SHL) forms an object by bonding sheets of material together. Powder bed fusion (PBF) uses thermal energy to selectively fuse parts of a powder bed. In case of directed energy deposition (DED) the fuse material is melted by a focused thermal energy e.g. laser, electron beam, or plasma arc and then deposited. In the last AM process, binder jetting (BJT), a liquid bonding agent is deposited to selectively join the powder material. (Godec et al. 2022, 6.) The processes and categorizations are illustrated in Figure 3.

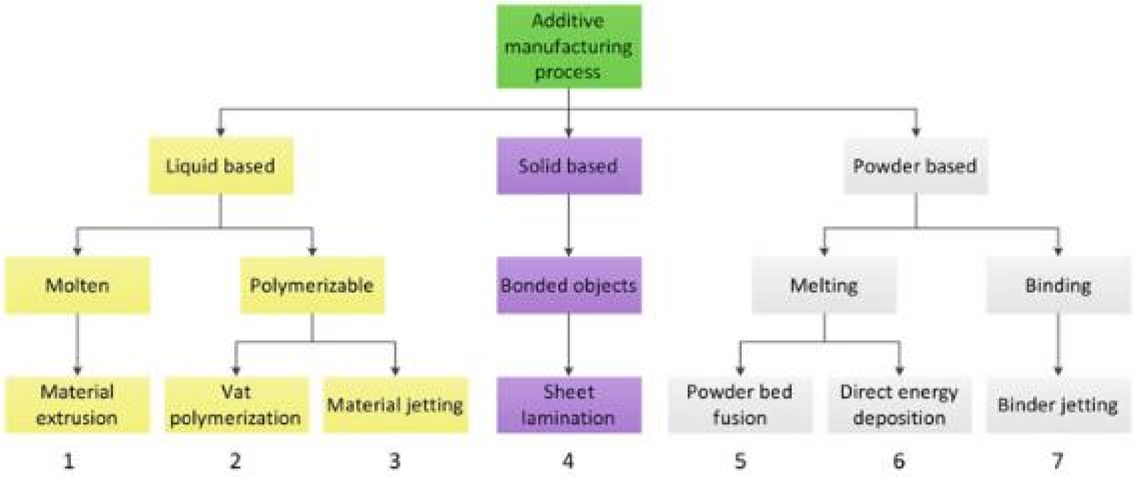

Figure 3. Additive manufacturing categories (Godec et al. 2022, 6)

3.2 Advantages of 3D printing

AM has a positive impact on the development and production phases of a product life cycle. This is achieved by rapid prototyping, as physical objects can be fabricated in rapid succession out of 3D CAD data. Due to shorter manufacturing cycles, more iterations are enabled to discover potential errors. Rapid prototyping assists for example in new designs, mould development, or pattern making. It also allows for aerodynamic testing of scaled models of automobile parts. Several different AM processes can be used for rapid prototyping, and fused filament fabrication (FFF) is one of them. (Maurya, Rastogi & Singh 2021, 3711, 3714.) This process will be discussed in detail in chapter 4.

Another advantage over conventional manufacturing methods is that with AM, parts or products with high geometrical complexity can be produced without increasing production cost. In other words, the manufacturing costs of more complex parts are going down and for simpler parts are going up. The layer upon layer approach enables designs without complex tooling or separating parts, which would need to be manufactured separately otherwise. (Diegel 2022, 75–76.) With AM, it is possible to produce interconnected moving parts in a single process. The not processed material inside these gaps can be removed afterwards. This means that some products can be manufactured already assembled. However, a minimum distance between the moving parts is needed to make this possible. A part with a tight connection requirement as finished assembly would be extremely difficult to achieve with AM. Combining several simple parts into one more complex part leads to less assembly costs. (Diegel et al. 2019, 11–17.)

4 MATERIAL EXTRUSION

Material extrusion (MEX) is among the most widely used processes. It is a technique where heated material is pushed through a nozzle and selectively deposited. It allows for a variety of materials to be used, such as thermoplastics, hydrogels, ceramics, and even bio-based or composite materials. (Daminabo, Goel, Grammatikos, Nezhad & Thakur 2020, 2–3.)

As a basic principle, the product is built up from bottom to top, one layer at a time. After one layer is fully drawn out, either the printing head or the platform moves along the Z-axis for the next layer to be deposited. MEX systems with a second nozzle can deposit a second material as support. The support gives overhanging parts of the product a surface to be printed on. These support structures are either broken off or dissolved after the finished process. The challenge for MEX is its anisotropic behaviour. The bonding of the material is less strong along the Z-axis, where the layers are connected, than along the X and Y-axis. This means that the products perform better under pressure than under tension, which can lead to delamination. (Diegel et al. 2019, 19–20.)

It can be differentiated into three types of material extrusion methods. An illustration of the three methods can be seen in Figure 4. One of them is material extrusion using plungers, where the material is forced through the orifice or nozzle due to piston pressure or e.g. compressed air. Materials used for this method should have low viscosity and a good shape retention after deposition. One example is Thermoplastic 3D-Printing (T3DP), where the thermoplastic feedstock material is deposited in droplets instead of strands. This technology usually requires a post-processing step to get the final product. Another method is material extrusion with screws. Not all materials possess the mechanical strength to be made into filament and are rigid enough to be pushed by a feeding mechanism to the liquefier and thereafter the extrusion head. For such materials, mostly thermoplastic pellets, screw extrusion machines are used. Screw extruders transport the solid pellets into a melting zone, where the pellets are being softened. After that, the molten material is transported to the nozzle under high pressure. The challenge of this technique is to provide a constant and controlled stream of material for the extrusion. (Godec et al. 2022, 34–35, 37–38.)

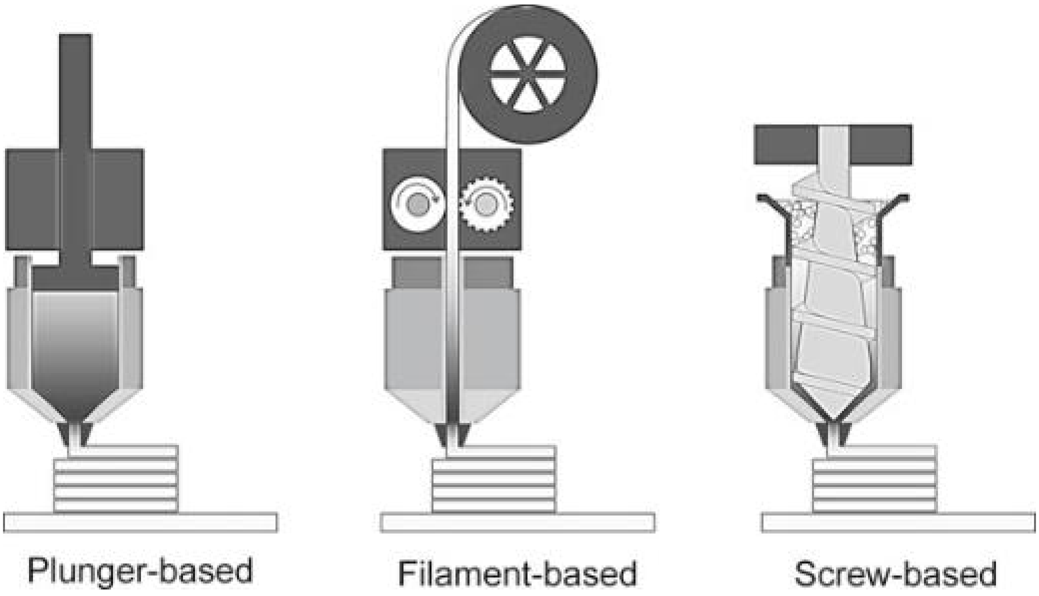

Figure 4. Material extrusion methods (Godec et al. 2022, 34)

Fused deposition modelling (FDM), also known as fused filament fabrication (FFF) is the most widely used MEX technique. Since FDM is a registered trademark of the Stratasys company, which first introduced the technology and the terminology can also be applied to other AM technologies, this thesis will thereafter only use the term fused filament fabrication (FFF) (Daminabo et al. 2020, 8).

FFF-machines are ram extruders. It means the filament pushes the softened material out of the printing head. The material is first being pulled by driving wheels and thereafter pushed into a liquefier and lastly into the nozzle. (Godec et al. 2022, 36.) The material flow is mostly related to the nozzle diameter and the viscosity of the softened material. The filament is pulled to the heater and acts like a piston. As a result, buckling of the filament is to be prevented and structural strength is needed to prevent the filament from snapping. (Daminabo et al. 2020, 8, 10.)

Material that fulfils the requirements for MEX include polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), polycarbonate (PC), polyamide (PA), polyphenylsulfone (PPSF), polyetherimide (PEI), polyethylene terephthalate

(PET), polymer with graphite, bronze, steel, brass, bamboo filler, thermoplastic polyurethane (TPU), thermoplastic copolyester elastomer (TPC), epoxy or biomaterials to name a few. For composite materials, the filler content is between 5 and 40 percent of the volume. (Godec et al. 2022, 36; Diegel et al. 2019, 22.)

4.1 Polylactic Acid (PLA)

Polylactic acid is a thermoplastic and high strength biopolymer made from renewable resources. It is non-toxic and a naturally occurring organic acid. It is typically obtained from sugarcane or corn starch. Furthermore, it is biodegradable and recyclable. (Farah, Anderson & Langer 2016, 368.) Depending on the source and synthesis technology, biopolymers are categorized in different groups. PLA stems from biotechnology and belongs to “Polymers from monomers which is chemically and conventionally synthesized (obtained from agro-resources)...” (Sharif & Hoque 2019, 3).

For the production process, firstly lactic acid which is a single monomer is chemically or by fermentation synthesized. To get PLA, a polymerization process is further needed. This can be done through different methods, which are illustrated in Figure 5. Polycondensation and ring opening polymerization produces low molecular weight PLA, and need additional steps for PLA with high molecular weight. Another method is azeotropic dehydration, which can directly produce high molecular PLA. (Lasprilla, Martinez, Lunelli, Jardini & Filho 2012, 324–325.)

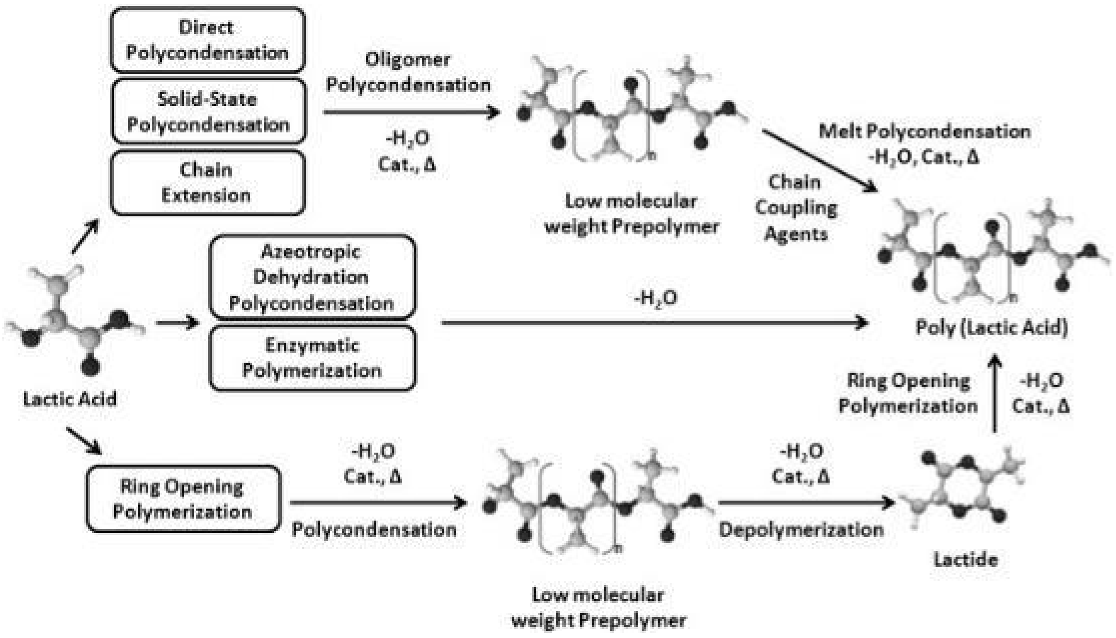

Figure 5. Polymerization methods (Lasprilla et al. 2012, 325)

In case of the physical properties of PLA, it has excellent transparency which makes it an applicable choice for drones, prototyping, automotives, aerospace, and more. It is suitable for biomedical applications, food packaging and its degradation outcomes are harmless. It can be used for various manufacturing methods, which include besides material extrusion, injection moulding, casting, thermoforming, foaming, blending, compounding and more. And lastly, PLA does consume less energy in its production than other polymers. (Sharif, Mondal & Hoque 2019, 234–235.) This aspect was also mentioned in chapter 2.

On the other hand, PLA is relatively brittle, which means it does not perform well at higher stress levels and bending purposes. The mechanical properties and degradation of PLA are dependent on the molecular mass. The processing temperature for PLA has to be carefully considered for preventing degradation of its molecular mass and physical properties. Thermal degradation happens at a temperature above 200 °C. Radical degradation starts at temperatures above 250 °C. (Farah et al. 2016, 373–374.) PLA has a fast hydrolysis rate and poor thermal resistance. Furthermore, it is a rather hydrophobic polymer and chemically passive, due to a lack of reactive side chains. Blending PLA with natural or inorganic filler material is often used and researched to strengthen its mechanical properties. (Sharif et al. 2019, 235–236.)

4.2 Development of Filament

A way to change the properties of thermoplastic materials used for MEX, is to blend or mix them with other materials. Thermoplastics together with so-called filler material show often improved mechanical properties, compared to their unfilled counterparts. It was also observed that semi-crystalline thermoplastics, such as PLA, containing fillers can prevent warpage of the material. This is because of a reduced shrinkage when solidifying, as well as better thermal conductivity and viscosity in a molten stage. (Ureña et al. 2022, 234.)

There are mainly three methods for producing composite material filaments. The first two methods are in-situ polymerization and solution intercalation. In the course of this thesis, the third method of melt processing will be used. Melt processing is more environmentally friendly and is moreover the simplest of the three methods. For the in-situ polymerization, particles of different sizes are dispersed in liquid monomers and afterwards polymerized. For this process it is possible to graft the polymer onto the particle surface which increases the mechanical properties of the material. Solution intercalation is a two-step process for fillers on the nano scale level. The particles are dispersed in a solvent, e.g. water, chloroform, or toluene. After mixing the solvent with the polymer, the polymer chains settle between the particles and remain in place after removing the solvent. The resulting structure is evenly distributed. For both methods, solvents compatible with both the polymer and filler particles are required. (Ureña et al. 2022, 234–235.)

Melt processing extruders can be differentiated between single and double-screw extruders (Figure 6). Typical diameter for the extruded filament are either 1.75 mm or 2.85 mm (Park & Fu 2021, 4). The 3DEVO Composer 450 for comparison is a single-screw extruder and will be introduced in chapter 6.1.

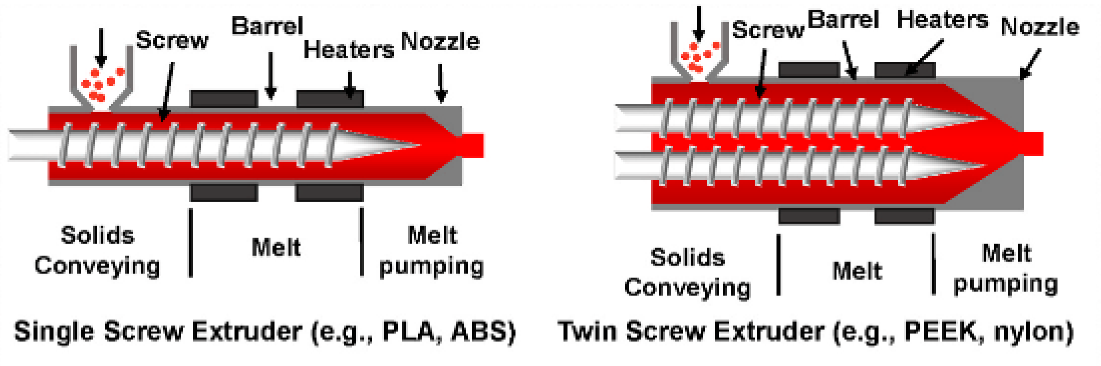

Figure 6. Single screw and double screw extrusion (Park & Fu 2021, 4)

For the production of filament, it is crucial, that the filament itself can sustain and provide the pressure needed for the 3D printing process. If the filament is too brittle, it could snap due to the pressure. Buckling on its way to the heater head should also be avoided. Another factor is the melt viscosity of the filament, as it influences its extrusion pressure. (Gkartzou, Koumoulos & Charitidis 2017, 4.)

5 STATE OF THE ART

This chapter presents research done on composite materials utilizing different kinds of wood filler and compositions. The conducted investigations looked into a variety of factors, which influence the overall performance of the composite material used for 3D printing. A summary of the filament content in the found research can be found at the end of chapter 5.1 in Table 1.

5.1 Polymer and composite material Filament

PLA as a feedstock material show a high visual quality and ease of printing compared to other commonly used polymers. Under visual quality falls surface properties such as smoothness. Ease of printing is represented by bed adhesion, speed of printing, ease of feeding to the printer, and frequency of print failures. PLA as a 3D printing material has a relative low melting temperature of 145-186 °C and can be easily made into filament at temperatures over 185-190 °C. It also possesses a relative high mechanical strength. (Park & Fu 2021, 3–5.)

Research for wood-based filament is already underway, and there already are wood based composite materials for printing available. There are multiple options of thermoplastics as core material and different methods for compounding the materials.

One such research paper investigated the physical, mechanical, and rheological properties of composite material using different percentages of wood dust. The wood dust was sieved through and only wood dust with a particle size of less than 0.237 mm was used. The particle size distribution was disregarded and is subject to further research. The wood-PLA pellets were extruded using a single screw extruder. The resulting filament diameter varied between 1.45 mm and 1.75 mm. The tested ranges of the wood content in the filament were 10%, 20%, 30%, 40% and 50% in weight. The results showed an increase in tensile strength and modulus of elasticity at lower percentages (10% and 20% respectively) and a decrease at higher percentages compared to the non-composite filament. Another problem that they faced was an uneven flow of the filament with higher content of wood particle and occasional clogging of the nozzle. With increasing wood content, the surface of the printed part would become rougher and would even start to contain voids due to uneven flow and clogging through the nozzle. And since the wood has a lower density than the PLA, the density of the composite material also decreased more with higher wood content. (Kariz, Sernek, Obućina & Kuzman 2018, 136–140.)

Another study researched the effects of particle size, shape, and content of wood in the material on printability and mechanical properties of composite materials. Two sorts of Australian wood were tested in combination with ABS. The wood particle size ranged from below 90 µm up to below 212 µm. The wood dust was dried and mixed with ABS, using maleic anhydride as a binding agent. (Huang, Löschke & Proust 2021, 2–3.)

They concluded that the physical and mechanical properties of the composite material depend on the circularity and convexity of the wood particles and not as much on the particle size. The content of wood in the composite material showed an improvement of tensile strength at lower percentages followed by a decrease at higher percentages, with a maximum around 29% weight. The stiffness also increases with the wood content. Other than the tensile strength, the stiffness does not decline at higher percentages, but the yields are decreasing. Another aspect is the effects of double extrusion on the filament. For this, the extruded filament was blended into small pieces and extruded for a second time without additional processing. The double extruded filament showed a significant increase in the consistency of the outcome, compared to the single extruded filament. Another advantage of the double extruded filament was a reduction in porosity and smaller voids present in the filament. The findings also suggest that composite materials with more circular and smooth wood dust particle contain smaller and fewer voids and overall possess better mechanical properties. (Huang et al. 2021, 6–10.)

Research of mechanical properties with different kinds of filler material, including wood, discovered an overall decrease in quality. This result confirms the negative impact of wood composite materials with higher content of wood particles, as the experiment was conducted with a ratio of approximately 40% wood content. The printed parts of the wood composite material also suffered from delamination defects. (Liu, Lei & Xing 2019, 3742–3745.)

The layer thickness used for printing has a direct effect on the roughness of the surface of the printed product. The higher the layer thickness is, the rougher the surface becomes. As the layer thickness influences the printing time, a 0.2 mm layer thickness was suggested as optimum for wood based PLA prints. (Ayrilmis 2018, 166.)

Research on flexural behaviour of PLA wood composite material with 22% wood dust content showed that the composite material is more porous and therefore fractures at lower forces than virgin PLA. On the other hand, the composite material is more flexible than virgin PLA and can sustain higher deformation before breaking. (Parikh, Chokshi, Chaudhary, Khan & Mistry 2023, 3.)

Another successful attempt in creating wood-based PLA was made using Aspen wood dust with a mean particle size of 14 µm. The wood dust as well as the PLA pellets were dried beforehand at 103 °C for 4 hours. The materials were blended with a wood content of 5% wood dust by weight. The composite material was extruded using a single screw extruder with a mixing temperature of 175 °C and extrusion temperature of 171 °C. The diameter of the Filament was 1.75 mm. The results under a scanning electron microscope (SEM) show that the surface of the composite material is less smooth, and gaps can appear between the PLA and wood particle. As wood is a hydrophilic and PLA a hydrophobic material, the interface force between them is rather poor. The wood particle can still be encapsuled by the polymer matrix of the PLA. (Tao, Wang, Li, Li & Shi 2017, 2–3.)

Even more research in mechanical, chemical, and optical properties as well as the printability of composite filament were conducted. In this case, the PLA was modified beforehand with acrylic core-shell rubber as impact modifier and acrylic processing aid to help against the brittle nature of PLA and low melt viscosity. This modified PLA is being mixed with teak wood of varying particle size and content ratio. 74 µm and 125 µm teak wood particles were blended in a ratio of 1, 3 and 5% of weight each with the modified PLA and melt processed into filament afterwards. The tensile strength decreased with higher wood content, but all the 125 µm samples performed worse than the 5% content of 74 µm wood particle. As for the printing test, the filament with the 125 µm wood particle could not be printed, due to a clogging of the printer nozzle, while the one with 74 µm particle size succeeded. (Petchwattana, Channuan, Naknaen & Narupai 2019, 171–172, 177, 184–185.)

Table 1. summary of researched polymer/wood composite filament

Base material	**Filler material**	**Wood particle size**	**Content ratio by weight**	**Filament**
PLA	Beech wood	237 µm	10, 20, 30, 40 and 50%	1.75 mm
ABS	Red gum wood	150 - 212 µm; 90 - 150 µm; below 90 µm	19, 29 and 39%	2.75 mm
ABS	Grey box wood	150 - 212 µm; 90 - 150 µm; below 90 µm	19%	2.75 mm
PLA	unknown wood	unknown	40%	1.75 mm
PLA	unknown wood	unknown	30%	1.75 mm
PLA	unknown wood	unknown	22%	1.75 mm
PLA	Aspen wood	14 µm	5%	1.75 mm
modified PLA	Teak wood	74 µm and 125 µm	1, 3 and 5%	1.75 mm

5.2 PLA Recycling

The property changes of recycled PLA in use of 3D printing are in two aspects important for this thesis. On one hand, the recycled PLA is being used as main material for mixing thermoplastics and wood particles in one of the experiments. If the degradation of the recycled material is too great, the chance of failure in producing a recycled PLA and wood dust composite material in the processing phase or later in the 3D printing phase can increase significantly. On the other hand, the improvements to the composite material achieved through a second extrusion cycle can be lessened or even negated, especially when using recycled PLA.

The results of a one-time recycling cycle showed that the material is still usable for 3D printing. The mechanical properties of the recycled PLA were only slightly less compared to the virgin PLA. More notable is the increase of standard deviations of the results for the recycled PLA. The consistency of the recycled PLA filament diameter is identical to the virgin PLA filament, and the surface finish also showed no signs of degradation. (Anderson 2017, 112–114.) The degradation of the material in the recycling process is more prominent in the 3D printing process than in the melt processing of the Filament (Zhao, Rao, Gu, Sharmin & Fu 2018, 1049).

The mechanical properties of recycled PLA are only slightly lower than of virgin PLA. These results do not differ significantly from recycled PLA, which was reprocessed multiple times (Beltrán, Lorenzo, Acosta, de la Orden & Martínez Urreaga 2018, 30). The more significant degradation happens to the viscosity of the recycled material, which influences the printability of the material. The addition of virgin PLA into the recycled PLA showed a significant increase in the material properties and printability of the reprocessed material. The two times recycled PLA, reprocessed with 50% virgin PLA, showed results that outperformed the single recycled PLA. (Zhao et al. 2018, 1049–1051.)

Another research assessed the mechanical, rheological, and thermal properties of multiple times recycled PLA. The PLA went through 6 iterations of extrusion, 3D-printing, property measuring, and shredding. The results show that thermal properties stay nearly the same, even over several recycling cycles. The viscosity of the PLA decreases with each cycle, and even more drastically following the sixth cycle. In case of printability and overall satisfactorily performance, PLA printed using large-format AM can be recycled up to 5 times, and using FFF up to 3 times without significant degradation of the material. (Romani, Perusin, Ciurnelli & Levi 2024, 10–11.)

6 EQUIPMENT

This chapter gives more insight into the equipment, which is being used for producing the wood PLA composite material. Starting with the Filament maker as its core and expanding to the shredder and the dryer used in pre-processing the PLA pellets and in the recycling process. All the equipment mentioned in this chapter is one part of the 3D printing laboratory of the Lapland UAS (Figure 7).

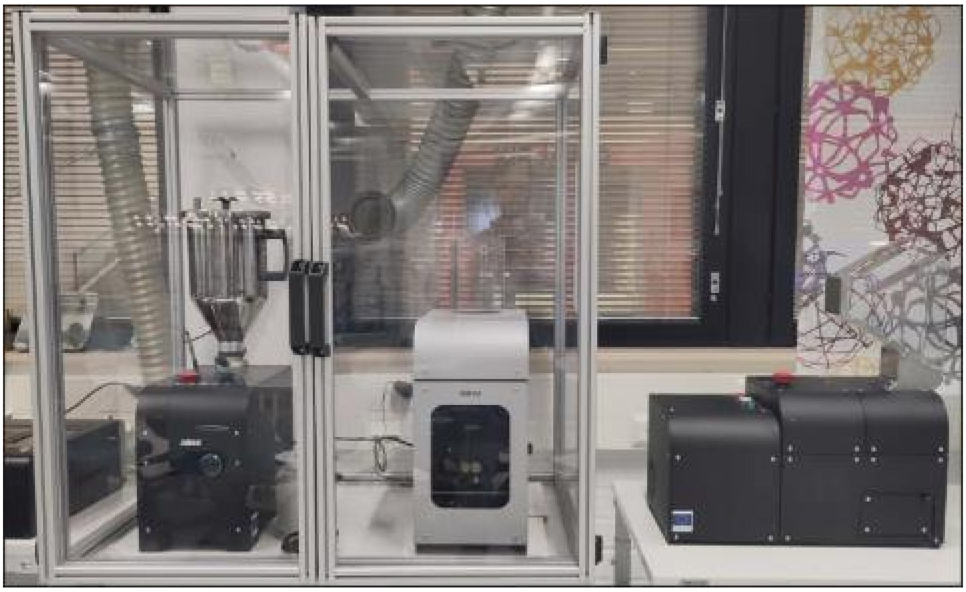

Figure 7. Filament fabrication station

6.1 3DEVO Composer 450

The main components of the 3DEVO Composer 450 filament maker are depicted in Figure 8 and are as follows.

The hopper in which the material is fed into the machine for processing. The material must be in a solid state while entering the barrel. The material will push the melted material forward and provide flow and pressure for the extrusion process. As mentioned before, the input material needs to be solid when entering the barrel or else the constant flow will be disrupted, and the hopper might clog. In case of additives, it is important to make sure that the materials are evenly distributed inside the hopper. Pre-compounding and starve feeding are possible techniques to ensure this. (3devo 2024d.)

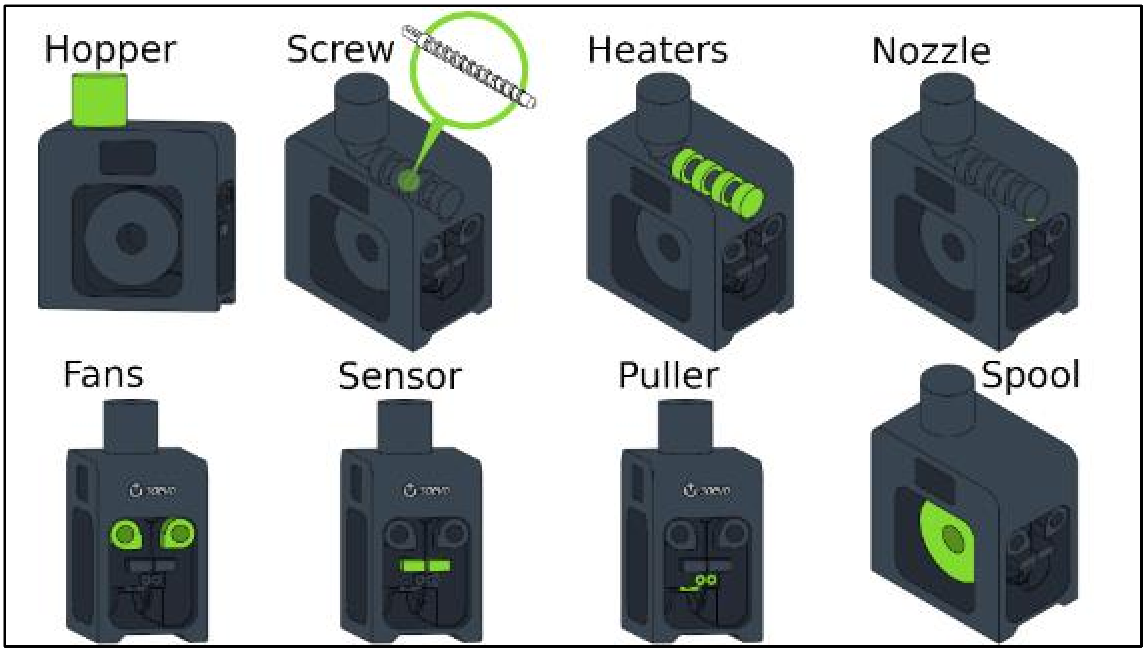

Figure 8. Components of the 3DEVO Composer 450 (3devo 2024a)

The screw, which transports the material fed into the machine forward through a barrel. The extruder screw is powered by a motor with a gearbox. The screw pushes the material further into the barrel. It should be noted that if the material is not melting, the screw will struggle to rotate. On the other hand, if the material melts too early, the output will be poor. The screw has a compression zone at the end, which reduces the flow, but adds pressure and friction for a more homogenous output. The rotation speed is between 2 and 15 rotations per minute (RPM) whereas a speed of 3 to 7 RPM is recommended. The desired operation point for the motor current is around 2000 to 2500 mA, and the rotation speed should only deviate between ±0.1 rpm. (3devo 2024g.)

The heaters, in total four separate ones, around the barrel, which melt the material. The heater is working through 3 separate zones. In the feeding zone, the heater nearest to the hopper is responsible for starting the melting process. The material should still be solid in the beginning of the barrel for reasons explained in the hopper section. In the second zone, the next two heaters are responsible for transitioning the material into its melted state. After passing the third heater, the material should be fully melted. This zone is called the transition or compression zone. The last zone is the metering zone. Here, the material is kept liquid by the fourth heater and gives texture to the material. It is then extruded through the nozzle. The heaters are insulated from each other, but a temperature difference greater than 30 °C can still affect adjacent heaters. (3devo 2024c.)

The nozzle, from which the hot and liquid material is extruded and ready for cooling. The size of the nozzle determines the filament diameter. The three different nozzle sizes available for the filament maker are 4, 3 and 2 millimeter. The standardized diameter for filaments is 1.75 mm and 2.85 mm. The melted material is stretchy by nature, and the desired filament diameter is achieved by gravity or pulling by the puller wheel. The 4 mm nozzle is the default size and has the lowest risk of clogging. If the material is not stretchy enough to achieve the desired filament diameter, a smaller nozzle is advised. It is highly advised that the particle size of the input material is never greater than the nozzle diameter. To further prevent clogging, the nozzle should not be cooled from the outside. This can happen by incorrect positioning of the cooling fans. (3devo 2024e.) The inner workings of the Composer 450 are illustrated in Figure 9.

The role of the fans is to cool and solidify the material on its way to the puller wheels. As there are two fans positioned opposite of each other, they need to be positioned symmetrically to avoid uneven cooling and warping of the filament. (3devo 2024b.)

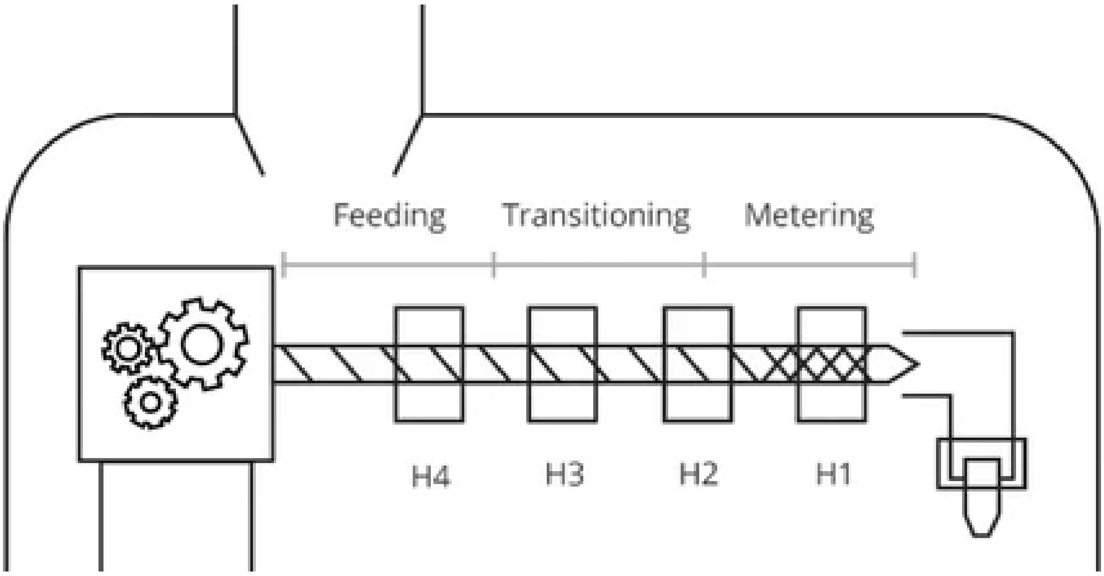

Figure 9. Composer 450 inner system schematic (3devo 2024c)

The Sensor measures the filament diameter. This information is provided to DecoVision (program) and the puller wheel and can help to fine-tune the whole process. For the sensor to work correctly, the filament needs to be cool and solid enough. The measurement will be displayed on the machine’s interface and shows a graph with the thickness in micrometers over the time in seconds. As the sensor only measures the thickness, the extruded filament still needs to be checked for inconsistencies. (3devo 2024h.)

The puller wheels automatically adjust according to the sensor data to allow for consistent spooling. There are two parallel wheels, of which one is motorized and coated in silicon, and the other is a free spinning metal wheel. The wheels can be operated in two different modes. In the manual setting, the wheel is spinning with a set turn speed. In the automatic setting, the wheel turning speed is determined by the sensor output. The average thickness over 20 seconds is calculated and if this differs from the set filament diameter, the speed will be adjusted. For the optimal outcome, the manufacturer advises starting in manual and adjusting the speed until a stable flow and consistent diameter is achieved and confirmed by the machine’s interface. Afterwards, switch from manual to automatic mode. If the puller wheels deform the filament, the cooling fans or heater needs to be adjusted accordingly. (3devo 2024f.)

The last part is the spooler, where the produced filament is spooled. The most important mechanism for the spooling process is the positioner. It moves back and forth to align the filament on the spool. The filament maker possesses a software feature that regulates that feature depending on the spool size. (3devo 2024i.)

6.2 3DEVO SHR3D IT

For the preparation of the recycled PLA for the mixing process, the 3DEVO SHR3D IT (Figure 10) is going to be used to pre-process the material for the mixing in the filament maker. Its components and general process is described here.

The material is inserted through the hopper into the shredder compartment. Here, the material is cut, torn, and shredded into smaller chunks and feed into the granular compartment. In the granular compartment, the material chunks are further cut until the granules are small enough to be sieved through the filter screen. The holes of the filter screen are 4 mm in diameter. After that, the granules are collected in the granulate collector. (3devo 2024j, 8–9.)

Figure 10. 3DEVO SHR3D IT

The operating temperature for the shredder is 0-55 °C and achieves a capacity of 5.1 kg polymers per hour. The rotation speed of the shredder is 9 rpm, and for the granulator it is 750 rpm. (3devo 2024j, 16.)

6.3 3DEVO AirID Dryer

The shredded recycled PLA will be dried in preparation for the mixing process. For the drying process, the 3DEVO AirID Dryer (Figure 11) is going to be used.

The material is loaded into a hopper, where the material is dried using hot air. The operating temperature is up to 160 °C. A stirring motor is located inside the hopper and keeps the material in motion to counteract clumping. The motor can be adjusted between 15 and 30 rpm. A hopper lid with a hot air outlet is used to maintain the temperature inside, but also provide an exit point for the evaporated moisture. The hopper has a volume of 5 liters and a drying capacity of 1 kg per 3 hours for nylon 6. The process can be adjusted using the user interface. Adjustable parameters are temperature, drying time, stirring speed, and blower speed. A variety of presets are available and custom-made settings are also possible. (3devo 2019, 5–8.)

Figure 11. 3DEVO AirID Dryer

6.4 Fused Filament Fabrication-Printer (Prusa I3 Mk3s)

The 3D printing laboratory of the Lapland UAS accommodate multiple different FFF-printers, such as 2 Cura Ultimaker, a Creality Ender 3 and several Prusa I3 Mk3s. For the test prints, the Prusa I3 Mk3s (Figure 12) is being used. It is a cartesian 3D printer, as the movements of the printing components are based on the XYZ coordinate system. The extruder head moves along the X and Z-axis, and the print bed moves along the Y-axis. (Stříteský, Průša & Bach 2019, 12.)

The main component of each FFF-printer is the extruder or print head. The filament enters the print head and passes through a heat sink. The heat sink’s purpose is to dissipate the heat coming from the heat break and keep the transition area between solid and melted filament at a minimum. The heat sink has a cooling fan mounted on the side. The heat break is a narrow tube, which lessens the heat rising up to the area, in which the filament remains solid. The heater block melts the filament, mostly using an electrical heating element. The melted filament is then pushed through the nozzle. A commonly used nozzle size is 0.4 mm in diameter. (Stříteský et al. 2019, 13.)

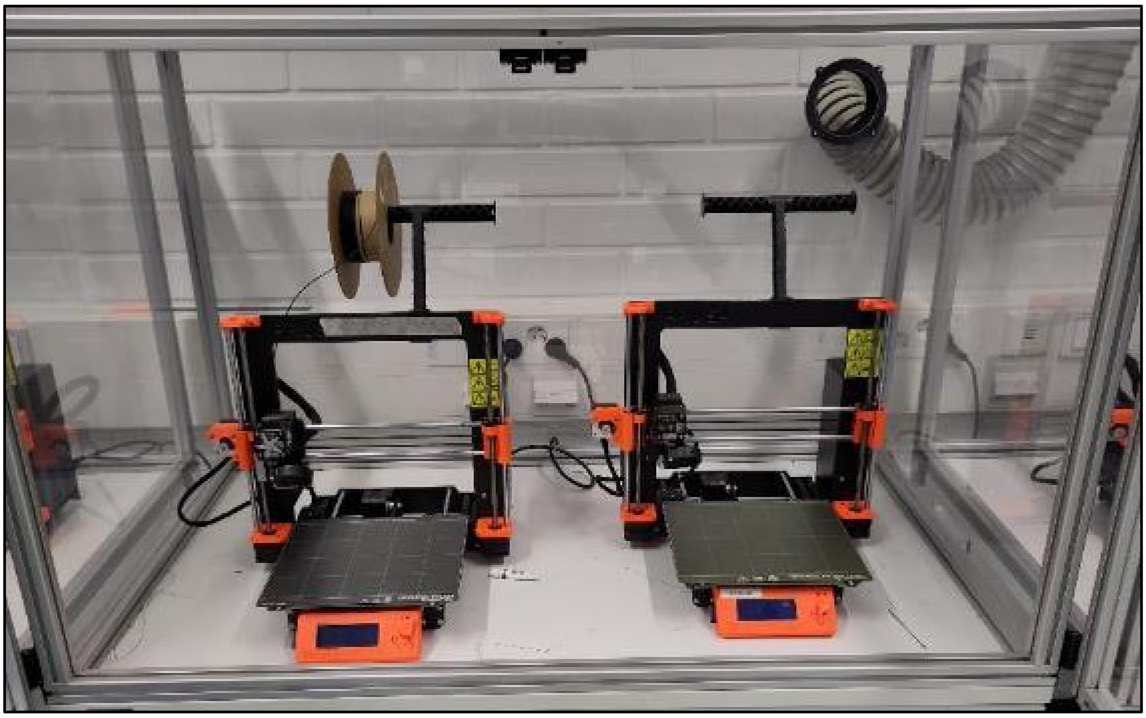

Figure 12. Prusa I3 Mk3s

The heat bed is responsible for stopping the printed object from bending, warping or detaching from the surface. A recommended heat bed temperature for PLA is 60 °C. Motors are responsible for the movement and positioning of the printhead, the heat bed and for the filament string supply. Stepper motors are being used, as they can be controlled precisely. The last component is a mainboard, which reads the G-codes, and controls the motors, heater, and heat bed. (Stříteský et al. 2019, 15.)

7 METHODOLOGY

This chapter describes in detail the used materials for this thesis, as well as the necessary preparations and steps. To produce the composite filament, commercial PLA is being used and compound together with the wood dust.

7.1 Preparation of the residue wood

The spruce and pine wood were provided by the local Vaara company as a residue from log production. Figure 13 shows the two wood types before any preparations for the subsequent process steps.

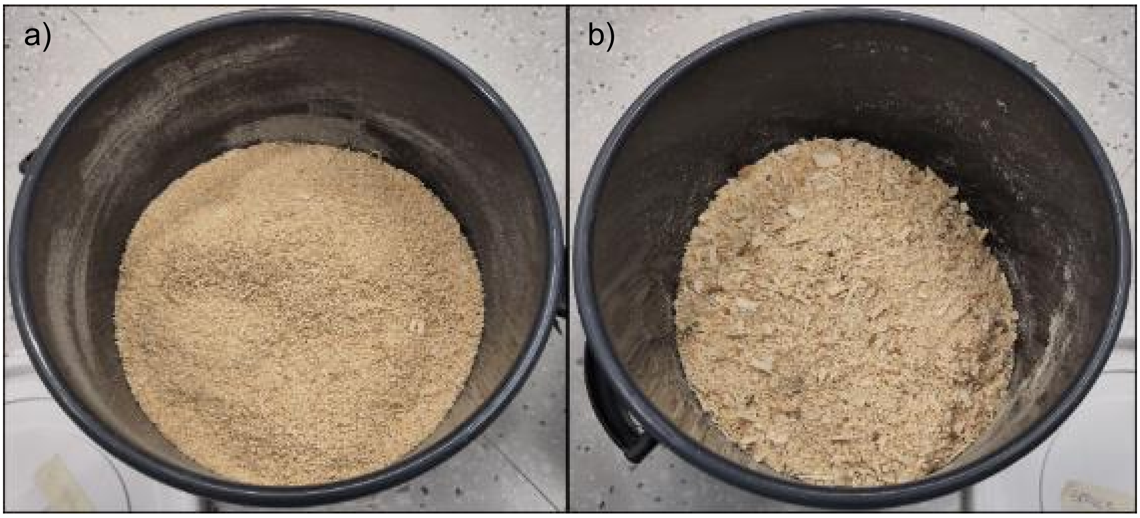

Figure 13. Wood batches: a) pine wood; b) spruce wood

A small sample of the unprepared wood was cast into resin to provide a means to look into the overall geometry of the wood. A closer look, as shown in Figure 14, reveals that the pine wood samples are more circular than the spruce wood, which has a straighter, fibre like geometry. This should result in a better outcome for the pine wood composite filament, as the findings from the literature research in chapter 5.1 would suggest. For successfully creating a wood based filament, small enough wood dust particle need to be extracted.

The wood needs to be prepared for the mixing process. For the next steps, the described processes will not differ between spruce and pine wood. In the first step, the wood dust will be screened by hand with a sieve with a 1 mm mesh. This is especially important for the spruce wood, as the provided batch contains much larger wood pieces than the pine wood batch. After the first screening, approximately 400 g of each wood type were collected. This was the maximum amount that could be collected out of the spruce residue. For the pine wood, it would be possible to accumulate a larger mass, but not by a significant amount.

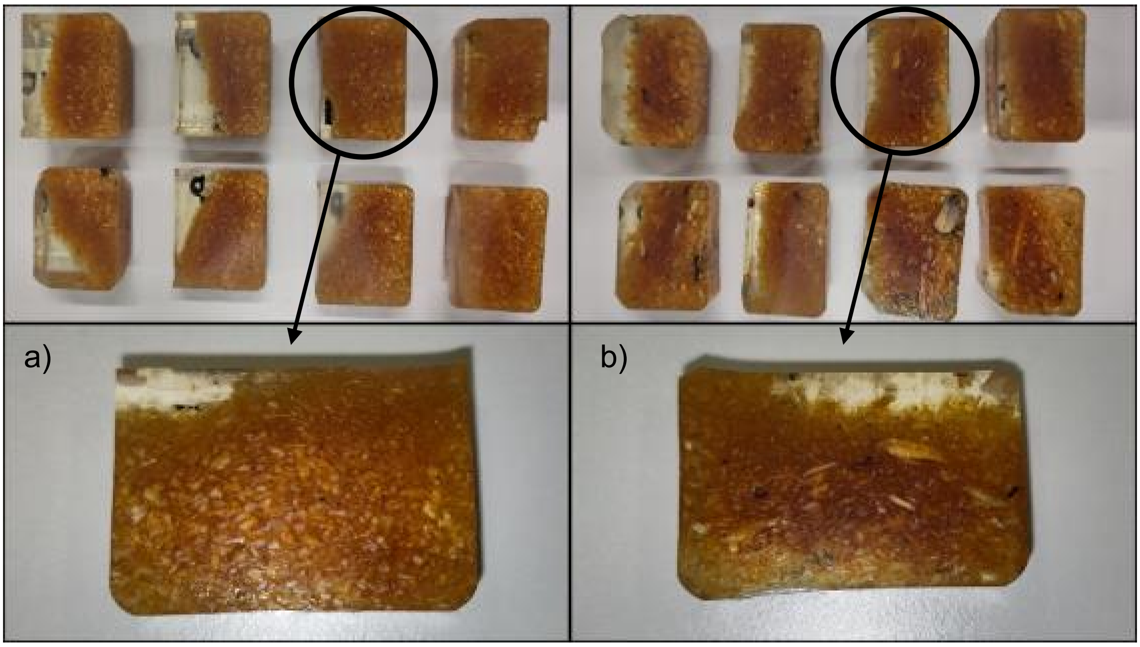

Figure 14. Wood dust Samples in resin cast: a) pine wood; b) spruce wood

The density of the wood is not only different between species but can also differ depending on the tree growth and parts of the tree. Branches are usually lighter than the trunk. The density of spruce ranges from 0.40 to 0.71 g/cm^3 and for pine from 0.35 to 0.85 g/cm^3 (Matmatch 2024; MT Copeland Technologies 2020). The density of the spruce wood dust seems to be almost half of the density of the pine wood dust. Under the same conditions, the trays with identical volume used in the following described drying process could hold 200 g of pine wood dust at a time, while another could only hold 100 g of spruce wood.

The 400 g of wood particles with a maximum size of 1 mm for each type of wood are being dried in a drying oven with natural convection at 105 °C until constant mass is achieved. As the AirID Dryer is only meant for plastics and other materials are potentially harmful for the machine, a separate oven dryer is being used for the wood (3devo 2019, 4). The drying process took over 8 hours and the moisture content of the wood was determined using the weight difference before and after the drying, according to ISO 18134-1, determination of moisture content for solid biofuels standard. The result for the Pine wood is 7.0% mass and for the spruce wood 6.8% mass as moisture.

As for the finer screening process, the vibratory sieve shaker AS300 is being used and for cleaning the sieves between the screenings of the two wood types a WUC-N ultrasonic cleaner is being used (Figure 15).

Figure 15. Screening equipment: a) AS 300 vibratory sieve shaker; b) WUC-N ultrasonic cleaner

Following this, the final step of the screening will be undertaken. The dried wood is being screened through the 0.25 mm and 0.125 mm mesh, which are stacked on top of the collection tray. As there is a maximum loading volume of 132 cm^3 for the 0.25 mm mesh, the screening process is being repeated until all 400 g of wood dust is being sieved. The maximum sample material size for the 0.25 mm sieve is 2.5 mm, and therefore adequate for the material obtained from the first screening process. The amplitude for the screening was set to 1.4 mm and each screening cycle lasted for 5 minutes. The amplitude is defined as the lifting height of the sieves from their stationary position. With an amplitude of 1.4 mm the displacement in the positive and negative direction is each 0.7 mm. This helps to orientate the particle and move them freely over the sieve for the screening. (Retsch 2023, 14–15, 34.)

Figure 16. Wood dust collection tray

While cleaning the equipment, fine gaps (Figure 16) were discovered in the collecting tray. As a result, a hard to estimate amount of losses occurred. Despite this circumstance, out of the 400 g for each wood type, an amount of 6.2 g of pine wood dust and 3.8 g of spruce wood dust was extracted successfully (Figure 17).

According to the manufacturer of the Composer 450, the size for the additive material with the best chance for good results is around 0.1 mm. It was also documented that wood based PLA with a wood particle size of a maximum of 0.237 mm was successfully produced (Kariz et al. 2018, 138–139). The acquired wood dust particles satisfy the requirements and therefore are being used as the additive for the filament. A content ratio of 5% wood dust by weight is being chosen for the material. This amount affects the tensile strength and elasticity negligibly, and it would make a clogging of the filament maker and the 3D printer more unlikely.

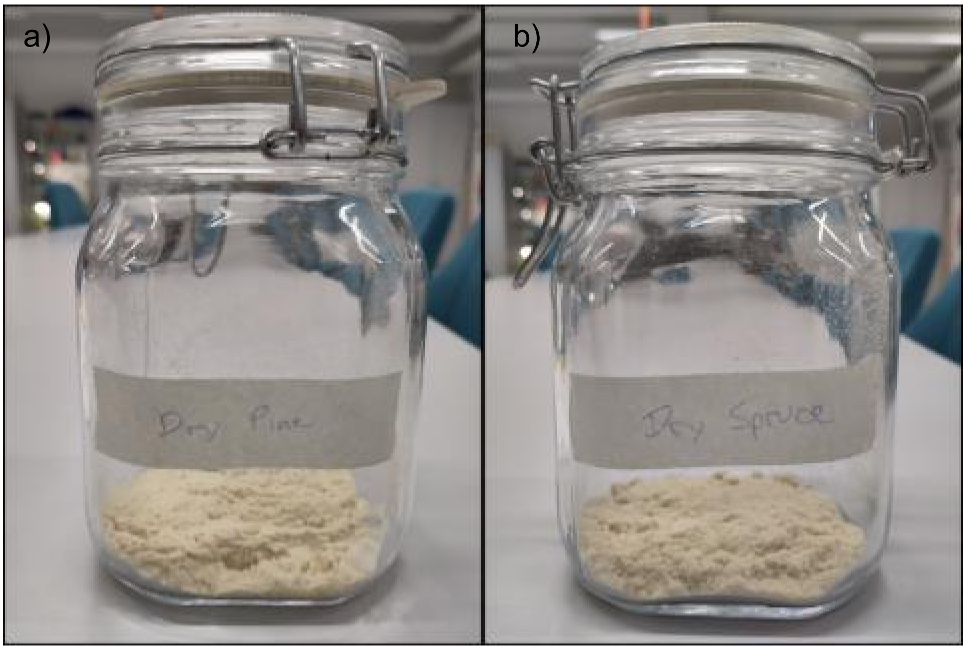

Figure 17. Wood dust 125 µm: a) pine wood; b) spruce wood

7.2 Virgin PLA/wood dust and Recycled PLA/wood dust

As the virgin PLA material, PLA 4043D transparent granules from 3devo are being used. The granules used for the filament and the wood dust are being mixed and fed into the hopper of the filament maker. As the yields from the screening process are not high enough to leave room for much experimentation, the filament maker is first fed with virgin PLA until an even flow and a satisfying outcome can be produced, as the composite material can be extruded with almost identical settings as virgin PLA. Only after this condition is met, the composite material is being fed to the filament maker to guarantee an optimal result and quantity of wood based PLA filament. The produced filament is being spooled as soon as the filament diameter is within the defined tolerance. The tolerance limits are 1.65 and 1.85 mm. The spooled filament is later being used for the 3D printing test. A small portion of the filament is also cut off, labelled, and stored for reference. The excess material of the single extruded filament is being shredded to chunks of a maximum size of 4 mm and fed again to the composer 450. The double extruded outcome is also being spooled as soon as the filament is within the tolerance limits and another 3D printing testing is being done afterwards. The procedure is illustrated in Figure 18.

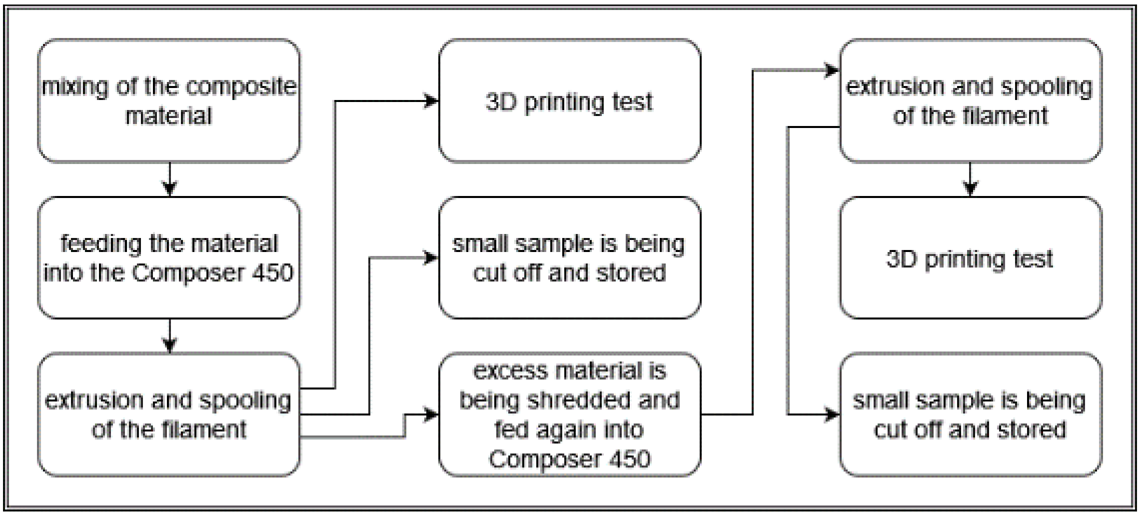

Figure 18. Illustration of the testing procedure

The current settings and actual values of the heater temperatures, filament diameter and rotation speed of the screw during the process will be monitored using the DevoVision program and are listed in the results. The setups for the consecutive tests are built upon the results of all the previous tests. The Composer 450 is being purged (i.e. cleaned) with a temperature of 200 °C for all heaters between each test to remove any remaining testing material still in the machine.

In the first test, the PLA/spruce wood composite material is being extruded. 3.5 g of wood dust was mixed with 66.5 g of PLA granules for a total amount of 70 g of composite material for 5% wood content by weight. This is the only test executed with spruce, as the yield only allowed for one type of test.

For the second test, PLA/pine wood composite material is being extruded. In accordance with the first test results, the content ratio was reduced to 3% and the temperatures were lowered. 2 g of pine wood dust was mixed with 65 g of PLA granules for a total amount of 67 g of composite material. Afterwards the content ratio was increased to 5% with a smaller sampling size of 1 g pine wood dust and 19 g PLA granules and the test was repeated.

As for the third test, a mixture of recycled PLA, virgin PLA granules and pine wood dust is being processed. As the viscosity and printability of recycled PLA is lower compared to virgin PLA and could further decrease with the addition of wood dust, a mix of recycled and virgin PLA is being used. With a ratio of 50/50 between recycled and virgin PLA, the degradation can be counteracted (Zhao et al. 2018, 1050–1051). To prepare the recycled PLA for the process, it is shredded into up to 4 mm chunks through the shredder and subsequently dried with the AirID Dryer. The dryer is set to a temperature of 55 °C for 4 hours, with a mixer speed of 15 rpm and automatic blower speed being turned on. The content of the composite material for this test is 2 g of pine wood dust, 19 g each of recycled PLA and PLA granules for a total amount of 40 g.

7.3 3D printing test

To test out the printing quality of the produced filament, a suitable 3D model needs to be selected. For this purpose, the 3DBenchy designed by Creative Tools is being chosen. It is the model of a small boat with various challenging features related to additive manufacturing in mind. The STL file is under the Creative Commons License (Creative Tools 2020) and was downloaded from thingiverse (https://www.thingiverse.com/thing:5293974). A preview of the model can be seen in Figure 19.

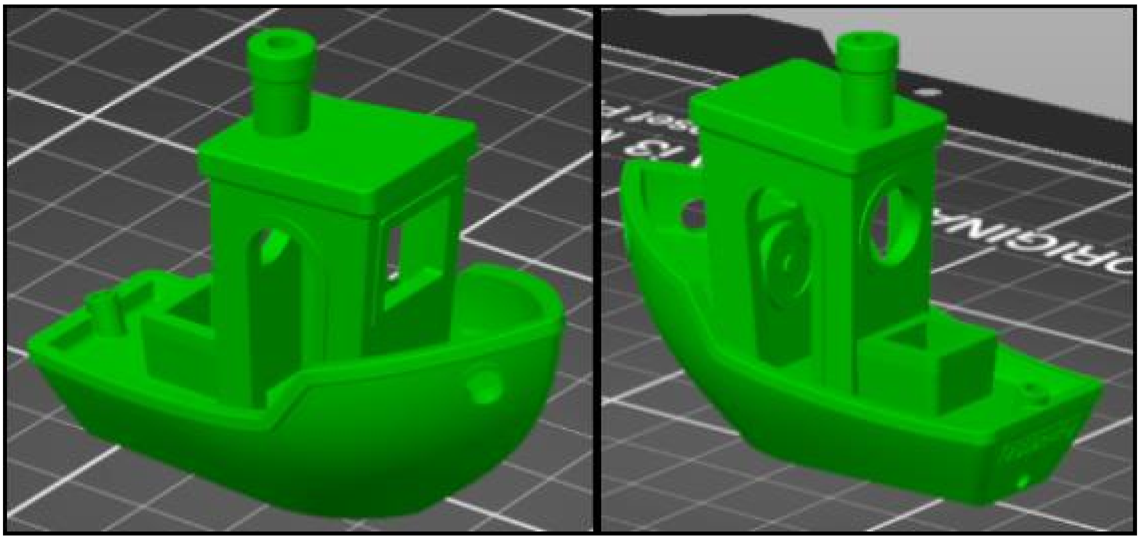

Figure 19. Preview of the 3DBenchy model

For the generation of the G-code, which is needed for the 3D printer, the PrusaSlicer 2.7.2 software is going to be used. The printing settings are listed below in Table 2. The calculated filament consume is 3.98 m and would take an estimated time of 1 h 22 min to finish. The weight of the final product is 11 g. To have a comparison, a 3DBenchy consisting of only virgin PLA is also being printed.

Table 2. 3D printing settings

Layer height	**Infill**	**Extrusion speed**	**Travel speed**	**Nozzle diameter**
0.2 mm	10%	up to 50 mm/s	up to 150 mm/s	Ø 0.4 mm
Printing temperature			**heat bed temperature**	
215 °C			60 °C	

8 RESULTS

The results for the spooling and printing are recorded in this chapter. Each test will be reviewed individually and is split between the two wood types. The settings for each test are shown below in Table 3. The number in the table indicates the percentage of wood dust, S stands for single extrusion and D for double extrusion. For the last row, PLA granules (vPLA) and recycled PLA (rPLA) were used.

Table 3. Settings for the filament extrusion process

	Heater [°C]					
	H1	**H2**	**H3**	**H4**	**Screw speed**	**Fan speed**
PLA default	170	190	185	170	3.5 rpm	50%
PLA/Spruce 5S	170	195	190	170	3.7 rpm	65%
PLA/Spruce 5D	175	195	190	170	3.4 rpm	65%
PLA/Pine 3S	170	185	180	165	3.0 rpm	35%
PLA/Pine 3D	170	185	180	165	2.8 - 2.5 rpm	35%
PLA/Pine 5S	170	185	180	165	3.2 rpm	35%
PLA/Pine 5D	170	185	180	165	2.7 rpm	35%
vPLA/rPLA/Pine 5S	170	180	175	165	3.2 - 2.9 rpm	35%

8.1 Results for spruce wood

In the first attempt, the PLA/spruce wood composite material was being extruded. The starting settings in this attempt were the default settings for PLA. The settings were adjusted with an increase in temperature of 5 °C for the heaters 2 and 3. In the transitioning phase from virgin PLA to composite material, a fluctuation in the filament diameter and a rougher surface of the filament were discovered. The spooling started as the transition was finished, and the filament was within the tolerance limits. Shortly after, the process was interrupted by an unknown error registered from the Composer 450. The data log for the second spooling attempt is missing, as the connection to the DevoVision was lost, due to restarting the filament maker. It was still possible to extrude the material and spool an amount of 27 g of filament in weight.

The recording with DevoVision was restarted after the machine shut off, due to high motor currents. As attempts to solve the issues with increasing temperatures and adjustments to the rotation speed failed, the first test was being stopped. The motor current and rotation speed are shown in Figure 20. While trying to purge the machine with devoclean purge mid temp, the output was declining drastically and a feeding problem in the hopper was discovered. To solve the issue, the Composer 450 was force-fed and purged at a temperature of up to 240 °C.

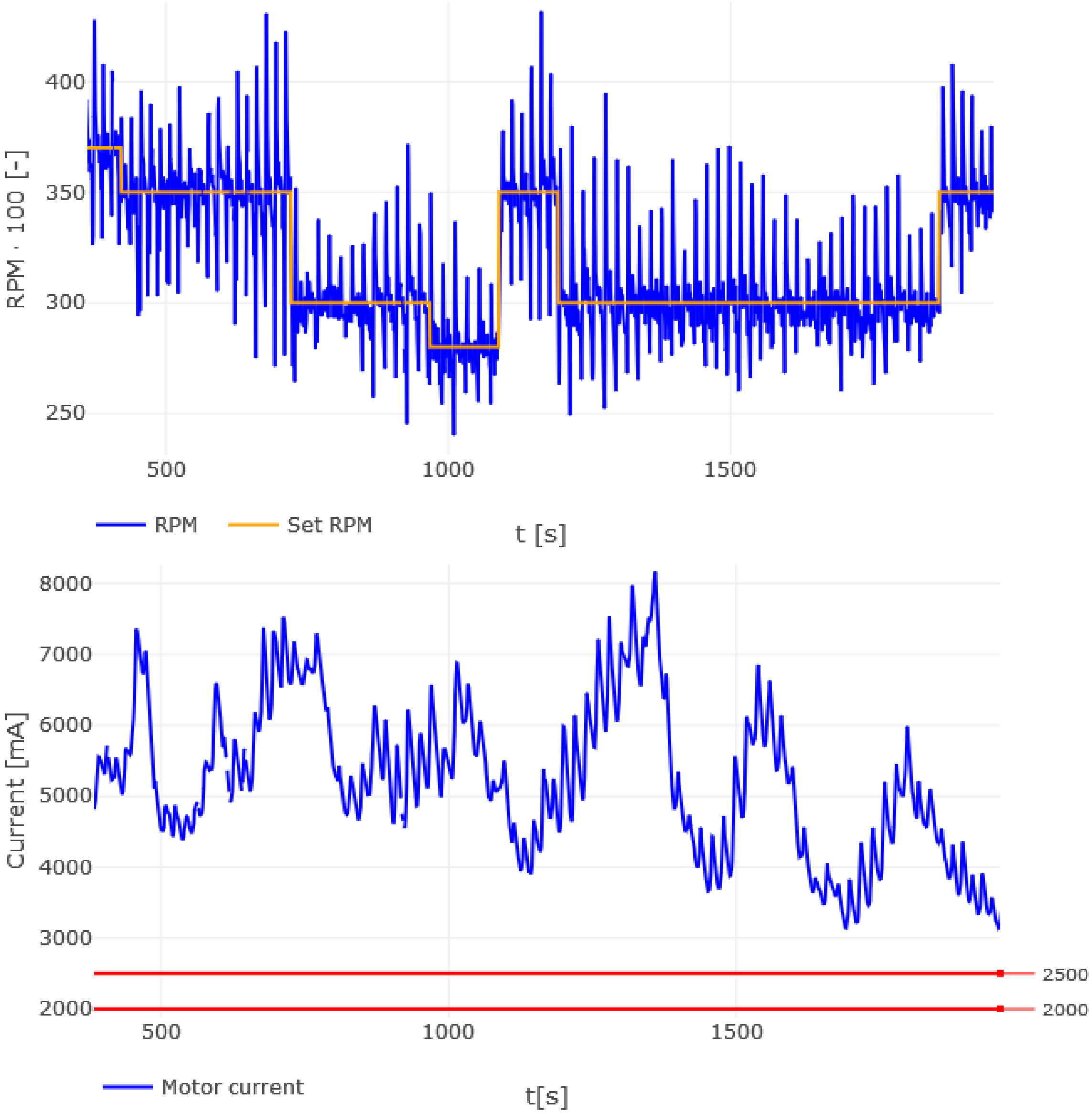

Figure 20. Rotation speed and motor current (Test 1; single extrusion)

Figure 21 shows the results from the first test. Although the filament diameter deviation seems to be within the tolerance limits, upon closer inspection the filament diameter is smaller than intended. The thickness of the filament has an average diameter around 1.5 and 1.6 mm for the most part. As there are no recordings of the spooling due to an error, a too strong pulling force from the winding mechanism of the spooler, is assumed to have caused this issue.

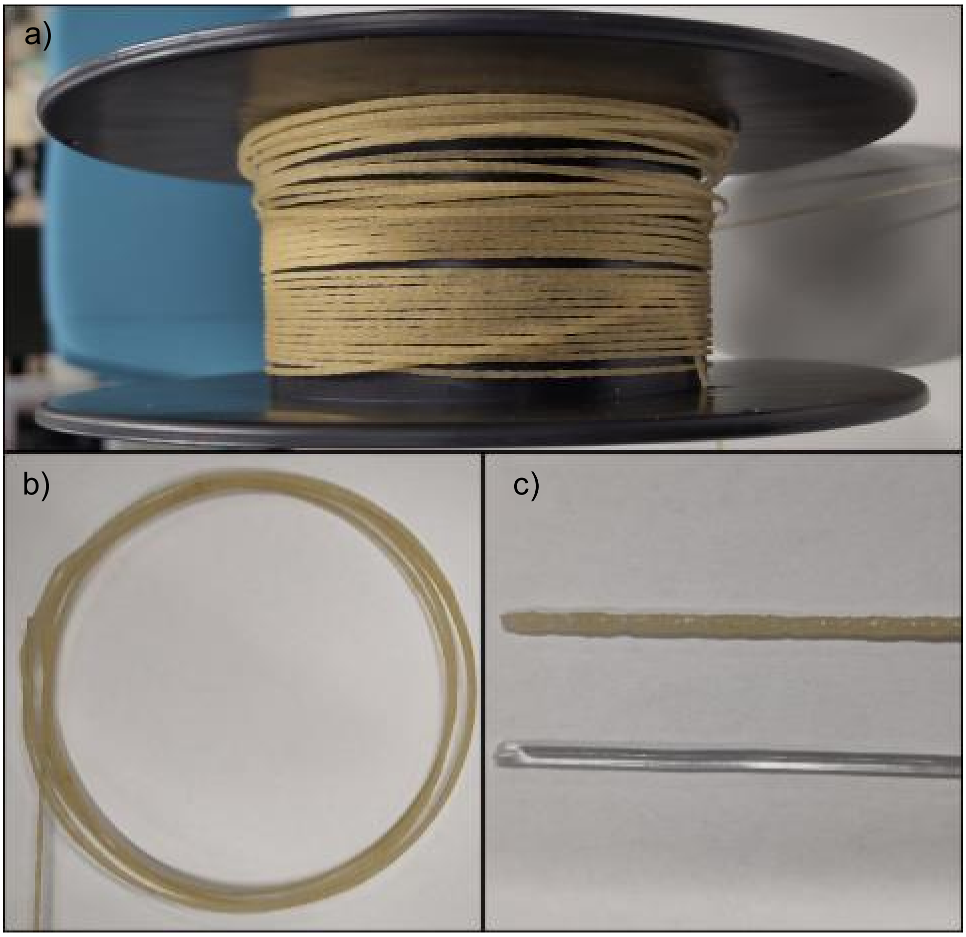

Figure 21. Results of the first test: a) filament after error message; b) first spooling attempt; c) virgin PLA and PLA/spruce wood filament comparison

In the second part of the test, the excess PLA/spruce wood filament, which could not be spooled but safely extruded, was shredded for a second run with the Composer 450. Assuming that the issues in the first attempt failed due to a material blockage at the nozzle, the temperature of heater 1 was initially increased to 175 °C and later to 178 °C. Although the rotation speed could be kept within the tolerance limits, the motor current started to rise to a maximum of 6700 mA and the test had to be stopped. Clumps of half molten material were discovered in the hopper, which suggests a feeding issue.

8.2 Results for pine wood

The first test showed that an increase in the temperature in contrast to the PLA preset, led to an increased motor current and high fluctuation in the rotation speed of the extruder screw, while the output through the nozzle diminishes. It is possible that the volume of the spruce wood additive was too high or that the PLA was not solid enough to push the wood particles effectively, which resulted in a clogging inside the barrel. As to verify, the Composer was set to a lower temperature and an attempt to extrude virgin PLA was conducted. The attempt was successful, and the second test with pine wood dust is being carried out with a lower temperature (see Table 3) and a reduced content ratio of 3% wood dust to analyse the new outcome.

The decrease in operating temperature proved to be the solution to the issues encountered in the first test, and the produced filament could successfully be spooled. The rotation speed stayed within the tolerance limits and the motor current is at a standard operation range around the 2500 mA mark as seen in Figure 22.

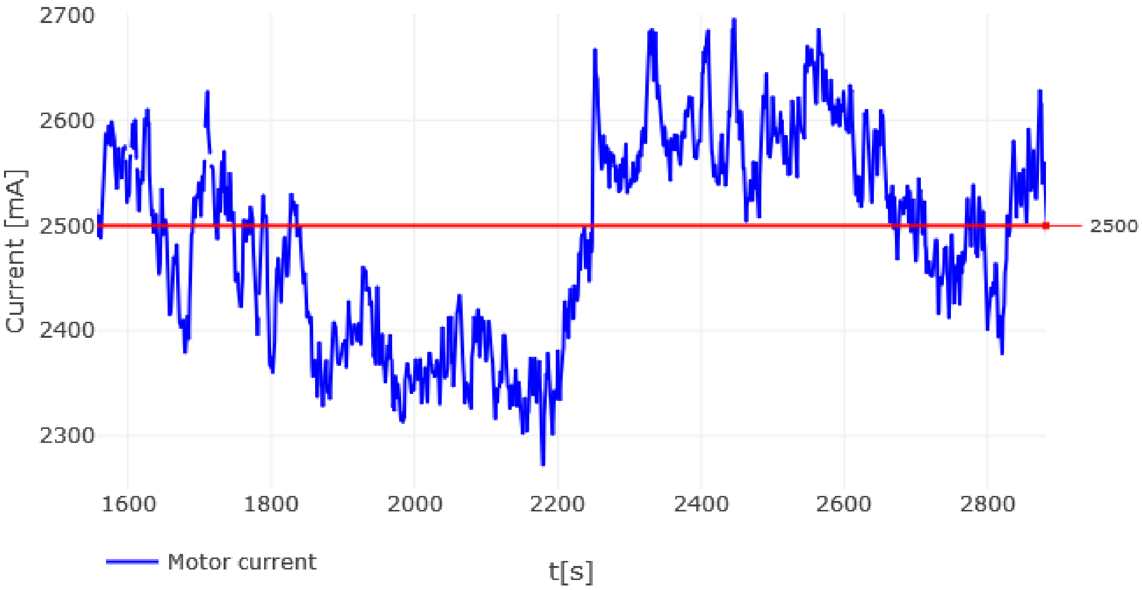

Figure 22. Motor current (Test 2; 3%; single extrusion)

While the average filament diameter is kept stable, small sections of pine wood clumps occurred as darker spots and can be seen in Figure 23. These clumps proved to cause an issue in the 3D printing test, as the printer head struggled to push the filament through the nozzle.

Figure 23. PLA/pine wood 3% filament and closeup of the wood dust chunks

As for the double extrusion, with 3% wood content, the same issues as with the double extruded spruce wood occurred. To counteract the rising motor current, the rotation was lowered from initially 2.8 rpm to 2.5 rpm, but only normalized after the composite material went through the machine and transitioned back to only PLA. It was still possible to extrude and spool enough filament to conduct a printing test. The filament also contained no more signs of wood dust clumps.

As the results for the smaller wood content with lower temperature settings showed a satisfying outcome, a smaller sample size of 20 g composite material with 5% pine wood content was conducted. This test was a major success, as the motor current stayed close to the optimum of 2000 mA, with a stable rotation speed (Figure 24), and no clumps of wood dust were detected in the filament. As there was not enough material for a 3D printing test being extruded, only a small sample was stored and the remaining material was shredded for the double extrusion. The outcome follows the same pattern as for the other double extrusion tests, but as the less material was used, the motor current only peaked up to 3600 mA, before it normalized again in the transition progress to PLA. As the filament diameter fluctuated too strong, no filament could be spooled. There were no signs of difference in coloration between 3% and 5% wood content.

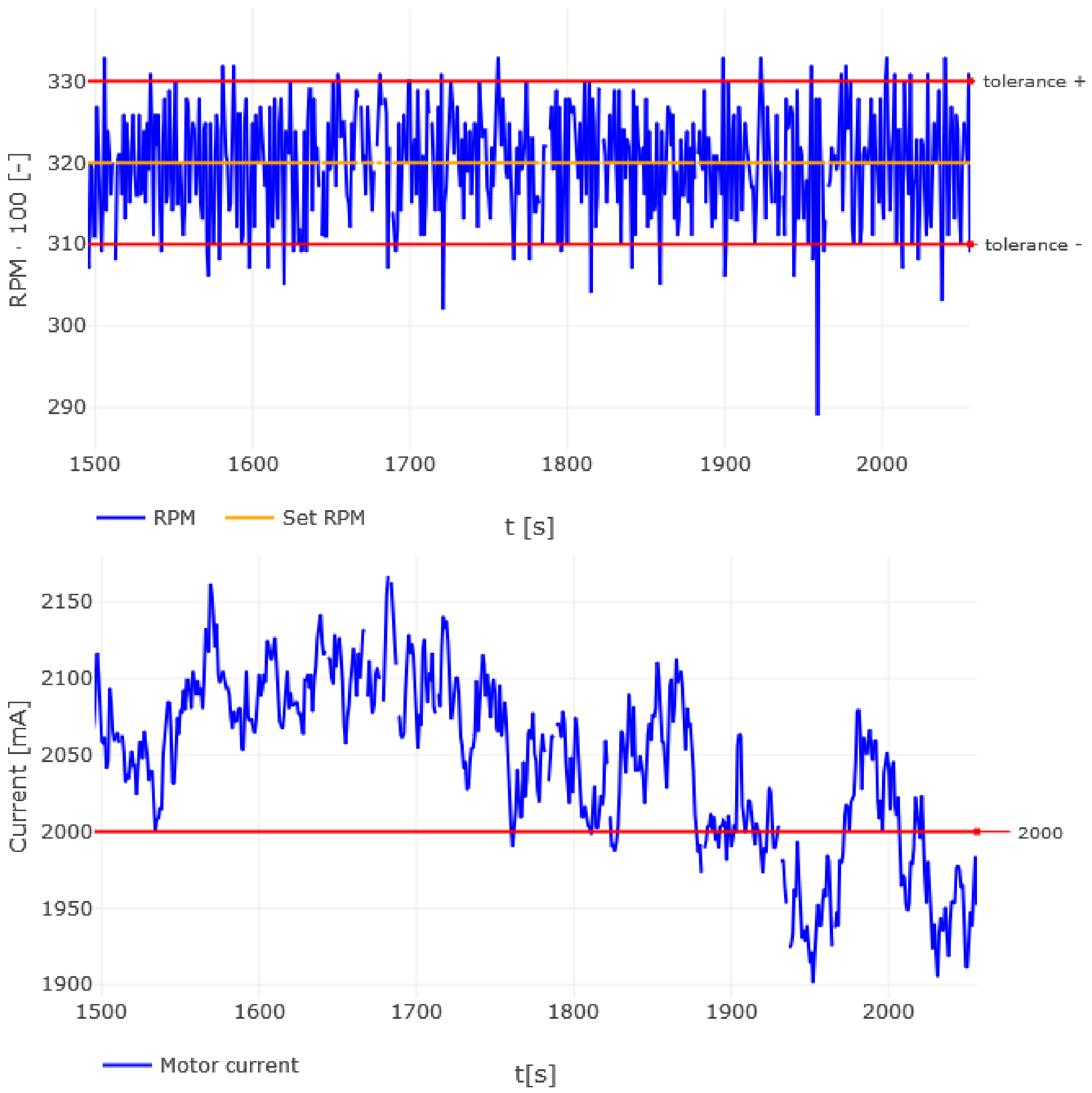

Figure 24. Rotation speed and motor current (Test 2; 5%; single extrusion)

8.3 Results for recycled PLA plus pine wood

As described in the methodology chapter, for this test, a mix of recycled and virgin PLA together with wood dust is being extruded. While transitioning to the composite material, a higher fluctuation in rotation speed and motor current than in previous tests were observed. A decrease in temperature for the heaters 2 and 3 by 5 °C down to 175 °C and 170 °C at the 2250 mark (Figure 25) began to stabilize the extrusion process, although the motor current with an average of 3300 mA stayed above the standard operation value. The filament could nevertheless be spooled in great success, until the outcome became unstable near the end of the test. As the performance in this test was not optimal and considering the results from previous tests, the second part where the excess material is shredded, and a second time extruded was excluded.

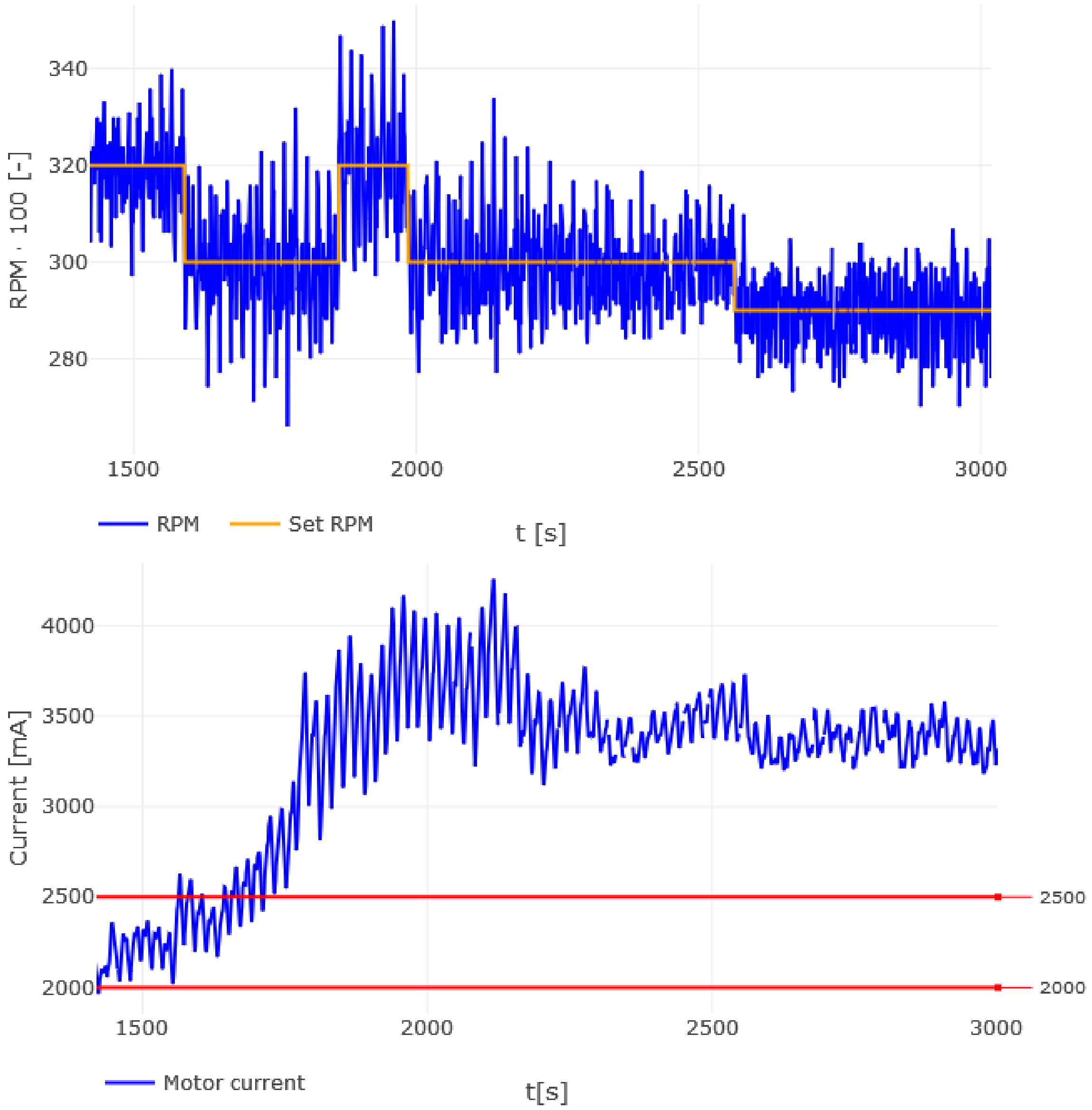

Figure 25. Rotation speed and motor current (Test 3; single extrusion)

The used recycled PLA and the outcome from the extrusion and spooling can be seen in Figure 26. The filament has almost completely taken on the coloration of the recycled PLA, without any visual indication of its wood content, except for the rougher surface.

Figure 26. Recycled PLA on the left and filament from third test on the right

8.4 3D printing results

The extruded and spooled filament from the extrusion attempts were gathered and with each of them a 3DBenchy model was printed. Out of the 8 desired filament rolls, only 4 were available for testing. The double extruded filament with 5% wood content of each spruce and pine wood could not be extruded successfully, the single extruded 5% pine wood filament has not reached the required amount of material and the double extrusion of recycled PLA with 5% pine wood content was not carried out.

As described under the results for spruce wood (chapter 8.1), the filament with 5% spruce wood content is thinner than intended. Despite that, the 3D printer could be loaded with the filament and the printing process was initiated. After the calibration, the process stopped immediately, prompting an unloading and reloading of the filament, due to a filament runout error. This means, the test could not be finished, and the outcome is undetermined.

The printing with the single extruded 3% pine wood filament started without complications and carried on until the clumps enter the printer head. At this point the puller had difficulty to push the filament and the printing had to be paused. The filament was unloaded, the chunk was cut off and the filament was reloaded to the printer. This way the print was carried out until completion with visible missing lines at positions where the print had to be paused.

The doubled extruded 3% pine wood filament was printed without issue until the filament diameter became too thick at the end of the printing process. The single extruded 5% pine wood with recycled PLA filament showed the best results with no difficulties throughout the printing process. Figure 27 shows all the printings with an additional virgin PLA print for comparison. From left to right the used materials are virgin PLA, single extrusion with 3% pine wood, double extrusion with 5% pine wood and the recycled PLA with 5% pine wood.

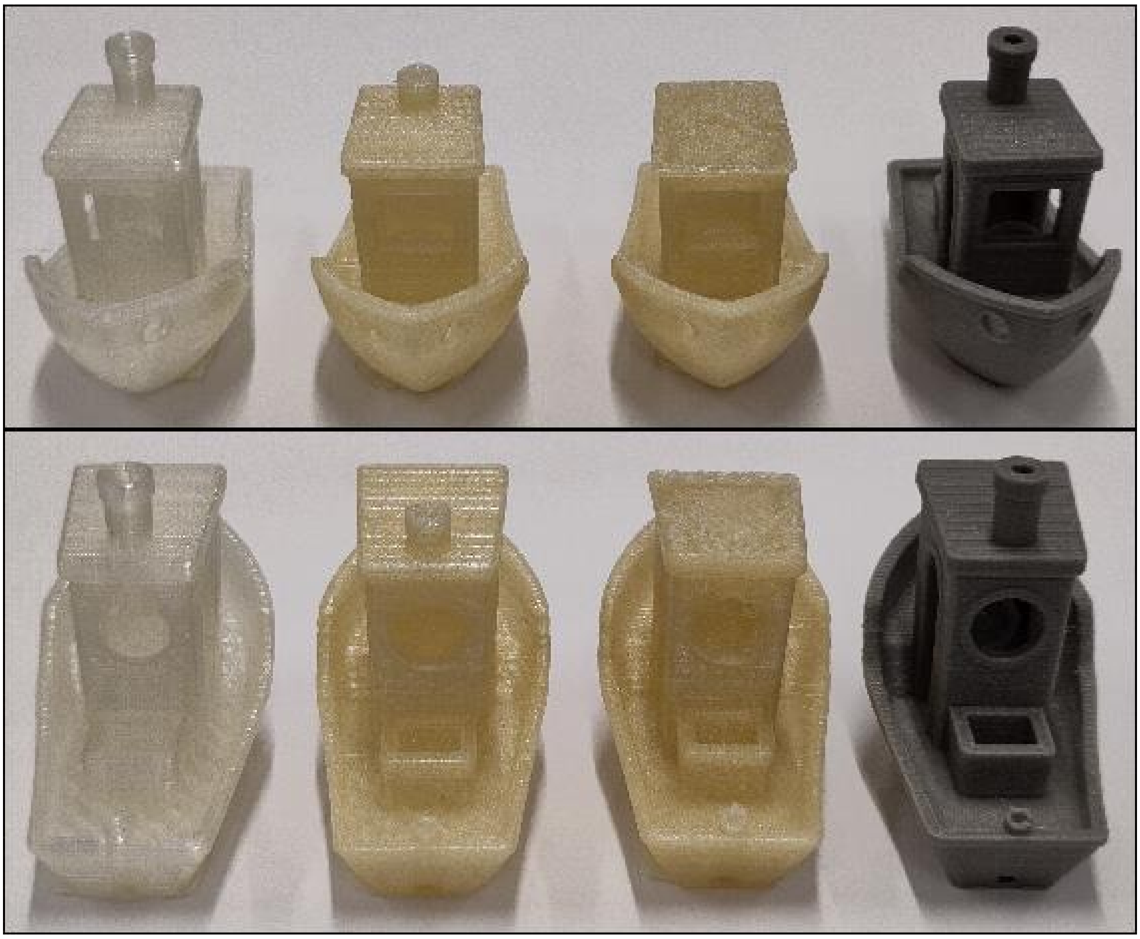

Figure 27. 3DBenchy printing results

9 DISCUSSION

In this chapter, all the findings throughout the process are gathered, summarized, and evaluated. Figure 28 shows the different filament samples, that were gathered during the testing.

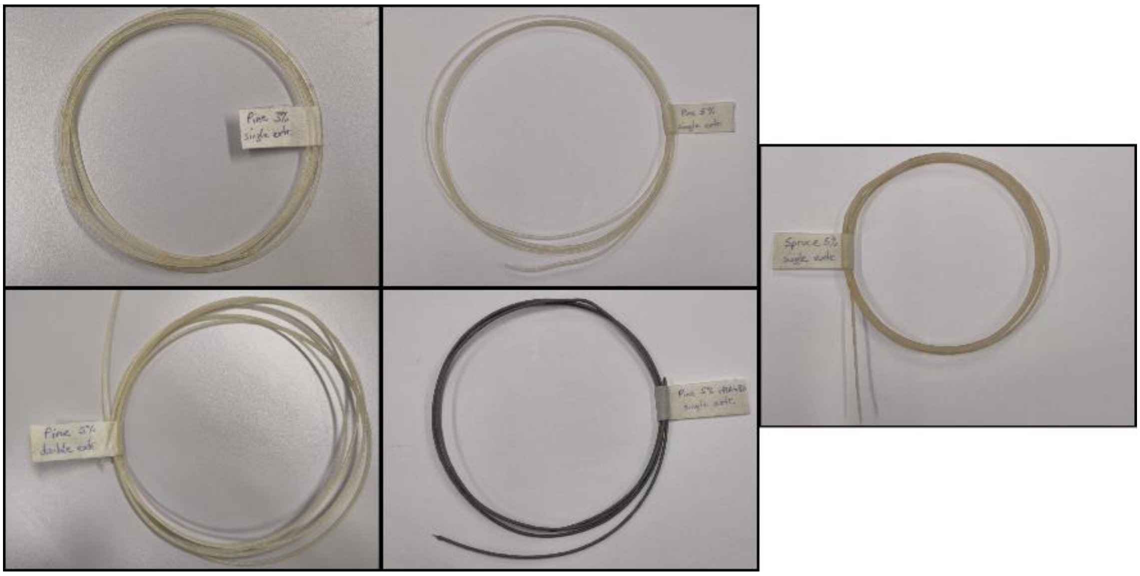

Figure 28. Filament samples

As for the residue wood, the yields of usable wood dust, without additional processing steps, such as grinding it down, are not enough to allow for producing large amounts of wood filled filament. Of the approximately 1340 g of pine wood residue, a total amount of 6.2 g of wood dust was extracted, which amounts to only 0.5% yield. And out of the 870 g of spruce wood, 3.8 g of wood dust was extracted, which amounts to 0.45% yield. Even considering the losses during the finer screening process, supposed they are half of the actual yield, the yield rate would still be under 1%. An increase in the particle size of the wood dust could still be processable, but the risks of clogging the filament maker or the 3D printer would also increase.

The filament making process proved to be a challenge, as the fine-tuning of the machine settings for an optimal outcome takes time and are influenced by various factors. Besides the composition of the material, the geometry of the material also seems to affect the outcome. This was observable in the difference of the single extrusion and double extrusion attempts. The final test with the recycled PLA showed a similar phenomenon. The cause could not be identified, and as the only found study that had the same approach used ABS instead of PLA as main material and has not mentioned any differences for processing, no conclusion can be provided (Huang et al. 2021, 3).

The single extrusion tests showed that the composite material needs to be extruded at lower temperatures compared to virgin PLA. Moreover, this means that virgin PLA has a wider range of operation temperatures than the PLA/wood material. The lower temperature requirement can be explained by a viscosity of the PLA, to be able to transport the wood dust alongside it through the barrel of the machine. If the PLA is too liquid, it could lead to a clustering of wood dust at the beginning of the barrel and would result in feeding issues and difficulties in maintaining a stable rotation speed. This correlates with the findings of the single extrusion spruce wood test. The fact, that lower temperatures are being used, coincides with the goals of a circular economy. The observation is further supported by the findings of the second test with the single extruded PLA/pine wood composite material. The existence of wood dust clumps in the 3% pine wood sample and their absence from the 5% pine wood sample suggest, that an even distribution of the two materials in the feeding process is essential for a satisfying outcome. As the sample sizes for the filament making processes were limited, the long-term implications for the fine-tuning of the Composer 450 could not be estimated. On the other hand, the achieved results indicate that only minor adjustments are necessary for a larger production.

For the optical and surface properties of the filament samples, the addition of wood particles led to a discolouration, although the effect is small and increases with the amount of wood dust used. Between the 3 and 5% pine wood content ratio, no difference in colouration was detected. The spruce wood sample showed a darker colour, as a higher volume of wood dust was being used. As for the recycled PLA, the grey colour of the recycled material dominates, and no signs of the wood colour remain. The surface of the filament samples is rougher than the surface of virgin PLA, which could be felt and observed with the naked eye. Considering this, the surface of the final product did not seem to differ between the virgin PLA and the other composite materials. The composite material filament and the final product took on a more wooden appearance, for the samples using transparent PLA as main material.

An interesting property of the filament diameter was discovered in the printing test. As described in the results for the single extruded 3% pine wood filament, if the filament is too thick, the print will fail as the filament gets stuck in the printer head and no more material leaves the nozzle. On the other hand, if the filament is too thin, the printing will stop automatically, and the printer asks for an unloading and reloading of the filament. After the filament is refilled, the printer continues with the printing. This means, a printing error is more likely to appear with a positive, than with a negative deviation of the filament thickness.

The goal of this thesis was to provide the knowledge on how to produce wood filled PLA filament usable for 3D printing. This goal could not be achieved in its entirety, as the material did not allow for excessive testing. Although the tests for spruce wood mostly failed, with the insight gathered from the subsequent tests, a successful extrusion is possible. The mechanical properties of the wood filled PLA sample in comparison to virgin PLA could be the object of another study.

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